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Original article

Three-dimensional orientation of the femoral curvature. How well does it match with the sagittal curvature of femoral implants?

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ABSTRACT

Background: The curvature of the femoral shaft is generally considered as residing in the sagittal plane. While many studies have measured the femur's radius of curvature, very few have studied the orientation of the plane in which it resides. The orientation of this plane may affect the rotation of intramedullary nails or revision stems with diaphyseal locking. This led us to conduct a three-dimensional (3D) anatomical study to: 1) analyze the 3D curvature of the femoral diaphysis by specifying the orientation of the plane in which it resides, 2) look for relationships between the curvature's orientation and anatomical parameters of the femur.
Hypothesis: We hypothesized that the femoral curvature resides in the anterolateral plane, not the sagittal plane.
Materials and methods: A computed tomography scan was performed on 45 dry femur bones provided by a cadaver laboratory. The 3D reconstructions were analyzed to characterize the curvature of the diaphyseal shaft, radius of its various portions and to determine the plane in which it resides relative to the standard coronal reference plane defined by three points: posterior side of both condyles and the greater trochanter. The following parameters were measured: length, neck-shaft angle, femoral valgus (between anatomical and mechanical axis) and neck anteversion.
Results: The largest curvature was in a plane oriented on average of 78.3° ± 14.9° (35.2° to 106.7°) anterolateral. The correlation between femoral curvature and neck-shaft angle (R = 0.172), size (R = 0.095), valgus (R = 0.104) and overall curvature (R = 0.60) was low.
Discussion: Implants with diaphyseal fixation are designed such that the femoral curvature resides in a strict sagittal plane. Long revision stems with diaphyseal fixation may have a tendency to rotate laterally (externally) during insertion. Correcting this external rotation to prevent anteversion may result in a less than satisfactory press-fit. The femoral curvature must be taken into account when designing intramedullary implants.
Level of evidence: IV, Cadaver study without control group.

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1. Introduction

The curvature of the femoral diaphyseal shaft is generally considered as being located in the sagittal plane with an anterior convexity, which simplifies its analysis on antero-posterior (AP) and lateral X-rays. Implants with intramedullary (IM) anchoring in the middle portion of the femoral shaft (nails, stems for revision total hip arthroplasty (THA)) have a curvature intended to reside in the sagittal plane [1].

Some authors [1–4] have found a mismatch between the femur's radius of curvature and these implants, but have not provided information about the plane in which it resides. The orientation of this plane could alter the rotational position of these implants and have consequences in THA and femur trauma

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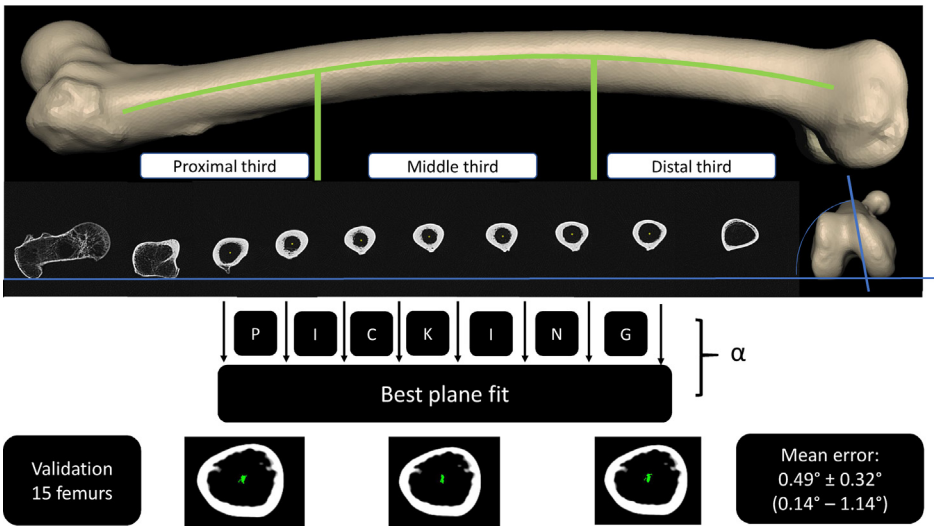

