The Design of Deformed Femur Osteotomy System

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Abstract. In order to achieve more accurate deformity femoral osteotomy, a software system for deformity femoral osteotomy was designed to facilitate the clinical preoperative simulation. First, 3D modeling was simulated using Mimics17.0 and saved as STL file. Then, MFC and OpenGL was utilized to build the deformed femur osteotomy system, the accurate osteotome position and osteotomy angle were obtained by fitting the axis of the deformed femoral shaft and the geometric center of the greater trochanter of femoral head. Finally, mock splicing was performed to determine the postoperative neck angle. A case of abnormal femoral STL model was introduced into the osteotomy system and whose collodiaphyseal angle was measured as 57.7 °, input osteotomy angle was 60 °, and the postoperative collodiaphyseal angle was measured to be 102.3 ° after completing the osteotomy simulation. The experimental results show that the system can quickly provide doctors with a more accurate osteotomy program, as well as preoperative surgical simulation, which will save the doctor's clinical diagnosis time and increase the accuracy of osteotomy.

1. Introduction

Human lower limbs load bear most of the human motor functions. The hip joint serves as a connection hub between the femur and the human main trunk. The correctness of its physiological function directly affects the most basic motor (motion) functions of the human body. The abnormal collodiaphyseal angle and abnormal bending of the proximal femur caused by hip inversion tend to have a great impact on the patient's daily life. The best way to treat this kind of deformed femur is to remove a wedge-shaped bone block, the underside of the wedge-shaped bone block is parallel to the horizontal plane. The angle between the upper surface and the bottom surface determines the size of the bone part to remove. Therefore, the position and angle of the wedge-shaped bone block directly affects the malformed femur osteotomy’s effect[1].

The traditional practice for deformed femur osteotomy is the following one. According to his own clinical experience, the doctor selects the position and the angle of the osteotomy. A V-shaped osteotomy line, referring to the removal of the wedge-shaped bone part in the real operation, is drawn on the 2D CT image slice[2]. In this traditional practice, the quality of two-dimensional slices is closely related to the patient’s posture and soft tissue conditions, resulting in a poor accuracy. Moreover, the doctor’s clinical experience differs from one to another, also impacting on the accuracy of this practice. As a result, traditional surgery is difficult to accurately correct in three-dimensional space[3].

In order to solve the problems existing in the above method, this article uses Mimics to perform 3D modeling and export the model data to the deformed femur osteotomy system in STL (ASCII) file format. A 3D interactive virtual environment was created using OpenGL and MFC, according to
fitting centerline of deformed femur and the greater trochanter of the femur. The exact position of the femoral osteotomy and the collodiaphyseal angle were calculated. (The degree of the wedge-shaped bone block that needs to be removed corresponds to the difference between the normal collodiaphyseal angle and the current malformed one) Providing the more accurate surgical osteotomy program to the clinician. This method improves the accuracy of the femoral osteotomy[4].

2. System design overview
The deformed femur osteotomy system was constructed by using MFC and OpenGL as the basic framework. As shown in figure 1, it was mainly composed of malformed femur STL (ASCII) data reading and display module, osteotomy position and collodiaphyseal angle calculation module, simulated surgical osteotomy and splicing module [5].

![System design framework diagram](image)

**Figure 1.** System design framework.

3. System algorithm design and software implementation

3.1. deformed femur STL(ASCII) data read rendering module
In this article STL file is generated by Mimics (A medical image control system is invented by Materialise company in Belgium), using a series of CT images and create a layer by layer 3D reconstruction. After then, it exports 3D models to STL format files later.

OpenGL for 3D image, is a powerful and convenient tool that calls the underlying graphics library. In addition, in order to make more stereo effect with 3D graphics, OpenGL virtual illumination function is used to add lighting effects to the whole scene. Figure 2 shows the three-dimensional model of deformed femur in the osteotomy system.
Figure 2. Three-dimensional model of the osteotomy system. The part (a) shows the femur model front view, the part (b) shows the femoral model oblique view.

