The Critical Dimension Definition of Femoral for Custom-made Total Knee Arthroplasty by the Application of Geometric Modeling

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Abstract: The main purpose for the design of knee prosthesis is to construct patient's individual anatomical, geometric model and satisfy his/her real geometric and physiology characteristic. The reconstruction of 3D knee geometric model is the basis of knee prosthesis related design. In this study, Mimics software was used to obtain CT image to construct the complete knee actual 3D geometric model, to analyze and define the critical dimension needed for the most complicated femur resection in custom-made total knee arthroplasty (TKA), including critical dimensions of anterior femur resection, distal femur resection and posterior condylar resection. Based on the obtained information, one can setup the critical dimensions and perform the location analysis that are suitable for knee arthroplasty for individual patient's knee characteristic, shape and damage conditions. Then, based on these data to design and manufacture custom-made knee prosthesis to fulfill press-fit design purpose.
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1. Introduction

In Total Knee Arthroplasty(TKA), the prosthesis under different resection and implantation parameters affect knee interior stress distribution is the subject that can hardly be solved by traditional anatomical research[1]. However, this is the unavoidable critical factor when performing TKA. Therefore, the establishment of the real human 3D knee model has become significant. According to the related research[2][3], better joint prosthesis and medullar cavity press-fit produced better surgical results, longer durability, less pain at the initial stage of implantation, and reduce loosening problems in the future.

2. Literature review

The study of computer image aided in medical care and knee arthroplasty has been going on for many years [4][5][6][7]. Among them, the use of CT (Computed Tomography) image reconstruction for knee 3D model to assist medical professionals performing surgery planning and guiding has the longest history and is the most mature one. The main reason is its advantage on bone identification.

Since the image format (DICOM) of CT/MRI cannot be read by CAD software, conversion software is needed to convert DICOM format into CAD readable format. Mimics, a commercial software, was chosen to do the format conversion. One can define various custom-made knee critical dimensions using 3D knee model. An integrated approach of CAD/CAM was presented for the concurrent development of custom-made femoral stem [8].

Mimics is a highly integrated and user friendly 3D image software and has performed well in [9][10][11]. Gray threshold is used in Mimics as the basis to build 3D geometric model from CT/MRI image. Human body can be categorized into 2000~4000 density levels. Gray threshold, base on human density, is used to represent human bone, ligament, muscle, blood vessel, etc [12]. Through the selection of the Gray threshold in CT/MRI medical image data, Mimics is able to generate 3D geometric model. Geometric model can accurately identify the required critical points and dimensions by observing this model from different view angle and direction, such as locating CT layer that contains lateral epicondyle and medial epicondyle. A design system combining clinical experience and engineering knowledge was developed for the manufacture for femoral component of knee prosthesis [13].

In the study of knee mechanics, dynamics model, and anatomical characteristics, Lewis etc. [14] suggested that the optimal fixed axis of rotation for the human knee joint should passes the centers of medial and lateral epicondyle. Mensch etc. [15] concluded that line connects center of medial and lateral epicondyle is very closed to transepicondylar axis (TEA). Therefore, TEA is considered the most reliable anatomical reference index. In total knee arthroplastry prosthesis, to reconstruct precise knee mechanical axis is very important at improving surgery field and increasing the life of prosthesis [16]. One of the critical factors for a successful surgery is to locate the precise femoral anatomic axis for

femoral prosthesis rotation to ensure the proper distal femoral resection surgery and the installation of prosthesis.

Transepicondylar axis connects femoral tips of lateral epicondyle and medial epicondyle. It is used to describe maximum flexion movement and define the alignment of femoral rotational axis for total knee arthroplasty prosthesis. If femoral prosthesis can be placed parallel to the transepicondylar axis, it is possible to obtain normal patellar track, decrease the stress between patellar and femur, and the friction between tibia and femur [17]. This is probably the only bone index in arthroplasty. However, it is not possible to visualize this axis during the surgery. The only way to locate this axis is by touching. With the assistance of CT image, one can locate the axis on the image in advance and use Mimics to construct 3D geometric model surgical procedure simulation. Furthermore, base on the patients' knee characteristic and damage condition, one can proceed on the defining of the critical dimension and resection alignment of arthroplasty and complete the definition of the necessary dimension and information of custom-made knee prosthesis.

3. Research method and results

To construct the knee geometry model, and to define and analyze the critical dimensions, one should obtains patient's CT image files; use Mimics to reconstruct knee 3D model; measure the location of the required TEA, femoral anatomic axis, mechanical axis and tibia anatomic axis for total knee prosthesis replacement surgery; refer to alignment angle of the total knee prosthesis replacement surgery tools; simulate surgery resection procedure; conduct the definition of the characteristic dimension and resection alignment for the knee arthroplasty and complete the definition of the necessary dimension and analysis required for custom- made knee prosthesis surgery.

