Comparison of Femoral Offset Measurement Accuracy between Three-Dimensional-CT and X-ray in Developmental Dysplasia of the Hip Patients and Normal People

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Research article

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Abstract

Background: Femoral offset (FO) is essential for the guidance of prosthesis choice in the Total Hip Arthroplasty (THA). In current clinical practice, X-ray is the primary method to measure FO. However, the X-ray measurement of FO has low accuracy, especially for DDH. In this study, three-dimensional (3D)-CT was conducted to provide more accurate measurements.

Methods: 3D-CT and X-ray measurements of FO from 55 DDH patients and 60 normal volunteers were conducted twice by two osteoarticular surgeons. The inter- and intra-observer reproducibility was analyzed by intraclass correlation coefficient (ICC). The FO values measured by 3D-CT and X-ray were compared and the absolute value of the difference was recorded as the error value of X-ray. These values were analyzed by paired-sample t-test, independent-sample t-test and Dunnett's t-tests, $p < 0.05$ was considered to be significant.

Results: Significant differences were founded between 3D-CT and X-ray in the FO measurements, the absolute values of these differences were 5.42 ± 4.66 mm in DDH patients and 3.74 ± 2.80 mm in normal people, which was regarded as the X-ray error values. According to 3D-CT measurement, the FO value of DDH patients (including Hartofilakidis-I, II, III) was lower than that of normal people. The FO value of Hartofilakidis-II DDH patients was lower than that of Hartofilakidis-I patients.

Conclusion: 3D-CT is more precise than X-ray in the measurement of FO in DDH patients and normal people. The 3D-CT method should be recommended to measure FO for the choice of prosthesis in DDH patients before THA.

1. Introduction

Developmental dysplasia of hip joint (DDH) is a common congenital malformation. The primary clinical manifestation of DDH is the loss of the ordinary relationship between the femoral head and the acetabula in the joint capsule, which leads to the abnormal development of hip joint both before and after birth (32). Total hip arthroplasty (THA) is one of the most preferred therapeutic methods of later stages of DDH in adults. FO is the vertical distance from the center of the femoral head to the anatomical axis of the femur. Both large and small postoperative FO could lead to adverse effects on postoperative hip function and prosthesis conditions, such as low abductor muscle strength, reduction of hip abduction range, gluteus medius gait, increased wear of the prosthetic polyethylene liner, loosening of prostheses, postoperative hip pain, etc. To provide reference for the choice of the prosthesis and restore the reasonable postoperative FO, it is necessary to accurately measure the femoral offset (FO) before THA (3; 7). Overestimate or underestimate of FO would induce various negative effects postoperatively.

X-ray is the primary method to measure FO in the current clinical practice due to its excellent accessibility, low price and low dose (10). However, FO could be either underestimated owing to the femoral anteversion or overestimated due to the divergence of X-ray beams (29)(Fig.1). Previous studies had observed these errors. In the cadaveric study of Weber M *et al,* the error of X-ray was calculated as 1.4 ±

5.2mm (33). Pasquier G *et al* found that the error of X-ray was 3.28 ± 4.11mm in osteoarthritis patients (22).

Under these circumstances, some researchers had developed new methods for the measurement of FO in recent years. In the studies of Weber M *et al*、Sariali E *et al* and Merle C *et al,* the coordinate systems were established and the landmarks were determined based on CT scanning. Afterward, the FO value was calculated by the formulation (19; 27; 33). Benjamin G et al and Jean Y et al measured FO by utilizing the empirical database of the French EOS imaging system (1; 8). These methods had some limits such as complex operation, low calculation speed, poor representation of landmarks, low popularization rate, the high financial burden on patients and dependency on the empirical database. To avoid the above limits, the 3D measurement of FO conducted by Mimics software may be more accurate than the X-ray method and briefer than CT and EOS methods.

For the sake of the precise measurement method of FO, the 3D measurement was conducted by Mimics software 21.0 (Materialise Inc., Belgium) in this study. The center of the femoral head and the axis femur was best-imitated the actual femoral head center and femur axis. Hence the FO measurement accuracy of it could be higher than 2D method, such as X-ray, CT and EOS measurement. Besides, the measurement error of X-ray in DDH patients would be more significant than that in normal people, as a result of the abnormal development of the femur and the larger torsion angle (14). Thus, this study aimed to statistically compare the error of X-ray measurement between DDH patients and normal people to provide reference for the further research of FO measurement.

2. Materials And Methods

2.1 Patients collection

The study was under the ethical standards laid down in the 1964 Declaration of Helsinki. This study was approved by the Ethics Committee of our hospital. Informed consent was obtained from all patients enrolled in the research and their families. Clinical information of all participants was kept confidential to respect and protect individual privacy. In this study, CT-scan and X-ray data were obtained from 55 DDH patients and 60 normal volunteers. All affected hip joints in DDH patients were classified into the DDH group, all hip joints in normal volunteers were classified into normal group. According to the classification of Hartofilakidis, the affected hip joints of the DDH group were divided into Grade-I subgroup, Grade-II subgroup and Grade-III subgroup, based on clinical radiodiagnosis. The sample sizes of all groups are 110 hips in DDH group (include 29 hips in Grade-Ⅰ subgroup, 45 hips in Grade-Ⅱ subgroup and 13 hips in Grade-Ⅲ subgroup) and 120 hips in the normal group.

