

3D Geometrical Assessment of Femoral Curvature: A Reverse Engineering Technique

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Objective: Investigate the 2D/3D geometry of femoral curvature and femoral length using the advanced technique of computerized tomography combined with reverse engineering techniques.

Material and Method: The present study was performed using reverse engineering technique based on CT data of 99 cadaveric femora. The femur was divided into three segments, proximal, mid-shaft, and distal regions by defining 35% and 65% of the femoral total length as a boundary of each region. The intramedullary canal in the mid-shaft region was mainly extracted to determine the set of circular center, which could consequence to approximate the 3D femoral radius of curvature using the 3D least square best fit. The 3D femoral curvature was then projected into A-P and M-L directions to investigate the correlation of 2D/3D femoral curvature as normal radiographic images.

Results: It was found that the average 3D Thai femoral curvature was 895.46-mm (SD = 238.06) and the average femoral total length is 421.96-mm (SD = 27.61). In addition, the 2D femoral curvature derived from sagittal radiographic image can be used to determine the 3D femoral curvature with this equation: $R_{3D} = R_{Sagittal} + 3.67$ with $r = 0.987$.

Conclusion: This described technique is a non-destructive method that can effectively assess the internal/external 3D geometric data of the femur. The obtained data is useful to develop a proper design of prosthesis that required inserting into the intramedullary canal. From the present study, it can be concluded that the 2D_{Sagittal} femoral curvature derived from standard radiographic image can be represented for the 3D femoral curvature.

Keywords: Femoral curvature, Femoral length, Intramedullary canal, Thai femur

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Closed intramedullary nailing is widely accepted as a treatment of choice to stabilize the femoral fractures⁽¹⁻³⁾. The intramedullary nail is inserted into the intramedullary canal to stabilize the bony fragments. It has been reported by several authors that inappropriate curvature and length of the intramedullary device may create clinical complications

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from mismatching between the implant and femoral medulla⁽⁴⁾. If the mismatch cannot be compensated by proper reaming, it may lead to the certain critical complications including; firstly, the improper position of nail that may lead to secondary fracture or bursting of femur, secondly, the weakening of the bone from overreaming of the femoral cortex for accommodating the nail into the medulla⁽⁴⁻⁶⁾.

In the previous reports, the studies on the femoral curvature, are mostly based on the two-dimensional radiographic image, manual measurement, or

destructive method, which may not be accurate for the evaluation of the intramedullary canal^(7,8). The present study aimed to apply the advanced three-dimensional assessment technique using computerized tomographic (CT) image integrated with the reverse engineering to analyze the femoral geometric data as well as establish the correlation among 2D femoral curvature which may be obtained from the radiographic image to that of 3D femoral curvature. This technique could lead to a better result, better accuracy in three-dimensions and easy for the surgeons to approximate the 3D femoral curvature where needed. Consequently, the proper design of the femoral fracture fixation devices for the certain population can be designed to reduce the mismatching problem.

Material and Method

Ninety-nine Thai cadaveric femora from the Department of Anatomy, Faculty of Medicine Siriraj Hospital were used for the present study. A set of nine femora was used in each CT scan with a Philips spiral CT scanner (Tomoscan AV). In the proximal and distal regions of the femur, CT scan acquisition was performed with 3 mm slice thickness and reconstruction was done with 1 mm interpolated slice thickness. For the femoral shaft, CT scan acquisition was performed with 10 mm slice thickness and reconstruction was done with 5 mm interpolated slice thickness⁽⁹⁾.

Data acquisition

After scanning, the CT data set previously scanned was imported to the medical imaging combined with reverse engineering software (Mimic and 3Matic, Materialise N.V., Belgium) to reconstruct 3D model to obtain the proper shape of the femur by developing the 3D graphic model of each femur using thresholding and region growing function. In order to optimize the geometry of both outer and cortical region, two thresholding values were applied: a lower thresholding value was applied to extract the outer cortical surface in including all proximal components and distal region; a higher thresholding was applied to extract the inner cortical surface of the intramedullary canal as illustrated in Fig. 2⁽⁹⁾. The resulting optimized inner and outer contours were then exported as STL format (Stereo-Lithography).