Fig. 1. Manual picking of the center of the femoral diaphysis at different heights to compute the best plane fit and define the orientation angle (α) of the femoral curvature, which is defined as the angle between the coronal reference plane and the femoral curvature plane. The validation procedure found a mean error of 0.49° ± 0.32° (range, 0.14–1.14°).

surgery. Clinical experience suggests there is a tendency for lateral (external) rotation of long, anatomical, cementless stems when they are inserted during revision THA [2,4].

Thus, there is uncertainty about the orientation of the femoral curvature plane, which may affect the rotation of intramedullary nails or revision stems with diaphyseal locking. This led us to conduct a three-dimensional (3D) anatomical study to:

- analyze the 3D curvature of the femoral diaphysis by specifying the orientation of the plane in which it resides;
- look for relationships between the curvature's orientation and anatomical parameters of the femur. We hypothesized that the femoral curvature resides in the anterolateral plane, not the sagittal plane.

2. Materials and methods

2.1. Materials

The femurs were provided by the cadaver laboratory of the Tours Faculty of Medicine through the organ donation program. Thus this study did not require approval from the Biomedical Research Ethics Committee. The femurs were prepared manually and then placed in an oven to generate dry bones. We used all the femurs available that had no signs of fracture fixation or arthroplasty. We had no data on the age, gender or ethnic origin of the donors.

3. Methods

Each femur was placed on a hard foam block resting on the posterior portion of the two condyles and the greater trochanter, as these three points defined the reference coronal plane. Computed tomography (CT) scans were carried out in the imaging department of the Tours University Hospital using a Siemens Somatom™ Definition AS+ unit (acquisition parameters: 80 kV, 11 mAS, SC–500.00 mm). The 3D reconstructions were generated from the 1-mm thick slices.

3.1. Measurement methods

There is currently no accepted method to measure the orientation of the femoral curvature. DICOM images were analyzed using custom software (Imascap™) which allowed us to view the files and adjust the plane by selecting multiples points on transverse views. The measurements were made by two raters who were blinded to each other's findings. Each rater repeated his measurements a second time, 15 days later, without any knowledge of the first set of measurements. The software was validated using a series of femoral diaphysis slices in which the orientation of the curvature was set to 90 degrees by imaging processing to allow us to first determine the gold standard. In these trials, the center of the femoral diaphysis varied only in the y-axis.

These two raters independently defined the center of the diaphysis on 10 slices that were evenly distributed along the length of the femur using the same measurement protocol (starting below the lesser trochanter and ending at the inferior metaphysis). The software statistically defined the best plane fit for these 10 points by calculating the root mean square (Fig. 1). The software then calculated the open angle toward the exterior between this plane and the coronal plane, thereby defining the plane in which the femoral curvature resides.

The 3D measurements were made based on the reference coronal plane. The femoral head was placed in a sphere to define its center. The femoral diaphysis started proximally below the lesser trochanter and ended distally on the superior edge of Heim's square (Fig. 2). The anatomical axis of the diaphysis was defined on an AP view as the line joining the center of the proximal and distal ends of the diaphysis. The femoral neck axis was defined as the line joining the head center and the middle of the femoral neck. The femur's mechanical axis was defined as the line joining the head center and the middle of the inferior epiphysis between the two femoral condyles.

The curvature was represented physically by joining the points in the center of the various slices through the diaphysis. The overall radius of curvature of the diaphysis was calculated in the curvature plane and on its projection in the sagittal plane. The curvature of each third of the diaphysis (proximal, middle, distal) was also calculated.