2.2 X-ray measurement:

X-ray measurement was conducted by two orthopedic surgeons and the measurements were repeated twice by each of them. FO was generally defined as the distance from the rotation center of the femoral head to the long axis of the femur (11). After the X-ray data was obtained, X-ray image was imported into the Digimizer Software (MedCalc Software bvba Inc., Belgium) for FO measurement. The centerline of the medullary cavity was created as the long axis of the femur and the center of the best-fitted circle of the femoral head was drawn as the rotation center of the femoral head. The vertical distance from the auxiliary point to the extra line was regarded as FO (Fig. 2).

2.3 3D-CT measurement:

3D-CT measurement was conducted by the same two orthopedic surgeons and the measurements were repeated twice by each of them. After CT data were imported into Mimics Software 21.0 (Materialise Inc., Belgium), the femur was distinguished from other physical structure based on density differences. Subsequently, 3D reconstruction of femurs was carried out to obtain the 3D model of femurs. Then in the 3D view, the center of auxiliary sphere best-fitted femoral head was created as the rotation center of the femoral head. The three-dimensional midpoint of each cross-section of the femur was extracted to form the center line as the long axis of the femur. Finally, the spatial vertical distance between them was measured as the FO value by the 3D distance measurement function (Fig. 3).

2.4 Statically analysis：

All data of this study were analyzed by SPSS Statistics software 21.0 (IBM Inc., America). After normal distribution test and parameters estimation for all groups were implemented, the intra-observer and inter-observer reproducibility for FO were evaluated by using the intraclass correlation coefficient (ICC) on 3D-CT measurement and X-ray measurement. Subsequently, FO measured by 3D-CT and X-ray were compared with the paired-sample t-test and the absolute values of FO differences between 3D-CT and X-ray were defined as the observational errors of X-ray. The comparison of X-ray errors between DDH group and normal group was conducted by independent-sample t-test. Finally, Dunnett's t-tests were utilized to analyze the FO measured by 3D-CT among different DDH subgroups and normal group. $P < 0.05$ was considered to be significant.

3. Results

The ICC for the intra-observer and inter-observer reproducibility on 3D-CT measurement and X-ray measurement were displayed in Table 1 and Table 2. Significant differences of FO between 3D-CT and X-ray were founded in both DDH group (3D-CT vs. X-ray, 35.68 ± 5.15 mm vs. 33.22 ± 7.60 mm，$p < 0.05$) and normal group (3D-CT vs. X-ray, 41.14 ± 5.22 mm vs. 40.12 ± 6.00 mm，$p < 0.05$). The details are presented in Fig. 4 and Table 3.

The observational errors of X-ray were significantly higher in DDH group (DDH group vs. normal group, 5.42 ± 4.66 mm vs. 3.74 ± 2.80 mm, $p < 0.05$) and the difference value was 1.68 ± 0.50mm. The specific results are described in Fig.5.

The values of FO measured by 3D-CT were 35.68 ± 5.15 mm in DDH group (37.68 ± 5.52 mm in Grade-Ⅰ subgroup, 34.25 ± 5.25 mm in Grade-Ⅱ subgroup and 34.42 ± 4.14 mm in Grade-Ⅲ subgroup) and 41.14 ±

5.22mm in the normal group. The values of FO in the normal group were significantly higher than the DDH group (include Grade-□, □, □ subgroups) ($p < 0.05$). The values of FO in Grade-□ subgroup were significantly higher than Grade-□ subgroup ($p < 0.05$). The details of each group are given in Fig. 6.

4. Discussion

The purpose of the DDH treatment is to reconstruct the normal biomechanical environment of the hip joint, which should be realized by THA (2). However, overestimate or underestimate of FO would be the barrier of the way towards this purpose. THA is the ultimate treatment for DDH patients with old age, severe hip pain and secondary osteoarthritis, whose effectiveness has been widely confirmed. FO is the vertical distance from the center of the femoral head to the anatomical axis of the femur (11). The biomechanical model of the hip joint is a lever and the abductor muscle arm is positively correlated with FO (17). The FO of DDH patients is generally less than that of normal people. Hence the restoration of FO is fatal in THA of DDH patients. Unreasonable FO would have adverse effects on postoperative hip function and prosthesis condition (4; 24).

The underestimate of FO could affect the function of hip. Small postoperative FO directly affects hip abductor muscles. Yamaguchi T *et al* demonstrated that small postoperative FO led to the insufficient lever arm of the hip abductor muscles, which were composed of the gluteus medius, gluteus medius, and tensor fasciae latae, resulting in high abductor muscle load and low abductor muscle strength (34). Moreover, the low abductor muscle strength affects the abduction function of the hip joint. McGrory BJ *et al* observed that the low strength of the abductor muscles and the lack of soft tissue tension due to little postoperative FO together led to a considerable reduction in hip abduction range (17). These changes will lead to gluteus medius gait. The study of Mahmood SS et al described that low abductor muscle strength and hip abduction function caused by small postoperative FO gave rise to insufficient abduction torque support on body weight. The insufficient torque brought out the gait support period to be compensatory tilted to the affected side, that is, the gluteus medius gait (15). At the same time, the injuries caused by small FO not only increase the probability of dislocation of the hip joint towards different directions, but also led to soft tissue collapse which cause pain in the affected hip after THA (13; 23; 31).