3.1 Femur 3D geometry construction

By using the better bone structure recognition capability feature of CT, CT image was imported to Mimics. Fig. 1 is the flow chart regarding the construction of knee geometry model.

The built in gray threshold was used to select femur to form different mask layers; use "image edit" feature to "add" and "erase" image boundary to increase the precision of the reconstructed image. Also, region growth feature was used to break up the image to obtain more precise femur voxel. Finally, Mimics 3D calculation feature was used to build up the femur. Fig. 2 shows the finalized femur 3D model structure.

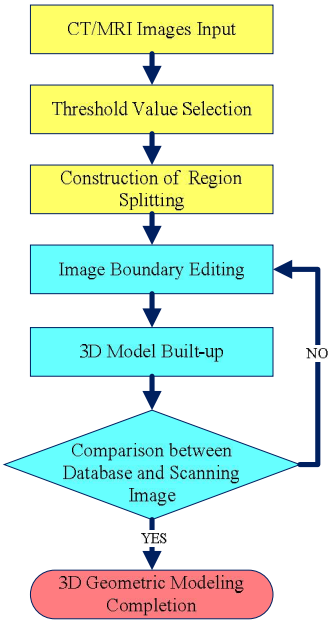

Fig. 1 Knee geometry model construction flow chart

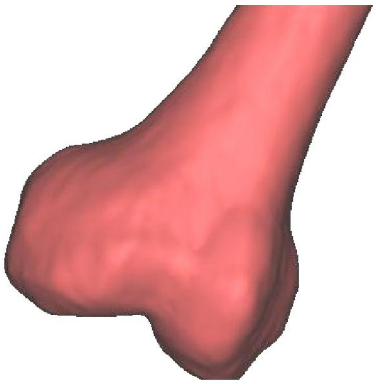

Fig. 2 Femur 3D geometry model

3.2 Femur critical dimension definition

The accuracy of the axes of knee prosthesis is very important. To define the knee critical dimensions, there base lines have to be located first; they are femoral anatomic axis, TEA and mechanical axis. By using the relationship among these three axes, anterior femur critical dimensions a, distal femur critical dimensions b, and posterior condylar critical dimensions c are defined. Fig. 3 shows the relationship between theses axis and is discussed in the following paragraph.

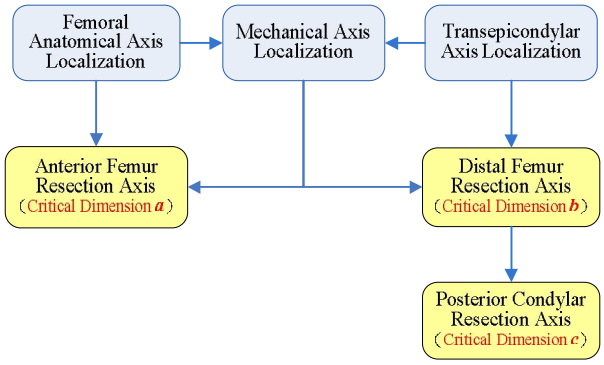

Fig. 3 Flow chart of the custom-made knee prosthesis critical dimension definition

3.2.1 Femoral anatomical axis

On CT image, two cross sections, located at 1/3 distal end, were selected at the proper location of femur medullary cavity, cancellous bone was identified and center was chosen at each cross section using Mimics. The axis connecting these center points is called femoral anatomical axis.

3.2.2 Transepicondylar axis and mechanical axis

By connecting the tips of lateral epicondyle and medial epicondyle, one can locate transepicondylar axis (TEA), also called the rotation axis. Mechanical axis can be located by using medial tip of distal femur as the reference point to obtain the locating axis that is parallel to TEA, then use the intersect of locating axis and anatomical axis as the rotation axis, rotate anatomical axis in the direction of medial side of knee, 7° for male and 5° for female to get mechanical axis, as shown in Fig. 4.

3.3 Femur critical dimension and resection axis

The purpose of knee truncation is to remove the excess worn or lesion affected knee surface and portion for the implantation of knee prosthesis. Therefore, the design dimensions of knee prosthesis have to closely match the shape and contour of the truncated knee bone; the knee resection is the most critical step in knee arthroplasty prosthesis. The precise location of each resection axis (surface) greatly affects the results of surgery.

Usually, the femoral resection has three steps: (1) anterior femur resection (2) distal femur resection (3) posterior condylar resection. These three resection axes were used to designate the critical dimensions a, b and c respectively, as shown in Fig. 5.

