The Study of Femoral 3D Reconstruction Process Based on Anatomical Parameters Using a Numerical Method*

** Department of Mechanical Engineering, Sogang University
1 Shinsu-dong, Mapo-gu, Seoul, Korea
*** Biomedical Research Center, Korea Institute of Science and Technology
P.O. Box 131, Cheongryang, Seoul, Korea
E-mail:choi@kist.re.kr

Abstract
Computer based three-dimensional (3D) reconstruction technique is widely used in clinical practices and its accuracy is still improving due to introducing of high resolution imaging modalities. Practically, two-dimensional X-ray image might be considered as one of major tools in orthopaedics, due to its lower cost and lower dose of radiation than computer tomography (CT).

The purpose of the current study is generating 3D model of femoral bone using conventional X-ray images incorporating the anatomical parameters into a referential 3D model. For the 3D reconstruction, the 2D shape and specific parameters of bone were firstly measured from X-ray images. Then, the referential CT model was modified as follows: the axial scaling, shearing transformation and radial scaling. In this study, the 3D reconstruction algorithm was tested using femoral X-ray images from the 28 years old male.

The current study showed that the 3D reconstruction technique by using X-ray images can be useful and feasible in clinical practices. It could easily generate 3D femoral model not only with saving time and costs, but also less radiation exposure to the patients.

Key words: 3D Reconstruction, Femur, Anatomical Parameters, Numerical Method, X-Ray Images

1. Introduction

Total hip replacement (THR) is an effective treatment for serious forms of osteoarthritis, disabling effects of rheumatoid arthritis, congenital deformities, and particular kinds of post-traumatic condition (1). One of fixation type, cementless fixation, is often promoted for use in many patients because of the relatively low fatigue strength of bone cement in comparison to the imposed stresses and the relatively active metabolic function (2)(3). The best method of cementless fixation is centralization of the stem with the least volume in the femoral canal. Unfortunately it is significantly difficult to design the optimal shape of cementless stems because of ready-made concept and the variation of patient’s femoral shape. Customized prosthesis was firstly introduced in 1975 and designed with reference to a specific patient in the anatomic aspect. Particularly, customized hip prostheses indicate that the stem shaft adapts to the endosteal femoral shape and the special neck angle. However, numerous different femoral components would be needed to ensure perfect conformity in every individual case (4). For that reason, individualized custom-made...
stems were set up via procedures to reconstruct the patient’s femoral geometry using multi-sliced CT images to record individual femoral geometries and to confirm the fitness of custom-made stems (5)-(9).

The 3D reconstructed femoral geometry of a patient from CT images were often used in Image Guided Surgery (IGS) system which provides surgeons objective information of operation process like decision making and surgical planning in Total Knee Replacement (TKR) or Total Hip Replacement (THR) (10)(11).

Clinical, it is widely accepted that CT scan is most the conventional technology to generating the 3D model of the object. However, it was practically criticized due to its accuracy issues (12), economical view points (time and costs), and safety issue (high radiation exposure). To overcome these practical limitations of CT scan, adaptation of two-dimensional (2D) X-ray images to generate 3D model was previously studied (12)-(14). They mainly focused on the morphologic difference between individual X-ray image and standard CT model based on several algorithms: the direct linear transformation (DLT), the non stereo corresponding points (NSCP) and the non stereo corresponding contour (NSCC). The DLT and NSCP methods are based on the precise identification of anatomical landmarks. On the other hand, the NSCC method enables the reconstruction from contour data and yields realistic and accurate geometrical models of distal or proximal femur using only two radiographs (13). Kurazume et al. showed it enabled to generate a precise 3D shape with only two fluoroscopic images of the proximal femur from prepared parametric models (15). However, these studies only focused on generating local regions of femur and had limitation to construct whole femur with important anatomical parameters such as the sagittal radius defined as the femoral curvature radius in the sagittal view.

Therefore the purpose of the current study is to improve 3D reconstruction process using conventional X-ray images incorporating the anatomical parameters for building up the whole femoral model.

2. Methods

The systematic procedure of 3D reconstruction of the whole femur is described in Figure 1. Before generating X-ray based 3D model, the referential 3D femoral model was built by multi-slice CT images. It has a controllable reshaping algorithm based on the anatomical parameters of the patient.

Fig. 1 Block diagram of 3D reconstruction procedure using 2D X-ray images.
2.1 Extraction of anatomical parameters from the referential 3D CT model

The 3D geometry of whole femur was composed by the edge detection method of image processing, which was known as a general method, using MATLAB 7.1 (The Math Works Inc., Natick, USA). Its anatomical parameters were able to be obtained by numerical methods from cadavers. This database also included the information of gender, age, weight, height and the specific disorder. This information was able to guide to select the referential model of the individual X-ray data. In the coordinate of femoral geometry, the medial-lateral and distal-proximal directions were defined by \( X \)- and \( Z \)-direction respectively, and the anterior-posterior direction was defined by \( Y \)-direction. In diaphyseal region, outer and inner contour were recorded separately, and each contour was composed of 72 points (Fig 2).

