2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
July 6-11, 2014, Beijing, China

An Automated Determination of Blumensaat Line Using Fuzzy System Based on Physician Experience from Femur CT Image

Yosuke Uozumi, Kouki Nagamune, Naoki Nakano, Kanto Nagai, Yuichiro Nishizawa, Yuichi Hoshino, Takehiko Matsushita, Ryosuke Kuroda, and Masahiro Kurosaka

***Abstract*— Blumensaat line is one of the most commonly used direct methods for the assessment of femoral diagnosis and therapy. Currently, the Blumensaat line is determined manually. Therefore, diversity of the determination happens due to the subjective judgment error. To reduce the diversity, we propose an automated determination of Blumensaat line by using fuzzy logic based on physician knowledge from femur multi-detector row computerized tomography (MDCT) image. The experiment employed six different knees. The six femurs were evaluated by the manual and proposed method. In the results, the length of Blumensaat line was 24.12 ± 3.23 mm (manual) and 23.90 ± 2.41 mm (automated). The angle between Blumensaat line and bone axis was 27.80 ± 6.08 degrees (manual) and 30.68 ± 5.76 degrees (automated). There was no significant difference between the manual and proposed method. We concluded that the proposed method has enough accuracy as same as expert.**

I. Introduction

BLUMENSAAT line that was described by Blumensaat in 1938 [1] is one of the most commonly used direct methods for the assessment of femoral diagnosis and therapy. Fig. 1. shows Blumensaat line in human knee joint, which uses the roof of the intercondylar notch as a reference line. The Blumensaat line, is a faint condensed line on the lateral radiograph of the knee joint in the condylar massif of the femur. It represents the tangentially contacting part of the roof in the intercondylar fossa.

In the past studies for the knee joint, it has been reported that Blumensaat line is widely used as landmark of the diagnosis and treatment of the following, tibial osteotomy [2], autologous transfer of the posterior femoral condyle [3], posterior cruciate ligament reconstructions [4], lateral collateral ligament reconstruction [5], and medial patellofemoral ligament reconstruction [6]. It has been reported particularly many that studies about patellar height [7] and anterior cruciate ligament reconstructions [8].

Although Blumensaat line is one of the most commonly used direct methods for the assessment of femoral diagnosis and therapy, to the best of our knowledge, no study reports the automatical and three-dimensional analysis of Blumensaat line. In the past study using non-automatic method as expert manual, the determination method of Blumensaat line has problems. The problems are massive measurement time, and subjective judgment error such as within-subject differences and between-subject variability. An automated and quantitative determination of Blumensaat line needs to be examined in detail.

To reduce massive measurement time and subjective judgment error, we propose an automated determination of Blumensaat line by using fuzzy logic based on physician experiment from femur multi-detector row computerized tomography (MDCT) image.

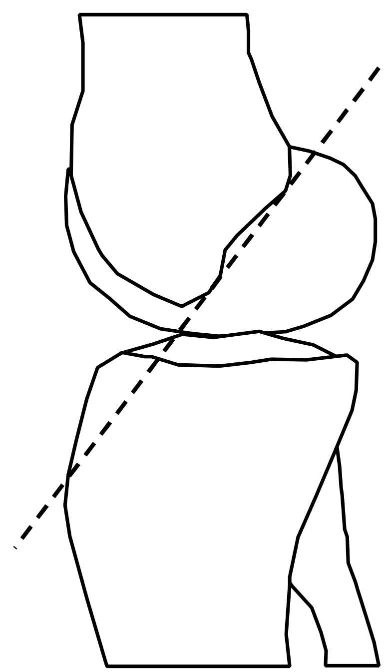


Fig. 1. Blumensaat line in human knee joint. Upper bone is the femur. Lower bone is the tibia and the fibular. Blumensaat line is a reference line based on roof of intercondylar notch of the femur.

