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Evaluating the Link Between Femoral 3D Spatial Torsion and Anteversion Angle via a Stationary Coordinate System

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Abstract: *Background*: Femoral neck anteversion is an important anatomical parameter that plays a major role in the clinical prognosis of interventions in developmental dysplasia of the hip (DDH), internal fixation of femoral neck fractures, and total hip arthroplasty. Conversely, the conventional two-dimensional computed tomography (CT) method, although commonly used clinically, is fundamentally inadequate to accurately resolve the complicated three-dimensional torsional anatomy of the femoral neck, thereby affecting the accuracy and reproducibility of measurements. *Objective*: This study compared 3D and Reikeras 2D techniques of femoral neck anteversion based on a fixed 3D coordinate system, evaluating reliability, method-specific variations, and the effect of torsion on deviation magnitude. *Methods*: We retrospectively reviewed CT data from 63 patients. Through axial cross-sectional image superimposition, we mapped the safe screw trajectory precisely. A fixed spatial coordinate system was then built to quantify femoral neck torsion and anteversion, with parallel 2D measurements completed using the Reikeras method. To assess reliability, we determined the intraclass correlation coefficient (ICC), used paired t-tests to compare 3D and 2D measurement results, and applied Pearson correlation analysis to investigate how torsion angles correlate with anteversion measurement errors. *Results*: The angle of femoral neck anteversion obtained using the fixed-coordinate 3D method was statistically significantly different compared to the results of the traditional 2D method ($P < 0.05$). The 3D method had better intra- and inter-rater reliability (ICCs of 0.96–0.98) as compared to the 2D method (ICCs of 0.72–0.82). Moreover, the difference in the angle of anteversion between the two techniques showed a significant positive relationship with femoral neck torsion ($r = 0.72$, $P < 0.001$), whereas torsion only showed a weak correlation with absolute measurements of anteversion angles (all $r < 0.2$). *Conclusion*: The 3D measurement technique is based on a fixed spatial coordinate system, which overcomes the drawbacks of conventional 2D methods and provides reliable measurements of femoral neck anteversion. This technique is extremely useful for pre-operative planning in complex hip reconstruction procedures.

Keywords: Femoral neck torsion; Assessment of anteversion; Three-dimensional measurement; Fixed reference frame

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1. Introduction

The anatomical shape of the femoral neck is crucial for the evaluation and treatment of hip diseases [1,2]. Accurate measurement of femoral neck anteversion is of paramount importance, especially in the diagnosis of developmental dysplasia of the hip (DDH), for evaluating reduction of fractures, and for implant positioning in total hip arthroplasty [3–10]. It has been shown that patients with DDH generally have a significantly increased anteversion angle, and the degree of deformity correlates with the magnitude of anteversion deviation, presenting significant challenges for intraoperative femoral reconstruction and implant choice. Furthermore, insufficient restoration of anteversion after total hip arthroplasty has been strongly associated with postoperative complications such as prosthesis impingement, dislocation, and limited range of motion. Moreover, considerable inter-individual differences in anteversion angles, influenced by sex, race, and pathology, highlight the need for individualized, accurate preoperative evaluation. Although imaging techniques like digital radiography (DR) [11,12], computed tomography (CT) [13–18], and EOS imaging [19] are widely used in clinical practice, they are limited by their own drawbacks. In particular, the accuracy of measurements is susceptible to various factors, and variability affects clinical decision-making.

To overcome these limitations, this research exploits real patient CT data to develop a new three-dimensional measurement technique based on a fixed coordinate system [20], and aims to characterize the three-dimensional spatial morphology of anatomical parameters of the femoral neck. The paper revolves around three main objectives: (1) to confirm the reproducibility of this novel 3D approach to measuring the angle of anteversion; (2) to elucidate the quantitative relationship between torsion of the femoral neck and anteversion; (3) to identify the causes of measurement errors in traditional 2D methods.

2. Materials and methods

2.1. Study population

The population of the study will consist of 100 students who will be randomly selected. Sixty-three patients were included in a retrospective study who had simultaneous CT scans of the femur and knee. Patients needed to have normal imaging results and intact anatomy to be eligible. The exclusion criteria included previous fractures, surgery, developmental abnormalities, osteoarthritis, bone tumors, or any apparent pathological alterations.

