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Automatic Measurement of Distal Femoral Parameters based on Statistical Models

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Abstract. Osteoarthritis and rheumatoid arthritis are common orthopedic complications, and Total Knee Arthroplasty (TKA) replacement is now the standard treatment for osteoarthritis and rheumatoid arthritis of the distal femur. The measurement of distal femoral parameters can help orthopaedic surgeons to select suitable replacement prostheses, and can also help prosthesis manufacturing companies to produce prostheses that are more compatible with the national population. The method uses an alignment algorithm to derive a representative statistical model of the femur, and on the basis of this model, the automatic measurement of the distal parameters of individual femurs is performed. The experimental results on the data set provided by the PLA General Hospital showed that the difference between the results measured using this method and the results measured manually by the physician was about 3 mm, and the method was able to automatically measure the distal femur parameters quickly and efficiently.

Keywords: distal femur, statistical model, alignment algorithm, automatic measurement of distal femur parameters

1. Introduction

The knee joint is the main motor joint of the human lower extremity and plays a vital role in keeping the human body upright and walking, but some studies have shown that the incidence of this joint is very high, such as osteoarthritis, rheumatoid arthritis, tumors, etc. Moreover, with the continuous development of society, the improvement of people's living standards and the rapid development of medical medical devices and other technologies, the average life expectancy of the country has increased and the problem of aging in China has come to a head. Knee diseases and joint degeneration in the elderly are also becoming more and more serious, and more and more elderly people need total knee arthroplasty (TKA) to solve bone diseases. At present, TKA has achieved great success, and reports from western scholars show that the excellent rate 20 years after TKA is around 90% [1], and reports from domestic scholars show that the excellent rate 10-15 after TKA is around 85%-90% [2-4], and it is certain that there is a gap between the excellent rate in China and that in foreign countries[5]. At the same time, some postarthroplasty complications have emerged one after another, such as poor prosthesis position, prosthesis loosening, knee joint infection,patellofemoral joint instability and postoperative pain, limited flexion and extension activities[6], and even periprosthetic fractures in severe cases[7-8].The presence of complications such as prosthesis loosening means the need for postoperative revision, which seriously affects the quality of life of the patient and increases the financial burden of the patient. Most of these complications are due to poor matching of the prosthesis to the femur.

At present, the main source of artificial knee prosthesis used in China is imported from western countries, and these prostheses are designed according to western ethnicity, while the anatomical parameters of a significant part of the current internal fixation products in China refer to the standards of foreigners. However, some studies have shown that the anatomical parameters of the femur in the national population do differ significantly from those of the Western population [8-9]. Therefore, in the surgeon's surgery, there exists the possibility that no matter which model of artificial prosthesis is chosen for knee arthroplasty, it is not possible to achieve a complete fit of the artificial knee joint to the distal femur. In this regard, it is very important to design and produce a prosthesis that fits the morphological characteristics of the femur in the national population.

Therefore, accurate measurement of the morphological parameters of the distal femur is particularly important, not only to provide the surgeon with preoperative guidance in selecting the appropriate prosthesis, but also to provide a basis for the design and production of a suitable prosthesis for the national population. Currently, most of the measurements in China are two-dimensional measurements based on X-rays, which are difficult to accurately compare and analyze with foreign three-dimensional measurements due to differences in the patient's shooting posture and the level of the measuring physician, and the accuracy of the measurements needs to be improved. In this experiment, we used CT data of adult femur to model accurately in software, and also developed a program for automatic measurement of anatomical parameters of distal femur to improve the measurement accuracy and speed, and provide methodological guidance for the establishment of a national skeletal database [10]. In this paper, the accuracy of the automatic measurement method of distal femoral parameters in this study was verified by comparing the automatic measurement results of 150 cases of distal femoral anatomical parameters with the manual measurement results.