II. Preliminary

A. Patients Selection

The number of patients is six femurs. The age of patients is 35 ± 11 (21 - 50). The sex of patients is four males and two females. They have informed consent based on the Institutional Review Board.

Y. Uozumi is with Department of Advanced Interdisciplinary Science and Techonology, Graduate School of Engineering, University of Fukui, Fukui, Japan (e-mail: uozumi@me.his.u-fukui.ac.jp).

K. Nagamune is with Department of Human and Artificial Intelligence Systems, Graduate School of Engineering, University of Fukui, Fukui, Japan (corresponding author to provide phone/fax: +81-776-27-8037; e-mail: nagamune@u-fukui.ac.jp).

N. Nakano, K. Nagai, Y. Nishizawa, Y. Hoshino, T. Matsushita, R. Kuroda, and M. Kurosaka are with Kobe University Graduate School of Medicine, Kobe, Japan.

Y. Hoshino is with Kaisei Hospital, Kobe, Japan.

B. MDCT Image

The MDCT has higher resolution and shorter acquistion time than traditional CT. The MDCT image has the coordinate axes and three planes (Fig. 2). The anatomical planes in the coordinate axes of MDCT image are the axial (X×Y), coronal (X×Z), and sagittal (Y×Z) planes, respectively. The anatomical directions in the coordinate axes of the MDCT image are the anterior (toward the front), posterior (toward the back), medial (toward the inside of the body), lateral (toward the outside of the body), proximal (toward the center of the body), and distal (toward the extremity of the body) directions, respectively. The acquisition parameters were as follows. The resolution on a slice was the 512×512 (X×Y) voxels. The color depth was 16 bits. The thickness of slice was 1.0 mm. The total number of slice was 200. The range of image along z-axis was 50 mm proximal from the femoral epicondyles and 50 mm distal from the tibial tubercles.

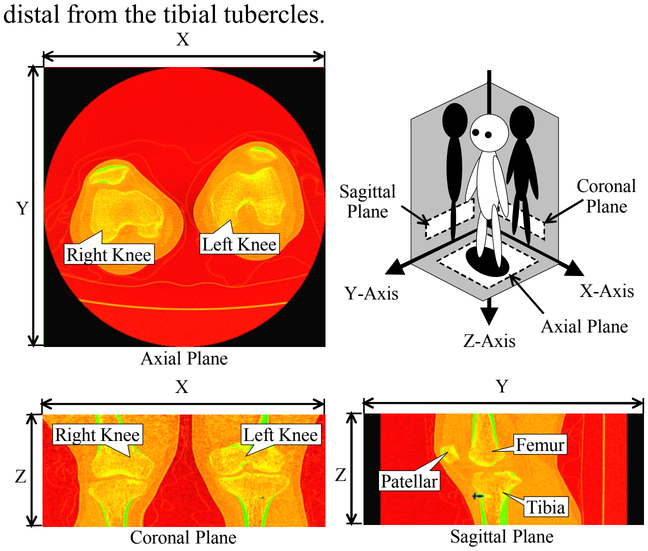


Fig. 2. Anatomical planes in coordinate axes of MDCT image.

III. Method

The proposed method has three steps. The first step corrects the femur lean in MDCT image. The second step extracts the femoral bone contour. The third step analyzes the Blumensaat line of the femoral bone.

A. Correction of Femoral Lean Error

The femur in a raw MDCT image usually has an inclination. The inclination causes an error of the following analysis, and requires to be modified based on a diaphysis axis of the femoral bone. In our previous method[17]-[24], the diaphysis axis was defined and determined, and the femur bone region was segmented. The femur in a slice of the proximal side comparatively shapes almost in a circle. A center point of the circle is detected. Then, the center points make the diaphysis axis (Fig. 3). The diaphysis axis **DA** is expressed as :

$$\mathbf{DA} = \mathbf{DS} - \mathbf{PS} \tag{1}$$

where **DS** and **PS** are position vectors of center point of distal and proximal in the femoral diaphysis, respectively.

