Optimal design and biomechanical simulation analysis of femoral stem based on trabecular bone structure

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Research

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Abstract

Background: In orthopaedic clinical treatment, the rigidity mismatch between prosthesis and bone will cause stress shielding phenomenon, affecting bone growth and leading to aseptic loosening and prosthesis failure, and thus a more serious secondary fracture.

Purpose: In this paper, the femur stem finite element model of human body standing on one foot and two feet was established, and the biomechanical properties of femur stems with three different structural designs were compared and analyzed, so as to provide theoretical guidance for the structural design and finite element simulation of femur stem.

Method: Round-hole femoral stem model and trabecular structural model were established via 3-matic software based on solid femoral stem model. Meshing work was performed by the finite element pre-processing software Hypermesh. The finite element analysis software Abaqus is introduced to analyze the mechanical characteristics of the models for simulating the two different motion conditions of human standing on one foot and on two feet.

Results and discussion: The results showed that stress concentration occurred in the femoral neck of all the prostheses with different motion conditions. The stress and displacement values of the three prosthesis models are about twice as much as those of the two-feet models when standing on one foot. The stress and displacement values of the trabecular femoral stem prosthesis were. The stress distribution of femoral stem prosthesis with trabecular bone structure was more uniform, and the force conduction was more obvious, which can effectively reduce the stress shielding effect and was beneficial to the patients' rehabilitation.

Background

Total hip arthroplasty is commonly adopted in the case of failure after conservative treatment to relieve the pain in the affected area of patients with hip joint damage, restore normal joint function and improve life quality^[1]. In the aim of avoiding surgical revision, optimizing the structure of hip joint prosthesis components to meet the long-term service life is the persistent pursuit of researchers. During which, one of the main concerns is the stiffness mismatch between femoral prosthesis and host bone^[2-3]. The mismatch can lead to stress shielding phenomenon^[4-6]. The main materials used in hip prosthesis replacement currently are titanium alloy, cobalt chromium molybdenum alloy and 316 stainless steel. The stiffness of these materials is much greater than that of bone tissues^[7-8]. Once the metal prosthesis is implanted into the femur, most of the physiological load would exert on the metal prosthesis. While the bone tissue with better flexibility bears less load when compared with the natural state. Wolff's law shows that bone is a kind of active tissue which is very sensitive to mechanical conduction^[9]. Bone formation occurs in the area where there are large loads while bone absorption occurs in the area where there are small loads^[9]. Stress shielding will cause the absorption of bone tissue around the prosthesis, resulting in atrophy of normal bone tissue and functional degradation of bone. In regard of reducing the stiffness

of femoral prosthesis, structure optimization is necessary to lower the stress shielding effect on patients. There are three ways to reduce prosthesis stiffness: optimization of geometry profile, optimization of prosthesis material and the combination of both^[10–11]. Al-Jassir et al.^[12] found that the femoral stems made of functional gradient materials can reduce stress shielding effect after surgery and avoid fast bone loss so as to increase the life service. Kim et al.^[13] conducted in vitro research using human cadaver femurs and concluded that a tapered geometry profile of a stem implant can decrease the stiffness of the prosthesis as well as the contact stress between the distal prosthesis and femur. Also, the increased load at the proximal stem decreased the stress shielding effect. The emergence and development of 3D printing technology presents significant convenience to the design, simulation and manufacture of new biomedical hip prosthesis^[14–17]. Sajad et al.^[1] performed dual optimization from material and structure of 3D printing femur stems and evaluated the amount of in vitro bone loss. Results indicated that bone loss with full porous prosthesis resulting from stress shielding reduced 75% compared with solid prosthesis. Fully porous structure, also described as trabecular structure, is a kind of structure of simulating natural bone tissue. Natural bone tissue consists of two layer bones: the outer firm cortical bone and the inner dense cancellous bone. Cancellous bone is composed of bone trabecular structure, which can bear loads from all directions at the same time^[18].