2. Related Techniques

2.1. 2.1ICP Algorithm

The basic principle of ICP algorithm[11-12] is that the nearest neighboring points(pi qi) are found in the target point cloud P and the source point cloud Q to be matched, respectively, according to certain constraints, and then the optimal matching parameters R and t are calculated to minimize the error function. The error function E(R, t) is shown in (1).

$$E(R,t) = \frac{1}{n}\sum_{i=1}^{n} \|q_i - (Rp_i + t)\|^2 \tag{1}$$

where n is the number of nearest point pairs,pi is a point in the target point cloud P, qi is the nearest point in the source point cloud Q, R is the rotation matrix, and t is the translation vector.

2.2. CPD Algorithm

The correlated point drift algorithm(CPD)[13-14] alignment algorithm is a point set alignment algorithm based on the hybrid Gaussian model (GMM), which converts the point set alignment problem into a probability density estimation problem. In the point set alignment using CPD algorithm, one set of point set data is used as the template point set data of the hybrid Gaussian model, and the other set of point set data is used as the target point set data of the hybrid Gaussian model, and the maximum likelihood estimation is optimized by the maximum expectation algorithm to finally find the transformation relationship and correspondence between the two point set data to achieve the non-rigid alignment of the two point set data. Assume $M_i = (M_1......M_n)^T$ as the template point set data of the hybrid Gaussian model,assume $T_i = (T_1......T_m)^T$ as the target point set data of the hybrid Gaussian model, and m and n represent the number of points in the two point sets, respectively. Taking each point in the target point set M as the center of each component in the hybrid Gaussian model and assuming equal probability of each component, the distribution model of the target point set M can be expressed as:

$$p(s) = \sum_{i=1}^{M+1} P(i)p(s|i) \tag{2}$$

where:

$$P(i) = \frac{1}{M} \tag{3}$$

$$p(s|i) = \frac{1}{(2\pi\sigma^2)^{D/2}} \exp\left(-\frac{\|s-m_i\|^2}{2\sigma^2}\right) \tag{4}$$

Since the effect of noise is taken into account by adding a uniform distribution function with weight ω to the distribution model, the above distribution model for the target point set M can be further expressed as:

$$p(s) = \omega\frac{1}{N} + (1-\omega)\sum_{i=1}^{M}\frac{1}{M}p(s|i) \tag{5}$$

The center of each component of the hybrid Gaussian model is related to the transformation parameters in the process of alignment, and the model parameters are obtained by minimizing the following negative log-likelihood function:

$$L(\theta, \sigma^2) = -\sum_{j=1}^{N} \log \sum_{i=1}^{M+1} P(i)p(s|i) \tag{6}$$

Solving θ and σ^2 using the maximum expectation algorithm[15-17],The algorithm consists of two steps:The posterior probability distribution is first calculated by the old distribution model $P^{D|d}(i|S_j)$:

$$P^{D|d}(i|S_j) = \frac{exp\left[-\frac{1}{2}\left\|\frac{s_j - T(m_{i^2}\theta^{D|d}}{\sigma^{D|d}}\right\|^2\right]}{\sum_{k=1}^{M} exp\left[-\frac{1}{2}\left\|\frac{s_j - T(m_{i^2}\theta^{D|d}}{\sigma^{D|d}}\right\|^2\right] + (2\pi\sigma^{D|d2})^{\frac{D}{2}}\frac{w}{1-w}\frac{M}{N}} \tag{7}$$

Then the model parameters θ and σ^2 are obtained by minimizing the loss function:

$$cost(\theta, \sigma^2) = \frac{1}{2\sigma^2}\sum_{j=1}^{N}\sum_{i=1}^{M} P^{D|d}(i|S_j)\left\|s_j - T(m_{i^2}\theta^{D|d}\right\|^2 + \frac{D}{2}\log\sigma^2\sum_{j=1}^{N}\sum_{i=1}^{M} P^{D|d}(i|S_j) \tag{8}$$

2.3. Definition and Measurement of Morphological Characteristics Parameters of the Distal Femur

Analyzing earlier studies about the morphology of the distal femur and summarizing the clinical phenomenon of mismatch between the distal femur and the prosthesis in TKA replacement, a total of nine important morphological characteristic parameters of the distal femur were found,which were also recognized by the physicians of 301 Hospital.