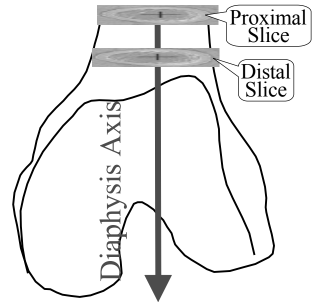


Fig. 3. Determination of diaphysis axis of femoral bone.

The raw image has an inclination of the femur (Fig. 4 (a)). Since the inclination has an unintended effect for the determination of an anatomical reference points, the inclination should be modified so that the following process works well. The diaphysis axis modifies a lean of the femur by image rotation (Fig. 4 (b)). The femoral image rotates by affine transformation. The affine transformation is expressed as :

$$\mathbf{I}' = \mathbf{RI} \tag{2}$$

where $\mathbf{I}'$ and $\mathbf{I}$ are the femoral images of before and after rotation. R is a rotational matrix, and is expressed as :

$$\mathbf{R} = \begin{bmatrix} C_2C_3 & C_1S_3 + S_1S_2C_3 & S_1S_3 - C_1S_2C_3 \\ -C_2S_3 & C_1C_3 - S_1S_2S_3 & S_1C_3 + C_1S_2S_3 \\ S_2 & -S_1C_2 & C_1C_2 \end{bmatrix} \tag{3}$$

where S_1, S_2, and S_3 are sine of a_1, a_2, and a_3, respectively. C_1, C_2, and C_3 are cosine of a_1, a_2, and a_3, respectively. The a_1, a_2, and a_3 are three rotational angles around the x-, y- and z- axes, respectively.

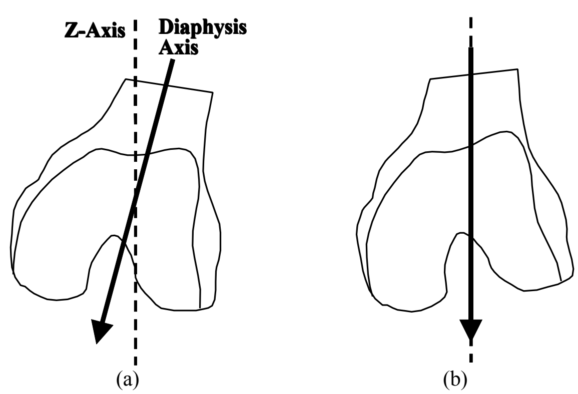


Fig. 4. Correction of femoral lean error. (a) Before and (b) after of rotation to fit diaphysis axis of femoral bone and z-axis of MDCT image.

B. Extraction of Bone Contour

The raw femur image (Fig. 5 (a)) is binarized (Fig. 5 (b)) and closed (Fig. 5 (c)) by same method of the previous method [17, 18]. The femur contour is extracted by using general contour tracing processing (Fig. 5 (d)). Also a contour of the femur bone is extracted from the closed bone region (Fig. 5 (c)) by the contour tracing processing (Fig. 5 (d)).

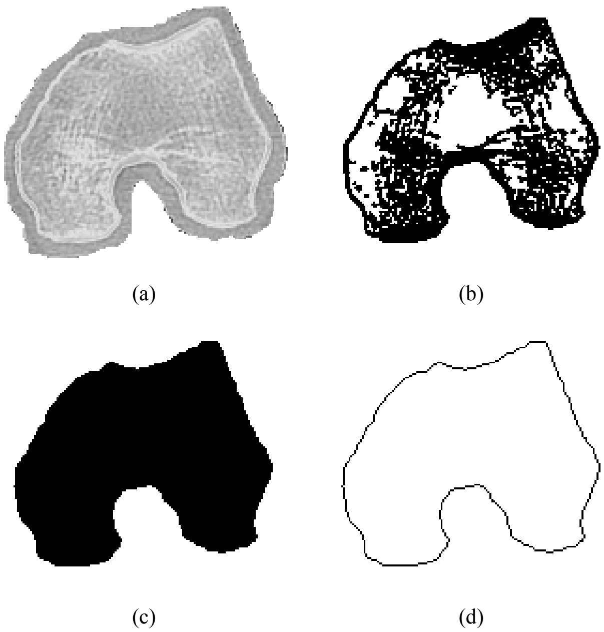


Fig. 5. Femoral contour processing. (a) raw, (b) binarization, (c) closing, and (d) contour.

