Abstract—Objective: In order to avoid the adverse consequences which cause by anthropogenic factor in the femoral neck fracture surgery and meet the requirements of selecting the most reasonable internal fixation way, from the viewpoint of biomechanics, an optimal selection system of internal fixation methods for femoral neck fracture are established which integrates preprocessing, solving and post-processing. Method: A reasonable simplified femur model is presented by analyzing a precise model of femur standing on one leg. After special patient’s femur model is set up, different internal fixation model are analyzed using finite element method (FEM). The interactive communication between APDL and object-oriented programming language is realized. Following evaluation parameters are got based finite element analysis: sinking displacement, lateral displacement, torsional displacement, sum displacement of femur head and gap displacement between fracture surfaces. According to the results, the evaluation algorithm is complied to select the optimal internal fixation method. This study is completed in 3/20/2012 at Harbin University of Science and Technology. Result: As the application of optimal selection program of internal fixation methods for femoral neck fracture, the best fixation way is got when fractures angle is 70°. The result show, without considering bone substance, materials and complications, only from the displacement changing trends of femoral head and fracture interfaces, the internal fixation method with two erect screws is the most reasonable one. Conclusion: The system can provide the number of tightening screw, the fixed angle and combinatorial way of the optimal result to doctors to perform operations.

Index Terms—Femoral neck fracture, Internal fixation, Optimal selection, Finite element method, Evaluation algorithm

I. INTRODUCTION

The treatment of femoral neck fracture is divided into conservative therapy and aggressive surgical therapy. But the nonunion rate of conservative therapy accounts for 48%. 34% of the patients may occur to femoral head necrosis[1], so doctors advocate aggressive surgical therapy in modern orthopedics. In common, surgical treatment is divided into 3 steps; they are fracture reduction, selecting internal fixation method and nail-pierced operation. Traditionally, the internal fixation method is controlled by doctors which relies solely on practical experience. This way usually leading to the rationality of structural mechanics ignored. According WOLFF principle, reasonable mechanical environment can promote the growth and healing of bone. During the process of surgical treatment, selection of internal fixation method is the only controlled variable and the only critical factor which can change the mechanical environment. Therefore, select the most reasonable internal fixation pattern is the fundamental guarantee of nail-pierced operation successfully. Aiming at selecting the optimal internal fixation method for femoral neck fracture in this paper, combining with doctors’ operation and theoretical research, propose an optimal system which is available for users from biomedical engineering perspective. ANSYS Parametric Design Language (APDL) is applied to establish finite element model; the nodal displacement of fracture site under the condition of special patient’s is fixed by personalized internal fixation pattern. Model is solved by FEM. Finally assisting the users find out the optimal operation plan of internal fixation based analysis results and evaluation rules.

II. METHODS

A. Fractured Types and Internal Fixation Methods

The number of tightening screw, fixed angles and combinatorial ways, these 3 develop several kinds of internal fixation patterns by permutation and combination. Taking the femoral neck fractures as research object, according to the clinical treatment methods in this paper, fixed angles are set from 30°to 70°; the number of tight screw is set from 1 to 3; Combinatorial ways are set as one screw, two horizontal screws, two slant screws, two erect screws, upside-down equilateral triangles, erect equilateral triangles[2,3]. This setting way depending on special patient’s fracture condition realizes the users can select the personalized best internal fixation method.

B. Assumed Conditions for Finite Element Modeling and Solving

Bone is anisotropic and is made up by a vast range of materials[4]. Because the computed result is not much contrast, the bone is assumed to be an elastic material and complies with linear elastic theory[5]. Some assumptions for finite element modeling are made in this paper:

Before any action, skeleton is in the unstressed natural state, without discontinuity inside.
The stress and strain of per point can be expressed by a continuous function of coordinate and has the same physical property and mechanical characteristic.

When bone is influenced under the condition of load or temperature variation, the deformation would restore if it is in elastic range. In addition, the deformation which is caused by external force is usually far less than the original size.

In view of these assumptions, the define method of element attribute and the assignment method of material properties are both based on the linear elastic theory.

For solving models by FEM effectively, some assumptions for solving have to be made before simulation study:

The study stage is set as the fracture reduction and internal fixation have just finished and the healing process is about to start.

