3D BONE AXIS ANALYSIS METHOD USING CT IMAGES OF THE LOWER LIMBS AND ITS EVALUATION

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Abstract

In this paper, we propose a method for automatic extraction of the knee gap line and the FTA between the 3D bone axes of the femur and the tibia by using X-ray computed tomography (CT) images and indicating whether they are images of the right or the left leg. In this technique, the first step involves the creation of virtual CR images of the coronal (frontal) and the sagittal (lateral) plane. Next, the 2D bone axes are computed for each virtual image, after which the 3D coordinates for the bone axes are computed in 3D space. This automatic analysis method can be used for providing assistance to doctors in preoperative planning, obtaining highly accurate preoperative plans and supplying additional information for 2D and 3D templating. In addition, the correct 3D bone axis geometrical information determined from CT images can aid the execution of previously challenging tasks, such as establishing the plane for osteotomy, which is perpendicular to the bone axis, determining the position and the angle of rotation of artificial joints centered at the bone axis, and performing quantitative evaluations and comparisons with respect to the load axis and bone axis.

Keywords: *Bone axis, automatic extraction method, femorotibial lateral angle, image of lower extremity, 3D templating*

1. Introduction

The number of cases of bone breakage caused by osteoporosis and knee osteoarthritis caused by abrasion is constantly increasing due to our rapidly aging society, and currently the main cure for such disabilities is total knee artroplasty (TKA). A process known as **2D templating** is used in preoperative planning of TKA, where the size and the location of the artificial joints are determined from computed radiography (CR) images, which are two-dimensional. However, in 2D templating, the size and the location of artificial joints are determined from independent frontal and lateral planes on the basis of 2D images, which entails the following problems: 1) it is difficult to determine the correct placement without inconsistencies, 2) the rotation angle (convolution) in the direction of an ideal load axis can not be determined, and 3) the placement and the size of the joints are prone to technical errors. In this regard, **3D templating** for CT images has been proposed as a method for alleviating these problems. In 3D templating, 3D artificial joints are placed in 3D space, which allows for correct placement without inconsistencies. Since the bone axis still constitutes an important and useful characteristic in 3D templating, it is possible to compute the femorotibial angle (FTA) by using the bone axis projected in the direction of the frontal plane.

In general, in methods for calculating the bone axis from 3D images, the center of the horizontal and the perpendicular axis in the cortical plane and the center of the volume of the medullary cavity are computed for each slice image, and although there are established methods for approximating the line which passes through each center, performing this automatically has been a difficult task requiring considerable time and effort. In this regard, by improving and extending the automatic

analysis method developed for CR images of the lower extremities, we propose a method for extraction of bone axis and knee gap in three dimensions on the basis of CT images.
In the first step of the proposed method, CT images are used for creating transparent virtual images (virtual CR images) for the coronal (frontal) and the sagittal (lateral) plane. Next, by calculating the 2D bone axis with respect to each CR image, the coordinates of the bone axis in three dimensions are obtained [1, 2, 3]. We refer to this information about the bone axis and the knee gap as bone fiducial point information, and regard it as an important criterion for objective evaluation of the bone section in CT images. In this paper, the methods for calculating the bone axis from CR and CT images are referred to as the automatic 2D bone axis analysis method and the automatic 3D bone axis analysis method. In addition, the extracted 3D bone axis is referred to as the CT bone axis (3D axis), which is different from the 2D bone axis extracted from CR images.

2. Automatic analysis method for bone axis extracted from CT images of the lower extremities

One of the important points in artificial joint implantation operations is the femorotibial angle, which is computed from the respective axes of the femur and the tibia. Although 2D-based commercial preoperative planning assistance systems provide drafting capabilities and angle calculation methods for obtaining the FTA, work is performed on the screen. For this reason, we have proposed an automatic analysis method for extraction of the knee gap line and the axis of the femur and the tibia by using CR images of the lower extremities and indicating whether they are images of the left or the right leg (hereafter referred to as leg information), which does not require interactive operation [1]. The automatic method for extraction of 2D bone axis consists of the following four processes: 1) clipping the analyzed image of the lower extremity, 2) extraction of the knee gap line, 3) extraction of the bone boundary points, and 4) extraction of the bone axis (2D) from the boundary points. Weighted images are produced by using distortion images obtained by applying luminance inversion to the original images. Next, using weight coefficients which take into account the standard deviation eliminates the soft tissue and produces weighted images showing only the cortical bone. In performing 16 case studies of gonarthrosis, the FTA values obtained manually by doctors and those obtained with the automatic 2D analysis method differed by less than 1°. Figure 1 presents the flow of the 3D bone axis analysis method [2], in which the area for bone axis analysis is determined by using the 2D bone axis analysis method and the bone and the medullary cavity are extracted. This method is characterized by high speed of bone axis calculation, and it allows for simultaneous extraction of the 2D perspective axis and the 3D axis.The CT images used in the evaluation were obtained from three healthy male subjects (aged 30, 51, and 64 years). The respective resolutions of the images for each subject are presented in Table 1. The pixel resolution in X and Y directions is 0.416 mm and that in Z direction is 0.630 mm.