The following measurements were made in the coronal reference plane:

- femur length = distance between a tangent line inferior to the femoral condyles and the tangent line parallel to the superior border of the head;

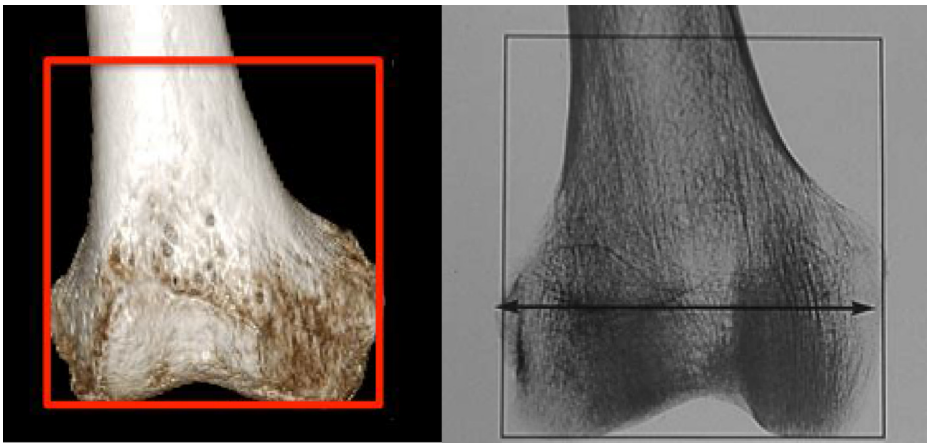

Fig. 2. Distal end of the femoral diaphysis defined with Heim's square.

Table 1
Femur characteristics. The orientation of the femoral curvature was 78.3 ± 14.9° (35.2 to 106.7°). There were no significant differences between left and right femurs.

Number of femurs	Entire set (45)	Left (24)	Right (21)	*p*
Total length	437.9 mm ± 31.8 (369 to 495 mm)	436.4 mm ± 27.6 (397 to 492 mm)	439.5 mm ± 36.8 (369 to 495 mm)	NS *p* = 0.7489
Neck-shaft angle	125.7° ± 9.1 (108 to 147°)	125.9° ± 8.5 (108 to 146°)	125.6° ± 10.0 (114 to 147°)	NS *p* = 0.91
Femoral valgus	5.7° ± 0.9 (2.6 to 7.5°)	5.5° ± 0.8 (2.6 to 6.9°)	6.0° ± 0.9 (4.3 to 7.5°)	NS *p* = 0.0549
Femoral neck anteversion	15.5° ± 8.8 (2.4 to 34.4°)	17.5° ± 8.9 (3.0 to 34.4°)	13.1° ± 8.8 (2.4 to 30.0°)	NS *p* = 0.1035
Radius of curvature in curvature plane	1802 mm ± 1296 (575 to 7489 mm)	1532 mm ± 888 (575 to 4411 mm)	2111 mm ± 1613 (817 to 7489 mm)	NS *p* = 0.1366
Overall sagittal internal 2D curvature	907 mm ± 180 (558 to 1212 mm)	923 mm ± 177 (566 to 1201 mm)	889 mm ± 184 (558 to 1212 mm)	NS *p* = 0.53
Proximal third	2104 mm ± 2183 (483 to 9212)	2555 mm ± 2346 (499 to 8326)	1588 mm ± 1905 (483 to 9212)	NS *p* = 0.14
Middle third	1006 mm ± 521 (291 to 2898)	1044 mm ± 440 (470 to 1940)	962 mm ± 610 (291 to 2898)	NS *p* = 0.604
Distal third	1816 mm ± 1788 (415 to 7726)	1952 mm ± 1904 (445 to 7726)	1660 mm ± 1677 (415 to 6867)	NS *p* = 0.59
Radius of curvature in coronal plane	2943 mm ± 1477 (919 to 6823 mm)	2984 mm ± 1456 (944 to 6823 mm)	2894 mm ± 1533 (919 to 5917 mm)	NS *p* = 0.84
Orientation of femoral curvature	78.3 ± 14.9° (35.2° to 106.7°)	76.0° ± 15.3° (35.2° to 101.4°)	80.9 ± 14.4° (57.4° to 106.7°)	NS *p* = 0.2768

- neck-shaft angle located between the anatomical axis of the diaphysis and the femoral neck axis;
- femoral valgus located between the anatomical axis of the diaphysis and the mechanical axis of the femur.