3.2. Calculation of osteotomy position and collodiaphyseal angle module.

In order to accurately obtain malformed femoral osteotomy position, the first step is to get the center line of the malformed femoral three-dimensional model. First, the data of femoral head and femoral neck must be eliminated by using three anchor points in the femoral osteotomy system (interferences with the data of center line should be avoided). Using “Thickness” as the layer Thickness, (The smaller the thickness is, the smoother the center line of the femur will be). This optimal value correspond to 10mm, cutting the model horizontally. Because the 3D model is composed of many triangles patch, we use solid geometry formulas to calculate the intersection of cutting plane and triangles patch. The series of intersection composition the boundary between the 3D model and the cutting plane. Bringing the coorinates data of boundary curve’s points into the formula (1), (2), to calculate the geometric center of discrete plane curve. \( x_0, y_0 \) correspond to the geometric center coordinates, the Z coordinates is same with the Z coordinates of cutting plane. The model is cut with a series of horizontal planes of different heights, and calculate the geometric center of every section, the femoral center line is constituted with the geometric center of every section[6].

\[
x_0 = \frac{\sum_{i=0}^{n} x_i}{n}
\]

\[
y_0 = \frac{\sum_{j=0}^{n} y_j}{n}
\]

The calculation process of the femoral centerline is shown in figure 3(a). The center line what we obtain through the above algorithm is not directly used. The data of center lines will be put into the formula (3). The principle of least square method is used to deal with the 5 points 3 order smoothing algorithm. (y coordinates are out of consideration here, only considering the discrete points in XOZ plane’s point, regardless of the z coordinates value at the same time, because the z axis is evenly spaced, just dealing with the x coordinate of discrete points), “\(a_i\)” is the data after smoothing, “\(b_i\)” is the raw data. To make sure the curvature is differentiable. (that is, in order to ensure the continuity of curvature), I'm going to do polynomials fitting, using the corresponding points data of the curve fitting, taking the place of the original data. Due to using least squares polynomial fitting, and polynomial fitting normal equations would produce to an ill matrix. Ill matrix is sensitive to subtle data jitter. Usually, equidistant node at the center of the translation algorithm and the compression transformation algorithm is used to deal with it [7]. The value of translation and the compression factor calculation method such as formula 4 to 6. The "s" is translation factor, "\(\bar{p}\)" is value after translation, the "p" is compression factor.
The experimental results show that the characteristics of the original discrete curve is retained by the seven fitting method, and the overfitting phenomenon is not generated [8]. Putting the Z coordinates of original discrete points into curve fitting equation, and calculate the X coordinates (depth values which are described as y value, are out of consideration here, only considering the fitted curve parallel to the XOZ plane). To get the new section geometric center coordinates in turns. Putting the data from the new geometry center coordinates into discrete point continuous curvature formula 7 to get curvature of every point [9]. In the curvature of each point, "k_i" is the curvature of the points \((x_i, y_i)\). "x'_i, y'_i, x''_i, y''_i" respectively represent the first and second order derivative of the "x_i" and "y_i".

\[
k = \frac{x' y'' - y' x''}{(x' x'' + y' y'')}
\]

Taking the derivative of the discrete data, to get the maximum curvature of the point, Treating Z coordinates of the point as the subface height coordinates after removing wedge-shaped bone block, namely, osteotomy positio coordinate coordinates[10]. Calculation flow chart is shown in figure 3.

\[
a_i = -3\cdot(b_{i-2} + b_{i+2}) \pm 12\cdot(b_{i-1} + b_{i+1}) + 17\cdot b_i
\]

\[
s = \frac{x_i + x_n}{2}
\]

\[
x_i = x_i + s
\]

\[
p = \left( \frac{n}{\sum_{i=0}^{n} x_i} \right)^{1/3}
\]
femoral greater trochanter is akin to a sphere. The center of the fitting sphere is the center of the femoral great trochanter. First, the data of femoral and femoral neck must be eliminated by using three anchor points in the femoral osteotomy system. At the same time, the data range of femoral great trochanter is also determined in Z direction. Calculating the geometric center coordinates of the section which produced by intersecting this plane and the 3D model. The geometric center is the core of the fitting sphere. According to the formula for 8 to 18, "A" is X coordinates of center point, "B" is Y coordinates of center point and the radius is "R".

