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A Simple and Practical Method to Determine Amount of Rotation in Femoral Midshaft Derotational Osteotomy: Geometric Arc and Chord Formulas

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ABSTRACT

Objective: Femoral derotational osteotomy is a surgical intervention that involves the derotation of the femur at certain sites to achieve the desired femoral anteversion angle. However, current intraoperative techniques measuring the degree of correction and adequately performing it is still insufficient to achieve the desired femoral anteversion angle. The aim of this study is to investigate whether the geometric arc and chord formulas are applicable to achieve the target femoral anteversion angle in mid-shaft femoral derotational osteotomy.

Methods: CT images of 20 femurs with excessive anteversion or retroversion deformities were retrospectively selected, and three-dimensional (3D) geometric models were obtained. 15° of femoral anteversion were chosen as the target angle. Geometric arc and chord formulas were separately applied on axial CT images at the mid-point of the femurs to calculate the degree of correction. Then, virtual mid-shaft femoral derotational osteotomy was performed, then post-op femoral anteversion angle was measured.

Results: There was no statistical difference between the postoperative measured anteversion angles and the targeted angle in all examples. The arc and the chord lengths were not statistically different which indicates both formulas can be used to estimate the degree of correction.

Conclusions: The arc and chord formulas provided an accurate target femoral anteversion angle. Using one of these formulas preoperatively can facilitate to achieve desired femoral anteversion angle without having the intraoperative measurements nor using any special equipment.

Keywords: Derotational osteotomy, femoral anteversion, geometric arc formula, femoral midshaft osteotomy

1. INTRODUCTION

Femoral version refers to the angle between the axis of the femoral neck and the axis of the femoral condyles in the transverse plane. Studies have shown that the normal femoral version in adults is typically in the range of 10-15 degrees of anteversion [1-3]. However, abnormal femoral versions can occur due to various reasons such as idiopathic factors, cerebral palsy (CP), or post-traumatic conditions like slipped capital femoral epiphysis (SCFE) [4, 5]. Untreated femoral versions can lead to several problems including labrum pathologies, gait disorders, coxarthrosis, hip and knee pain, and patellofemoral disorders [6-8]

Femoral derotation osteotomy needs to be performed to address femoral version issues which can be applied at proximal, diaphyseal and distal femur. Among these techniques, midshaft femoral derotational osteotomy is often preferred due to its less invasive nature, stable fixation, and lower risk of complications [9, 10]. During the femoral derotation surgery, the distal femur fragment is rotated from the osteotomy site and fixed to the proximal part to achieve the desired femoral version angle. However, accurately determining the required amount of rotation to reach the target version angle is challenging, and it may not always be possible to achieve the precise femoral version angle.

Pre-operative calculation of the distal femur fragment rotation using the geometric arc and chord formulas on axial CT image can be useful to overcome this challenge. This method can also allow for easy access to the target femoral version angle without the need for additional measurements

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during surgery which reduces the duration of the operation and minimizes the use of fluoroscopy. However, the reliability and validity of this approach are yet to be established. Therefore, this study aimed to investigate the applicability and reliability of the geometric arc and chord formulas to achieve the target femoral anteversion angle for midshaft femoral derotational osteotomy.

2. MATERIALS AND METHODS

2.1. Sample Size and Image Acquisition

Lower extremity computed tomographic (CT) angiography scans retrospectively obtained between October 2021 and January 2020 from 50 randomly selected patients were examined along with their clinical records. All collected CT images of femurs were included except the femurs whose femoral anteversion angle was between 10^{o} and 15^{o}. Patients with evidence of lower-extremity trauma, acetabular dysplasia, avascular necrosis of the femoral head, and femoral or pelvic implants were excluded.

A total of 20 femurs with excessive anteversion or retroversion deformities were selected from 20 patients (14 male and 6 female; 12 right and 8 left) with a mean age of 49±16 (range: 20-76 years). Group 1 included 10 femurs with excessive anteversion deformity ranging between 18.2^{o} and 46^{o} and Group 2 included 10 femurs with retroversion deformity ranging between – 9.7^{o} and 3.7^{o} determined by evaluating three-dimensional (3D) femur models. All scans were fully anonymized, and the study protocol was approved by University Research Ethics Board (No. 2019-17/27). DICOM format CT data of each CT scan were imported to Mimics software (version 21.0, Materialize, Leuven, Belgium) to reconstruct a three-dimensional geometric femur model and to perform measurements.