Table 1 Resolution of CT images

Sample CT	Resolution
A	512 x 512 x 1499
B	512 x 512 x 1595
C	512 x 512 x 1240

Regarding the virtual CR images of the lateral plane, the leg information is always for the left leg. Table 2 presents the computation times required for the construction of frontal and lateral virtual CR images from CT images. Table 3 presents the computation times for the compilation of the 3D bone axes after computing the 3D bone axes from virtual CR images in both directions. Although $\alpha_1 = 1.0$ and $\alpha_2 = 0.1$ in each of the 3 virtual frontal CR images, $\alpha_1 = 1.0$ and $\alpha_2 = 2.0$ was used only for the lateral virtual CR image in data set C. The 3D bone axes from Figs. 2, 3, and 4 are applied to each of the CT images in Table 1. Regarding the lateral CR images, the leg information is for the left leg.

In Fig. 5, the computed location of the 3D bone axes are overlapped with the CT slices image. The center of the cross marks the center of the bone axis, and it is clear that it is located in the center of the medullary cavity.

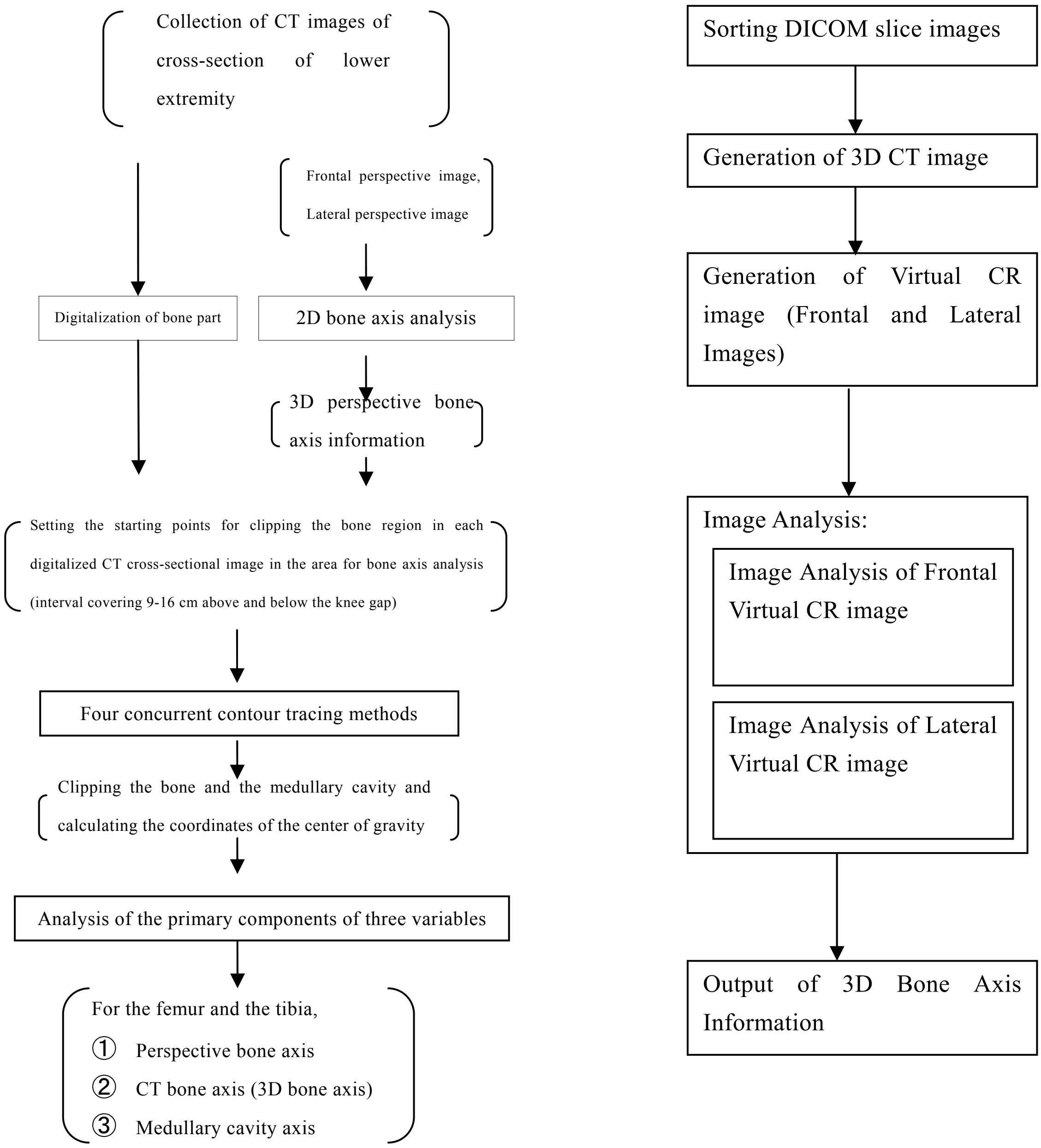

Fig. 1 Flow chart of the proposed method for automatic 3D bone axis computation.

Table 2 Computation time for generation of virtual CR images (CPU time, average of 3 trials)