2.2. The imaging protocol

A Siemens SOMATOM Perspective 64-slice spiral CT scanner (Siemens Healthineers, Germany) was used to capture imaging data with the following scanning parameters: tube voltage of 130 kVp, effective tube current-time product of 106 mAs, reconstruction matrix of 512×512 pixels, and slice thickness of 1 mm. After acquisition, three-dimensional volume rendering was done on the Syngo Acquisition Workplace post-processing station to produce standardized multiplanar reconstruction images. In this study, the reference planes were defined as follows: the axial plane was defined perpendicular to the central axis of the femoral neck; the sagittal plane was parallel to the longitudinal axis, whereas the coronal plane was perpendicular to it, intersecting the centroid of the femoral neck.

2.3. Coordinate system and definition of a safety passage

Procedure for defining the safe target area: Axial CT scans of the femoral neck of each hip specimen were imported into Adobe Photoshop to process the images. Image slices were superimposed and aligned consecutively without altering their original spatial orientation. Regions that were not common between successive slices were eliminated in a systematic manner, and only the common region shared by all the slices was kept (**Figures 1A–D**). Once layer-by-layer superposition of the whole series of axial images of the femoral neck was done, the overlapping area that was obtained was termed the Axial Safe Target Area (ASTA), which is the best path to place the screw.

Establishment of coordinate system: A two-dimensional Cartesian coordinate system (YOZ) was created with the basal edge of the triangular ASTA used as the reference plane. The Y-axis in this coordinate system is parallel to the base of the triangle, and point O is considered the origin (**Figure 1D**). The X-axis was positioned along the middle longitudinal axis of the femoral neck (**Figure 1E**). These axes were integrated to create a full three-dimensional Cartesian coordinate system (XOYZ), which gives a precise spatial reference for surgical navigation (**Figure 1F**).

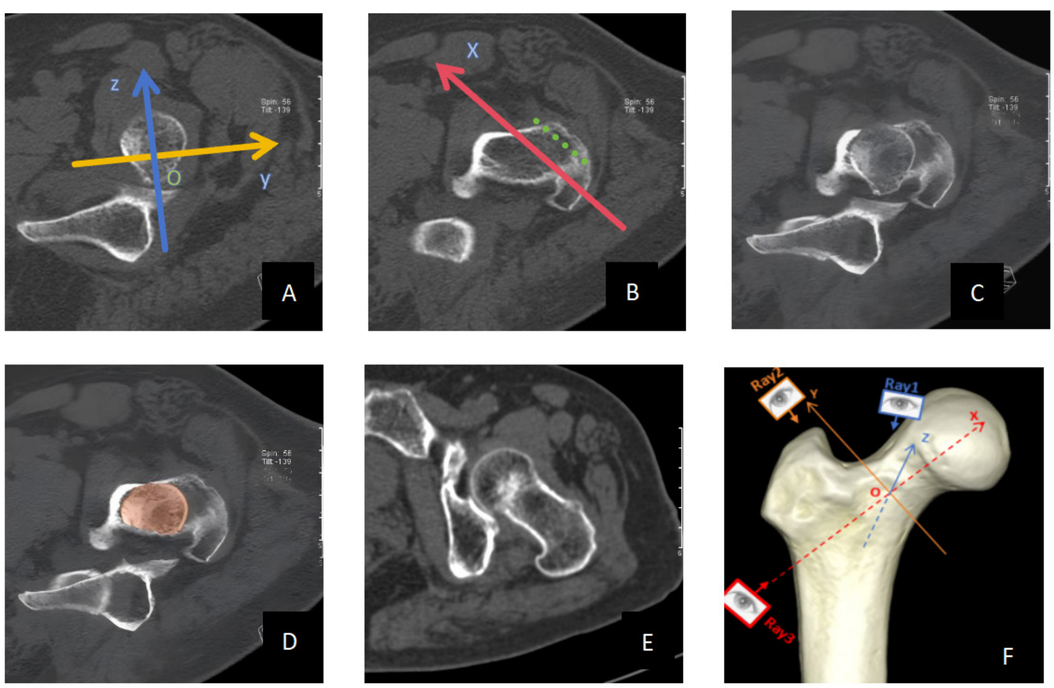

Figure 1. Definition of the safe target zone and space coordinate system. (A) First cross-sectional section of the femoral neck. (B) Next slice of the femoral neck. (C) Co-registration of panel (A) and panel (B). (D) The intersection of the orange-shaded areas is the Axial Safe Target Area (ASTA). Coordinate system: Y-axis is parallel to the anterior cortical surface of the femoral neck, Z-axis is perpendicular to this cortex, and O is the origin. (E) Reference frame construction: X-axis (red solid arrow) corresponds to the anterior femoral neck cortex (green dashed line). (F) Volume-rendered (VR) reconstruction of the study-specific coordinate system.

