Finite Element Analysis of Absorbable Sheath to Prevent Stress Shielding of Tibial Interlocking Intramedullary Nail

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Abstract. The nail with absorbable sheath (AS nail) is designed to reduce the stress shielding effect of internal fixation with interlocking intramedullary nail. In order to verify its feasibility, two types of the finite element models of internal fixation of tibia with the AS nail and the common metal nail (CM nail) are established using the Softwares of Mimics, Geomagic, SolidWorks and ANSYS according to the CT scanning data of tibia. The result of the finite element analysis shows that the AS nail has great advantages compared with the CM nail in reducing the stress shielding effect in different periods of fracture healing. The conclusion is that the AS nail can realize the static fixation to the dynamic fixation from the early to the later automatically to shorten the time of fracture healing, which also provides a new technique to the interlocking intramedullary nail.

1. Introduction

Domestic and foreign scholars believe that the fixation of interlocking intramedullary nail belongs to rigid internal fixation and the disadvantage is the stress shielding effect can be generated [1]. At present, the main solution is to realize the static and dynamic transformation of the interlocking intramedullary nail. The commonly used method in clinic is the screws of one end of the intramedullary nail are removed in the metaphase of fracture healing to make fracture ends produce fretting and stimulate the growth of callus, but this requires patients to undergo surgery again [2].

In order to avoid the defects mentioned above, the nail with absorbable sheath (AS nail) is designed by combining the absorbable sheath with the common metal nail (CM nail) as shown in figure 1. The basic principle is sheathed the absorbable sheath on metal screws using the degradation of absorbable materials to reduce the stress shielding effect. This paper is to verify whether the AS nail can reduce the stress shielding effect of tibial locking nail using the method of finite element analysis (FEA).

Figure 1. (a) the CM nail; (b) the AS nail.
2. Materials and methods

2.1. Data acquisition
A healthy adult volunteer is selected, aged 25 years old, 60kg body weight. The LightSpeed VCT is used for continuously scanning the left lower limb from the ankle to the knee joint, and the scanning results are stored in the format of DICOM (Digital Imaging and Communications in Medicine).

2.2. Establishment of finite element model of tibial internal fixation

2.2.1. Establishment of the 3D model of middle tibial fracture with callus. First of all, the CT scanning data of tibia is imported into the Mimics. The triangular surface of tibia is calculated after threshold setting (226-2311HU), region growing and holes filling. And the NURBS (Non-Uniform Rational B-Splines) surface is generated by surface thinning, contour editing and surface fitting in Geomagic. Then the 3D solid model is generated in SolidWorks. Finally, the transverse fracture of the 1.5mm [3] is removed by transverse stretching in the middle, and the bony callus of the same size is lofted in the gap. So far, the 3D model of middle tibial fracture with callus is established.

2.2.2. Establishment and assembly of the model of internal fixation. In this study, the diameter of CM nail is 4.0mm and 5.0mm; the inner and outer diameter of the absorbable sheath is 4.0mm and 5.0mm. The AS nail is got by combining the absorbing sheath and the CM nail with a diameter of 4.0mm. All the internal fixation devices are established in SolidWorks including the absorbable sheath, which is divided into A, B, C three parts because of the different absorption rate in bone and tissue fluid. The thicknesses of them are calculated by the absorption rate [4] in Table 1. Then the reamed tibial model with screw holes is established named no fixed group after the Boolean operation as shown in Figure 2a. Finally, models of internal fixation are assembled as shown in Figure 2b and Figure 2c.

| Material properties | Grouping(months) | 1  | 3  | 6  | 9  | 12 |
|---------------------|------------------|----|----|----|----|----|
| Young’s modulus(MPa)| Callus           | 2  | 800| 1000| 6000|17000|
| Poisson’s ratio     | Absorbable       | 0.167| 0.3 | 0.3 | 0.3 | 0.3 |
| Young’s modulus(GPa)| tissue           | 5.23| 4.14| 1.88| 0.42| 0   |
| Poisson’s ratio     | Absorbable       | 0.3 | 0.3 | 0.3 | 0.3 | 0   |

2.2.3. Parameter setting and meshing. The models of tibial internal fixations (a total of 15) are imported into ANSYS respectively and given the following assumptions [5]: The components of the models are homogeneous, continuous and isotropic linear elastic materials, and tibia is totally composed of cortical bone. The material properties of callus and absorbable sheath in different periods of fracture healing [4, 6] are listed in Table 2. Among them, the material of absorbable sheath is poly l-lactic acid (PLLA); the interlocking nail and CM nail are Ti6Al4V. Then the 10 node tetrahedral element solid 92 [7] is selected to mesh the model which is shown in Figure 2d. The material properties [4, 8], the number of nodes and elements in the rest of the model are shown in Table 3.
Figure 2. (a), (b), (c) are the models of tibial internal fixation with no fixed, AS nail and CM nail; (d) is AS nail group after meshing.