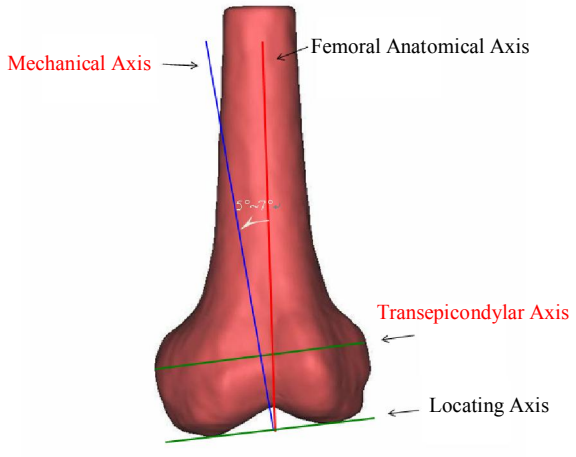

Fig. 4 Definition of femoral mechanical axis

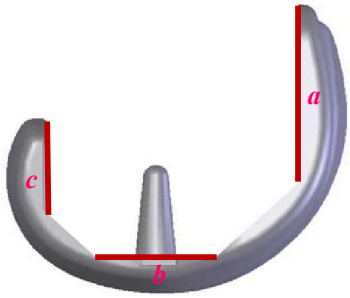

Fig. 5 Femur critical dimensions

3.3.1 Anterior femur critical dimension *a*

The first step of knee femoral resection is anterior femur resection. There are three methods to determine anterior femur resection axis: 1. Parallel to transepicondy line; 2. Posterior condylar connecting line 3-degree turning outward; 3. Vertical line of whiteside line (trochlear axis). These three methods are equally good, however, the first method was used in this study. The key is to make sure the resection axis and TEA are parallel, as shown in Fig. 6. It is critical that the resection surface and bony cortex surface of femoral shaft are even to avoid damaging femur bony cortex. The resection length ***a*** is one of the prosthesis critical dimensions, as shown in Fig. 7.

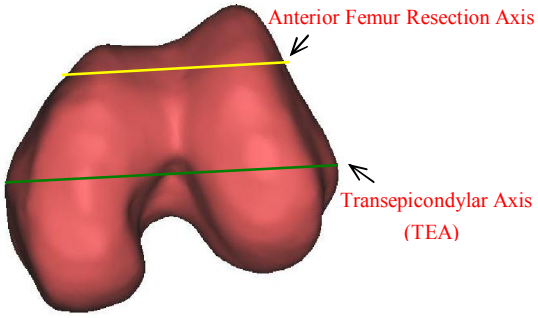

Fig. 6 Schematic of anterior femur resection axis

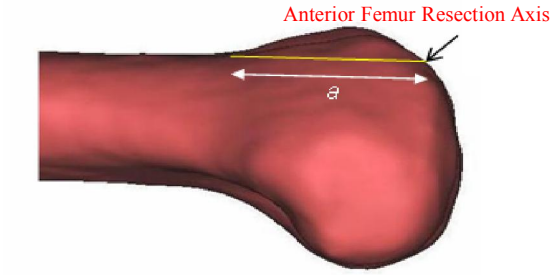

Fig. 7 Schematic of anterior femur critical dimension ***a***

3.3.2 Distal femur critical dimension *b*

Transepicondylar axis (TEA) is the index used to define distal femur critical dimension since distal femur resection axis has to parallel to TEA. Because it is very difficult to locate TEA during knee arthroplasty prosthesis, one can use medial tip of distal femur as a reference point to setup the locating axis that is perpendicular to mechanical axis as shown in Fig. 8. Base on the characteristics of distal femur and the damage conditions, one can moves the locating axis parallel upward about 8mm~10mm to obtain distal femur resection axis, as shown in Fig. 9 where ***b*** is the second critical dimension.

3.3.3 Posterior condylar critical dimension *c*

Posterior condylar resection is the last step to perform at knee arthroplasty prosthesis. The resection surface must be parallel to anterior femoral resection axis as shown in Fig. 10.