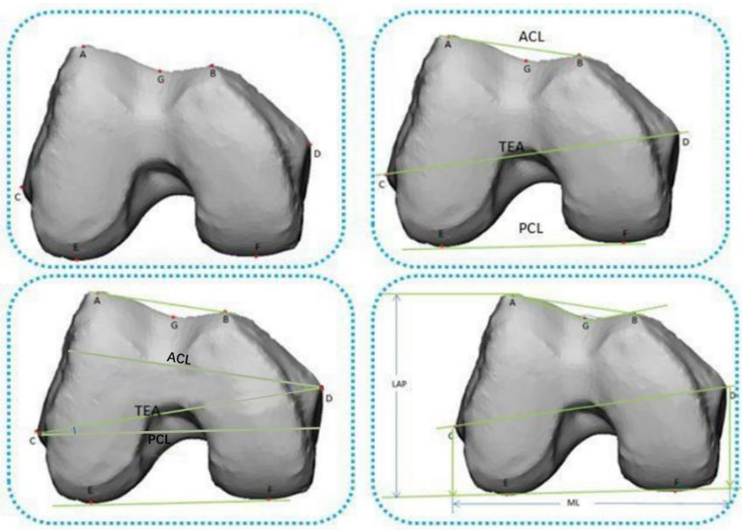

Fig.1. Distal femur parameters

As shown in Figure 1, top left, there are seven key marker points for calculating important parameters of the distal femur: the highest point of the distal femoral epicondyle(A), the highest point of the distal femoral medial condyle(B), the most convex point of the distal femoral epicondyle(C), the most concave point of the distal femoral medial condyle(D), the lowest point of the distal femoral epicondyle(E), the lowest point of the distal femoral medial condyle(F), the two distal femoral epicondyles and the medial condyle superior to the the most concave point(G) in the transverse section. The definitions of the relevant parameters based on these seven key points and the methods of measurement are as follows.

- transepicondylar axis (TEA): the distance between the most convex point of the distal femoral epicondyle and the most concave point of the distal femoral medial condyle.
- posterior condylar line (PCL): the line between the lowest point of the distal femoral epicondyle and the lowest point of the distal femoral medial condyle.
- anterior condylar line (ACL): the line between the highest point of the distal femoral epicondyle and the highest point of the distal femoral medial condyle.

- Angle of the glide sulcus (AOB): The highest point of the distal femoral epicondyle is A, the highest point of the medial epicondyle is B, and the lowest point of the intercondylar concavity in the two cross-sections is O. The angle formed between them is AOB.
- medial-lateral (ML): The distance between the most concave point of the medial condyle and the mostconcave point of the medial condyle and the most convex point of the epicondyle in the PCL vertical projection.
- LAP: The vertical distance from the highest point of the lateral epicondyle of the femur to the PCL.
- Femoral surface ratio:ML/LAP.
- PCA:The angle between PCL and TEA.
- ACA:The angle between ACL and TEA.

3. Experimental Procedure

In this paper,we propose a method for automatic measurement of morphological characteristic parameters of the distal femur based on statistical models. The input of the method is a large CT dataset of 3D femurs, and the output is the specific values of the distal morphological characteristic parameters of each femur to assist orthopedic surgeons in the treatment of patients with TKA replacement and the design and optimization of prostheses. The method in this paper is shown in Figure 2. The method consists of three stages: (1) Femoral CT dataset generates the data of the 3D coordinate point set of the femur. (2) Solving the statistical model of the femur. (3) Automatic measurement of morphological characteristic parameters of the distal femur.