Three-dimensional measurement of femoral curvature and femoral length

Each femur model obtained from the previous described technique was divided into three segments,

proximal, mid-shaft, and distal by defining 35% and 65% of femoral total length as segmentation's rules^(10,11). The intramedullary canal in mid-shaft was extracted with 1-mm slice interval. The "fit circle" function, which was the optimal least square circular approximation to a 2D point cloud, were applied to point cloud in each cross-section. The "fit arc" function, which was the optimal least square arc approximation to a 3D point cloud, were applied to a set of intramedullary canal center obtained previously, in order to obtain 3D arc which was a 3D femoral curvature as shown in Fig. 1.

Two-dimensional measurement of femoral curvature and correlation to 3D femoral curvature

The prediction of the 3D femoral curvature based on 2D femoral curvature, the 3D femoral curvature was projected on coronal and sagittal plane to obtain the 2D radius curvature. The "multiple regression" was applied to investigate the correlation among 2D curvature on coronal and sagittal plane (Designated as $R_{Sagittal}$ and $R_{Coronal}$, respectively) to that 3D femoral curvature (Fig. 2).

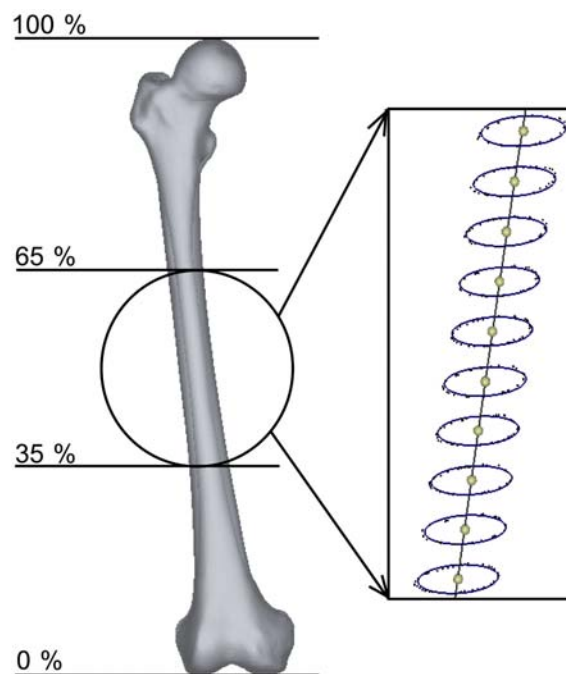


Fig. 1 The 2D best fit circle in mid-shaft region for approximation the femoral radius of curvature and mid-shaft axis

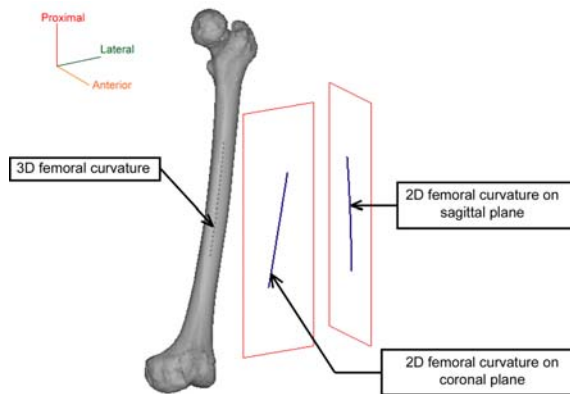


Fig. 2 The projection of 3D femoral curvature along A-P and M-L direction

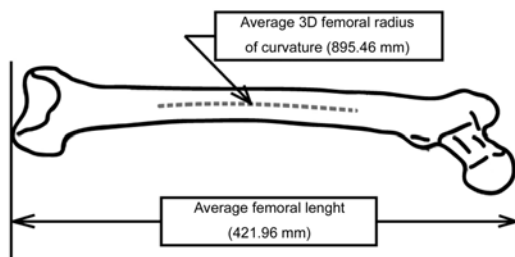


Fig. 3 The average 3D femoral radius of curvature and femoral length

Table 1. The average 3D femoral curvature and length (unit: mm, n = 99)

Parameters	Mean	Stdev	Max	Min
Total length	421.96	27.61	501.84	356.06
3D femoral radius of curvature	895.46	238.06	1627.70	475.79

Table 2. Average 2D femoral curvature (unit: mm, n = 99)

Parameters	Mean	Stdev	Max	Min
2D femoral curvature on coronal plane	4854.55	2660.98	15666.34	532.35
2D femoral curvature on sagittal plane	891.46	234.87	1684.70	497.05

Table 3. Typical values of correlations coefficients for pairwise correlation of Thai femora (n = 99)

Variables	Correlation Coefficient (r)	p-value
3D vs. R_{Coronal}	0.352	-
3D vs. R_{Sagittal}	0.987	<0.06
3D vs. R_{Coronal} and R_{Sagittal}	0.989	<0.11
R_{Coronal} vs. R_{Sagittal}	0.283	-

Results

Measurement on 3D femoral curvature and length

The results showed that the average 3D femoral curvature was 895.46-mm with 238.06-mm standard deviation while the femoral total length was 421.96-mm with 27.61-mm standard deviation as illustrated in Table 1 and Fig. 3.