The fracture site is fixed by cylindrical screws which closely integrated with bone. Even if load is applied there is no relative displacement, which is the reason that screws are simplified as cylinders.

Assume the strength of cylindrical screws is enough which cannot be broke.

According to the rough situation of bone, the frictional factor is set as 0.9.

C. Modeling

For we focus on the mechanical characters of femoral neck and overcome shortcomings of modeling by finite element software, the model is simplified in this paper. Create a precise model and calculate it by finite element software under the condition that standing on one leg. So the physiological load has to be known. Because the mechanical environment of femur is complicated, we only can get the composition of forces. According to the accurate mechanical model of femur which proposed by Scige[6] that when standing on a single leg, there are 3 composed forces, they are the joint reaction force J, iliotibial tract muscle force R, abductor force M. The mechanical model is shown in Fig.1.

After calculating, following conclusions are got: the leading force J which transfers from femoral to femoral shaft. The upper side of femoral neck which is in the middle is subjected tension stress, and the downside is subjected compressive stress. The stress of great trochanter is little, so the finite element model is simplified at this part.

Aim to establish special patient finite element model, parameterized method is adopted in this paper. A finite element model of femur and an internal fixation model are created. Set anatomy parameters such as neck-shaft angle(b), the diameter of femoral head(d) which got from X-ray film as variables by *SET function of APDL[7]. These parameters are input into the interface of the system then form an individualized APDL file. The definition of each unit and the assignment of material property are set by EX, ET functions of APDL.

After femur neck fracture geometry model and finite element mechanical model are gotten, the number of tightening screws, the fixed angle and combinational way are set as variables which are selected by users. Due to APDL cannot distinguish string type, define the 6 kinds of combinational ways as macros combing with condition control statements for APDL to read. Create cylindrical screws and define the materials are stainless steel. Insert them into the femoral neck by Boolean operations. The radius of the screws is chosen by thread series of international standard based on constant section. Finally 6 cases of internal fixation finite element models are shown in Fig.2.

D. Solving

FEM is adopted to solve internal fixation models. Expect the functions of APDL mentioned above, in order to apply load to the fixed node, use the function asel with the parameter loc of APDL to select nodes which should apply load J, M, and R. Meanwhile select the region to apply all constraints. Forces of J, M, and R are applied to the fixed nodes and start to solve.

Establish the FE mechanical simulation model:

\[
M\ddot{x} + C + Kx = f
\]

M represents a mass matrix, C represents a damping matrix and K represents a stiffness matrix.

The tetrahedral element is adopted, so the displacement function is expressed by determinant:
\[
\begin{align*}
\mathbf{u} &= \frac{1}{6V} \left\{ \left( a_i + b_i x + c_i y + d_i z \right) \mathbf{u}_i + \\
&\quad \left( a_j + b_j x + c_j y + d_j z \right) \mathbf{u}_j + \\
&\quad \left( a_m + b_m x + c_m y + d_m z \right) \mathbf{u}_m + \\
&\quad \left( a_p + b_p x + c_p y + d_p z \right) \mathbf{u}_p \right\}
\end{align*}
\]

\(V\) represents the volume of a tetrahedron.

The strain matrix verified as follows:

\[
\varepsilon = B \varepsilon = \begin{bmatrix} B_1 \end{bmatrix} \varepsilon
\]

\[
B_i = \frac{1}{6V} \begin{bmatrix}
\frac{\partial N_i}{\partial x} & 0 & 0 \\
0 & \frac{\partial N_i}{\partial y} & 0 \\
0 & 0 & \frac{\partial N_i}{\partial z}
\end{bmatrix}
\]

\(N_i = \left( a_i + b_i x + c_i y + d_i z \right) / 6V\)

Change the corresponding subscript, other submatrices can be got.

E. Judgment Criteria

For the patients only can do moderate physical activity which is a static analysis, so standing on one leg is considered in this paper. According to AO principles, judging from the following parameters:

The displacement of femoral head (US): When standing on one leg, femoral head would subject load and cause displacements including lateral displacement which influence the tensile strength and immobility of fracture surfaces in x-axis; sinking displacement which influence shearing resistance in y-axis; torsion displacement which influence resisting to torsion in z-axis. The values of these 3 displacements are the smaller the better. For the sake of evaluating UX, UY, UZ, set evaluation parameters named US which represents resultant displacement of 3 directions, which is the smaller, the better.