These undesirable hip function which was induced by small FO can damage the prosthesis condition as well. In the study of Matziolis G *et al,* changed abduction torque due to small FO led to increased stress between the femoral head and acetabular cup of the prosthesis, resulting in increased wear of the prosthetic polyethylene liner (16). Besides, the loosening of prostheses was also a negative effect of small FO. In the uncemented THA study, Kochbati R *et al* observed that the prosthesis suffered abnormal stress at the prosthesis-bone contact surface when FO is small. The long-term accumulation of this stress resulted in difficulty in bone ingrowth and loosening of prostheses (9).

Compared with the effect of small FO, although large postoperative FO has less negative impacts, the impacts cannot be ignored in clinical practice. Bjordal F *et al* demonstrated that the large postoperative FO caused the abductor muscle and soft tissue long-term stretched, resulting in high tension. The immense tension led to postoperative pain and even affected hip function (2). Abnormal stress direction can cause the loosening of the prosthesis. In the bone cement THA of Harrington M et al ‘s study, large FO caused the stress direction of the prosthesis deviated, resulting in increased stress at the prosthesis-cement interface, leading to early dissociation, prosthesis loosening and even osteolysis. In the uncemented THA of Otani T et al ‘s study, large FO caused stress abnormality at the prosthesis-bone interface, resulting in difficulty of bone ingrowth and loosening of the prosthesis(6; 21). In terms of prosthesis wear rate, the study of Dastane M et al illustrated that when the FO is large, the increased torque caused excessive stress on the interface between femoral head and acetabulum of the prosthesis, increasing the wear of polyethylene liners (5).

In a word, accurate measurement of FO is necessary before THA (3). In this study, compared with X-ray, CT and EOS measurement, the 3D-CT measurement method of this study is not only accurate but also brief, convenient and popularizable. In terms of accuracy，according to the results of this study, a significant difference between 3D-CT measurement and X-ray measurement was found ($p < 0.05$)（2.4% in normal people and 6.9% in DDH patients）, which was caused by different measurement theory. The X-ray method is to find the approximate femoral head rotation center and the approximate femoral shaft anatomical axis on the X-ray film. After measurement of the vertical distance between them, the actual FO is estimated according to the scale on X-ray film. Although X-ray measurement method has excellent accessibility, its low measurement accuracy has been demonstrated by numerous studies (1; 8; 18; 19; 22; 26; 27; 33). That is the reason why X-ray measurement is limited to a two-dimensional plane, which is greatly influenced by the choice of imaging plane and the X-ray beam divergence (20; 30). Briefly, Actual FO is a 3D distance between point and line, but X-ray measurement was conducted on 2D planes to simulate the 3D distance. As mentioned above, FO measure by X-ray could be underestimated or overestimated due to the femoral anteversion and divergence of X-ray beams. Compared with X-ray measurement, CT measurement provides an opportunity to view the femur and pelvis from positive, lateral and axial perspectives, which lead to high accuracy. The methods of Sariali E et al, Pasquier G et al, and Weber M et al were conducted in the same theoretical framework(22; 27; 33). The CT measurement method are still conducted on two-dimensional planes, which lack the intuitiveness of 3D femur reconstruction. Thus, the anatomical features of hip joint and femur cannot be completely restored. Fortunately, these errors could be overcome by 3D-CT measurement. The 3D model reconstructed by Mimics software reproduces the actual shape of the femur based on CT data. The 3D measurement of FO was performed on the stereo model intuitively, which simulate the real FO in the maximum extent, improving the accuracy of the measurement.

For DDH patients, the 3D-CT method has higher measurement accuracy and more considerable clinical significance. From the results of this study, the error of X-ray in DDH patients is higher than that in normal people (1.68 ± 0.50mm, $p < 0.05$). The error rate of DDH patients (the percentage of the error value in the actual value) is 15.19%, while that of normal people is 9.09%. The error rate of DDH patients increased by 67.11% compared with normal people. Therefore, for measurement in DDH patients, the error would be more serious, which is more likely to cause various clinical problems. The reason for this phenomenon could be that the femoral developmental malformation of DDH patients may cause the secondary hipspine syndrome, that is, secondary spinal deformity (12). This deformity increases the angle of torsion in DHH patients compared with normal people, which lead to a greater extent of femoral anteversion, resulting in lower accuracy. Besides, the flat shape of the femoral head in DDH patients is different from the ordinary round femoral head. Therefore it is hard for the auxiliary circle to fit the DDH femoral head, which leads to proximal or distal deviation of the simulant femoral head center, resulting in X-ray error (25). The 3D model reconstructed by 3D-CT measurement directly displays the actual shape of the femur in DDH patients. The center of deformity femoral head can be defined by Mimics software. The choice of landmarks and the measurement of distances are conducted in a 3D perspective, which avoids anatomical distortion in the 2D plane. The 3D-CT method can availably avoid the enormous error of X-ray measurement of FO in DDH patients. Hence, 3D-CT measurement has clinical significance to a certain extent when measuring FO before THA in DDH patients.