Measurement on 2D femoral curvature and correlation among measured parameters

The results showed that the average 2D femoral curvature coronal plane was 4854.55-mm with 2660.98-mm standard deviation while the average 2D femoral curvature on sagittal plane was 891.46-mm with 234.87-mm standard deviation as illustrated in Table 2.

The results in Table 3 represent the correlation among parameters, 3D femoral curvature, 2D femoral curvature on coronal and 2D femoral curvature on sagittal plane.

Discussions

Method of data assessment

The present study presented an advanced method of 3-dimensional integrated CAD/CAM technique in evaluation of actual femoral curvature in 3D and femoral length. To the authors' knowledge, no previous reports have described such a method of evaluation. The data from the previous report may not be directly compared regarding the different measurement methods; the measurement technique was mostly done on the outer femur geometry and even when the measurement was done based on the cavity of intramedullary canal, 2D assessment radiography technique or direct measurement with destructive method was applied⁽⁷⁻⁹⁾.

Using this 3D assessment technique, the advantages include:

- a) The allowance to examine the intramedullary canal without destroying the specimen⁽⁹⁾.

b) The ability to access to the better accuracy for determining actual three-dimension of the radius of curvature based on intramedullary canal. For three-dimensional method integrated CAD/CAM technique, the set of center point in the mid-shaft region as a single set, but for 2D assessment technique the combination of position of each canal center on 2D radiographic image may lead to some errors.

c) The slice interval using CAD/CAM technique enables the authors to divide the intramedullary canal less than 1 millimeter, while the other techniques may have critical limitations.

Correlation

According to Table 3, it has revealed that 2D projection image of femoral curvature on coronal plane is less significant compared to sagittal plane. Although, the “multiple regression” correlation coefficient (r) of 2D femoral curvature on both planes approximated to the 3D femoral curvature is up to 0.989, only the 2D femoral curvature on the sagittal plane with the correlation coefficient 0.987 is accurate enough to predict the 3D femoral curvature. Regarding the “linear regression” of $2D_{Sagittal}$ and 3D femoral curvature, the scatter plot with 95% confidence interval is shown in Fig. 4. The equation to calculate the 3D femoral curvature based on the $2D_{Sagittal}$ femoral curvature is $R_{3D} = R_{Sagittal} + 3.67$.

Advantage for implant design

The 3D femoral curvature is useful for proper design and dimension of the femoral fracture fixation

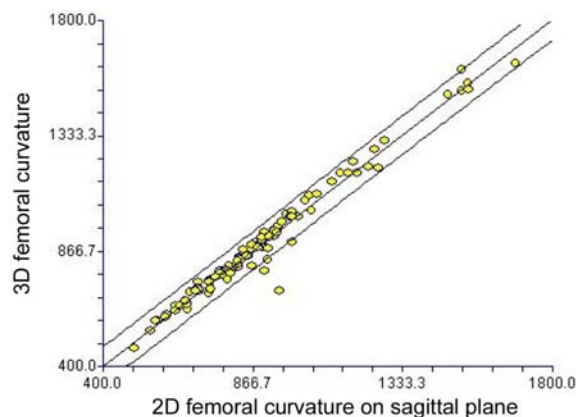


Fig. 4 The relationship between the radius of curvature in 2D image in sagittal plane and from 3D assessment

device, especially the intramedullary nail. This will help in reducing the risk or complication related to the mismatching of the device dimension and shape to that of the femoral bone. Consequently, the over-reaming of the femoral canal to compensate mismatching can also be avoided. This phenomenon has been proven by Hipp et al⁽⁶⁾, the more cortical bone reaming, the more weakening the intact bone strength.