Sample CT Image	Generation of virtual CR images (sec)
A (α_2= 0.1)	73.093
B (α_2= 0.1)	77.942
C (α_2= 0.1)	60.503
C (α_2= 2.0)	60.661

Table 3 Computation time for image analysis parts
(Extracting 3D bone axis from the 2 virtual CR images)

Sample	Image Analysis (sec)
A $(\alpha_2 = 0.1)$	2.370
B $(\alpha_2 = 0.1)$	2.552
C $(\alpha_2 = 0.1)$	1.745
C $(\alpha_2 = 2.0)$	1.771

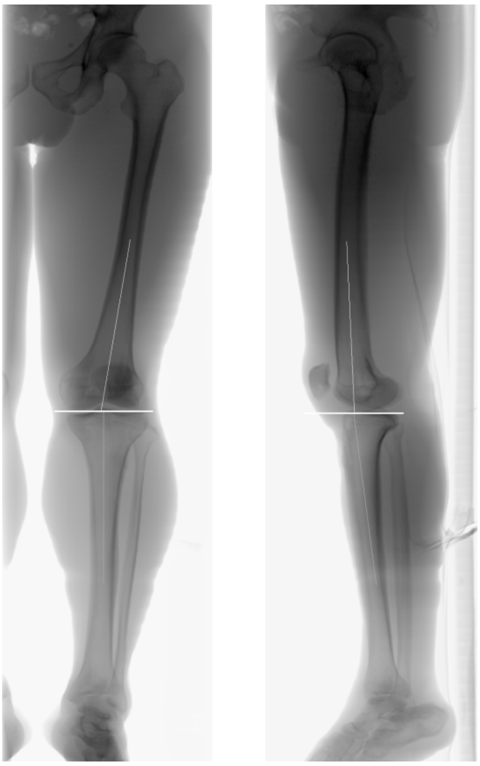

Fig. 2 Result of 3D bone axis computation (A). $\alpha_1 = 2.0$, $\alpha_2 = 0.1$

Fig. 3 Result of 3D bone axis computation (B). $\alpha_1 = 2.0$, $\alpha_2 = 0.1$

The machine used for conducting the evaluation was a DELL PC with Windows Vista Home Premium SP2 (64bit), a Core 2 Quad Q8200 2.33GHz processor and 8.00GB of RAM. The measurements were conducted as independent applications, and the CPU times for 3 measurements were averaged.

Table 4 and Table 5 present the cumulative CPU times required for pixel transformation and clipping of image analysis regions, respectively, for the construction of frontal and lateral virtual CR images. For each image, the computation of the bone axes requires 2–3 seconds, and the largest portion of CPU time is consumed by the creation of virtual CR images, as shown in Table 6.