The CT scans were obtained with a Somatom Force device (Siemens Healthineers Global, Germany) using standard techniques at 100 kVp and 256 mAs, with a slice thickness of 0.5–0.9 mm and a resolution of 512 × 512 pixels (voxels approximately 0.7 × 0.7 × 0.5 mm3).

2.2. Construction of Coordinate System

Establishing the femur-customized anatomical coordinate system was important for the validity of the measurements. Hence, after the reconstruction of the geometric femur model, an idealized coordinate system was reconstructed using specific femur bony landmarks to normalize the femur orientation. Two planes perpendicular to each other, representing the global Cartesian *X-Y* and *X-Z* planes were created. The *X-Y* plane (femur coronal plane) was created contacting the posterior-most prominent aspects of the lateral and medial femoral condyles and the greater trochanter, and the *X-Z* plane (femur horizontal plane) was created contacting the most distal aspects of the medial and lateral femoral condyles (Figure 1). The *Y-Z* plane (femur sagittal plane) was created perpendicular to both *X-Y* and *X-Z* planes.

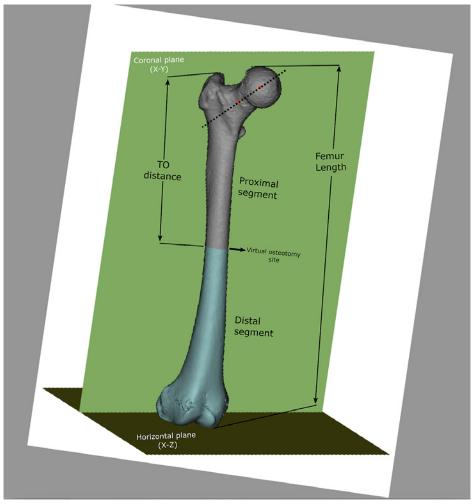

Figure 1. *Virtually created 3D femur model and calculated TO distance*

2.3. Measurement of Pre-op and Post-op Femoral Anteversion Angles

The reconstructed femur model was imported into the 3-Matic software (version 13.0, Materialise N.V., Belgium) in STL format, which geometry was triangle mesh to conclude the center of the femoral head and the neck more precisely and to avoid observer error. The surface of the head and the neck were marked using "Wave Bruch Mark" in the software and extracted from the reconstructed femur. Then, the point cloud model of the surface of the femoral head and the neck were exported as ".txt" extensions. A best-fit sphere that can fully contain the entire femoral head and just tangent to the femoral neck was defined using a least-squared approach on the point cloud model, and the center of the sphere was indicated on the 3D femur model. The center of the femoral neck was calculated via the center of gravity equation using the point cloud model and the center of the femoral neck was indicated on the 3D femur model.

The femoral neck axis was defined on a superior view of the 3D femur model as a line passing through the center of the femoral head and the center of the femoral neck. The pre-op femoral anteversion angle was measured as the angle formed by the femoral neck axis and a horizontal line (Figure 2). After measuring the pre-op femoral anteversion angle, the virtual mid-shaft femoral derotational osteotomy was performed. Then, a new femur-customized anatomical coordinate system was constructed for the virtually operated femur model, and the post-op femoral anteversion angle was measured in the same way as the measurement of pre-op femoral anteversion angle.

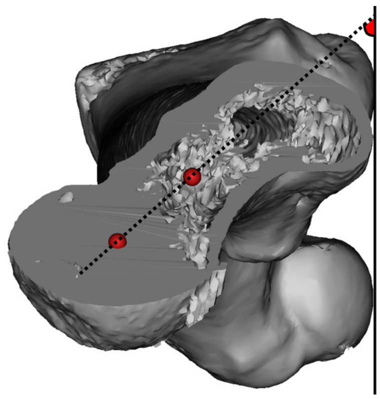

Figure 2. *Determination of femoral anteversion*

2.4. The Virtual Mid-Shaft Femoral Derotational Osteotomy

All data were measured in the MPR plane and then measurements were applied on the 3D femur model to perform the virtual mid-shaft femoral derotational osteotomy. The femur length was measured on the coronal CT image. After measuring the femur length, the mid-point of the femur was decided as the site of the mid-shaft femoral derotational osteotomy. During surgery, estimating the correct location of the mid-point of the femur is important to decide the level of the mid-shaft femoral derotational osteotomy. Therefore, the distance between the tip of the greater trochanter and the osteotomy site (TO-distance) was noted. The femur length and the TO-distance were also indicated on the 3D femur model in the *X-Y* plane (Figure 1).