2.4. Angle measurement

The conventional two-dimensional method measures the angle of anteversion as the angular difference between the axis of the femoral neck and the condylar axis, with the former being defined as the line segment joining the geometric center of the head of the femur to the midpoint of the base of the femoral neck [20] (**Figures 2A–C**).

The 3D method quantifies the angle with respect to the X-axis and the line connecting the medial and lateral femoral condyles (**Figure 2D**).

The femoral neck torsion angle: the angle between the anterior cortical surface of the proximal femur and the Y-axis (**Figures 2E–F**).

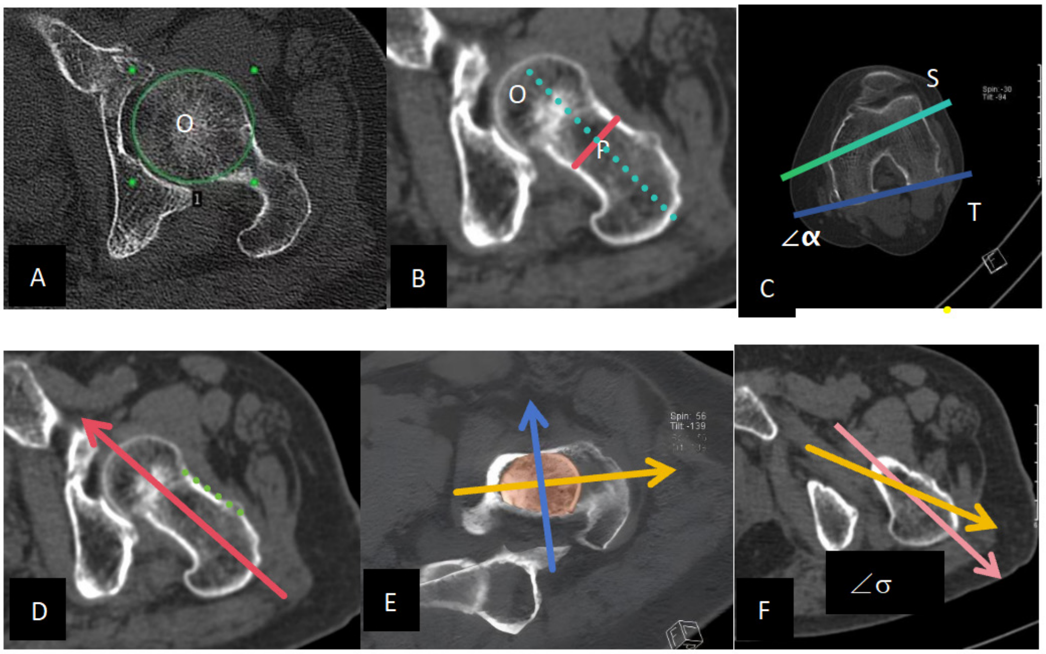

Figure 2. Femoral anteversion evaluation using Reikeras method. (A) O is the geometric center of the femoral head, which is determined on the cross-sectional slice with the largest diameter of the femoral head. (B) Point P is the middle point of the isthmus of the femoral neck. In this case, point O is the orthogonal projection of the center of the femoral head (which can be obtained by taking the slice with the greatest diameter) onto the isthmus plane; the cervical axis S is then defined as the straight line between points O and P. (C) Femoral anteversion calculation using the Reikeras method: angle α is used to determine the angular deviation between the cervical axis S and condylar axis T. (D) The X-axis is parallel to the anterior cortical boundary. (E) Coordinate system definition: the Y-axis is aligned with the anterior cortex of the femoral neck, and the Z-axis is at right angles to this reference plane. (F) This step quantifies the angle between the coronal central axis N of the proximal femoral plane and the Y-axis that defines the safe target zone.

2.5. Statistical analysis

SPSS version 26.0 was used to perform analyses. Once the normality of the data distribution was confirmed, paired or two-way repeated-measures ANOVA was used to measure the differences between the two measurement methods. $P < 0.05$ was considered significant. The intraclass correlation coefficient (ICC) was obtained based on a two-way mixed-effects model to determine reliability. The levels of reliability were stratified as follows: ICCs above 0.75 were considered high, between 0.40 and 0.75 were moderate, and below 0.40 were low. Moreover, Pearson correlation tests were conducted repeatedly to examine the relationship between the femoral torsion angle and the femoral anteversion angle, and the strength of the relationship was determined by the R coefficients obtained.