The current work focuses on the effect of different model design on the stress distribution and conduction of femur stems. Femoral stem model with trabecular structure design was built based on natural trabecular bone. Solid stem model and stem with round holes model were also set to simulate the natural bone loading conditions. Finite element method was conducted to determine the stress states of prosthesis models.

Results

As shown in Fig. 1(a)-(c) were the stress distribution conditions of three different stem models under one-foot standing while (d)-(f) were two-feet standing conditions. In general, the stress distribution of the femoral stem was basically the same under the two kinds of gait transient load conditions. The stress concentration was mainly occurred in the neck and the inner and outer sides of the distal stems. All the trabecular stems showed the greatest maximum stress levels and next to which were the round hole stems, the solid stems exhibited smallest maximum stresses. Figure 2 showed the stem displacements of the two transient gaits. The trabecular stems demonstrated maximum displacement values compared with the other two models. The stress distribution of the solid stems and the round hole stems were not obvious at the internal area of the femoral stems. Owing to the lowered stress shielding of the porous structure, the trabecular stems showed more uniform stress distribution than that of the other two models. Additionally, trabecular structure stems showed more uniform stress distribution and greater areas. Also, the inside stress distribution of the trabecular stems were more uniform.

Discussion

This study simulated the stress and displacement of femoral stem prosthesis by exerting 400N loads under two-feet standing condition and 800N loads under one-foot condition respectively. Results showed that the deformation of all the three models were within the range of elastic deformation and no plastic deformation and yield were found. It indicated that the structural design of the three models was reasonable under the well defined material properties, which can provide guiding significance for the design of femoral implants. Table 1 showed that the volume of solid femoral stem was the largest, followed by round hole femoral stem, and the volume of bone trabecular stem was the smallest. With regard to the negative relation between the volume and whole stiffness, the displacement deformation of the trabecular femoral stem under the same loading condition was the largest. Figure 1 showed the stress concentration areas of the three stems were roughly the same, and they all appeared at the femoral neck. But for the round hole stem, obvious stress concentration can be observed at the area between the second hole and the inner side of the stem. The peak value of the trabecular stem was the greatest compared with the other two models owing to the lowered elastic modulus. Results showed that the load conduction effect of the trabecular stem was better when implanted into human body and the stress distribution was more uniform. Previous studies have shown that the femoral stem is the weakest part of the hip prosthesis component under the influence of stress concentration [21–24]. Therefore, optimizing the middle part of the stem with porous structure is reasonable for reducing stress concentration and improving life service. The optimization of prosthesis should take into account the mechanical properties itself and the growth characteristics of bone. In natural bone, the femur bears forces from all directions. Force-bearing effect promotes bone growth, that is, bone grows towards the direction of force. Hip joint bears compressive stresses. The geometry feature of the femoral stem determines that the inner side of the stem bears more stresses than the outer side. Stress comparison of the femoral stems in Fig. 1 showed that the shielded stress at the middle area of stems without trabecular structure mostly interrupted at the middle area and stresses conducted through the outer side of the stem. Hence, the stress distribution areas mostly existed in distal stem and are more concentrated while the trabecular stem can conduct stresses well in the inner area of the stem. The load on the outside of the stem can be easily conducted into the inside through trabecular structure owing to the compressive stress. The lowered stress level of the outside distal area and the force distribution of the inner area on the results nephogram confirmed that.

From the mechanics perspective, the stiffness of materials is negatively proportional to the square of the relative density. Trabecular structure can conduct stresses more effectively under the same loading conditions, which contributed to more uniform overall stress of the femoral stem and the lowered stress shielding effect, thus avoiding bone absorption and loosening [25]. From the biomechanics aspect, although Ti and Ti-alloys have been widely used as biomedical metal materials due to their excellent mechanical properties and physiological characteristics, the solid Ti can lead to a metastable bone-prosthesis interface and shorten the service life, while the Ti prosthesis with trabecular structure can promote the growth of bone cells and provide a more stable bone-prosthesis combination. However, there are few studies until recently on the comparative analysis of stress conduction effect of prosthesis with different structural design under load.