C. Analysis of Blumensaat line

Fig. 6. shows a measurement method for Blumensaat line. Blumensaat line is a line connecting two landmark positions such as anterior distal $\mathbf{L}_{AD}$ and posterior proximal $\mathbf{L}_{PP}$. Fig. 7. shows information to determine Blumensaat line defined by us. Anterior distal and posterior proximal landmarks has three characteristic anatomical information that are a convex shape, distal and posterior positions. In this study, the landmark positions of anterior distal $\mathbf{L}_{AD}$ and posterior proximal $\mathbf{L}_{PP}$ are determined from three characteristic anatomical information based on physician experience.

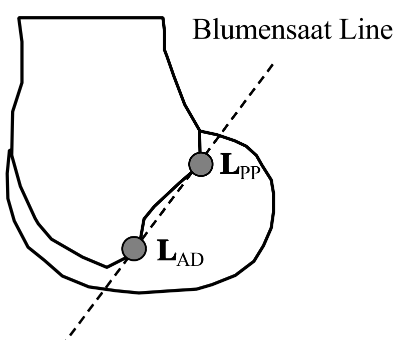


Fig. 6. Measurement method for Blumensaat line defined by us. Blumensaat line is a line connecting two landmark positions such as anterior distal $\mathbf{L}_{AD}$ and posterior proximal $\mathbf{L}_{PP}$.

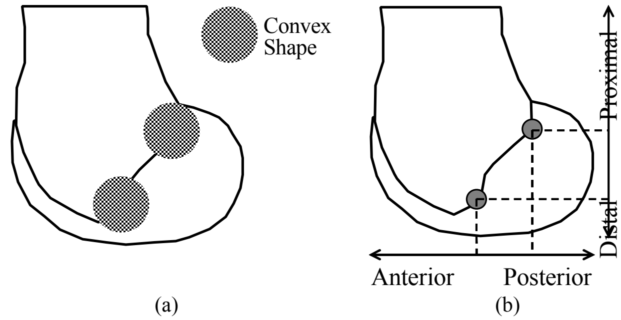


Fig. 7. Information of physician experience to determine Blumensaat line defined by us. Anterior distal and posterior proximal landmarks have (a) a convex shape, (b) distal and posterior positions.

Fig. 8. shows a direction of contour tracing for femoral cross-sectional contour on sagittal plane. Starting point is defined the most proximal and anterior point on femoral cross-sectional contour. The contour line is determined by general contour tracing processing. Curvature of the contour line is calculated by an inverse trig function(Fig. 9.). The inverse trig function represents a bending state of the digital line shape, and is widely used in the recognition of various types in general. The inverse trig function $\theta(p)$ is expressed as :

$$\theta(p) = \arccos\left(\frac{\mathbf{c}_{\mathrm{p}}(p)\cdot\mathbf{c}_{\mathrm{n}}(p)}{\left|\mathbf{c}_{\mathrm{p}}(p)\right|\left|\mathbf{c}_{\mathrm{n}}(p)\right|}\right), \tag{4}$$

where p is a point on the femoral cross-sectional contour on sagittal plane, and is defined over $0 \le p \le p_{limit}$. p_{limit} is a limit of the perimeter number. q which is calculation range, is set experimentally as 20 in this study. $\mathbf{c}(p)$ is a position vector on the femur contour. $\theta(p)$ is defined over $-180° \le \theta(p) \le 180°$. Directional vectors $\mathbf{c}_{\mathrm{p}}(p)$ and $\mathbf{c}_{\mathrm{n}}(p)$ are given by

$$\begin{cases}\mathbf{c}_{\mathrm{p}}(p) = \mathbf{c}(p+q) - \mathbf{c}(p)\\ \mathbf{c}_{\mathrm{n}}(p) = \mathbf{c}(p) - \mathbf{c}(p-q)\end{cases}. \tag{5}$$