The axial CT image at the virtual osteotomy site was viewed. The center of the medullary cavity was obtained by drawing an inner best-fit circle by indicating the lateral and medial boundaries of the medullary cavity on the axial CT image. An outer circle originated from the center of the medullary cavity and tangent to the lateral cortex of the femur was drawn (Figure 3). To perform the virtual osteotomy, the 3D femur was transversely cut using 3D Tools of Mimics software at the level of the osteotomy, and the femur separated to the proximal and the distal segments (Figure 1). The CT axial image of the osteotomy site was then embedded on the transversely cut surface of the 3D femur distal segment to confirm the correct location of the center of the medullary cavity and the state of the tangency of the outer circle (Figure 3).

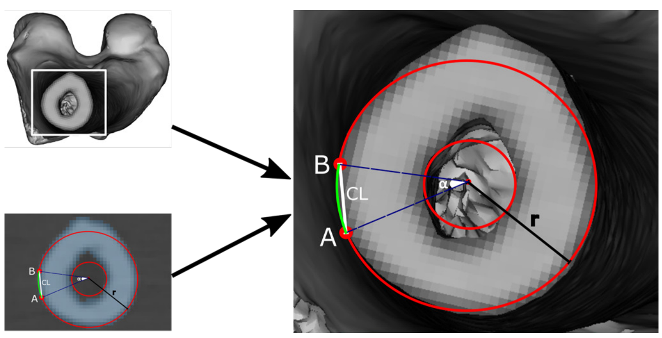

Figure 3 *Finding the ideal circumference tangent to the lateral cortex using the best-fit circle and determining the guide points for the cortical distance (A-B distances)*

The radius of the outer circle was noted (r) which was used for the geometric arc and chord formulas. The angle of 15^{o} was chosen as the target femoral anteversion angle. In Group 1, the correction angle (α) was measured by subtracting the 15^{o} from the pre-op femoral anteversion angle, while in Group 2, the correction angle (α) was measured by subtracting the pre-op femoral anteversion angle from the 15^{o}. *Arc* is a segment of a curve distance between two points, and *chord* is a segment of a line joining two points on a curve. The arc length was calculated by using the geometric arc formula [$2\pi r(\alpha/360)$] and the chord length by using the geometric chord formula [$2r\sin(\alpha/2)$]. The arc and the chord lengths, within the margins of the correction angle, indicated on the lateral cortex of the distal segment of the 3D femur with two points (A, B) (Figure 3). The distal segments of the Group 1 femurs were externally rotated about the center of the medullary cavity in the transverse plane from point A to point B to correct excessive femoral anteversion deformity and Group 2 femurs were internally rotated from point B to point A to correct femoral retroversion deformity (Figure 4). The distal and the proximal segments were then united to measure the post-op femoral anteversion angle.

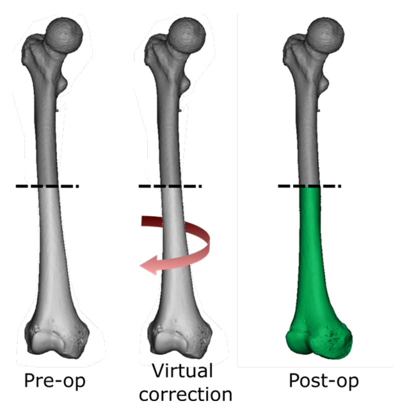

Figure 4 *.Implementation of virtual femoral derotation*

2.5. Statistical Analysis

SPSS software (SPSS Inc, Chicago, IL) was used for statistical analyses. The variables were investigated using virtual and analytical methods to determine whether they were normally distributed. Descriptive statistics were provided as mean±standard deviation. One sample *t*-test was used to compare the target femoral anteversion angle and the post-op femoral anteversion angle. Student's *t*-test was used to assess differences between right and left femurs. The differences between the arc length and the chord length were assessed with a paired *t*-test. A p-value of less than .05 was considered to show a statistically significant result.

3. RESULTS

The femur length and the TO-distance were measured to establish the location of the osteotomy site during surgery (Table 1). The calculated arc length and the chord length were presented in Table 2. The mean±SD of the outer circle radius (r) was 15±1.5 (min 11.8, max 17.4). After performing the virtual rotation of the distal segment, post-op femoral anteversion angle was obtained and it was not statistically different from the target angle of 15^o (Table 3). The mean ± SD difference between the post-op femoral anteversion angle and the target angle in Group 1 and Group 2 were 0.5±1, 0.7±1.4, respectively.