Conclusions

In this study, three femoral stems with different structural design and the finite element models simulating one-foot standing and two-feet standing conditions were established. Finite element analysis results showed that the stress distribution of trabecular stem was more uniform and the load conduction effect was superior to the other two stems, which can contribute to theory guidance of prosthesis design. Although this study performed the simulation analysis for the femoral stems with different structure design, shortcoming also exists. This study established the simplified human body standing model regardless of muscle and ligament tissues engaged in during various motions, which is also the direction of the follow-up research.

Materials And Methods

The solid femoral stem model this study used was shown in 3(a). Based on which,three models with different porous structure were designed in 3-matic 11.0(Materialise, Belgium). The models well designed were solid stem model, stem with round holes model and trabecular structure model. The basic design element of bone trabecular structure used was decahedral element. For the convenience of comparing stress distribution, the alignment of the round holes of the femoral stem prosthesis was distributed according to the way the trabecular femoral stem was. The volume and surface area parameters of the stems were presented in Table 1.

Table 1
volume and surface area of femoral stems

	Solid stems	Round holes stems	Trabecular stems	
			Porous area	Solid area
Surface area(mm ²)	5839.29	6106.49	5252.68	5605.84
volume(mm ³)	13917.38	13367.93	835.28	11157.00

The constructed models were imported into finite element software Hypermesh 14.0(Altair, USA) to generate meshes. To avoid the effect of different mesh size on the analysis results, all stem models mesh density were set as the same. With regard to the particularity of trabecular structure, the meshes in this area needed to be optimized finely. The number of points and elements of meshed models were shown in Table 2.

Table 2
mesh points and elements of stems

	Solid stem	Round hole stem	Trabecular stem	
			Porous area	Solid area
point	5222	5157	8400	2877
element	17399	17081	23580	8889

The material property assignment referred to Charles et al^[19]. Ti-6Al-4V alloy was used as metal material owing to its superior mechanical behavior and non-toxicity to the human body. The elastic modulus of Ti-6Al-4V alloy was 110GPa, the equivalent elastic modulus of trabecular area was 37GPa, Poisson ratio was 0.3. Models assigned were imported into Abaqus 6.14(Simulia, USA) to simulate the kinetics of two extreme conditions of a 80 kg person, one-foot standing and two-feet standing. The distal stem was fixed fully, the centroid of femoral head was set as reference point, the femoral head was coupled with the reference point^[20]. Two forces of 800N and 400N were set vertically downward at the reference point. The established finite element models were presented in Fig. 4.

Declarations

Ethics approval and consent to participate

Not applicable

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Consent for publication

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Authors' contributions

Junjun Bai is responsible for modeling ; Fengyi is responsible for proofreading;Jia Lv,Zhi Lv,Chaojian Xu are responsible for finite element analysis;Zhuangzhuang Wu and Zhi tian are responsible for writing

Competing interests

The authors declare that they have no competing interests

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Availability of data and materials

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Figures

Figure 1

femur stem stress distribution(a)-(c):one-foot standing (d)-(f):two-feet standing

Figure 1

femur stem stress distribution(a)-(c):one-foot standing (d)-(f):two-feet standing

Figure 2

femur stem displacement distribution (a)-(c): one-foot standing (d)-(f): two-foot standing

Figure 2

femur stem displacement distribution(a)-(c):one-foot standing (d)-(f):two-feet standing

Figure 3

femoral stem models with different designs:(a)solid stem; (b)round hole stem; (c)trabecular stems

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femoral stem models with different designs:(a)solid stem; (b)round hole stem; (c)trabecular stems

Figure 4

Finite element models

Figure 4

Finite element models