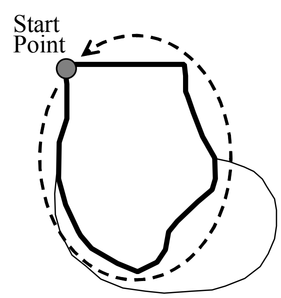


Fig. 8. Direction of contour tracing for femoral cross-sectional contour on sagittal plane.

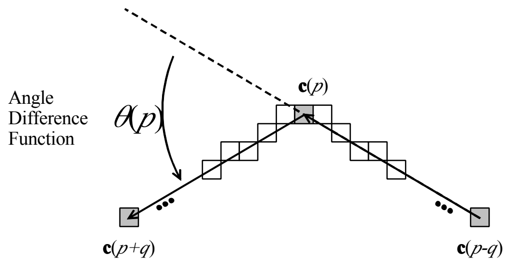


Fig. 9. Angle difference function $\theta(p)$ of femoral contour. p is perimeter number of femoral cross-sectional contour on sagittal plane. q is calculation range. $\mathbf{c}(p)$ is a position vector of the contour of the femur. $\theta(p)$ is the angle between the $\mathbf{c}_p(p)$ and $\mathbf{c}_n(p)$.

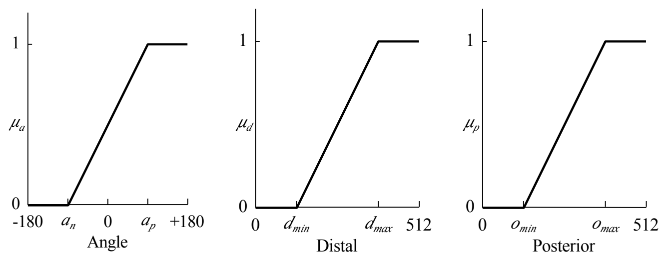


Fig. 10. shows membership functions for Blumensaat line of (a) angle, (b) distal, and (c) posterior evaluations. To determine Blumensaat line, we define three membership functions for angle, distal, and posterior. The membership function $\mu_a(p)$ is expressed as :

$$\mu_a(p) = \frac{\theta(p) - \theta_n}{\theta_p - \theta_n}, \quad (6)$$

where θ_n and θ_p are given by

$$\begin{cases} \theta_n = \arg\min_p \theta(p) \\ \theta_p = \arg\max_p \theta(p) \end{cases}. \quad (7)$$

The membership function $\mu_d(p)$ is expressed as :

$$\mu_d(p) = \frac{d(p) - d_{min}}{d_{max} - d_{min}}, \quad (8)$$

where $d(p)$ is a position vector of distal direction on the femur contour. d_n and d_p are given by

$$\begin{cases} d_{min} = \arg\min_p d(p) \\ d_{max} = \arg\max_p d(p) \end{cases}. \quad (9)$$

The membership function $\mu_o(p)$ is expressed as :

$$\mu_p(p) = \frac{o(p) - o_{min}}{o_{max} - o_{min}}. \quad (10)$$

where $o(p)$ is a position vector of posterior direction on the femur contour. o_n and o_p are given by

$$\begin{cases} o_{min} = \arg\min_p o(p) \\ o_{max} = \arg\max_p o(p) \end{cases}, \quad (11)$$

From (6), (8), and (10), we can get the equation of total grade of membership $\mu_t(p)$:

$$\mu_t(p) = \mu_a(p) \cdot \mu_d(p) \cdot \mu_p(p). \quad (12)$$

(a) (b) (c)

Fig. 10. Membership functions for Blumensaat line. (a) Angle, (b) distal, and (c) posterior evaluations. θ_n and θ_p are most negative and positive angle value. d_{min} and d_{max} are minimum and maximum distal position. p_{min} and p_{max} are minimum and maximum posterior position.