Neck anteversion was defined as the angle between the neck-shaft axis and the coronal reference plane.

3.2. Statistics

The inter- and intra-rater reliability was determined by calculating Cohen's kappa [5] and the intraclass correlation coefficient (ICC) [6], and then represented graphically on Bland–Altman plots. The agreement between observers was deemed low for values < 0.45, moderate for values between 0.45 and 0.75 and excellent for values > 0.75 [6]. The radius of curvature of each third of the diaphysis was compared to the other thirds using an analysis of variance and Tukey post-hoc test. Statistical tests were performed using MedCalc statistical software (version 15.2, MedCalc Software bvba, Ostend, Belgium; 2015). Correlations were determined using linear regression lines. Mean values were compared using *t* tests with $\alpha = 0.05$.

4. Results

Forty-five femurs were analyzed, 24 left and 21 right. Morphological data for the femurs are shown in Table 1. Validation of the measurement method on the test diaphysis slices found a mean error of 0.49° ± 0.32° (0.14 to 1.14°) on the 15 sets of measurements (Fig. 1).

The curvature of the diaphysis resided in a vertical plane angled anteriorly and laterally, while making an open angle with the coronal reference plane of 78.3° ± 14.9° (35.2 to 106.7°) on average for the two raters; rater 1 had an average value of 77.6° ± 15.5° and rater 2 of 78.9° ± 14.6° (Table 2). This orientation was due to curvature residing in both the sagittal and coronal planes (Fig. 3).

The intra-rater correlation based on the ICC for rater 1 was 0.9594 (confidence interval (CI): 0.9226 to 0.9774) and 0.9774 (CI: 0.9586 to 0.9877) for rater 2 (Table 3 and Fig. 4). The inter-rater correlation was 0.9743 (CI 0.9452 to 0.9870) for the first set of measurements (Kappa = 0.810; standard error 0.030; CI 0.751 to 0.869) and 0.9531 (CI 0.9158 to 0.9741) for the second set of measurements (Kappa = 0.776; standard error 0.034; CI: 0.710 to 0.843). The differences in the inter-rater measurements are given in Table 3.

In the sagittal plane, on average, the radius of curvature of the middle third (1006 mm ± 521 mm (291 to 2898 mm)) was

Table 2
Measurement of orientation of the femoral curvature by each rater.

Results in degrees	First set of measurements		Second set of measurements		Difference for each rater between sets		Mean difference between rater 1 and 2			Mean orientation of femoral curvature
	Rater 1	Rater 2	Rater 1	Rater 2	Rater 1	Rater 2	First set	Second set	Overall	
Mean	77.9	79.3	77.4	78.5	3.59	2.31	2.8	4.0	3.1	78.3
SD	15.5	14.8	15.6	14.6	2.62	2.21	2.0	2.9	2.6	14.9
Minimum	31.7	36.8	35.1	37.2	0	0	0	0	0	35.2
Maximum	106.7	108.1	108.9	103.1	9.4	8.3	9.9	11.8	11.8	106.7

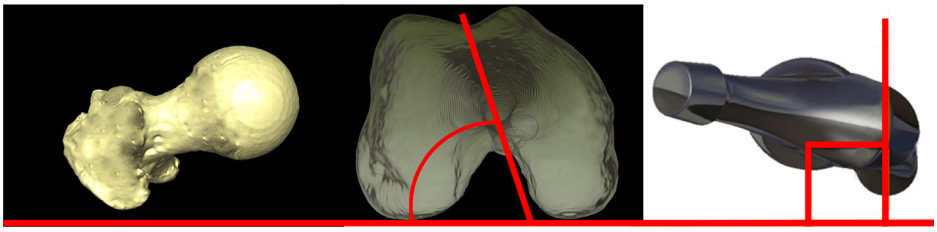

Fig. 3. Anterolateral orientation of femoral curvature compared to sagittal orientation of a femoral stem.