In consideration of the superiority of the 3D-CT method in measuring FO, the FO values of DDH patients (including Hartofilakidis-Ⅰ, Ⅱ, Ⅲ) and normal people were compared based on 3D-CT measurements. The FO of normal people was higher than that of DDH patients ($p < 0.05$), indicating a general trend that FO of DDH patients is lower compared with normal people. Additionally, the FO of Hartofilakidis-Ⅰ patients is higher than the FO of Hartofilakidis-Ⅱ patients（$p < 0.05$）. According to the Hartofilakidis classification, this result represented that the FO of simple acetabular dysplasia is greater than the FO of the incomplete dislocation of the hip joint. The probable mechanism of the lower FO value in incomplete dislocation hip joint was shown as follows. The posterior acetabular tilt collides with the femoral neck, resulting in a flat femoral head(28). Flat femoral head shortens the distance from the center of rotation of the femoral head to the anatomical axis of the femur, resulting in a lower FO. Besides, in the previous studies, the absolute value was not used to represent the X-ray error. However, FO obtained from X-ray might be either large or small. Hence directly calculating the mean value would underestimate the error value. In this study, the absolute value was used to represent the X-ray error value, which presents the error more comprehensively. The FO data measured by X-ray and 3D-CT of all groups in this experiment could provide a more accurate reference range for THA preoperative design in Northeast China.

5. Conclusion

In terms of FO measurement, this study illustrated that the 3D-CT measurement method has higher accuracy than X-ray. Additionally, 3D-CT measurement is not only accurate but also brief, convenient and popularizable. Moreover, the error of the X-ray measurement of FO in DDH patients is more significant than normal people. Hence 3D-CT is recommended to measure FO for preoperative design and prosthesis choice in DDH patients before THA.

Declarations

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Conflicts of interest

The authors have no conflict of interest in this manuscript.

Ethics approval

This study was approved by our institutional internal review board (No. 202 in 2018).

Consent to participate

The volunteer enrolled in the study provided written informed consent.

Author's contributions

Qing Han: Methodology, Investigation, Writing-Review & Editing, Funding acquisition; Xinyu Xu: Software, Writing-Original Draft, Formal analysis; Aobo Zhang: Data Curation, Writing-Review & Editing; Bingpeng Chen: Conceptualization, Funding acquisition; Yanguo Qin: Supervision, Writing-Review & Editing; Jincheng Wang: Resources, Project administration, Funding acquisition.

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Tables

Table 1 Intra-Observer and Inter-Observer Reproducibility (ICC) of Femoral Offset for 3D-CT

	DDH	Normal	Grade-[illegible]	Grade-[illegible]	Grade-[illegible]
Intra-observer	0.950 (0.924-0.967)	0.932 (0.904-0.952)	0.924 (0.845-0.964)	0.978 (0.961-0.988)	0.912 (0.737-0.972)
Inter-observe	0.969 (0.952-0.980)	0.967(0.952-0.977)	0.974 (0.944-0.988)	0.985 (0.973-0.992)	0.958 (0.862-0.987)

Average values with 95% confidence intervals are shown

Table 2 Intra-Observer and Inter-Observer Reproducibility (ICC) of Femoral Offset for X-ray

	DDH	Normal
Intra-observer	0.976 (0.963-0.984)	0.966 (0.951-0.976)
Inter-observe	0.962 (0.942-0.975)	0.980(0.971-0.986)

Average values with 95% confidence intervals are shown

Table 3 The FO difference between X-ray and 3D-CT in DDH group and normal group

	X-Ray	3D-CT	Mean Difference (mm)	*p*-value	The absolute value of the difference (mm)
DDH	33.22±7.60	35.68±5.15	2.47±6.73***	<0.001	5.42±4.66
Normal	40.12±6.00	41.14±5.22	1.01±4.58**	0.017	3.74±2.80

** denote statistically significant differences ($p < 0.05$). *** denote statistically highly significant differences ($p < 0.001$)