Fig. 11. shows a membership grade of function $\mu(p)$. The membership grade is decrease noise using a smoothing method. The membership grade $\mu(p)$ is expressed as :

$$\mu(p) = \frac{1}{2s_r + 1} \sum_{s=-s_r}^{s_r} \mu_t(p+s), \quad (13)$$

where s_r is a range of smoothing process, is experimentally set as five in this study. Two landmark parameters p_{AD} and p_{PP} are anterior distal and posterior proximal points, that determines Blumensaat line.

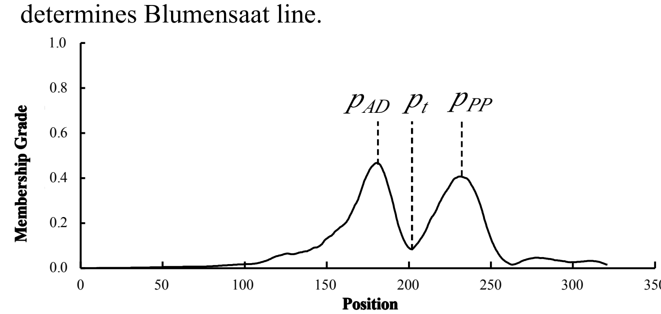


Fig. 11. Membership grade in proposed method. Horizontal axis is a point number of the femoral contour on sagittal plane. Vertical axis is membership grade. Anterior distal p_{AD} and posterior proximal p_{PP} are two landmarks that are required to determinate Blumensaat line. p_t is borderline between p_{AD} and p_{PP}.

In Fig. 11., it is necessary to obtain the p_{AD} and p_{PP}, a borderline between the p_{AD} and p_{PP} obtains the first. We defines the borderline p_t that locates between p_{AD} and p_{PP}. The borderline p_t between p_{AD} and p_{PP} is determined by a discriminant analysis. The discriminant analysis proposed by Otsu [25] is generally used for automated determination of the thresholding value in the binarization processing. The discriminant analysis is evaluated using a separation metrics. The separation metrics is obtained from a intra-class variance and inter-class variance. The intra-class variance and inter-class variance can be calculated by sum, mean, and variance of $\mu(p)$. When given the borderline thresholding value t defined over $0 \le t \le p_{limit}$, the sum, mean, and variance of $\mu(p)$ are expressed as follows. The sums $\omega_{AD}(t)$ and $\omega_{PP}(t)$ of anterior distal and posterior proximal are expressed as :

$$\begin{cases} \omega_{AD}(t) = \sum_{p=0}^{t} \mu(p) \\ \omega_{PP}(t) = \sum_{p=t}^{p_{limit}} \mu(p) \end{cases}, \quad (14)$$

The means $m_{AD}(t)$ and $m_{PP}(t)$ of anterior distal and posterior proximal are expressed as :

$$\begin{cases} m_{AD}(t) = \frac{1}{\omega_{AD}(t)} \sum_{p=0}^{t} p \cdot \mu(p) \\ m_{PP}(t) = \frac{1}{\omega_{PP}(t)} \sum_{p=t}^{p_{limit}} p \cdot \mu(p) \end{cases}. \quad (15)$$

The total mean m_{total}(t) is expressed of $\mu(p)$ as :

$$m_{total}(t) = m_{AD}(t) + m_{PP}(t). \quad (16)$$

The variance $\sigma_{AD}^2(t)$ and $\sigma_{PP}^2(t)$ of anterior distal and posterior proximal are expressed as :

$$\begin{cases} \sigma_{AD}^2(t) = \frac{1}{t+1} \sum_{p=0}^{t} p \cdot (\mu(p) - m_{AD}(t))^2 \\ \sigma_{PP}^2(t) = \frac{1}{p_{limit} - t} \sum_{p=t}^{p_{limit}} p \cdot (\mu(p) - m_{PP}(t))^2 \end{cases}. \quad (17)$$