Table 3
Inter- and intra-rater reliability, intraclass correlation coefficient (ICC) and Cohen's Kappa. The reliability was excellent.

	Inter-rater reliability	
	ICC	Kappa
First set	0.9743	0.810 (standard error 0.030)
Confidence interval	0.9452 to 0.9870	0.751 to 0.869
Second set	0.9531	0.776 (standard error 0.034)
Confidence interval	0.9158 to 0.9741	0.710 to 0.843
	Intra-rater reliability	
	ICC	Kappa
Rater 1	0.9594	0.779 (standard error 0.036)
Confidence interval	0.9226 to 0.9774	0.709 to 0.850
Rater 2	0.9774	0.837 (standard error 0.031)
Confidence interval	0.9586 to 0.9877	0.776 to 0.898

smaller than that of the proximal third (2104 mm ± 2183 mm (483 to 9212 mm), $p = 0.0058$) and smaller than that of the distal third (1816 mm ± 1788 mm (415 to 7726 mm)) but not significantly ($p = 0.0567$). There was no significant difference between the proximal and distal thirds ($p = 0.6732$). There was no difference between left and right femurs.

The correlations were very low between the orientation on the plane of the curvature and the neck-shaft angle, length, femoral valgus and overall curvature (Table 4).

5. Discussion

This is the first study to look at the orientation of the femoral curvature in 3D. Based on our clinical experience, long anatomical cementless stems have a tendency to rotate laterally (externally) when they are inserted during revision THA procedures. This led us to hypothesize that the femoral curvature was anterolateral, thus a poor match with the purely sagittal curvature of existing femoral implants. A 3D analysis of the femoral curvature confirmed our hypothesis. The femoral curvature resides in the anterolateral plane at $\alpha = 78.3° \pm 14.9°$ (35.2 to 106.7°) not in the sagittal plane ($\alpha = 90°$).

However, there was a large dispersion in the radius of curvature measurements (919 mm to 6823 mm) and the 3D orientation of the curvature (35.2° to 106.7°). This may be related to measurement errors, although the excellent inter-rater and intrarater reliability of our method makes us believe that these measurements are valid. This leaves us to wonder about anatomical variations and the use of custom or modular implants. In a 3D CT scan study, Chantarapanich et al. [7] found that the 2D radius of curvature in the sagittal plane was only one assessment of the 3D curvature, as it was a combination of sagittal and coronal curvatures. However, they did not determine the plane on this curvature. The radius of curvature of the main commercially available IM nails (1500 and 3000 mm) is much higher than the values found in our study and other published studies (600 to 2020 mm) [1–3,8,9]. This may explain the risk of anterior cortex breach that has been reported [7,10]. This can be reduced by placing the entry point [11] more anterior and more medial, or deviating the IM nail using the Poller screw system [2,12]. However, the latter studies only looked at this problem in the sagittal plane. The orientation of the curvature plane anteriorly and laterally may also explain the apparent external rotation of the nail, which modifies the direction of the distal locking screws. In practice, these findings led us to question the match between the femoral diaphysis and IM nails and long stems used for revision THA (Fig. 3). Preoperative planning for THA is most often done using a single coronal plane, which does not take the orientation of the diaphysis into account. The clinical consequences are likely relative given the excellent outcomes of current THA procedures. However, our findings highlight the complex anatomy of the femur in the axial plane and the relevance of 3D evaluations. Revision of THA stems, which is becoming more common, often requires long anatomical stems with diaphyseal fixation, which have the same problems as IM nails. In our practice, these implants have a tendency to rotate laterally (externally) when they are inserted in the shaft. This observation can be explained by our findings on the orientation of the diaphysis curvature plane. The consequence of this hyper-anteversion can be anterior instability, or an internal foot angle during walking.