3. Results

3.1. Results of FNAA and femoral torsion angle measurement

The mean values of the femoral anteversion angles measured through the anterior cortex-based coordinate system at the base of the femoral neck and Reikeras method were 15.9 ± 6.1° and 13.6 ± 6.2° respectively; the femoral torsion angle was 13.5 ± 3.7°. There was a statistically significant difference between the two methods of measurement ($P < 0.05$) and the results are detailed in **Table 1**.

Table 1. Femoral neck anatomical parameters measurement

Items	Anterior femoral cortical-based method within 3D-R-FCS	Reikeras	Torsion angle
Range	6.8–38.3	4.2–35.3	7.6–24
Mean	15.9	13.6	13.5
Standard deviation	6.1	6.2	3.7
P	0.03	-	-

3.2. Intra- and inter-rater reliability of the measurement method of femoral neck anatomical parameters

In the case of Evaluator A, intra-rater reliability between the first and second measurements provided intraclass correlation coefficients (ICCs) of 0.98 (95% CI: 0.96–0.99) with femoral anteversion measured by the 3D method, 0.82 (95% CI: 0.74–0.90) with femoral anteversion measured by the Reikeras approach, and 0.97 (95% CI: 0.95). In this regard, Evaluator B showed intra-rater ICCs of 0.97 (95% CI: 0.95–0.98) with the 3D-based femoral anteversion, 0.76 (95% CI: 0.68–0.84) with the Reikeras method, and 0.96 (95% CI: 0.92–0.99) with the torsion angle. Inter-rater agreement between the two observers, evaluated using ICCs, was very good in all three parameters with values up to 0.99 (95% CI: 0.98–0.99), 0.83 (95% CI: 0.75–0.92), and 0.98 (95% CI: 0.96–0.99) respectively, as summarized in **Table 2**.

Table 2. Intra- and inter-rater reliability tests among raters who use different methodologies

Items	ICC (Evaluator A)	ICC (Evaluator B)	Inter-evaluator ICC (A vs. B)
Anterior femoral cortical-based method within 3D-R-FCS	0.98 (95% CI: 0.96,0.99)	0.97 (95% CI: 0.95,0.98)	0.99 (95% CI: 0.98, 0.99)
Reikeras	0.82 (95% CI: 0.74, 0.90)	0.76 (95% CI: 0.68,0.84)	0.82 (95% CI: 0.75,0.92)
Torsion angle	0.98 (95% CI: 0.95,0.99)	0.96 (95% CI: 0.92,0.99)	0.98 (95% CI: 0.96,0.99)

3.3. Pearson correlation analysis

The torsion angle showed a significant positive correlation with the difference in measurements obtained by the two methods ($r = 0.72$), but showed no significant linear relationship with the anteversion angle measured using either the three-dimensional ($r = -0.13$) or the two-dimensional method ($r = -0.21$). See **Figure 3**.

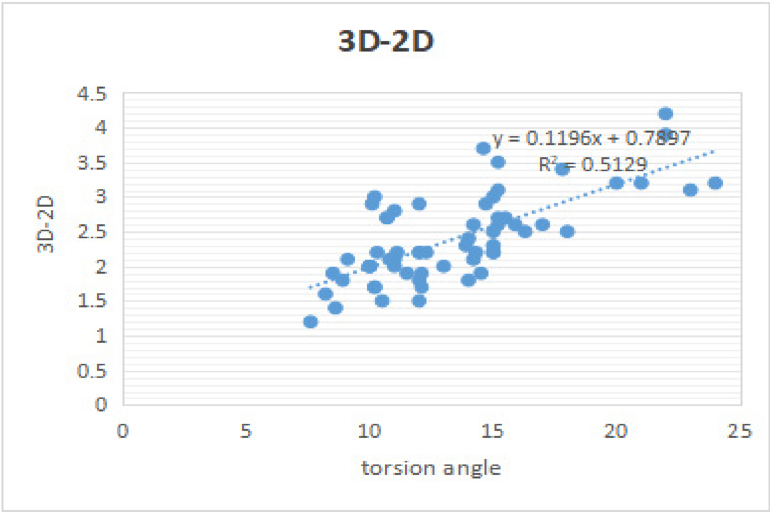

Figure 3. The X-axis is the mean torsion angle, and the Y-axis is the difference in femoral anteversion angles between 3D and 2D measurements.