From (14), (15), (16), and (17), we can get the equations of the intra-class variance and inter-class variance. The intra-class variance $\sigma_w^2(t)$ is expressed as :

$$\sigma_w^2(t) = \frac{\omega_{AD}(t) \cdot \sigma_{AD}^2(t) + \omega_{PP}(t) \cdot \sigma_{PP}^2(t)}{\omega_{AD}(t) + \omega_{PP}(t)}. \quad (18)$$

The inter-class variance $\sigma_b^2(t)$ is expressed as :

$$\begin{aligned} \sigma_b^2(t) = & \left(\omega_{AD}(t) \cdot (m_{AD}(t) - m_{total})^2 \right. \\ & \left. + \omega_{PP}(t) \cdot (m_{PP}(t) - m_{total})^2 \right). \\ & / (\omega_{AD}(t) + \omega_{PP}(t)) \end{aligned} \quad (19)$$

From (18) and (19), the borderline t_p is expressed as:

$$t_p = \arg\max_t \frac{\sigma_b^2(t)}{\sigma_w^2(t)}, \quad (20)$$

where $\sigma_b^2(t)$ / $\sigma_w^2(t)$ is the equation of separation metrics. When given the borderline t_p, we can get two landmark parameters of anterior distal p_{AD} and posterior proximal p_{PP} that are required to determinate Blumensaat line. The landmark parameters p_{AD} and p_{PP} are obtained as follows :

$$\begin{cases} p_{AD} = \arg\max_{p \in [0, t_p]} \mu(p) \\ p_{PP} = \arg\max_{p \in [t_p, p_{limit}]} \mu(p) \end{cases}. \quad (21)$$

From (21), the landmark positions $\mathbf{L}_{\mathrm{AD}}$ and $\mathbf{L}_{\mathrm{PP}}$ are expressed as:

$$\begin{cases} \mathbf{L}_{\mathrm{AD}} = \mathbf{c}(p_{AD}) \\ \mathbf{L}_{\mathrm{PP}} = \mathbf{c}(p_{PP}) \end{cases}. \quad (22)$$

IV. Experiment

This study had two experiments. The first experiment investigated a comparison between manual determination and automated determination as proposed method for a length between anterior distal and posterior proximal landmarks of Blumensaat line (Fig. 12.(a)). From (22), the direction vector **BL** is given by

$$\mathbf{BL} = \mathbf{L}_{\mathrm{AD}} - \mathbf{L}_{\mathrm{PP}}. \quad (23)$$

From (23), the length l is expressed as :

$$l = \|\mathbf{BL}\|. \quad (24)$$

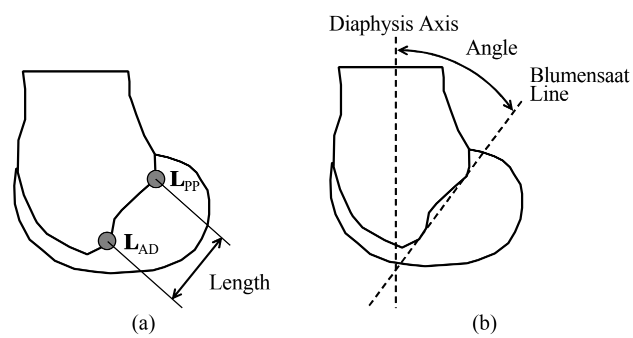


Fig. 12. Experiments for Blumensaat line. (a) Length between anterior distal $\mathbf{L}_{\mathrm{AD}}$ and posterior proximal $\mathbf{L}_{\mathrm{PP}}$ landmarks of Blumensaat line. (b) Angle between diaphysis axis and Blumensaat line.