In practice, this anteversion induced by the external rotation can be corrected:

- if a modular stem with separate metaphysis and diaphysis portions can be used, although there is a risk of implant fracture;
- by locking the desired anteversion with less press-fit; a smaller diameter one-piece stem with 3-point fixation [13,14] increases

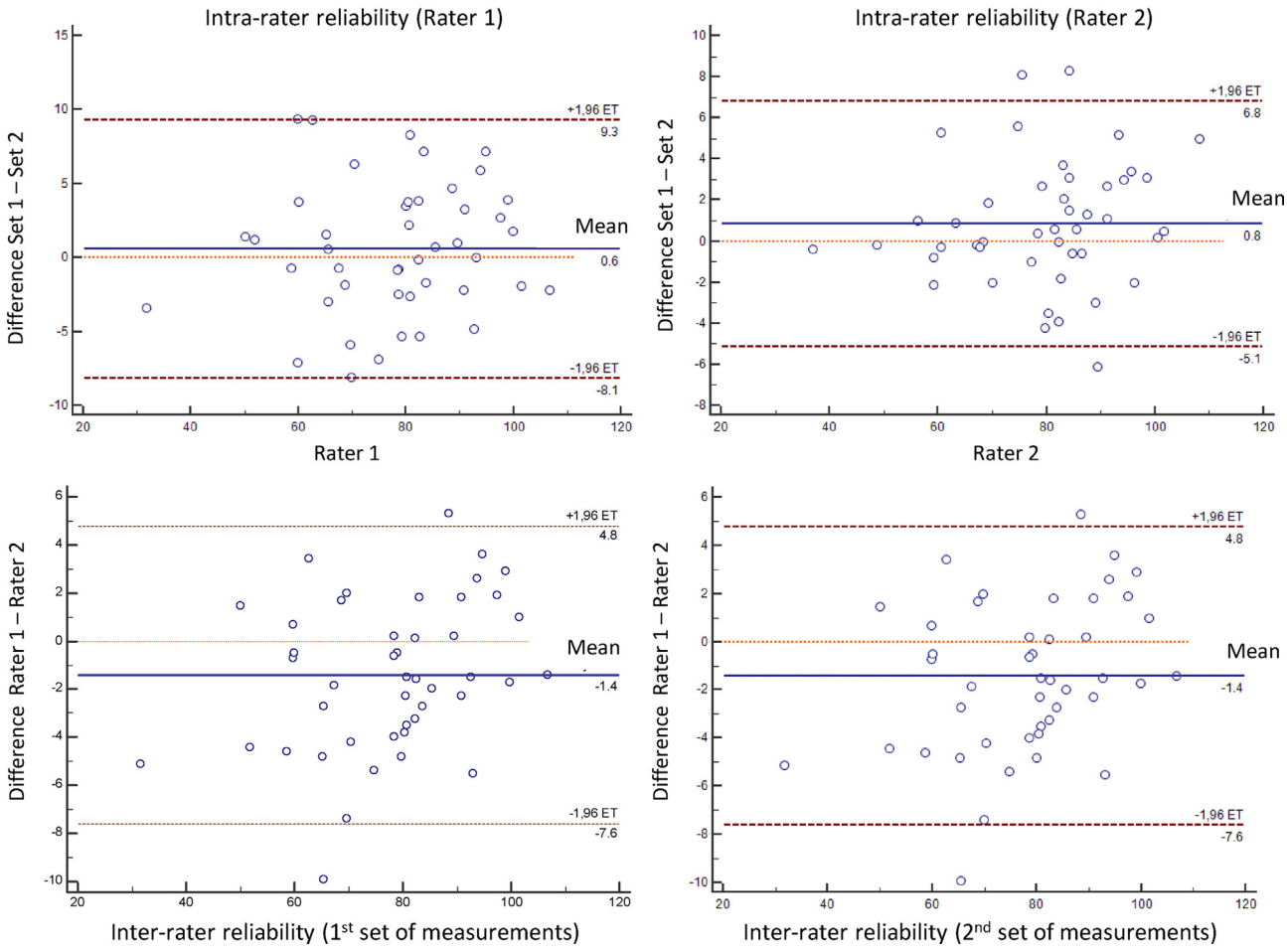

Fig. 4. Inter-rater and intra-rater correlation shown on Bland–Altman plots.

Table 4
Linear correlation between the orientation of the femoral curvature and the various anatomical parameters of the femur. R: correlation coefficient RSD: Relative standard deviation.

Correlation	Neck-shaft angle	Length	Valgus	Overall curvature
Orientation of femoral curvature	R = 0.172 R^2 = 0.02978 RSD = 9.0934	R = 0.095 R2 = 0.009090 RSD = 32.0947	R = 0.104 R^2 = 0.01092 RSD = 0.9191	R = 0.060 R^2 = 0.003625 RSD = 181.302

the risk of poor bone integration and of implant fracture in the long-term;
- by altering the design of long, one-piece stems if the aim is maximum press-fit, by taking into account the anteversion induced by the plane of the diaphyseal curvature, thus avoiding having excessive anteversion of the implant itself.

We found no correlation between the orientation of the curvature plane and the other anatomical parameters, possibly because the sample size was too small. (Table 4). The limitation of this study are the small number of femurs studied (45) when compared to certain published studies. Since no donor information was available, we had no anthropometric data to use. According to the literature [15–17] there appears to be a link between morphometric data and sex [18], age [19], ethnicity [20] and body mass index. Nevertheless, our sample was representative of the general population since the anatomical data followed a Gaussian distribution and the standard anatomical parameters were consisted with the literature for the neck-shaft angle, neck anteversion and femoral valgus angle [21] (Table 1). Published values for the radius of curvature in the sagittal plane range from 600 to 2020 mm. In our study, the values on the sagittal plane were similar