4. Discussion

The correct measurement of the femoral neck anteversion angle has an indispensable central role in clinical diagnosis of hip diseases, development of individual surgical strategies, and scientific evaluation of postoperative results. In the meantime, since one of the major indicators of the anatomical position of the proximal femur is the femoral torsion angle, accurate measurement of this parameter is also crucial to clinically determine biomechanical imbalance in the hip joint and maximize the implantation angle of internal fixation devices. These two parameters constitute a vital anatomical foundation of diagnosis and treatment of hip disorders.

Traditional measurement methods include digital radiography (DR), computed tomography (CT), and EOS imaging systems. While plain X-ray films are easy to use, they cannot provide an accurate measurement of the femoral torsion angle. Moreover, their measurements are easily influenced by various factors such as different patient positions, femoral rotation, projection geometry, and subjective interpretation of the observer, which makes the coefficient of variation of the measurement data very large. More critically, these approaches cannot avoid the influence of abnormal femoral torsion angles on the measurement of femoral neck anteversion angles, which further increases the error in measuring the anteversion angle [11,12]. EOS imaging has verified that it is possible to measure femoral parameters (such as the femoral torsion angle under full-weight-bearing conditions of the whole body [19]; however, because of the low penetration rate of this equipment in China, there are still many challenges in its clinical application. Conventional CT scanning has enhanced the accuracy of measurements to some degree [13–17], but its reconstruction principle based on discrete two-dimensional slices cannot completely restore the spatial anatomical features of the femoral torsion angle, nor can it fundamentally eliminate the spatial projection error due to the inherent torsion of the femoral shaft itself. This not only leads to bias between different research groups, but also directly impacts clinical decision-making, ultimately resulting in a substantial bias in anteversion angle measurement due to the lack of femoral torsion angle measurement [18].

The three-dimensional measurement technique that was created in this paper, which is founded on a fixed spatial coordinate system, has great benefits in reliability and accuracy and completely fulfills clinical needs for accurate quantification of core anatomical parameters of the proximal femur, the femoral neck anteversion angle and the femoral torsion angle. This method provides an overall reconstruction of the anatomical structure of the proximal femur at the three-dimensional level with a unified and stable spatial coordinate system as the reference frame. Not only does it fundamentally remove systematic errors inherent to two-dimensional measurements, including those introduced by deviation in projection angle, overlapping anatomical landmarks, and patient positioning changes, to allow the accurate quantification of the femoral neck anteversion angle, but also concurrently captures the spatial features of the femoral torsion angle with high accuracy. This method entirely eliminates the confounding effect of abnormal femoral torsion angle on the measurement of femoral neck anteversion angle, and is more in line with the actual spatial anatomical morphology of the proximal femur. This conclusion is also supported by evidence of past literature: the values of the femoral neck anteversion angle of healthy populations measured using the three-dimensional CT technology are very similar to the ones ($15.9 \pm 6.1°$) measured in the present study, which confirms the scientific soundness and accuracy of this approach completely, and offers a valid solution to the clinical issue of measurement bias in the evaluation of anteversion angle due to femoral torsion angle.

This research used real-world patient cohort data to validate the clinical usefulness of the three-dimensional measurement model based on a fixed coordinate system for the first time in China. Based on multi-dimensional comprehensive analysis such as reliability and validity analysis, correlation analysis, and error tracing, it verified the significant benefits of this model, providing a reliable basis for the accurate measurement of femoral neck anatomical parameters.

4.1. The high level of reliability and validity of the 3D measurement model underscores its benefits in terms of accuracy and stability

The 3D measurement plan that was created in this paper, which is founded on the safe target region and fixed coordinate system, has proven to be reliable and valid much more than the conventional methods. Its intra-rater and inter-rater ICC values are as high as 0.98 and 0.99, respectively, compared to the traditional methods whose ICC values range between 0.72 and 0.82. These findings intuitively illustrate the absolute advantage of the 3D model regarding the stability of measurements.

This benefit is based on three fundamental design features: first, the use of CT image overlay to automatically define the safe target region, thus entirely removing the subjective influence of manual outlining and providing objectivity in data; second, the use of well-defined anatomical landmark points to define the coordinate system, which ensures spatial consistency of the measurement plane and removes errors due to variations in patient positioning or surgical technique; third, direct derivation of the midline axis based on the coordinate system, which essentially eliminates interference by factors of femoral torsion.