In stage (1), the CT data is imported into MIMICS software to segment the femur by threshold segmentation and other operations and export the femoral model in stl format, then it is read and transformed into 3D coordinate point set data using python and displayed in slicer software. In stage (2), a statistical model of the femur is derived using an alignment algorithm based on the 150 femurs processed in stage (1). In stage (3), the specialist marks the key marker points of the distal femur to be measured in the femoral statistical model generated in stage (2), aligns the individual femur with the femoral statistical model to find the key points on the individual femur, and further calculates the distal morphological parameters of the individual femur.

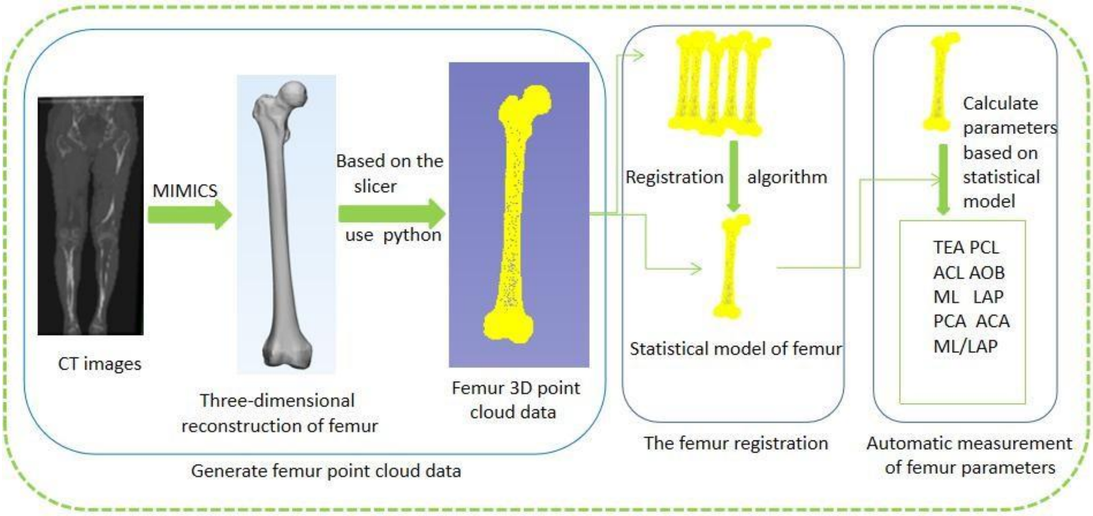

Fig. 2. The experimental framework

3.1. Data Collection and Preprocessing

In this study, 300 femoral models (150 on the left and150 on the right), which were representative of the 150 national femoral models library, were used as study subjects. A CT scanner was used to scan each patient at the General Hospital of the Chinese People's Liberation Army, and CT images of the human skeleton were taken from three angles: main view, left view, and top view. The image field of view was 512 *512 pixels, resolution 0.625 mm *0.625 mm, and thickness of each slice was 1.200 mm. all CT image data of these patients were saved as digital images in medical format and imported into the reverse engineering software MIMICS version 21.0 for 3D reconstruction of the femur, exported as point cloud data, and prepared for statistical modeling of the femur.

3.2. Statistical Modeling of the Femur

The process of generating the femur statistical model is as follows.

- Treat the N femur model as a set containing N nodes and define the initial weight of each node as 1.
- Two nodes are randomly selected from the set and rigidly aligned using the ICP algorithm and non-rigidly aligned using the CPD algorithm, so that the two femurs have the same topology and a new average femur model is generated.
- Remove the two randomly selected nodes from the set, and add the generated new average femur model to the set as a new node whose weight is the sum of the weights of the two deleted nodes.
- Repeat step two until the last node remaining in the set is the statistical model of the femur.
- On this statistical model, the seven marker points introduced in the second part are marked by an orthopedic expert for the automatic measurement of distal femoral parameters.

