

Three-dimensional geometrical modelling of the femoral intramedullary cavity using ring cyclide model

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The femur has a natural bowing in the shaft region, which is unique in large bones.^[1] Any implant that will be put into femoral intramedullary cavity must be bowed. Any significant mismatch between the implant and femoral bowing may lead to complications.^[2-6]

The existing femoral shaft geometry studies are usually performed as a cross-sectional study^[7] or as a bowing measurement study.^[8] During the measurement of femoral bowing from the plain radiographs, the maximal femoral bowing axis is not always perpendicular to imaging direction.^[9] Hence, the measurements will be different than the actual values. On the other hand, cross-sectional studies are mostly related with structural anatomy. Three-dimensional (3D) modelling allows very accurate determination of the maximal bowing plane. The 3D design method is virtually equivalent to the direct measurement of the bisected dried femur *in vitro*.^[10] During pre-study evaluations, we noticed that intramedullary structure of femur shaft have a close resemblance to a geometrical model called ring cyclide (Figure 1).^[11] For this purpose, the femoral shaft intramedullary cavity was resembled into a chord of a ring cyclide (Figure 2), where the rotational radius was centered approximately at its smallest

ABSTRACT

Objectives: This study aims to investigate if geometrical modelling in addition to three-dimensional (3D) modelling will standardize models and allow performing mathematical calculations easily for the compatibility of femoral implant curvature.

Patients and methods: The study included 50 subjects (27 males, 23 females; mean age 55 years; range, 21 to 84 years). The femoral shaft intramedullary cavity was resembled into a chord of the ring cyclide, where the rotational radius was centered at its smallest radius. A 3D evaluation of the left femoral computed tomography data of the subjects was used to investigate the population parameters. The fitting was defined as being between the anterior and posterior border radii in the sagittal plane.

Results: The best fitting radius of implants was in between 90 to 99 cm in 72% of subjects in our sample. These radii values were lower than the mean intramedullary and cortical centerline radii which had only 62% and 50% fittings, respectively, among our population sample. The bowing radii and the smallest intramedullary width increased with the femoral length. These values were not affected by gender.

Conclusion: This modelling may have value for understanding femoral shaft intramedullary cavity geometry and may be a good tool to assess implant fitting.

Keywords: Anthropometry, bowing of the femur, humans, ring cyclide.

radius (Figure 3). Therefore, in this study, we aimed to investigate if geometrical modelling in addition to 3D modelling will standardize models and allow performing mathematical calculations easily for the compatibility of femoral implant curvature.^[12]

PATIENTS AND METHODS

This study was conducted at Faculty of Medicine Hospital, Pamukkale University between November 2015 and April 2016. The femoral computed tomography (CT) scans which were taken before in our institution for another reason between January 2011

Received: March 05, 2019

Accepted: September 26, 2019

Published online: March 02, 2020

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Doi: 10.5606/ehc.2020.65258

Citation: Akman A, Demirkan AF, Sabir Akkoyunlu N. Three-dimensional geometrical modelling of the femoral intramedullary cavity using ring cyclide model. Jt Dis Relat Surg 2020;31(1):14-19.

and December 2011 were retrospectively evaluated for suitability. *Inclusion criteria were* (i) use of a standard protocol while taking CT scans (12 kV, 195 mAs), (ii) the whole femur scan including adjacent joints being in a single field of vision, (iii) a scanning resolution of 512×512 pixels, (iv) the scanning being sequential and in a standard slice thickness of 5 mm thick and 5 mm apart, and (v) being aged more than 18 years. *Exclusion criteria were* excessive osteoporosis as a result of aging or previously taken chemotherapy or radiotherapy etc., previous operations, a present

deformity, metallic objects/implants at the lower extremity and/or pelvis, any tumoral lesion and/or metastatic lesion in lower extremity and/or pelvis. After application of inclusion and exclusion criteria, 50 consecutive patients (27 males, 23 females; mean age 55 years; range, 21 to 84 years) were chosen for a 3D evaluation. The study protocol was approved by the Pamukkale University, Denizli, Turkey, Ethics Committee. A written informed consent was obtained from each subject. The study was conducted in accordance with the principles of the Declaration of Helsinki.