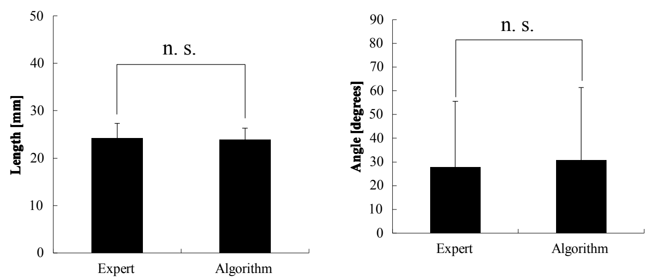
The second experiment investigated a comparison between manual determination and automated determination as proposed method for an angle between diaphysis axis and Blumensaat line (Fig. 12.(b)). From (1) and (23), the angle a is expressed as :

$$a = \arccos\left(\frac{\mathbf{DA} \cdot \mathbf{BL}}{|\mathbf{DA}|\,|\mathbf{BL}|}\right). \quad (25)$$

V. Results

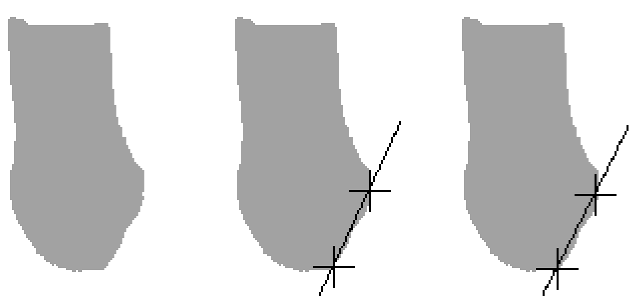
We investigated an automated determination of Blumensaat line using fuzzy system. Fig. 12.(a) shows a length between anterior distal and posterior proximal landmarks were 24.12 ± 3.23 mm (manual) and 23.90 ± 2.41 mm (automated). There was no statistically significant difference between manual determination and automated determination. Fig. 12.(b) shows angles between diaphysis axis and Blumensaat line were 27.80 ± 6.08 degrees (manual) and 30.68 ± 5.76 degrees (automated). There was no statistically significant difference between manual determination and automated determination.

Fig. 13. shows examples of analyzed Blumensaat line for (a) raw, (b) manual determination, and (c) automated determination on sagittal femur image. The examples indicated that there was no difference between the manual determination and automated determination.



(a) (b)

Fig. 13. Comparison between manual determination and automated determination of analyzed Blumensaat line. (a) Length between anterior distal and posterior proximal landmarks of Blumensaat line. (b) Angle between diaphysis axis and Blumensaat line. All value is the average of measured six patients.



(a) (b) (c)

Fig. 14. Examples of analyzed Blumensaat line for (a) raw, (b) expert, and (c) algorithm on sagittal femur image.

VI. Discussion

To reduce massive measurement time and subjective judgment error, we propose an automated determination of Blumensaat line using fuzzy system based on physician experiment from femur MDCT image. The proposed method was flexible, reliable, and effective for medical uses.

The proposed method has developed the determination of Blumensaat line to extract landmarks of anterior distal and posterior proximal automatically. Diversity of evaluation in the past studies that are performed manually, can arise due to the subjective judgment error and a lot of measurement time. We solved the subjective judgment error and measurement time by automating the evaluation method.

Since this study analyzed only six of the femur on a pilot study, the number of patients was small. The proposed method should be applied more data to examined statistical significance. However, the femoral result has shown a good correlation in the morphometric dimensions between the right and the left.

VII. Conclusion

To reduce massive measurement time and subjective judgment error, we propose an automated determination of Blumensaat line using fuzzy system based on physician experiment from femur MDCT image. The experiment employed six different knees. The six femurs were evaluated by the manual and proposed method. The results indicated that there was no difference between the manual and proposed method. We concluded that the proposed method has enough accuracy as same as expert.

Acknowledgment

This study was supported by JSPS Grant-in-Aid for Young Scientists (B) Grant Number 25870273.

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