Figures

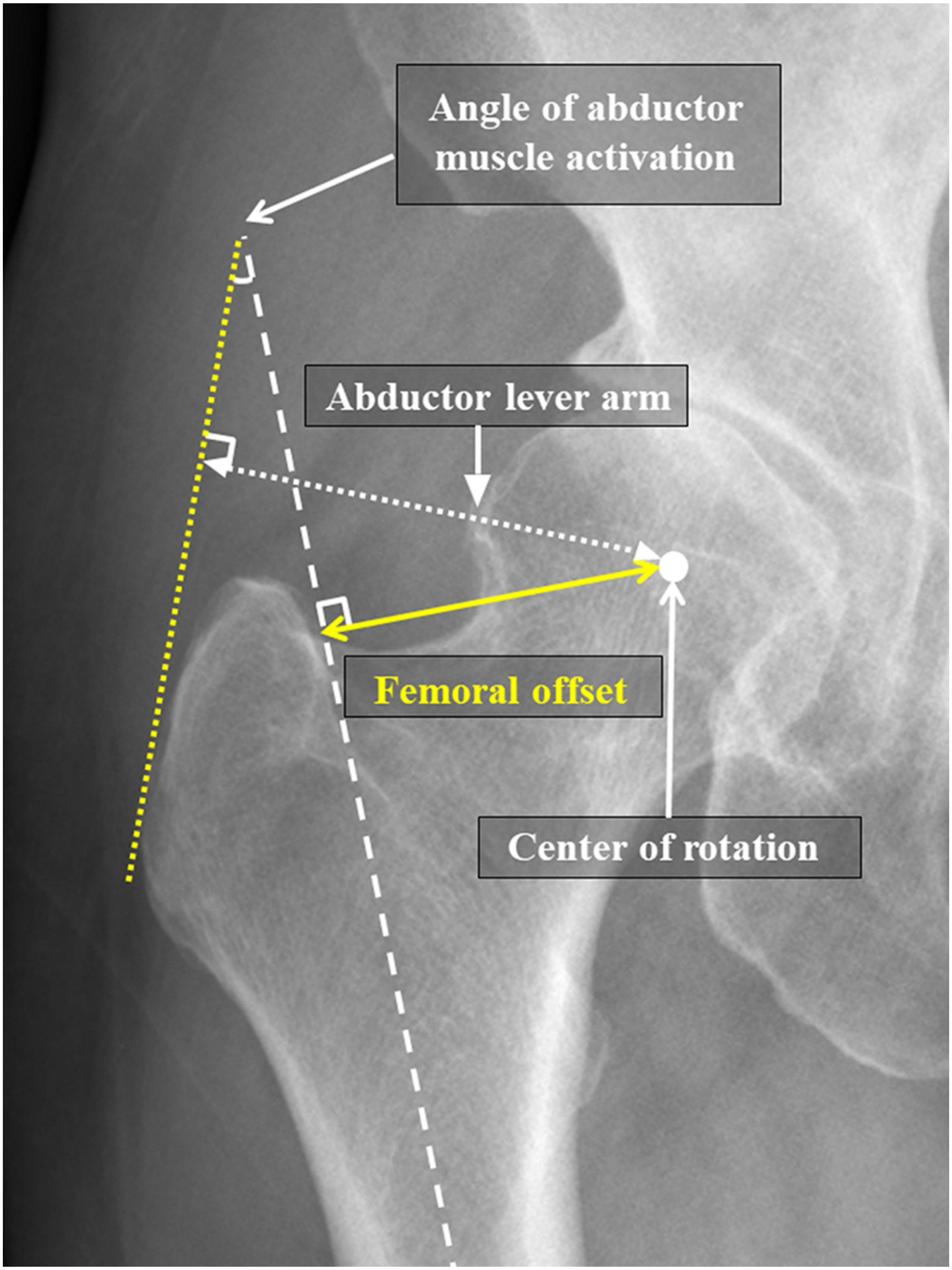

Figure 1

X-ray measurement. Measurement of FO, abductor muscle lever arm and angle of abductor muscle activation.

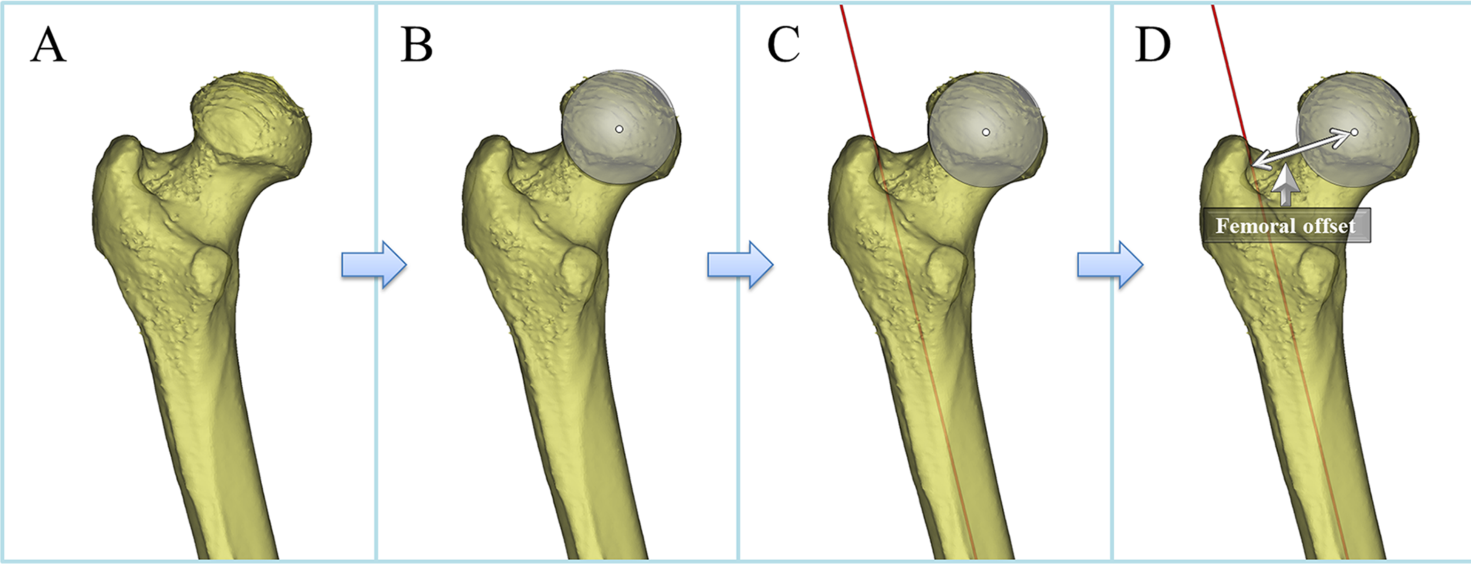

Figure 2

2: 3D-CT measurement. (A) The femur was reconstructed by Mimics Software. (B) A best-fitted auxiliary sphere of femoral head was drawn in 3D view. (C) The central axis of femoral shaft was settled in 3D view. (D) FO was calculated as the 3D perpendicular distance from the center of the auxiliary sphere to the central axis.