By using CT data, models were created with the Mimics version 10 (Materialise, Leuven, Belgium) 3D modelling program, as previously described.^[2] The minimum thresholds used were in accordance with findings of Kang et al.^[13] Two masks for each of the left femur were created to separate bones effectively. After that, a corresponding ring cyclide was virtually defined for each femur model (Figures 3, 4). The intramedullary and cortical centerline bowing radii were also calculated by using the sagittal centers of the radii calculation points, as previously described by Harma et al.,^[14] however, the environment was 3D. The smallest coronal and sagittal intramedullary cavity widths were also found. Whole bone models were used to measure the axial femur length, which was the distance

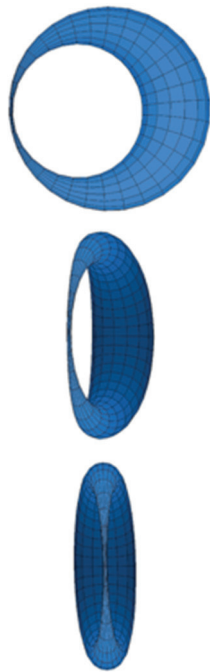


FIGURE 1. A ring cyclide's structure.

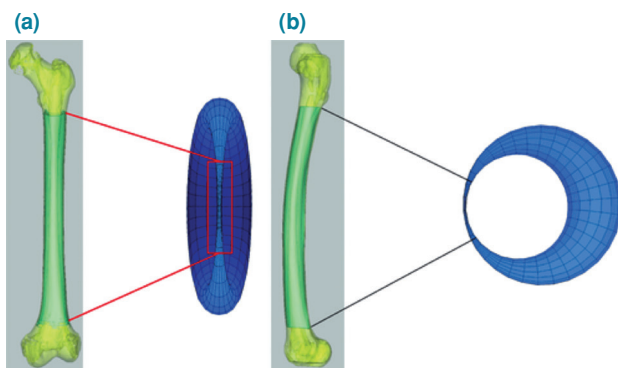


FIGURE 2. Structure of femoral shaft intramedullary cavity resembles a chord of ring cyclide. Three-dimensional whole bone model with superimposed shaft model and fitting ring cyclide in (a) coronal and (b) sagittal views.

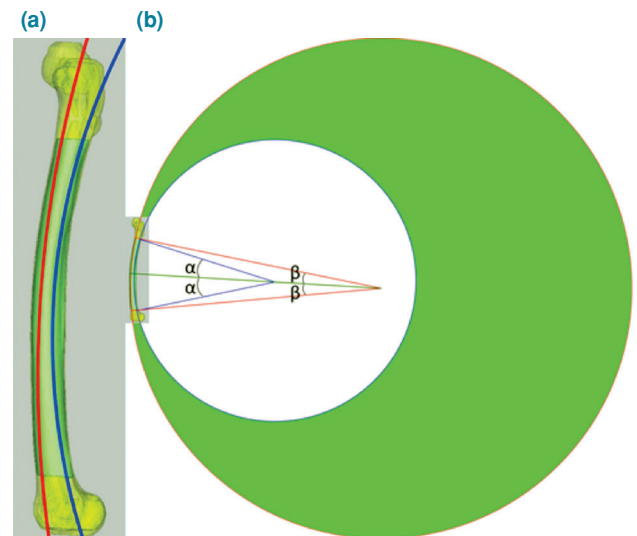


FIGURE 3. (a) Illustration of placement of anterior (blue circle) and posterior (red circle) border of fitting ring cyclide at its circular cross-section where rotational radius is centered -as opposing angles are same- approximately at its smallest. Green area illustrates fitting range in ring cyclide. (b) Close-up of fitting of borders.

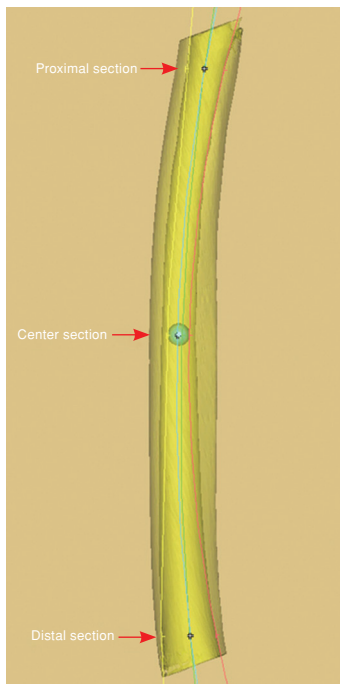


FIGURE 4. Measurement of fitting radii with three-point calculations. Yellow line is anterior border of fitting ring cyclide, red line is posterior border of fitting ring cyclide, light green line is centerline cortical radius, and light blue line is centerline intramedullary radius. Arrows showing sections that were used for three-point diameter determinations.

from the piriformis fossa to the intercondylar notch. The curved sagittal nail length and bowing angle were geometrically calculated as previously

described by Harma et al.^[14] Each measurement was repeated six times per subject, and the highest and lowest readings were discarded. The average of the four measurements was used. The thickness measurements of this study resulted in an error range between 5.3% and 10.8%, which is 3.2% and 7% for the best fitting radius. The groups were female and male femur models.