Table 4 Total time for computation of pixel transformation

Sample	CPU Time (sec)
A	1.650
B	1.802
C	1.187

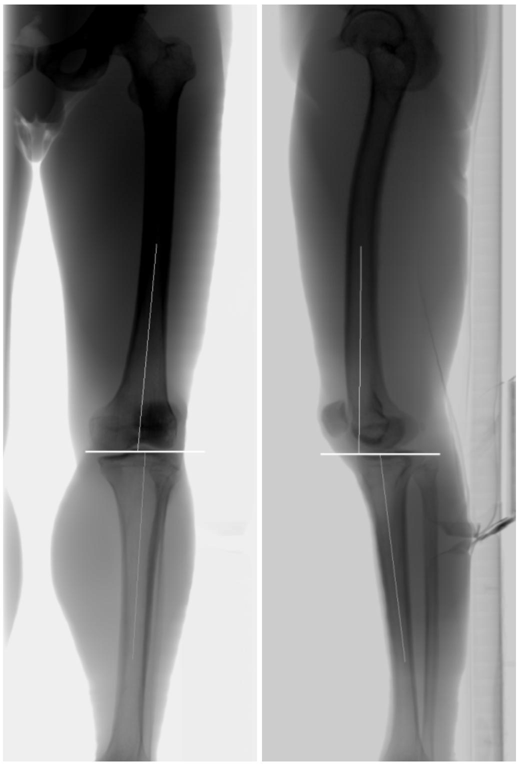

Fig. 4 Result of 3D bone axis computation (C).
α_1 = 2.0, α_2=0.1 (Left image)
α_1 = 2.0, α_2=2.0 (Right image)

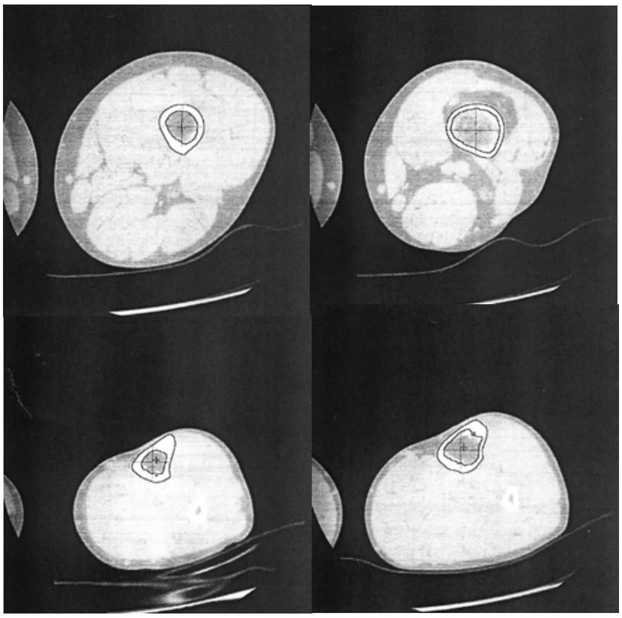

Fig. 5 Slice Image (Number of Slices:
553 (top left), 653 (top right), 960 (bottom left),
1060 (bottom right)

Table 5 CPU time for computation of clipping of image analysis regions

Sample	CPU Time (sec)
A	0.098
B	0.108
C	0.072

Table 6 Ratio of CPU times for computation of virtual CR images

Sample	Ratio of Total CPU Time (%)
A	98.268
B	96.989
C	97.213

3. Case study using 3D bone axes

3. 1. Initial placement of artificial joints

In preoperative planning assistance systems which provide 3D templating functionality for implantation of artificial joints (knee TKA, thigh TKA), it is necessary to choose and compare different artificial joint templates in order to select the optimal size and location for the joint. Therefore, in performing initial positioning of artificial joints, it would be possible to select a near-ideal position by using 3D bone axis information.

Figure 7 presents an example of simultaneous display of a complete image of a lower extremity and a volume rendering of its 3D bone axis and bone shape. Furthermore, by combining the 2D bone axis obtained from CR images with the 3D bone axis obtained from CT images, it is possible to position the CT images onto the CR images much faster [4].