This design not only accurately examines the spatial coupling relationship between torsion angle and anteversion angle, but also allows for accurate measurement of anatomical parameters, laying the groundwork for individualized surgical planning and screw trajectory optimization, while minimizing the risk of complications such as cortical penetration. As found in previous studies, the measurement model based on the fixed coordinate system is more consistent and reproducible than traditional methods; moreover, this model overcomes the major drawback of traditional methods—that is, failure to consider the effect of torsion angle interference— leading to better reliability and validity performance.

4.2. Spatial correlation analysis of the torsion angle and anteversion angle: Explaining the cause of two-dimensional measurement biases

The correlation analysis shows that the anteversion angle and the torsion angle measured directly using a fixed coordinate system are only weakly correlated (all R-values <0.2), which means that there is no linear relationship between the two variables. The most important result, however, is that the difference between three-dimensional measurement values and those measured by traditional two-dimensional techniques is significantly positively correlated with the torsion angle ($r = 0.72$, $P < 0.001$), and this clearly indicates that the torsion angle is the key variable that causes two-dimensional measurement biases.

These findings reveal the fundamental flaws of the traditional two-dimensional measurement techniques: these conventional methods entirely disregard the spatial distribution properties of the femoral neck torsion angle and do not address the influence of torsion on the construction of the neck axis; even when the actual anatomical value of the anteversion angle is not affected by torsion, variations in the construction of the neck axis can still result in measurement distortion. This paper employs a three-dimensional model to accurately capture this relationship, thus unraveling the cause of two-dimensional measurement biases from a spatial perspective and providing a critical basis for understanding the mechanisms behind measurement errors. This is one of the fundamental benefits that are not fully covered by the majority of current research.

4.3. Tracing the error sources of conventional two-dimensional measurements and demonstrating the error-correction value of three-dimensional models

This paper also elucidates the error processes that are inherent in conventional two-dimensional measurements. Using the Reikeras method as an example, the neck axis is created by joining the midpoint of the narrowest part of the femoral neck to the center of the femoral head. But the femoral head is not a perfect sphere, and when the femoral neck is under torsional conditions, the geometrical center of the femoral head moves relative to the central axis of the femoral neck. Proximal femoral torsion causes displacement of the femoral head: the larger the degree of torsion, the more pronounced the downward displacement of the proximal center point with respect to the center of the femoral head. This results in tilting of the neck axis medially and eventually results in underestimating the anteversion angle. Although past researchers have observed that the traditional two-dimensional techniques are prone to interference due to manual operation, no one has been able to systematically include the interfering effect of torsion angle on the construction of the neck axis. Conversely, this paper correctly identifies the fundamental cause of this error, which is the fundamental strength of three-dimensional models: it locks anatomical structures into a fixed coordinate system, eliminating the torsion interference in constructing the neck axis, fundamentally addressing the measurement distortion issue of conventional methods, accurately reconstructing the anatomical parameters of the femoral neck, and offering a standardized and reliable solution to clinical measurement.

Even though the sample size of this study ($n = 63$) is sufficient to provide statistical power, it is still necessary to increase the sample size to a multi-center clinical cohort to confirm the generalizability of the results. Also, although we have derived regression equations that explain the effect of torsion angle, detailed analysis of the biomechanical mechanisms involved is lacking. Further studies should aim at creating artificial intelligence-assisted measurement systems in order to achieve fully automated three-dimensional modeling and parameter extraction. Simultaneously, the creation of large-scale anatomical databases will facilitate the creation of individual medical device design and precision medicine.

5. Conclusion

This experiment, which was conducted in a three-dimensional coordinate system, systematically compared and verified the differences and reliability of measurements of femoral neck anteversion angle using the three-dimensional method and the Reikeras two-dimensional method. The findings indicate that the three-dimensional technique is much more accurate and repeatable. Moreover, this research was the first to determine the femoral neck torsion angle as a fundamental cause of measurement deviation in the two-dimensional approach. This study met the predetermined research objectives; the results can be used quantitatively to support clinical diagnosis, treatment, and prosthesis fitting, lay the groundwork to develop a standardized measurement protocol, and open the door to future studies to increase sample size, incorporate artificial intelligence, and further enhance the clinical usefulness of this procedure.

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Disclosure statement

The authors declare no conflict of interest.

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