\[
C = (N \sum X_i^2 - \sum X_i \sum X_i)
\]
\[
D = (N \sum X_i Y_i - \sum X_i \sum Y_i)
\]
\[
E = N \left( \sum X_i^3 + N \sum X_i Y_i - (\sum X_i^2 + \sum Y_i^2) \right)
\]
\[
G = (N \sum Y_i^2 - \sum Y_i \sum X_i)
\]
\[
H = N \sum X_i^2 Y_i + N \sum Y_i^3 - (\sum X_i^2 + \sum Y_i^2) \sum Y_i
\]
\[
a = \frac{HD - ED}{CG - D^2}
\]
\[
b = \frac{HC - ED}{D^2 - GC}
\]
\[
c = -\frac{\sum (X_i^2 + Y_i^2 + a \sum X_i + b \sum Y_i)}{N}
\]
\[
A = \frac{a}{-2}
\]
\[
B = \frac{b}{-2}
\]
\[
R = \frac{1}{2} \sqrt{a^2 + b^2 - 4c}
\]

A point on the extension line of the femoral greater trochanter geometry center and the narrowest point of the femoral neck center must be selected as femur bifurcation point [12]. As shown in figure 6 (selected by the doctor in the osteotomy system by the mouse to click complete) click operation only determines the X, Z value of femoral bifurcation point. The existence of a femoral angle of anteverision impacts on the femur bifurcation point (depth y coordinates). The y coordinates of the femur’s bifurcation point must be recalculated. Using the line between femoral greater trochanter geometric center and the femoral bifurcation point in XOZ coordinates system, and finding the point A which in the axis of femoral and has shortest distance from the line. And then, through point A coordinate \((x_A, y_A)\) and the femoral greater trochanter center coordinates \((x_0, y_0)\) in XOY coordinates system. Using the triangle similarity theorem and getting the new y coordinates of femoral bifurcation point (depth coordinates). Figure 4 is the calculating diagram.

Trochanter center coordinates, the femur bifurcation point coordinates, distal femur midpoint coordinates, and putting these coordinates data into two straight line angle formula, and calculating the malformed colliodiaphyseal angle. Then the doctor getting a degree of femoral osteotomy according to the differences between normal colliodiaphyseal angle and current colliodiaphyseal angle. Algorithm flow chart of structure is shown in figure 5.
Figure 4. Femur bifurcation point y value calculation diagram. The part (a) is XOZ perspective diagram. The part (b) is XOY perspective diagram.

Figure 5. Neck dry corner calculation flowchart.

3.3. simulated femoral osteotomy and splicing module

Through the previous steps, identified the femoral osteotomy angle and femoral osteotomy position. And then, making deformity femoral osteotomy simulation operation, to provide preoperative simulation for doctors, in order to test the effect of femoral osteotomy [13].

The basic principle of segmentation is divided a STL file into many new STL file, which uses many different faces to make a STL model divided into several parts, each part to composition a new STL file, each new STL file corresponding to a new generation of STL model. In this article, using two plane with a certain angle and perpendicular to the XOZ plane to cut the femoral three-dimensional model.

For an arbitrary spatial triangle, there are three kinds location relationship between it and the cutting plane. All above the plane, all under the plane, and intersect with plane. Three conditions constitute three congregation, and the triangle are stored in "vector_up", "vector_down", vector_intersect ("vector_up", "vector_down" and "vector_intersect" are the vector structure type
variable) [14]. For the first and two cases, just need to retain or give up all. We are mainly dealing with the third situation. If the triangle and the plane intersecting, there also has three situation: when the intersecting point is only one, in the other word if any of the triangle vertices intersect with the cutting plane, in the later process will encounter a lot of trouble. So, slice height perturbation method is needed to use. The specific method is: the triangle along the direction of plane normal to move up or down a tiny displacement, to ensure that any of the triangle vertices doesn't fall on the plane; When triangle patch intersect with cutting plane in a straight line ,in other words, plane intersecting the two vertices of the triangle patch. If the third vertex is above the cutting plane, the triangle data would be stored in "vector_up", whereas the triangle data would be stored in "vector_down". When the cutting plane intersect with the two sides of the triangle, the first thing is to calculate the intersection. The spatial triangle which intersect with cutting plane is divided into two parts: one part is a triangle, the other part is a quadrilateral. Quadrilateral cannot appear in STL file, so, it must be divided into two triangles. Because the storage order of STL file is counterclockwise, if it is stored order for "D","E","F", Synthesize the previous statement, there would have six kinds of circumstances which is shown in figure 6. "D", "E", "F" stand for triangle vertex, "L" stands for cutting plane, "m" and "n" stand for intersecting point of cutting plane with the edge of the triangle, the red line divided quadrilateral into two triangles. The shadow part of the triangle will be put in "vector_up", white part of the triangle will be put in the "vector down".