The evaluation parameters include lateral displacement of femoral head UX, the sinking displacement UY, the torsion displacement UZ and sum displacement US.

Boundary conditions are to restrain the sagittal plane, longitudinal plane, coronal plane of distal femur.

Among the evaluation parameters, US and UF is the most directly evaluation parameters which can reflex the fixed-effect. However, the size relationships of US and DS are not conformity in practical situations. In addition, summarize the biomechanical experiments the other universities did, we find that the ratio of US among reasonable fixed patterns would not larger than 114% and DS would not larger than 153%. So, one third of the optimum results are selected to define US and DS. Therefore, the following criteria are proposed which compile into an evaluation algorithm by C++. The criteria are shown in Tab. 1, and the flow chat is shown in Fig.4.

| \(\text{US}_{\min} = \text{DS}_{\min}\) | Select the internal fixation pattern which minimum of US and DS correspond to. |
| \(\text{US}_{\min} \neq \text{DS}_{\min}\) | \(\frac{\text{US}}{\text{US}_{\min}} \leq 1.047\) |

\[
\frac{\text{DS}}{\text{DS}_{\min}} \leq 1.177 \quad \text{Select the internal fixation pattern which the minimum of US correspond to.}
\]

\[
\frac{\text{DS}}{\text{DS}_{\min}} > 1.177 \quad \text{Do not find the most reasonable internal fixation pattern. Please reselect.}
\]
Start optimization

Find $US_{\text{min}}$ and $DS_{\text{min}}$

$m=1$

$m=m+1$

$m=n$

Select $DS_{\text{min}}$ from $DS_{\text{got}}$

$US_{\text{min}}/US_{\text{max}} \leq 1.047$

Yes

Acquire $DS_{\text{min}}$

No

$DS_{\text{min}}/DS_{\text{max}} \leq 1.177$

Yes

Fixation method $DS_{\text{min}}$ counterpart is preferred

No

Figure 4 The flow chat of the evaluation algorithm

The program include:

(1) Compile the communication codes between object-oriented language and APDL, to realize that collect information from interfaces and transfer to APDL to model, solve and show the results.

(2) According to the information collected, such as anteverision angle, neck-shaft angle, the diameter of femoral neck and so on, transfer them to the parameters of APDL to establish the geometry model of femur.

(3) According to the medical history of patients, considering the disease which may affect the selection of internal fixation pattern, like osteoporosis, the system will warn the users that one screw is preferred[8].

(4) Combining with patients’ actual situation, initially select a method. This method does not indicate the optimal plan and can be reset frequently. Transfer the int and float type parameters of operative plan by the codes of step1 to establish the fixation finite element model which is fractured.

(5) Simulate standing on one leg, base on the calculation model Scige put forward and the assumptions above, the equilibrium equations of force and moment are list. Then calculate the 3 forces load on femoral head.

(6) The results computed by step 5 are transferred to finite element model to solve the model by FEA (finite element analysis), and the analysis results will show on the interface.

(7) The system calls the APDL codes of post-processing, show the numerical results of each internal fixation method the user chosen on the interface. Compare the results the system will give the user the optimal result by the evaluation algorithm back stage, and show it on the window.

According these steps, the flow chat of the system is shown in Fig.5.

F. Optimal Program of Internal Fixation Method for Femoral Neck Fracture

Modularized programming ideas and object-oriented programming language are used in the system. Ever problem to be solved is considered as a module [9]. The whole system is divided into 3 modules which are parameterized preprocessing module, the solving module and post-processing module.

Parameterized preprocessing module. The main function of this module is summarized as build
parameterized models of femur and internal fixation models. Though building the two cases of finite element models has different APDL frame codes, the way of getting parameters and the way of transferring are the same.

The method of getting the parameters and transferring is running through the whole system which is used not only in preprocessing to build finite element models but also in calculating the forces on femur. This method realizes variable parameterized design that means assigning the relevant parameters in APDL frame codes through the visualization interfaces.

MFC cannot select file as save path, so this drawback is worked out in this system first. Class CPathDialog and CPathDialogSub are friends and derived from class CWnd. Expect the constructed function, 9 functions are defined either. The classes mainly include callback function BrowseCallbackProc inside which a SWITCH statements are used to judge the situations and handle. 2 situations are considered: the first is initialization, the other is when the save path changes. The function MakeSurePathExists checks if the path exists. The function IsFileNameValid is to check if the path is valid, and the functions of Touch, ConcatPath which are able to connect the save path.