Statistical analysis

An independent samples t-test was used for the analysis of age- and gender-related data whereas a dependent samples paired t-test was used for the measurement of data by using Stata version 8 (Stata Corp., Texas, USA) software. The data were analyzed with a 95% confidence interval and a $p < 0.05$ was considered statistically significant. A priori power analysis was not performed; this was considered as a pilot study.

RESULTS

The bowing angles ranged between 12° to 36°, with a mean of 22.2°. The mean values were not statistically significantly different between males and females ($p = 0.756$).

The intramedullary centerline radius did not change with age, but the cortical centerline radius was decreased with age. Both radii did not differ by gender, but they were increased with an increase in the curved femoral length. The coronal and sagittal intramedullary cavity width were increased with an increase in the curved femoral length, but it did not alter with the changes to the intramedullary centerline radius ($p = 0.868$ and $p = 0.283$, respectively). The sagittal width did not change with age, but the

TABLE I

Summary of ages of subjects and measured parameters

Parameter	Mean±SD	Min-Max
Age (year)	55.2±14.6	21-84
Axial femoral length (cm)	38.2±3.5	26-45.6
Bowing angle* (degrees)	22.2±5	12-36
Curved femoral length* (cm)	38.6±3.6	26.2-46
The smallest intramedullary cavity width* (cm)	13.7±2.6	8-19.1
The smallest coronal intramedullary cavity width (cm)	11.2±2.1	6.7-15.2
The anterior border radius* (cm)	147.8±56	73.3-288.6
The cortical centerline radius* (cm)	137.9±44.4	68.8-262.5
The intramedullary centerline radius* (cm)	107.4±28.9	61.1-195
The posterior border radius* (cm)	78.7±19.4	45.8-151.6

SD: Standard deviation; Min: Minimum; Max: Maximum; * In sagittal plane.

Parameter	Age	Gender	Curved femoral length
The smallest sagittal intramedullary cavity width	0.089	<0.001*	<0.001*
The smallest coronal intramedullary cavity width	<0.001*	<0.001*	<0.001*
The cortical centerline radius	0.004*	0.336	0.027*
The intramedullary centerline radius	0.108	0.783	0.012*

* Accepted as statistically significant.

coronal width was increased with age. Males had a larger cavity width in both measurements (Table I).

To suggest whether implant fitting at the mean intramedullary centerline radius was better or not, fitting of an implant with a radius of 107.4 cm was evaluated and the fitting was determined to be worse (62%) ($p=0.024$). The fitting at the mean cortical intramedullary centerline radius of 137.9 cm had much lower fitting (50%), but was not different from the previous ($p=0.110$) (Tables I and II). The best fitting implant radius was seemed to be around 90 to 99 cm in a fitting range analysis with 72% fitting. The fitting of the intramedullary centerline radius was worse than the best fitting range radii ($p=0.004$ for 90 cm and $p=0.006$ for 99 cm) (Figure 5 and Table III).

DISCUSSION

Our design showed that for defining a corresponding ring cyclide model of femoral intramedullary cavity, just three parameters are needed which are the anterior border radius, the posterior border radius and the smallest cavity width. This study also resulted in the establishment of two important parameters for

curvature fitting analysis, which were the largest fitting radius (the anterior border radius) and the smallest fitting radius (the posterior border radius). The difference between them formed the fitting range for a person. As expected, the best fitting curvature was close to the mean of intramedullary bowing. However, the sample results in this study showed that the best fitting curvature was more bowed than that with a size of 90 to 99 cm but was limited to 72% of subjects in our sample. Femoral intramedullary cavity sizes have wide variation for optimal implant curvature fitting in the population and a single curvature size may not be sufficient (Figure 5).