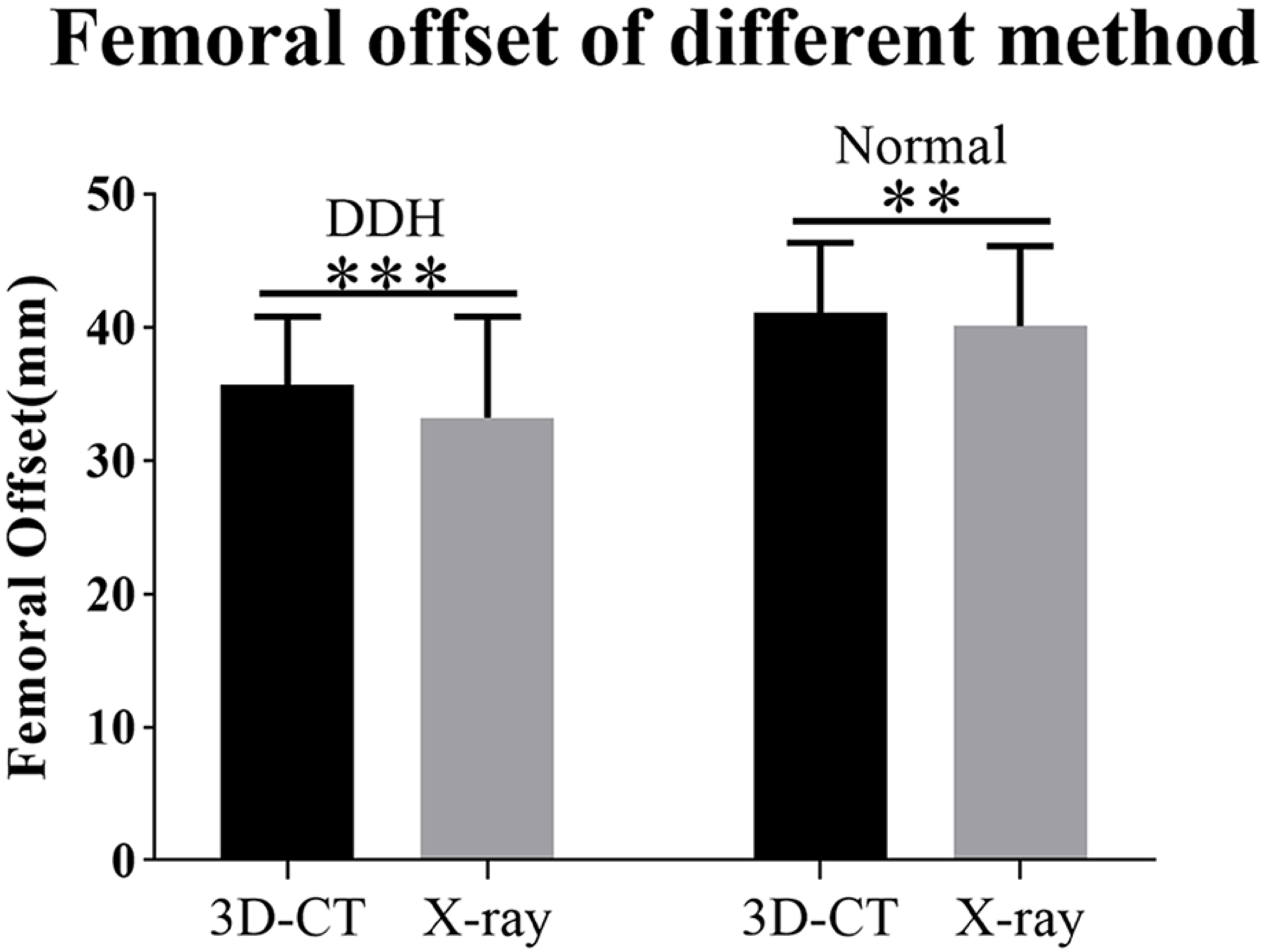

Figure 3

Comparison of femoral offset between 3D-CT and X-ray in DDH group and normal group. Error bars denote SDs. ** denote statistically significant differences ($p < 0.05$). *** denote statistically highly significant differences ($p < 0.001$)