Conclusion

With use of the computerized tomographic (CT) and reverse engineering technique, it enables us to determine the inner and outer morphometric data of the femur without the destructive method. The precision and accuracy of femoral curvature and total length can be obtained from this technique as well. The 3D femoral curvature obtained from this technique is useful in designing the implant, especially the intramedullary nail devices based on the Thai morphometric data. Regarding the equation, it can be concluded that the $2D_{Sagittal}$ femoral curvature measured from the conventional 2D radiographic image can be represented for the 3D femoral curvature with very small error.

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การศึกษารัศมีความโค้งของกระดูกต้นขาคนไทยโดยใช้วิศวกรรมย้อนรอยในการจำลองรูปทรงสามมิติ

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วัตถุประสงค์: งานวิจัยนี้ทำการศึกษารัศมีความโค้งของกระดูกต้นขาในแนวสองมิติและสามมิติและความยาวทั้งหมดของกระดูกต้นขาด้วยเทคโนโลยีขั้นสูงจากภาพถ่ายทางการแพทย์จากเครื่องเอกซเรย์คอมพิวเตอร์ (CT Scanner) และเทคโนโลยีวิศวกรรมย้อนรอย (Reverse Engineering)

วัสดุและวิธีการ: การศึกษาเริ่มจากการแบ่งกระดูกต้นขาออกเป็น 3 ส่วน โดยใช้เกณฑ์ร้อยละ 35 และ 65 ของความยาวกระดูกต้นขาทั้งหมดในการแบ่งเป็น ส่วนต้น ส่วนกลาง และส่วนปลาย จากนั้นนำกระดูกต้นขาสองส่วนกลางมาตัดแบ่งตามภาคตัดขวางเป็นส่วนย่อย ๆ ตามที่ต้องการ และทำการคำนวณเส้นรอบรูปของภาคตัดขวางดังกล่าวเป็นวงกลม เพื่อให้ได้จุดศูนย์กลางของวงกลมแต่ละวง จากนั้นจะนำจุดศูนย์กลางเหล่านั้นมาทำการคำนวณเพื่อหารัศมีความโค้งของกระดูกต้นขาในแนวสามมิติโดยใช้วิธีกำลังสองน้อยที่สุด แล้วจึงทำการฉายรัศมีความโค้งในแนวสามมิติดังกล่าวไปในแนวสองมิติในทิศทางด้านหน้า-ด้านหลัง (A-P) และทิศทางด้านข้างใน-ข้างนอก (M-L) เพื่อศึกษาความสัมพันธ์ระหว่างรัศมีความโค้งในแนวสองมิติและสามมิติ

ผลการศึกษา: จากการศึกษาพบว่ากระดูกต้นขาของคนไทยจำนวน 99 ชิ้นงานตัวอย่าง พบว่ามีรัศมีความโค้งในแนวสามมิติเฉลี่ย 895.46 มิลลิเมตร ด้วยค่าเบี่ยงเบนมาตรฐาน 238.06 มิลลิเมตร และมีความยาวเฉลี่ย 421.96 มิลลิเมตร ด้วยค่าเบี่ยงเบนมาตรฐาน 27.61 ในขั้นถัดไป ภาพรัศมีความโค้งสองมิติ ทิศทางด้านใน-ด้านนอก (M-L) เพียงมุมมองเดียว สามารถใช้บอกรัศมี ความโค้งในแนวสามมิติได้ โดยใช้สมการ $R_{3D} = R_{M-L} + 3.67$ ($r = 0.987$)

สรุป: ด้วยเทคโนโลยีดังกล่าวนี้ทำให้สามารถตรวจสอบและวิเคราะห์ข้อมูลทางเรขาคณิตทั้งภายในและภายนอกของกระดูกต้นขาโดยไม่ทำลายชิ้นส่วนกระดูกที่ใช้ศึกษา และรัศมีความโค้งที่ได้มาเป็นประโยชน์ในการพัฒนาและออกแบบอุปกรณ์ตามยึดตรึงกระดูกที่ต้องใช้สอดเข้าสู่โพรงกระดูกได้เป็นอย่างดีมาก จากการศึกษาสรุปได้ว่ารัศมีความโค้งในแนวสองมิติจากมุมมองในทิศทางด้านใน-ด้านนอก (M-L) ด้วยภาพถ่ายเอกซเรย์ทั่วไป สามารถนำมาใช้แทนรัศมีความโค้งในแนวสามมิติได้เนื่องจากมีความคลาดเคลื่อนน้อยมาก