Define a function named OnApdlfile in CDialog class. Create a txt file inside OnApdlfile function by strPath+"="+input1.txt which is used to store the complete codes of APDL. Moreover, realize transfer the parameters. 11 pieces of information are need to model. So, 11 variables of CEdit, int and char types are defined, then call the member function GetWindowText to cast (atoi). Read and write the APDL frame codes to the txt file which already defined by the class fstream, the class wfstream. User-defined function void OnRunansys is the crucial function to solve models by finite element method inside which create a thread by AfxBeginThread (Simulation,this,THREAD_PRIORITY_NORMAL). The first parameter does not only include the definition of AnsysPath, ApdlPath and buffer but also the Macro file Bone_Ansys.mac. The function WinExec (CommandStr,SW_HIDE) is also important which realizes the batch mode is applied by finite element analysis software. The command is CommandStr =""+""+""+MacFile+"" -o output.txt". This function connects the path of finite element analysis software and the path of APDL file and saves the results solved by finite element method to the output.txt.

Moreover, the parameters need in operative plan are the number of tightening screw, combinatorial ways which cannot distinguish by APDL. In order to make this happen, define the number of screw and the combinatorial ways as Macro in the system for APDL to distinguish. The interfaces of information and parameter acquisition and the selection of internal fixation pattern are shown in Fig.6. 2 vertical screws setting software implementation

*IF, VAL4, EQ, 20010
CYL4, 0, 0, 0, 0, 6, 360, m
Wpoff, 0, 6

Figure 6 The interface of information acquisition. In this figure, we can see fracture angle(\( \alpha \)), antversion angle(e), neck-shaft angle(b), femoral shaft angle(c), the diameter of femoral head(d), the diameter of femoral shaft(d1), the diameter of femoral neck(d2), the height of the cone between femoral head and femoral neck(b), the arm of muscular contraction(f).

The solving module. This module is applied to calculate the load on the femoral head when standing on one leg under normal circumstance. In fact, femur is subjected complicated stress. Through many researchers have simulated the stress of muscles around femur in vitro, it’s far too difficult to act load in every muscle. Taylor[10] holds the opinion that there is much nondeterminacy such as the selected quantity, the direction of load and so on, especially dynamic loading. Therefore they propose to analyze the load of leading role. The simplified mechanical model which is presented by Scige is shown in Fig.1. The primary external loads are joint reaction force J, Iliotibial tract force R, abductor force M which stress distributions are generally the same as femur interface.

J,M,R have certain relationship with body weight when standing on one leg. The gravity line of body locates the rear of public symphysis. Aim to maintain balance on one leg, the reacting force of ground is W which represents body weight, the 1/6 of W is borne by leg, and the left part bears 5/6W.

When calculating, divide the hip joint into upper separation and lower separation. 3 formulas of moment and force balances are need, and schematic of 3 forces are shown in Fig.7. 

\[
\begin{align*}
5 & \frac{W \times b - M \times f + R \times d}{6} = 0 \\
\end{align*}
\] (1)
There into:

\[ b = 2f \]

\[ \theta = 29.5^\circ \], so according to Fig. 8:

\[
M_X = M \times \sin \theta \\
M_Y = M \times \cos \theta
\]  

(2)

According to the lower separation, the balance formula:

\[
M_X - J_X = 0 \\
M_Y - J_Y = 1/6 W + W - R = 0
\]  

(3)

(4)

\[ \phi = 22.4^\circ \], so, the force J is shown in Fig. 9:

\[
J_X = J \times \sin \phi \\
J_Y = J \times \cos \phi
\]  

(5)

Figure 7 Force diagram of upper separation. When calculating, divide the hip joint into upper separation and lower separation. 3 formulas of moment and force balances are need. The parameters in the 3 formulas are shown in this figure. R means iliotibial tract muscle force. M means abductor force. Q means a central point of a femoral head.

In order to show the essential information of fixed model and get W and f which are need to calculate J, R, M; the third interface should acquire parameters from the first interface which have already input. But MFC only can realize transmit the parameters between adjacent dialogs, therefore, the technique we use is set 9 invisible Static Texts to collect the parameters from the first interface and then transfer to the third interface.