Five anatomical parameters were defined and extracted from referential CT models to define geometric characteristics of whole femur (Fig 3). Neck angle and head offset length were defined as the 2D parameters. The neck angle was measured by the angle of two lines: the projected line of anatomical axis and the line of head centre and neck axis. Also, the head offset length was defined as the horizontal distance from head centre to the intersection of the neck axis and anatomical axis in the frontal view of femur (Fig 3). A length of femur was defined by the distance from the center of femoral head to the intercondylar fossa of distal femur. The center position and radius of femoral head was measured by a nonlinear regression algorithm prior to the total length (Fig 4). The anatomical axis was obtained by fitting the curve for the center points of endosteal contours which was able to be calculated by the elliptical regression (Fig 4). The elliptical regression was effective in measuring the more exact center point and scaling contours by offset skill in comparison with the circular regression. The reason was demonstrated in this discussion section.

The sagittal radius indicated the curvature of femur in the sagittal view and was a vital factor in applying to design the customized hip implant. Sakai et al. (16) reported that the distal canal filling of hip stem inversely correlated with the ratio of the proximal portion and the distal portion of the stem curvature on the sagittal view. Due to its technical limitation in measuring the sagittal radius, in the current study, it was measured according to the region of femur and the maximum value was selected as the parametric value.
2.2 Extraction of contours and anatomical parameters from the 2D X-ray images

Prior to X-ray scan, the lower limbs were aligned with device which aid to extract the exact views from X-ray image in the frontal and sagittal plane (Fig 5a). The outward shape of whole femur was obtained by the image processing algorithm of MATLAB program semi-automatically (Fig 5b). The proximal and distal region manually obtained and the diaphyseal region automatically obtained from X-ray images using the conventional Canny edge detection algorithm with the pre-treatments: the Gaussian mask for the removal of image noise and the gamma correction to strengthen the image contrast of boundary region. Then, frontal and lateral views of X-ray images were taken and the following anatomical parameters were obtained by the nonlinear regression method: head centre, anatomical axis, sagittal radius, and the specific length of landmarks. In this study, two subjects for the healthy and young femurs (28 and 29 year old males) were performed in order to validate the 3D reconstruction process.

2.3 Re-Scaling of the referential 3D CT model

After digitizing outer shape and measuring geometric parameters of whole femur from the 2D X-ray images, the referential 3D CT model was reshaped as following procedures: the axial scaling, shearing transformation and radial scaling.
Fig. 5 Digitizing geometric outward shape of femur from 2D X-ray images: (a) X-ray scan with the device of alignment, (b) the proximal and distal region and (c) whole femoral data.

Fig. 6 Re-scaling of the referential 3D CT model: (a) initial model, (b) length scaling, (c) shearing transformation and (d) radial scaling.

To modify the referential CT model, the data of nth contour were transformed by the following equation:

\[ x_{\text{mod}}^n = \alpha^n (x_{\text{ref}}^n - \beta^n) \]  

where \( x_{\text{mod}}^n \) is a contour data modified about X-ray images and \( x_{\text{ref}}^n \) is a referential CT data. \( \alpha^n \) and \( \beta^n \) were respectively indicated a scaling factor, and a differential factor between centre of the X-ray image and CT model for the each nth contour. The factors of the shearing transformation and radial scaling can be obtained from the fitting data of X-ray outer shapes because the data of each contour of the 3D CT model may not correspond to the dots of outer shapes of the 2D X-ray image.

The axial scaling of a selected model drawn from the referential 3D CT models is performed in order to conform to the total length and the other lengths from the head centre to four specific geometric positions: the proximal lateral condyle, the medial lesser trochanter, the distal medial condyle and the distal lateral condyle. The anatomical axis and the sagittal curvature of CT model are matched with those of X-ray image by shearing.
transformation, and the inner and outer contours of CT model are modified by the interpolating offset method by consideration of the quadrant points of X-ray images (Fig 6). Matching error of reconstructed 3D model was calculated as comparing the anatomical 2D parameters between regenerated 3D model and original X-ray images. Iteratively, the anatomical axis transforming and the radial scaling were accomplished till the error became less than the pre-specified criterion. In the current study, X-ray images obtained from the 28 years old male were used to confirm the 3D reconstruction algorithm.