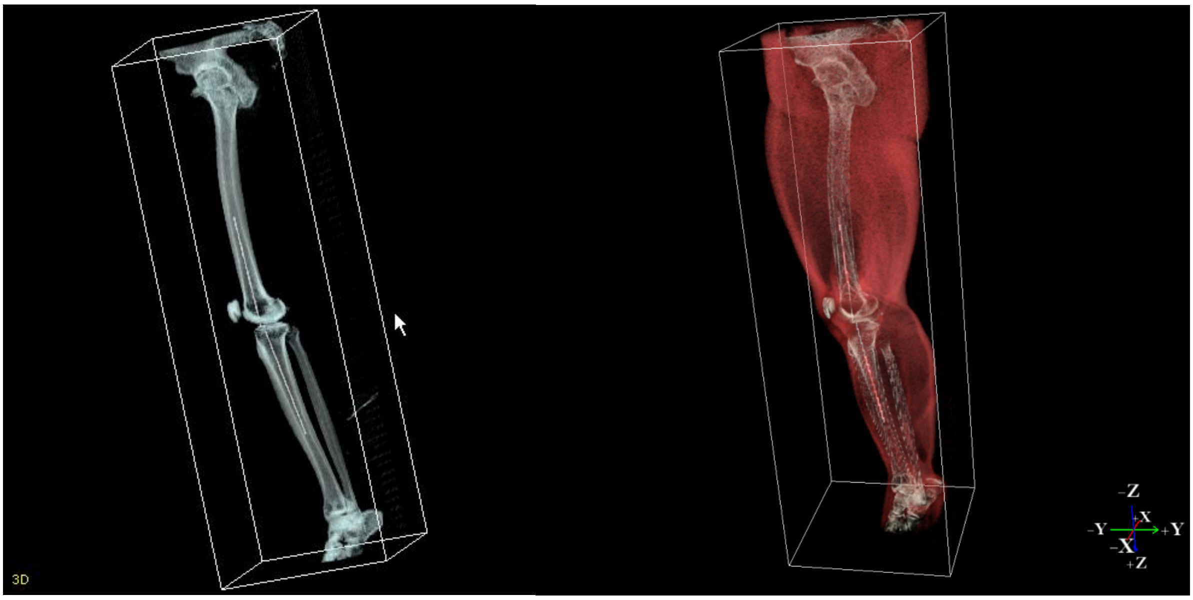

Fig. 6 Example of 3D bone axis computed from images of a lower extremity (left: (A), right: (B)).

4. Discussion

Similarly to the automatic 2D bone axis analysis method, the automatic 3D bone axis analysis method can be used to extract only the horizontal line of macroscopic knee gaps. Therefore, an analysis method which is capable of extracting the shape of the knee gap is necessary in order to be able to obtain further details. Also, this automatic analysis method suffers from the following disadvantages.

① It can be said that the stability of the analysis is not sufficient due to image noise.

② It is necessary to indicate manually whether the data is for the left or the right leg.

In order to resolve the abovementioned problems, it is useful to introduce a partially interactive process. Specifically, the user indicates in advance 3 representative points on the screen which determine the location of the bone axis and the knee. In this way, an interactive processing method for analyzing bone axes and knee gaps can be devised by taking these 3 points as a first-order approximation. In addition, it is necessary to enable the doctor to perform final amendments to automatically computed bone axes.

The time for preparation of virtual CR images accounts for most of the time for computation of 3D bone axes. Since virtual CR images are computed by adding independent pixels to the area and performing a final division, it is possible to accelerate the computation through parallelization by using GPUs (Graphics Processing Units). In particular, following the recent advancement of multi-core CPUs, it is also possible to accelerate the process by using threaded programming.

5. Summary

In the present paper, we have proposed a method for automatic extraction of 3D bone axes for the femur and the tibia at the knee joint by using CT images of the lower extremities. In the developed image processing method, virtual CR images of the frontal and the lateral planes are first prepared from CT images of the lower extremities, after which the 2D bone axis is computed for each virtual CR image. Next, the coordinates for the respective 3D bone axis are computed for 3D space. We applied the proposed method to CT images of the lower extremities of 3 healthy subjects and evaluated the computation time and accuracy.

Bone axis information obtained with the proposed automatic analysis method can assist doctors by reducing the effort required in creating preoperative plans, producing highly accurate preoperative

plans, and providing support for 2D and 3D templating. In addition, the accurate 3D bone axis geometrical information obtained from CT images can aid the execution of previously challenging tasks, such as establishing the plane for osteotomy, which is perpendicular to the bone axis, determining the rotation angle of artificial joints centered at the bone axis, and comparing the load axis and the bone axis in 3D space.
Orthostatic CR images differ from recumbent CT images since loading due to body weight is not applied. However, operations for implantation of artificial joints are performed after using orthostatic CR images (Röntgen images) for preparing preoperative plans and calculating the FTA[5, 6]. In regard to this problem, it is possible to construct orthostatic CT images without inconsistencies even in the depth direction by performing correct registration of partial images of the femur and the tibia onto orthostatic CR images. In the future, it is believed that bone fiducial point information including 3D bone axis information will become an increasingly important factor in 3D-based preoperative planning assistance systems and robotic operations.

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