with a radius of curvature of 907 mm ± 180 mm (558 to 1212 mm). Since all of these values were consistent with the literature, there is no evidence the various processing steps used to preserve this set of dry bones altered their dimensions. The sub-group analysis lacked statistical power. Nevertheless, our study provided a descriptive analysis of femur anatomy and more specifically the orientation of the anterolateral femoral curvature.

6. Conclusion

The anatomy of the femur has not yet been fully defined. This preliminary study showed that the orientation of the diaphyseal curvature is anterolateral, not sagittal. A similar study with a larger number of femur bones could better refine the results. Our findings should be taken into account when designing implants with diaphyseal fixation.

Disclosure of interest

The authors declare that they have no competing interest.

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Contributions

Antoine Schmitt: data acquisition and analysis of data, drafting of manuscript, measuring of femoral curvature orientation with the specific software, revising the manuscript and final approval of the data submitted.

Hoel Letissier: processing of images to perform data analysis and interpretation, measuring of femoral curvature orientation with the specific software, statistical analysis, help in drafting and revising the manuscript and final approval of the data.

Sergii Poltaretskyi: created the specific software to measure femoral curvature orientation, provided statistical software and helped in statistical analysis, revised the manuscript and did the final approval of the data submitted.

Damien Babusiaux: designed the study, revised the manuscript and did final approval of the data.

Philippe Rosset: designed and supervised the study, validation of the collected data and measurements, revised the manuscript and did final approval of the data submitted.

Louis-Romée Le Nail: designed and supervised the study, validation of the collected data and measurements, revised the manuscript and did final approval of the data submitted.

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