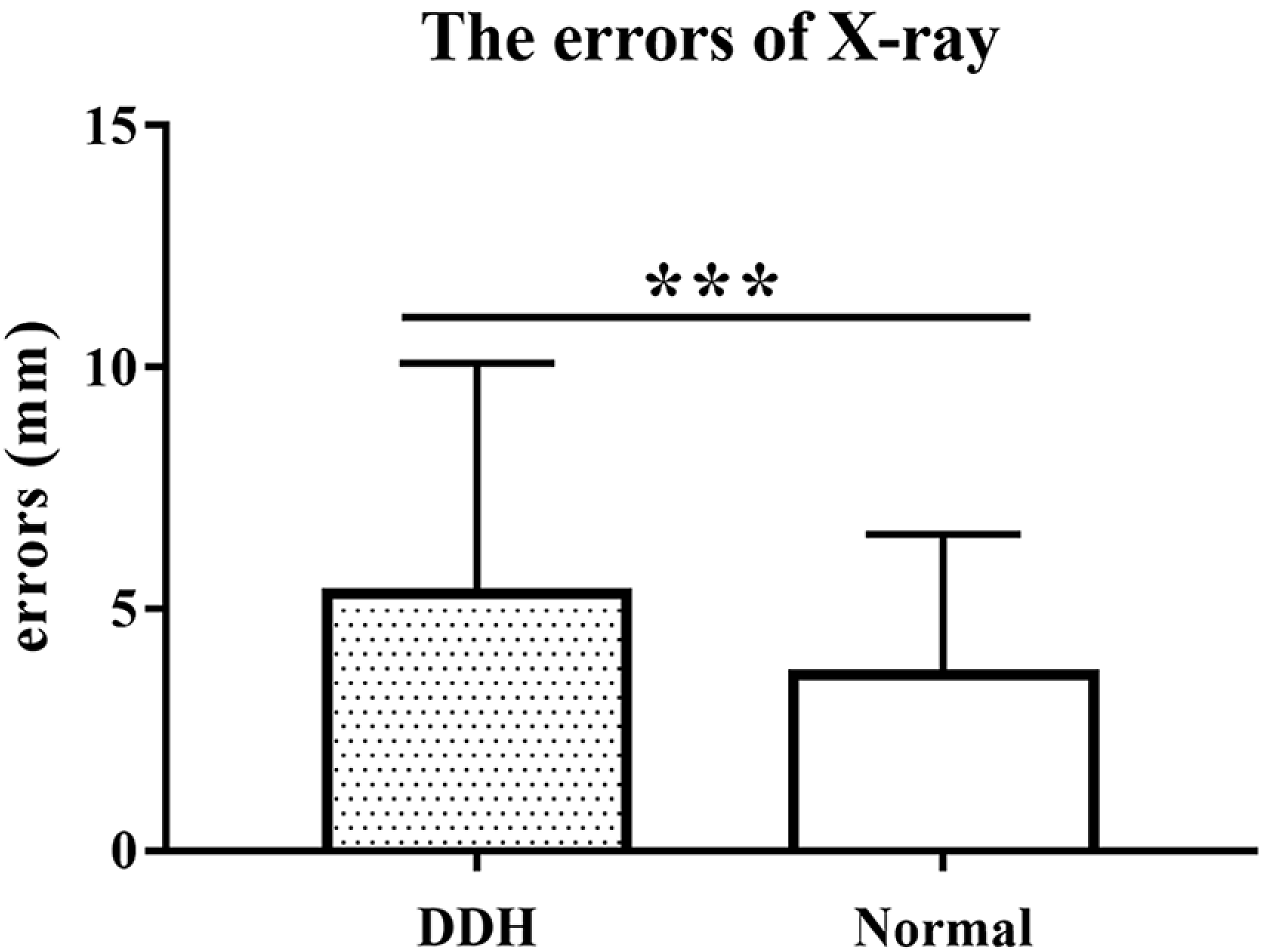

Figure 4

Comparison of observational errors of X-ray between DDH group and normal group. Error bars denote SDs. *** denote statistically highly significant differences (p < 0.001)