![Figure 6. Triangle cutting schematic](image)

Through the above operation, we make all triangle data stored in vector_up or vector_down entirely, so that the malformed femur model is divided into two parts [15]. The model is shown in figure 8, the cutting result is shown in figure 7.

![Figure 7. Cut the bone in osteotomy system. The part (a) shows the divided femoral view. The part (b) shows the divide femoral oblique view.](image)
putting two femoral data into the same vector container [16]. Concrete implementation method is as follows.

"Choice" is a kind of powerful features of OpenGL, it allows us to click the mouse somewhere in the PC window, and determine which object is clicked. First of all, 3D models must be named in the scene when we use it to the select. In this article, the red femur will be named GUGU_UP and the green femur will be named GUGU_DOWN. We will see the results of which object you are currently selecting, and then follow up on it. As shown in figure 8, the system tells us which object is choosed.

After get the information of the selected object, we use OpenGL glRotatef () and glTranslatef () function to carry out rotation and translation operation. Because the rotation and translation operations of OpenGL, which making the model view matrix changed. That is to say, only the observer's point of view has changed, Leading the effect of two femoral splices seen together, But the position and data of the object itself in rendering environment did not change. If you want to make two models really splices together. The specific method is using the model data multiply rotation and translation matrix as flow.

Rotating $\alpha$ Angle around the X-axis, and the transformation matrix is:

$$T_{\alpha} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha & 0 \\ 0 & -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (19)$$

Rotating $\beta$ Angle around the Y-axis, and the transformation matrix is:

$$T_{\beta} = \begin{bmatrix} \cos \beta & 0 & -\sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ \sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (20)$$

Rotating $\gamma$ Angle around the Z-axis, and the transformation matrix is:

$$T_{\gamma} = \begin{bmatrix} \cos \gamma & \sin \gamma & 0 & 0 \\ -\sin \gamma & \cos \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (21)$$

Translation matrix is:
Femur osteotomy system provide another way to cut femur for clinical doctors. The doctor can independently determine the position and angle of femur osteotomy according to their own clinical experience, and draw the cutting line to cut femur. As shown in figure 9, the red triangle in painted bone, parts of the red triangle and femoral intersect intercept.

\[
T_m = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
X & Y & Z & 1
\end{bmatrix}
\] (22)

Figure 9. Free osteotomy mode rendering. The part (a) shows the three dimensional of the femur. The part (b) shows the transparent femur three-dimensional model. The part (c) shows the effect of osteotomy. The part (d) shows the result of stitching.

4. Results and conclusions
This design aims to develop a software system for malformed femoral osteotomy. It’s purpose is to establish a virtual environment in the computer which can provide doctors with a sense of reality and immersive by using STL file data and virtual reality technology. Doctors with the aid of the information in the virtual environment performs simulation surgical. The results are shown in figure 10. After the malformed femoral model was entered into the osteotomy system, as shown in figure 10(a), the collodiaphyseal angle was 57.7 °. The normal femoral neck dry angle of different ages and different sexes is different [17]. If the patient's other femur is healthy, we need refer to the contralateral femoral collodiaphyseal angle to calculate the angle of osteotomy. As shown in figure 10(b), assuming the input osteotomy angle is 60°. After the osteotomy and splicing operation, we obtained a new femur. As shown in figure 10(c), measuring the collodiaphyseal angle again is 102.3°. Due to leaning forward angle of the femur, the depth of the femoral trochanter, the depth of the femoral bifurcation, and the midpoint of the distal femur (y-value) are not the same, so the 60-degree wedge-shaped bone was intercepted, and splice later. However, it can not be restored to 117.5°. But through this rapid osteotomy system for surgical simulation, the clinician can achieve normal angle by multiple osteotomies and splicing operations until. Through this malformed femoral osteotomy system, the inaccuracy of diagnosis will be reduced comparing to traditional two-dimensional CT laminae in the operation, the uncertainties caused by differences in clinicians' personal experience is reduced, too. It provides clinicians with a platform for performing simulated surgery and pre-observation of surgical results, which can improve the efficiency and effectiveness of clinical diagnosis.
Figure 10. Deformity femoral osteotomy results rendering. The part (a) shows the distal femoral neck dry corner. The part (b) is entering the degree. The patr (c) shows the neck dry corner after stitching.

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