3. Results

When the referential 3D CT model overlaid on the frontal X-ray image on the basis of the head centre, two models were different in the anatomical axis and the femoral length at the distal part (Fig 7a). After applying 3D reconstruction algorithm, the result of the subject 1 showed that the modified 3D model and X-ray image were matched for the outline and the anatomical axis (Fig 7b). The values of total length, head diameter, neck angle and head offset in subject 1 were 404mm, 47.8mm, 127° and 37.6mm respectively. For 3D parameters, the sagittal radius and the width of minimum sectional contour at the isthmus region were 630mm and 25.6mm (Table 1). The result showed that total length, neck angle and head offset were more accurate than the other values which were 3D parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Initial CT model</th>
<th>Subject 1 X-ray image</th>
<th>Subject 1 Modified CT model</th>
<th>Subject 2 X-ray image</th>
<th>Subject 2 Modified CT model</th>
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<tbody>
<tr>
<td>Total length [mm]</td>
<td>366</td>
<td>404</td>
<td>404</td>
<td>459</td>
<td>459</td>
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<tr>
<td>Neck angle [deg]</td>
<td>121</td>
<td>127</td>
<td>127</td>
<td>126</td>
<td>125</td>
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<tr>
<td>Head offset [mm]</td>
<td>38.1</td>
<td>37.2</td>
<td>37.6</td>
<td>40.9</td>
<td>40.2</td>
</tr>
<tr>
<td>Sagittal radius [mm]</td>
<td>874</td>
<td>628</td>
<td>630</td>
<td>747</td>
<td>762</td>
</tr>
<tr>
<td>Sectional min. width [mm]</td>
<td>26.2</td>
<td>25.7</td>
<td>25.6</td>
<td>27.6</td>
<td>24.8</td>
</tr>
</tbody>
</table>

![Fig. 7 The projected shape of 3D model on 2D X-ray image: (a) Initial model (b) modified model](image-url)
4. Discussion

4.1 Anatomical parameters of CT model

In 1989, Thomas et al. proposed the circular regression method based on not the circumference but its area \(^{(17)}\). We applied two methods, the circular regression method and the elliptic regression method, to the curve regression of inner and outer sectional contours and compared these methods for three specific sections: the basic section located at the lesser trochanter section, the matching section located at 20mm lower than the lesser trochanter section and the end section located at 70mm lower than the lesser trochanter section. To compare with two methods, the errors of two methods were indicated by a root mean square error (RMSE) (Eq. 2).

\[
\text{RMSE} = \left[ \frac{1}{N} \sum_{i=1}^{N} D_i^2 \right]^{1/2}
\]

where \(N\) was the point number of each sectional contour and \(D_i\) was the difference of two corresponding points. In figure 8 (a), red (inner) contour denoted the endosteal surface and blue (outer) contour denoted outward surface of femoral diaphysis. The blue contours in figure 8 (b, c) denoted the numerical regressions. This process was used in defining the offset scaling factor and direction for the reconstruction of the referential CT model from 2D projected images. In result, the elliptic regression was more accurate than the circular regression (Table 2). This result showed that the elliptic regression method was effective to obtain the center points of the sectional contours and rescale their inner and outer contours of the prepared CT model (Fig 8).

Figure 9 showed the sagittal radius was changed by increasing the fitting region and had the maximum value. Considering the only proximal region, the sagittal radius was the minimum value, 400mm. By increasing the fitting region, however, the sagittal radius was increased to the value of 870mm and decreased to 600mm in the total region. The reason for the selection of the maximum value was that the value was more feasible considering the previous straight hip implant in total hip replacement which used the sagittal radius as the important design factor.

Table 2 Contour errors in comparison with raw data of each section

<table>
<thead>
<tr>
<th></th>
<th>Error of the circular method</th>
<th>Error of the elliptic method</th>
</tr>
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<tbody>
<tr>
<td>End section</td>
<td>2.70</td>
<td>0.0988</td>
</tr>
<tr>
<td>Matching section</td>
<td>8.56</td>
<td>0.0790</td>
</tr>
<tr>
<td>Basic section</td>
<td>17.0</td>
<td>0.0984</td>
</tr>
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</table>

Fig. 8 Comparison between circular regression and elliptic regression for the end section: (a) original contours of end section, (b) circular and (c) elliptic regressions
4.2 Limitations

In the current study, there were the effective errors for trochanters and knee condyles due to the referential CT model had the low resolution for the proximal and distal parts (Fig 8). However, this error can be significantly reduced by increasing a resolution of CT scan for the referential model.

The other limitation was that this paper only applied to the healthy-young subjects because it focused on the process of 3D reconstruction for whole femur. Then, it needs to study 3D reconstruction procedure of various ages, genders and pathological cases such as bone collapse with osteonecrosis. However, the current parameters obtained from X-ray images can be used to provide surgeons basic information to select hip and knee implant for each patient and this model might be used for pre-clinical simulation in osteoplasty.

5. Conclusions

The current study showed that the 3D reconstruction technique by using X-ray images can be useful and feasible in clinical practices. It could easily generate 3D femoral model not only with saving time and costs, but also less radiation exposure to the patients.

References

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