3.3. Automatic Measurement of Distal Femoral Parameters

The method of automatic measurement of distal femoral parameters based on the femoral statistical model. The multivariate group G={S, P, H, M} is defined to describe the femoral model S, the feature point P, the distal femoral parameter H, and the mapping relationship M. The specific meanings of each parameter are as follows.

S ={SA , SB} , SA is the femur statistical model, SB is the target femur statistical model to be measured.

P = {PA , PB}, PA is the feature point on the femur statistical model, and PB is the feature point on the target femur statistical model to be measured.

H = {HA , HB}, HA are the distal femoral parameters on the femoral statistical model, HB are the distal femoral parameters on the target femoral statistical model to be measured.

M is the mapping relationship between PA and PB.

The specific steps of the method for the automatic measurement of distal femoral parameters based on the femoral statistical model are shown below.

- The iterative nearest point algorithm (ICP) is used to make a rigid alignment from the target femoral model to be measured to the femoral statistical model, so that the target femoral model is aligned to the statistical model. In this process, the closest point on the two models is selected as the corresponding point, and the rotation matrix and translation vector are calculated by minimizing the distance between the corresponding points, and then the rotation matrix and translation vector are used to update the position of the target femoral model, and so on until the local minimum.
- A consistent point drift algorithm (CPD) is used to make a non-rigid alignment of the femoral statistical model to the target femoral model to be measured, so that the shape of the femoral statistical model is close to that of the femoral model to be measured. This process transforms the point set alignment problem into a parameter estimation problem for the Gaussian model function.
- Find the corresponding feature points on the target femur to be measured according to the feature points on the femoral statistical model, and complete the automatic measurement of the parameters at the distal end of the target femoral model to be measured according to the parameter calculation method defined in Part II.

4. Analysis of Experimental Results

4.1. Parameter Measurement Evaluation Indexes

In this paper the measurements of distal femoral parameters are numerical, so statistical methods are used for evaluation, and the evaluation indexes used in this paper are comparing the Variance and Mean bias.

- Variance.The variance indicates the degree of dispersion between the measurement results and the mean value of the two measurement methods, because the morphological parameters of the distal femur in normal human have a certain range, so if the variance of the automatic measurement results is too large, it indicates that the performance of the method is not stable, and it also indicates that the automatic measurement method is inaccurate in some cases. Conversely, if the variance of the automatic measurement results is similar to the variance of the manual measurement results, then the automatic measurement method has a stable line.

- Mean bias. The average deviation reflects the overall difference between the automatic and manual measurement methods on the test set. By calculating the mean deviation it is possible to assess the overall performance difference between the two methods and also to avoid the one-sided results from affecting the overall performance assessment of the automatic parameter measurement method. Thus, the purpose of evaluating the automatic measurement method of distal femoral parameters proposed in this paper from an overall perspective is achieved.

4.2. Analysis of Results

EXCEL software was used to record the parameters measured by the two methods, and SSPSS 19.0 statistical software was used to calculate the variance and average deviation of the parameters measured by the two methods, and the data were statistically analyzed. The statistical results are shown in Table 1.

As table 1 shows the average deviation between the manual and automatic measurement is about 3.1 mm, show that automatic measurement effect is better, so as to prove that the proposed model based on statistical parameters of distal femur is better, the effect of the automatic measurement method is beneficial to help doctors prosthesis selection in TKA surgery, but also to help prosthetic design and production.

Table1 Quantitative analysis of the measurement results

	TEA(mm)	*PCL(mm)*	*ACL(mm)*	*AOB*	*ML(mm)*	*LAP(mm)*	*PCA*	*ACA*	*ML/LAP*
Mean bias	3.3	3.1	2.9	1.5°	3.2	2.8	0.8°	1.4°	0.02
Variance	1.53	1.53	1.35	0.95°	1.55	1.36	0.53°	0.84°	0.01

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