Table 3. Material properties, nodes and elements in the model.

| Material types      | Young’s modulus (MPa) | Poisson’s ratio | Nodes   | Elements |
|---------------------|-----------------------|-----------------|---------|----------|
| Cortical bone       | 17000                 | 0.3             | 624769  | 256993   |
| Callus              | —                     | —               | 12051   | 6699     |
| Interlocking nail   | 112000                | 0.3             | 76356   | 50013    |
| AS nail             | —                     | —               | 53605   | 37379    |
| CM nail             | 112000                | 0.3             | 40144   | 27464    |

2.3. Contact conditions
The absorbable sheath is bonded with the CM nail by the glue command in ANSYS; the relationship of contact between absorbable sheath, interlocking intramedullary nail and tibial screw holes, the callus and the fracture sections are bonded in AS nail group. All types of contact are set to the bond in CM nail group. The friction between intramedullary nail and medullary cavity is ignored for them.

2.4. Loading and boundary conditions
Human knee joint bears about 85.6% of body weight when human normal walks [9]. The weight of the volunteer is 60kg. So about 250N is loaded on the unilateral tibial plateau vertically in a way of uniformly distributed load. And the degree of freedom of all nodes in the ankle joint is set to zero as a boundary condition. Then the three groups are calculated after setting load step and other parameters.

3. Results

3.1. Average stress of callus in different periods of fracture healing
The stress nephogram of callus is obtained according to the results of FEA as shown in Figure 3. The average stress of callus is calculated based on the stress values of all nodes in callus at 1, 3, 6, 9 and 12 months respectively, and the results are shown in Table 4, in which showed that the average stress of callus of the AS nail group is higher than that of the CM nail group in different periods of fracture healing. The results indicated that the degradation of absorbable sheath reduced the gap of fracture ends, which caused the callus to produce larger stress and reduced the stress shielding effect.
Figure 3. (a, b, c), (d, e, f), (g, h, i) are the no fixed group, the CM nail group and the AS nail group of the stress nephograms of callus at 3, 6, 9 month respectively.

Table 4. Average stress of callus in different periods of healing (Pa).

| Grouping(months)   | 1   | 3   | 6   | 9   | 12  |
|-------------------|-----|-----|-----|-----|-----|
| No fixed group    | 58613.3 | 799875.8 | 802293.4 | 903767.7 | 1285344.1 |
| CM nail group     | 34050.7 | 613306.9 | 638626.0 | 690224.5 | 959393.0 |
| AS nail group     | 40944.8 | 687347.7 | 719961.9 | 791171.0 | 1014994.6 |

3.2. Stress shielding rate of callus caused by internal fixation.

The stress shielding rate is used for representing the stress shielding effect in orthopaedics, and the two groups are calculated by the equation (1) [10]. The results are shown in Figure 4.

\[ \eta = \left(1 - \frac{\sigma_{\text{fixed}}}{\sigma_{\text{no fixed}}}\right) \times 100\% \] (1)

where the \( \eta \) represents the stress shielding rate, the \( \sigma \) represents the average stress of callus.

The analysis showed that the stress shielding rate of AS nail group is significantly lower than that of CM nail group in different periods of fracture healing. And most obvious, the reduction percentage is about 50% compared with the CM nail group at 6 month. The simulation result shows that AS nail can reduce the stress shielding rate of the interlocking nail, and has more advantages than the CM nail.

Figure 4. Stress shielding rate in different periods of healing.
4. Conclusion
The result shows that the average stress of callus of the AS nail group is always higher than that of the CM nail group without fretting effect in the different periods of fracture healing.

The average stress of callus in AS nail group is 20% and 12% higher than that of CM nail group in the first month and the third month, 12% higher in the sixth month, 14% and 6% higher in ninth month and the twelfth month. These results indicate that the interlocking intramedullary nail with AS nail has high stress, high strength and good healing quality. However, stress shielding rate instead, AS nail group is lower than that of CM nail group, in the early low 28% and 39%, in the medium low 49%, in the late low 47% and 43%. These results demonstrate that AS nail can reduce the stress shielding effect of tibial interlocking intramedullary nail on fracture ends and promote fracture healing.

These results also provide a theoretical basis for the subsequent animal experiments, and lay a solid foundation for the clinical application of AS nail as soon as possible.

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