Table 1. *Measured lengths to locate osteotomy site*

Measurements	Mean (mm)	Standard Deviation ± (mm)	Minimum (mm)	Maximum (mm)
Femur length	439.2	37.6	363.1	507.7
TO-distance	204.3	19.5	170.7	241.6

TO-distance: the distance between the tip of the greater trochanter and the mid-shaft osteotomy site in the coronal plane

Table 2. *Measured lengths to determine the amount of distal femoral segment rotation to achieve target angle*

Measurements	Mean (mm)	Standard Deviation ± (mm)	Minimum (mm)	Maximum (mm)
Arc length	3.5	1.6	0.9	7.5
Chord length	3.5	1.6	0.9	7.4

Table 3. *Measured Femoral Anteversion Angles (^{o})*

Group	Pre-op Angle (Min — Max)	Target Angle	Post-op Angle (Min — Max)	Difference
Group 1	26.2 ± 7.6 (18.2 — 46.0)	15	14.4 ± 1.0 (12.9 — 15.8)	0.5 ± 1.0
Group 2	-1.4 ± 4.1 (-9.7 — 3.7)	15	15.7 ± 1.4 (13.9 — 18.4)	0.7 ± 1.4

Note: Data are mean ± SD.

The arc length and the chord length were not statistically different (p>.05) (Table 2). Since the chord length is a linear measurement, it can be used as a reference line by drawing it on the outer lateral cortex of the femur during the mid-shaft femoral derotational surgery to determine the amount of the distal segment rotation.

There was no statistical difference between the right and the left femurs in any variables.

4. DISCUSSION

The striking finding of this study is that applying the preoperatively calculated cortical distance using the geometric arc or chord formula is a reliable method to achieve the desired femoral anteversion angle in virtual midshaft femoral derotation osteotomy. With this method, cortical distance between the points A and B, which represents the amount of bone to be rotated, can be easily calculated preoperatively on the axial CT and then, the calculated distance can be practically marked intraoperatively to achieve the targeted femoral anteversion. We observed no statistical difference between the arc and chord formulas for measuring the cortical distance (Table 2). Although the difference between chord and arc distances is theoretically expected to increase with the diameter of the circumference, the radius of the femur's diaphysis in humans is too small for such a difference to occur [11]. Hence, even when a high degree of derotation (30-45 degrees) is required, there will be no statistical difference between these distances.

To the best of our knowledge, no study has been reported on human femurs to investigate the validity of arc/chord formula mathematically. In this study, we demonstrated how surgeons calculate the required cortical distance (chord length) to achieve desired femoral version angle preoperatively and then, how to implement the cortical distance on the femur during the surgery (Table-4). Moreover, intraoperative steps including the marking of cortical distance and performing the rotation are shown in Figure 5.

Table 4. *Steps of determination of the degree of rotation using arc/chord formula to achieve target femoral anteversion angle*

Preoperative steps	1. Decide the mid-shaft osteotomy site on the femur coronal CT image and measure the distance between the osteotomy site and the tip of greater trochanter (TO distance). 2. Calculate arc length or chord length (cortical distance) using the formulas at osteotomy site on axial CT image as shown in the Figure 3.
Intraoperative steps	3. Locate the mid-shaft osteotomy site using TO distance. 4. Expose the femur osteotomy site and mark the calculated arc or chord length (A-B line) on the lateral cortex (Figure 5). 5. Cut the femur shaft and rotate the distal segment of the femur by the amount of the arc or chord length (Figure 5).

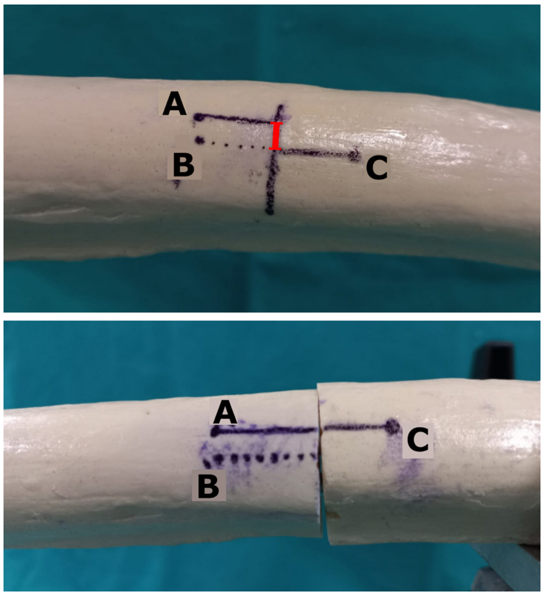

Figure 5. *Marking the arc length on lateral cortex of osteotomy. Upper image: Preoperatively calculated chord length (cortical distance) is marked as a red line at osteotomy site between point A and B. Point C is also indicated on the distal segment of the femur in line with point B. Lower image: The distal segment is rotated by the amount of the chord length and the rotation is finished when the point aligns with point A.*