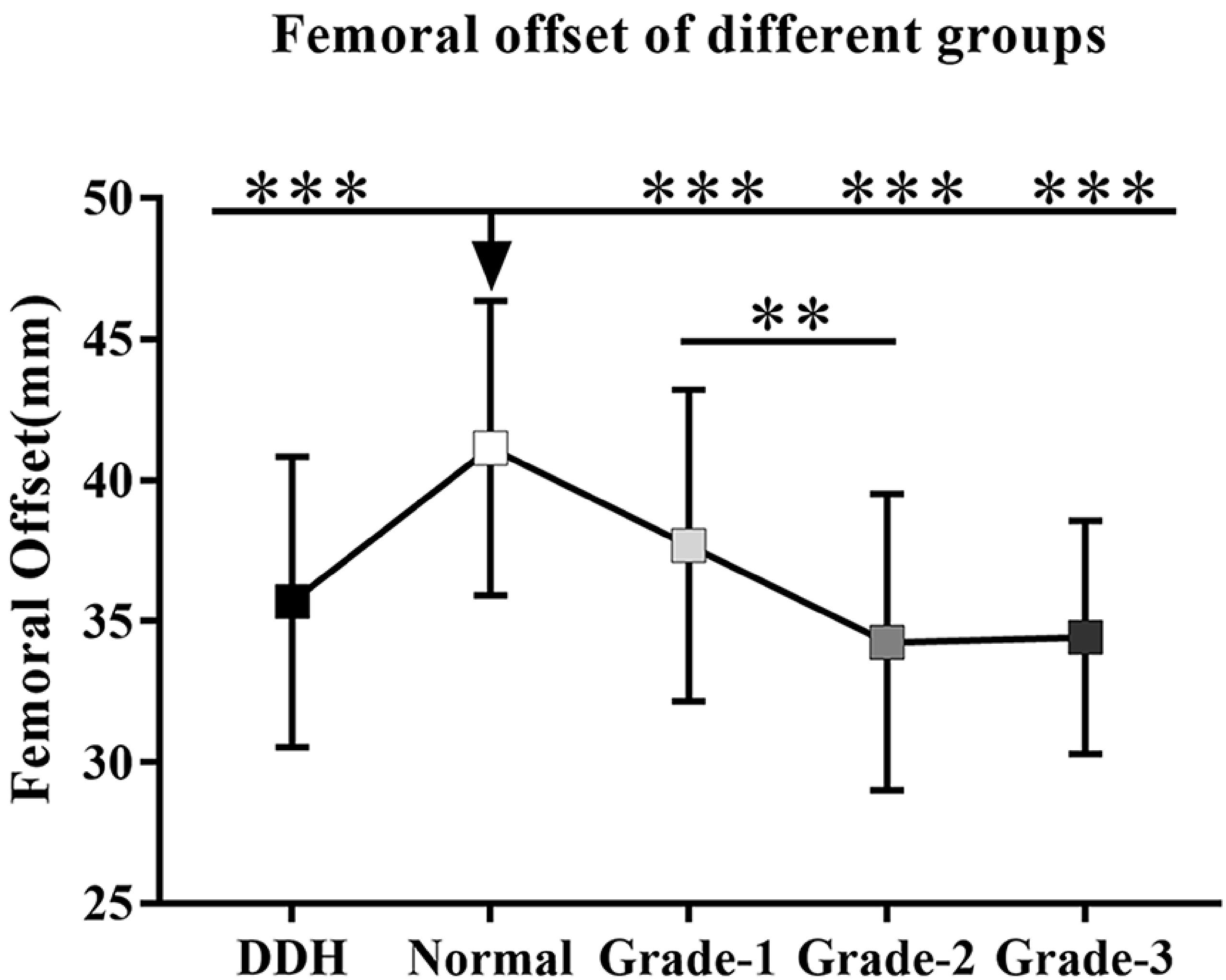

Figure 5

Comparison of femoral offset among DDH group, normal group. and Grade-Ⅰ, Ⅱ, Ⅲ subgroups Different-colored squares denote mean values of femoral offset in different groups. Error bars denote SDs. ** denote statistically significant differences ($p < 0.05$). *** denote statistically highly significant differences ($p < 0.001$)

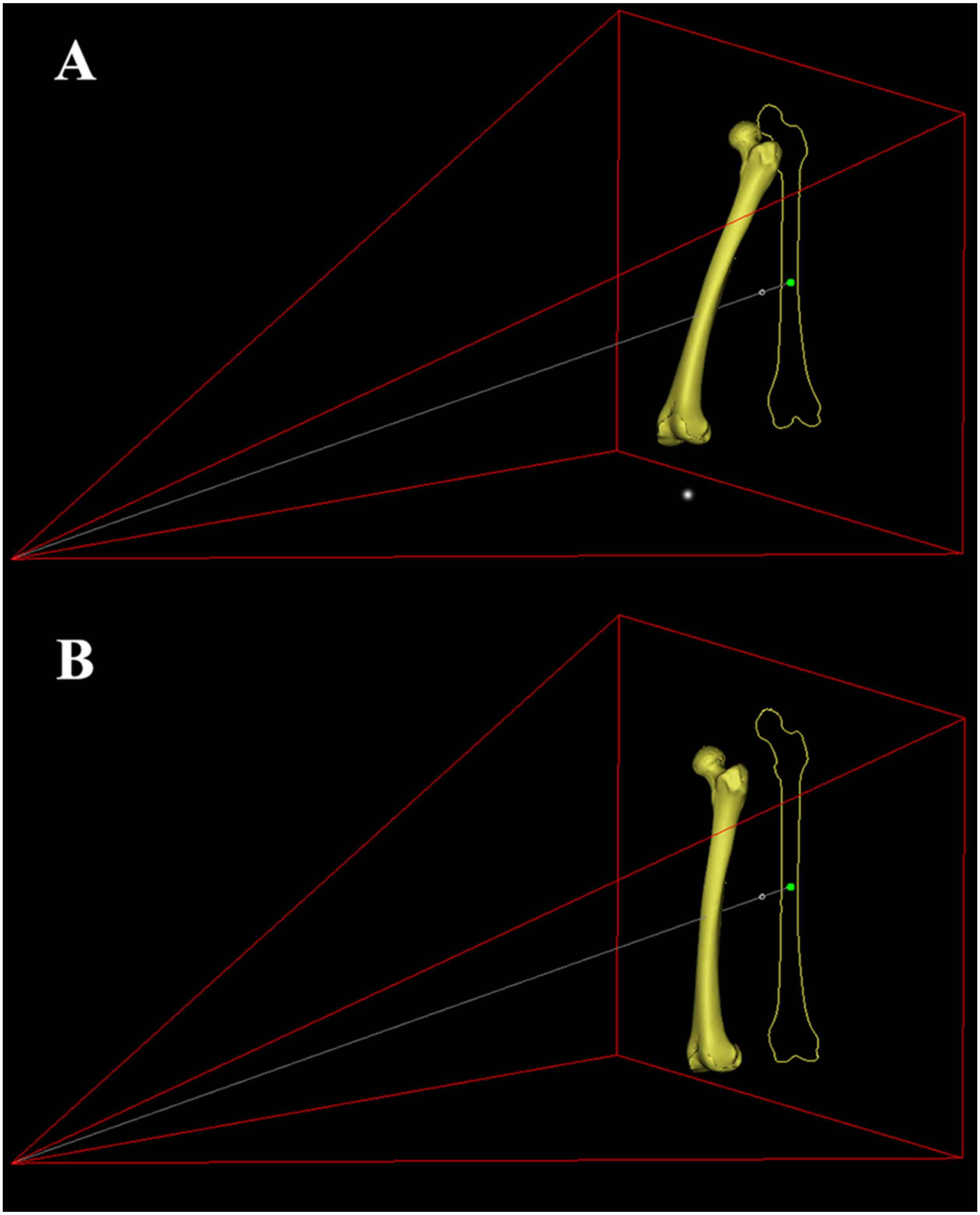

Figure 6

The mechanism of X-ray observational error (A) The mechanism of underestimate caused by the rotation of femur. (B) The mechanism of overestimate caused by the divergence of the X-ray.