Post-processing module. This module includes the submodule of showing finite element biomechanical model solving results and the submodule of result optimization. The solving results can be shown in real-time. The results output into an output.txt document by ANSYS batching mode in function winexec. When the content of flag.txt is 1, the ANSYS is running. The content which is saved in output.txt can be read and kept in buffer by the function Open of class CFile. Then the data in buffer are shown in edit box of which ID is IDC_STATUS through function Read. Then, according to the judgment criteria, US and DS are considered to optimize.

III. RESULTS

Consider a female patient of intertrochanteric fractures in 70° and measure the anatomical parameters by X-ray film. Then input them into the interface (fig. 10) and create a femur finite element model. Select an internal fixation method. We select the two horizontal screws with 40° and create an internal fixation model. The system acquires the information from the interface automatically and calculates the load which applied on femur. Next, the system gets the results computed and solves by finite element software. The analysis results show on the interface (fig. 11) in real-time. Analyze the internal fixation methods of one screw with 40° and upside-down equilateral triangles and show all the result on the interface (fig. 12 and fig. 13). Finally, sort the result and find out the most reasonable internal fixation method (fig. 14).

The same as the results provided by Zhang Meng[8], under the conditions of intertrochanteric fractures in 70°, we can see that without considering bone substance, materials and complications, only from the displacement changing trends of femoral head and fracture interfaces, the internal fixation method with two erect screws is the most reasonable one. Though people always hold the opinion that the number of fixed screws more, the structure is more stable. All that results is not the same. Meanwhile the result got by the system is proved to be correct and reliable.
Figure 10 Acquire the patient’s information

Figure 11 Calculating the load and solving the two model of two erect screws in 40°

Figure 12 Calculating J, M, R and solving the FE model of one screw in 40°. J means joint reaction force. R means iliotibial tract muscle force. M means abductor force.

Figure 13 Calculating the load and solving the FE of model with upside-down equilateral triangles

Figure 14 Results optimization. The same as the results provided by Zhang Meng[8], under the conditions of intertrochanteric fractures in 70°, we can see that without considering bone substance, materials and complications, simply from the displacement changing trends of femoral head and fracture interfaces, the internal fixation method with two erect screws is the most reasonable one.

IV. DISCUSSION

The simulation and optimal selection results show the internal fixation method with two erect screws is the most reasonable. Though people always hold the opinion that the number of fixed screws more, the structure is more stable. All that results is not the same. The result got by the system is proved to be correct and reliable.

Combing finite element method with the objected-oriented programming language, an optimal selection system of internal fixation method for femoral neck fracture is developed in this paper. According different fracture situations, the system can select the most proper method of the number of fixed screw, fixed angle and combinatorial ways intelligently and reasonably which has guiding significant for the treatment of femoral neck fracture in clinic. Meanwhile it provides an innovative and convenient method to help doctor to decide the better fixation way. From the research, the following conclusions are obtained:

The relationship between bone fracture and mechanics are studied, the parameters which are adopted to evaluate fixed effect are presented. The parameters include displacement of femoral head and the maximal
interfragmentary movement. According to the biomedical experiments summarized relation, propose evaluation criteria and compile into evaluation algorithm by object-oriented programming language to optimize the internal fixation method.

A reasonable simplified femur model is presented by analyzing a precise model of femur standing on one leg which makes the modeling process can be realized by finite element parameterized language. The size of the femur model and the methods of internal fixation can change as need through interface input parameters. Then all the steps including preprocessor, solving and post-processing are realized in our optimal selection system software.

Realize the interactive communication between APDL and object-oriented programming language. In the same software, doctor can complete optimal selection based bone biomechanical analysis results.

The optimal selection system of internal fixation methods for femoral neck fracture is an executable program which compiled by C++ programming language in Visual C++6.0. Ran the optimal system software, a computer with more than memory 512MB is necessary and the assistant software ANSYS have to be installed in the computer. The running time of the optimal system is 3 minutes at least.

In addition, only testing the rationality and reliability of the system, we don’t focus on the anisotropy of bone or dynamic loading. Moreover, the influence of rub, contact and bone substances also should be taken into account. In order to make our optimal selection system more perfect, we will do further research in real-time computer and accurate model in the future.

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