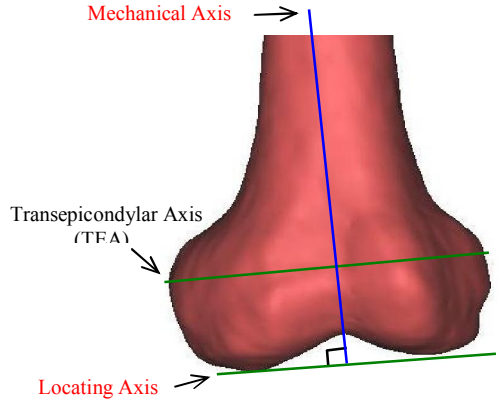

Fig. 8 Schematic of the locating axis for the distal femur critical dimension

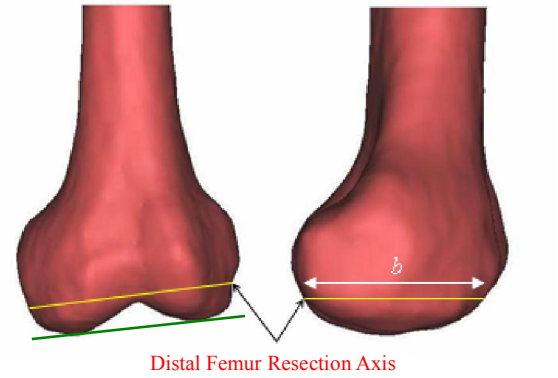

Fig. 9 Schematic of distal femur critical dimension ***b***

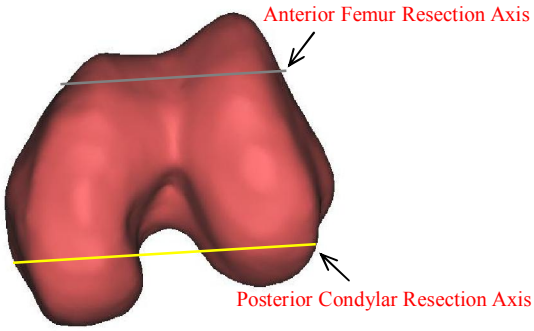

Fig. 10 Schematic of posterior condylar resection axis

The resection location is related to patients' condyle characteristic (including damage conditions) and knee prosthesis. The resection length c is the third critical dimension as shown in Fig. 11. In general, posterior condylar resection axis is perpendicular to distal femur resection axis. The ideal situation is knee joint space of distal femur and posterior condylar after resection is the same at flexion and extension.

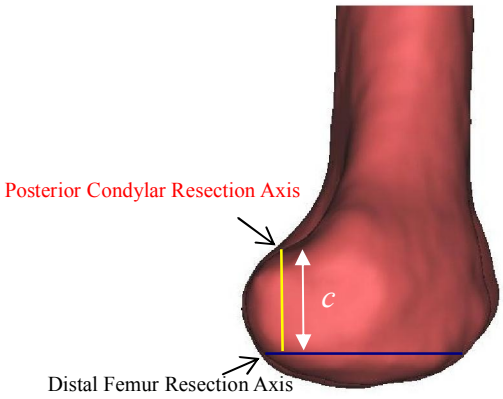

Fig. 11 Schematic of posterior condylar critical dimension ***c***

4. Conclusion

(1) Mimics is used to construct 3D model according to CT and MRI image. Its section method is based on the proper choice of the gray threshold to obtain the precise knee structure contour figure. Because the highly complexity of the knee structure, manual figure section is necessary. It is even difficult to quickly section MRI image. Since manual section requires more experience and technique, the reconstruction efficiency is low.

(2) CT has a better recognition capability of identifying the bone structure. Bone contour can be shown more clearly. MRI has better recognition capability on ligament, muscle and blood vessel. The proper use of the advantage of these two images can construct a much better knee 3D model.

(3) The gray threshold range of Mimics to identify the bone structure is from 226 to 1729. The 3D model prototype is constructed base on this threshold. After the refinement of 3D prototype, the reconstructed model is more close to the actual condition. The refinement includes the comparison/repair of the prototype with CT image from different view angles, directional characteristics etc. The precision of the 3D model built by Mimics is related to the CT/MRI scanning layer thickness. Thinner layer produces better resolution.

(4) To define the knee critical dimensions, three base lines have to be located; they are femoral anatomic axis, transepicondylar axis and mechanics axis. By using the relationship between these three axes, anterior femur critical dimension ***a***, distal femur critical dimension ***b***, and posterior condylar critical dimension ***c*** are defined. These dimensions need to be adjusted according to knee size, bone contour characteristics and damage conditions to fulfill the requirement of the individual custom-made knee prosthesis design.

(5) It is easier to measure the axes, which difficult to be located in actual surgery, by using 3D geometry model defined dimensions, such as transepicondylar axis, etc. In this study, femur resection procedures are setup based on the actual surgical experience simulation. By observing characteristics of the 3D model from different view angles, direction, etc., it is possible to greatly improve the precision of the critical dimension alignment to ensure the knee prosthesis design to fulfill the press-fit purpose.

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