Midshaft osteotomies are typically performed on the femur lateral cortex using a lateral approach. Hence, this study includes the calculations (best-fit circle tangent to the lateral cortex, guide points A and B) based on the lateral cortex of the midshaft femur. It is important to note that the femoral diaphysis does not have a perfect circular shape. Therefore, when drawing the outer best-fit circle during preoperative planning (Figure 3), the drawn circle on the axial CT must be in contact with the lateral cortex where marking of intraoperative cortical distance will be made (Figure 5). Thus, when drawing a circle whose center is at the midpoint of the femoral medulla, it is crucial to ensure that the circle aligns accurately with the lateral cortex of the femur (green arc in Figure 3). Otherwise, the calculations will yield different results. Since the midshaft region closely resembles – not perfectly – the tubular shape of the femur, it can be concluded that this method provides accurate results specifically at midshaft femur not at the distal or proximal femur.

There is no clear information in the literature regarding the optimal location for performing midshaft osteotomy. In this study, we calculated the midpoint of the femur based on femur length and decided midshaft osteotomy site. Then, we determined the distance between the tip of greater trochanter and midpoint of the femur, TO distance (Trochanter to Osteotomy), calculating which is especially important to match the preoperatively decided osteotomy site on the femur during the surgery. Since the tip of the greater trochanter can be easily found during the surgery, using a tape or a metal tape with fluoroscopy can be a practical method to obtain TO distance and the correct midpoint osteotomy site.

Various suggestions and technical skills for controlling femoral rotation can be found in the literature [12-19] . Some of these authors traditionally recommend using Steinmann pins on the proximal and distal segments to control rotation and then measuring the angle between these wires using a goniometer, triangular guide, or visual estimation after derotation [12, 14-16, 18, 19]. However, these methods primarily require surgical experience. Additionally, the use of fluoroscopy is necessary for the application of guide transmission pins or K-wires, which are used for rotation, exposing the patient to radiation. Sterile goniometers or triangular guides are also required. In the absence of these materials or if their sterility is compromised during the operation, it can lead to prolonged surgical time and potential difficulties. On the other hand, the preoperative calculation method described in this study offers significant convenience and confidence during surgery.

In two studies, smartphones were used to determine rotation [13, 17]. However, implementing these methods requires additional hardware such as a smartphone, a specialized app, and equipment to mount the smartphone. Moreover, using these methods is more likely to compromise the sterility of the surgical site. The installation of these instruments and their alignment with the femur can also lengthen the operation time. Although there is no information available about the learning curve for these methods, it can be inferred that they require substantial surgical experience.

The technique described in this study based on preoperative calculations on the axial CT does not require any additional materials or calculations during the surgery which can further facilitate the operation. Furthermore, since the markings are made with a mini-open incision over the lateral cortex, there is no need for fluoroscopy during the derotation phase. It is also likely that even surgeons with limited surgical experience can achieve success with this practical method.

We believe that the geometric arc/chord method can also be applied to the human humerus bone since its shaft is also tubular-shaped [11]. By using this method, nail fixation, which is a less invasive approach, can be preferred for derotation osteotomies in adult patients with CP or for treating humeral malrotations. However, the suitability of this method for human humerus derotation osteotomy needs to be thoroughly researched.

However, this study has its limitations. We conducted the study on a 3D reconstructed bone model, although it may be more advantageous to perform the method on cadavers. Furthermore, the success of the application of this method in intraoperative experiences also requires it to be evaluated. However, this study proved that mathematically calculation of the cortical distance and performing it on the virtual femurs is a reliable method to achieve desired femoral anteversion angle. Additionally, we used software which includes best-fit circle tool to calculate cortical distance. Surgeons who intend to use this method should consider the requirement of having such software having specific tools.

Hereby, the geometric arc and chord method is a reliable approach for midshaft derotation osteotomies, effectively addressing rotational issues of the femur. This method allows surgeons to achieve the desired femoral version without the need for intraoperative measurements or additional radiation exposure.

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Design of the study: SI, AVI
Acquisition of data for the study: SI, ZS
Analysis of data for the study: AVI
Interpretation of data for the study: ZS
Drafting the manuscript: SI, AVI, ZS
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