The bowing radii (intramedullary or cortical) and the smallest intramedullary width (sagittal or coronal) were increased with the femoral length in this sample. These values were not affected by gender. The findings are comparable with those of Maratt et al.^[8] who postulate that femoral length is important for intramedullary bowing, while aging or gender have no effect. There is an increase in coronal intramedullary cavity width with aging; however, there is no statistically significantly different change in sagittal width. These findings are in concordance with those of Feik et al.^[7] who pointed out that aging causes a differential circumferential modeling and the effect of osteoporosis is mainly on the anterior cortex. The intramedullary bowing does not have a

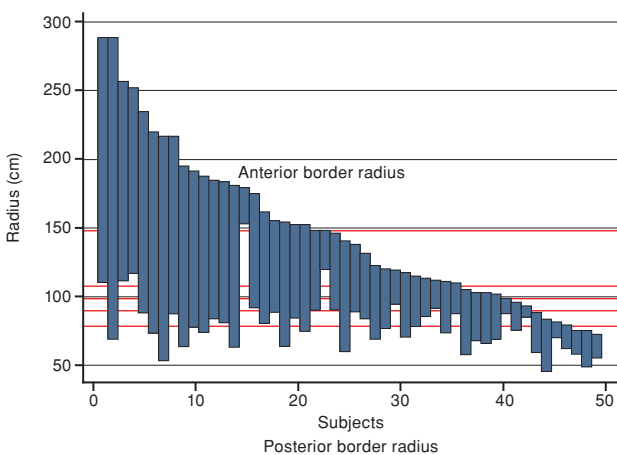


FIGURE 5. Comparative fittings between largest and smallest fitting radii of subjects: Fitting range analysis. (Subjects are in descending order according to anterior border radius.)

Radius (cm)	Fitting subject & ratio	
	n	%
78.7	23	46
90	36	72
99	36	72
107.4	32	62
137.9	25	50
147.8	21	42

statistically significant correlation with aging, but the cortical bowing decreases similar to findings of Maratt et al.^[8] suggesting that there is no change of intramedullary bowing with aging.

The previously published results of femoral bowing range between 109 and 144 cm,^[3,4,6,15] however, there are differences in the measurement techniques. In a recent study performed by Maratt et al.,^[8] the mean medullary radius of curvature of the femur was found as 110.4 cm in Caucasian Americans, which was 122.2 in African Americans and 101.1 in Asian Americans. The mean inner anterior cortex radius of curvature of the femur was found as 145.5 cm, 154.5 cm and 129.7 cm, respectively. Our results were comparable with them, particularly with Caucasian Americans. In a study by Buford et al.,^[2] in 19 cadaveric femur specimens (largely Caucasians) using a similar protocol to that used in this study, the anterior medullary canal radius of the curvature was shown to have a mean of 147.8 cm (calculated from given data) which is in accordance with this study. In a recent study with 3D design, Schmutz et al.^[16] found mean radius of curvature in the natural 3D antecurvature plane as 97.4 cm for Caucasians which was close to our findings (107.4 cm in our study). However, a digital lateral radiogram work of Harma et al.^[14] have reported a value of 77.2 cm in Anatolian people which remains the lowest value reported before in the literature for Caucasians.^[16] In another study, Biçer et al.^[17] found a mean of 100 (one observer) and 120 cm (two observers) for anterior cortex curvature at 84 cadaveric femora of Anatolian people with no gender discrimination.

The established parameters for defining a corresponding ring cyclide model for a femoral intramedullary cavity can be calculated from the plain radiograms if magnification is standardized. However, the major problem will remain, which is the maximal bowing plane in that the circular cross-section of the ring cyclide lies. Its determination before taking radiograms will be very difficult particularly in subjects with coronal femoral bowing. However, 3D modelling allows accurate determination of the maximal bowing plane. The 3D modelling method is virtually equivalent to the direct measurement of the bisected dried femur *in vitro*.^[14]

The limitations of this study are the subjective nature of reference point selection for the measurement of bowing radii and distances and its inherent error.^[2] Additionally, it is conceivable that reconstruction artefacts occur in the process of creating the 3D-CT models.^[2] The sample size of

this study may be considered small for definitive conclusion. Furthermore, the sample was derived from 5 mm-thick and 5 mm-apart sequential CT data, which reduce the resolution.

In conclusion, the design of this study which is based on a ring cyclide model may have an important value for understanding femoral shaft intramedullary cavity geometry and may be a good tool to assess implant fitting for population studies. Furthermore, the method of modeling may lead to a new way of thinking in the interpretation of femoral geometry.

Declaration of conflicting interests

The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding

The authors received no financial support for the research and/or authorship of this article.

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