Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2013, 5(12):390-395

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Finite element analysis of thermal stress for femoral prosthesis

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ABSTRACT

Based on the thermo elasticity, using finite element method to analyze the stress of femur-prosthesis system when the hip joint has been replaced, a reference for the selection of prosthesis material is presented after discussing the thermo physical property of material which has an effect on the stress of femur-prosthesis system. We assume that prosthesis, bone cement and femur are linear elastic and isotropic materials which construct a concentric cylinder in this paper. Considering the thermal effect, the axial stress of prosthesis, bone cement, femur and the interface shear stress along axial of the prosthesis/bone cement and bone cement/femur when the prosthesis are made of titanium alloy and cobalt-chromium alloy are acquired separately by mechanical analysis and FEM simulation .The results indicate that the interface failure is the primary failure mode of the femur-prosthesis system. The interface failure, prosthesis stem loosening and the stress shielding are accelerated because of the thermal effect. Therefore, the prosthesis with low expansion coefficient should be selected which can moderate the interface failure in a certain degree.

Keywords: Femur, Prosthesis, Thermal stress, Finite element analysis.

INTRODUCTION

Recently, artificial joint replacement has been developing rapidly. More than 1500000 people perform artificial joint surgery, of which, hip replacement is most frequently used [1]. The force of hip joint is complicated which receives the tension, the pressure, the torsion, shear stress and the combined action of repeated fatigue and wear. The prosthesis is implanted in human body for a long time, so it is subjected to the corrosion, that's the reason the higher requirement is needed about the prosthetic material of hip joint. The stainless steel, cobalt-chromium alloy, titanium alloy, aluminum oxide ceramics and zirconium oxide ceramics are the main prosthetic materials of femur at present [2]. Considering 6 properties of biological tissue compatibility, biomechanical compatibility, biomechanical friction, corrosion resistance, fatigue durability and preparation technology, we conclude that the stainless steel performs much worse than the cobalt-chromium alloy and titanium alloy[3]. Even aluminum oxide ceramics and zirconium oxide ceramics also have excellent performance, but the cost is high, therefore, the cobalt-chromium alloy and titanium alloy are the most common materials currently[4]. Comparing the cobalt-chromium alloy to the titanium alloy, the toughness of the former is poorer which is not fitting for machining and the latter is wear-out easily[5-8]. Which material is the most suitable one is still discussing. Hence, finite element method is applied to analyze the cobalt-chromium alloy and the titanium alloy in the view of thermal effect in this paper.

EXPERIMENTAL SECTION

Thermo elasticity Calculation

Modern thermal elasticity theory is first presented by Duhamel from France and Prof. Neumann from German in 1835-1841[9]. According to thermo elasticity, the strain is composed of two parts. One is caused by stress and another is caused by temperature variation.Because of the complexity of geometric construction and force condition of hip joint, it's necessary to properly simplify and idealize the carrier when analyzing and calculating by

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biomechanics. The influence of thermal physical property of material on stress distribution regularity is considered in the research. It is assumed that prosthesis, bone cement and femur are material of linear elasticity and isotropous. They are cylinder of concentric and combine perfectly after replacement. Considering heat effect, according to thermo elasticity the relationships of axial stress-strain of prosthesis handle (P to express), bone cement (C to express) and femur (F to express) are showed as follows respectively[10,11]:

$$\varepsilon_P(z)=\frac{du_P(z)}{dz}=\frac{\sigma_P}{E_P}+\alpha_P\Delta t \tag{1}$$

$$\varepsilon_C(z)=\frac{du_C(z)}{dz}=\frac{\sigma_C}{E_C}+\alpha_C\Delta t \tag{2}$$

$$\varepsilon_F(z)=\frac{du_F(z)}{dz}=\frac{\sigma_F}{E_F}+\alpha_F\Delta t \tag{3}$$

ε, u and σ are strain, displacement and stress respectively. α is coefficient of thermal expansion. E is elastic module. Δt is the range of temperature from some high temperature(the body temperature is 37℃ in this paper) to room temperature(20℃). Δt is negative number usually.

Shear stresses of bone cement and femur are expressed as follows:

$$\tau_{\mathrm{C}}(r,z)=G_C\frac{du_C(r,z)}{dz} \tag{4}$$

$$\tau_{\mathrm{F}}(r,z)=G_F\frac{du_F(r,z)}{dz} \tag{5}$$

In the equation, τ is the shear stress. G is shear elasticity.

Shear stress of prosthesis stem, bone cement and femur meet the continuity condition and boundary conditions:

$$\tau_C(r=a,z)=-\tau_P(z) \tag{6}$$

$$\tau_F(r=b,z)=-\tau_C(r=b,z) \tag{7}$$

$$\tau_F(r=c,z)=0 \tag{8}$$

Average value of bone cement and femur in axial stress is:

$$\overline{\sigma_C}(z)=\frac{2}{b^2-a^2}\int_a^b\sigma_C(r,z)rdz \tag{9}$$

$$\overline{\sigma_F}(z)=\frac{2}{c^2-b^2}\int_b^c\sigma_F(r,z)rdz \tag{10}$$

The relationship between axial stress and interface shear stress of prosthesis stem and femur is:

$$\frac{d\sigma_P}{dz}=\frac{2}{a}\tau_P(z) \tag{11}$$

$$\frac{d\overline{\sigma_F}(z)}{dz}=-\frac{2b}{c^2-b^2}\tau_C(b,z) \tag{12}$$

In the equation, $\tau_P(z)$ is the interface shear stress of prosthesis/bone cement. τ_C（b, z） is the interface shear stress of bone cement /femur.

Axial displacement of prosthesis stem, bone cement and femur meets condition of continuity as follows:

$$u_P(z)=u_C(a,z) \tag{13}$$

$$u_C(b,z)=u_F(b,z) \tag{14}$$

The axial stress of prosthesis stem and average axial stress of bone cement and femur meet the equilibrium relation as follows:

τ_F

$$\sigma_P(z)a^2 + \overline{\sigma_C}(z)(b^2 - a^2)\sigma + \overline{\sigma_F}(z)(c^2 - b^2) = a^2 \qquad (15)$$

σ is the pressure stress on the single hip joint in condition of weight of a standing human.

The axial stress of prosthesis, bone cement and femur and the interface shear stress of prosthesis/bone cement, bone cement/femur can be solved by simultaneous equation (1)-(15).

Finite element analysis of thermo elasticity

Cobalt-chromium alloy and titanium alloy are used as prosthetic materials in this paper. Due to almost all the spongy bone are replaced for the prosthesis, so we assume the material of femur is compact bone approximately.

The material properties of compact bone, bone cement, Cobalt-chromium alloy and titanium alloy are shown in table 1.

Table 1 Material property [12-14]

material	elastic modulus （E/Gpa）	Poisson's ratio	thermal expansion coefficient （α /℃-1）	Pyroconductivity (k/wm-1℃-1)
compact bone	12.4	0.3	0.1×10-6	0.434
bone cement	2.4	0.33	72.2×10-6	0.2
Cobalt-chromium alloy	200	0.3	13.9×10-6	23
titanium alloy	115	0.33	10×10-6	22

The variation of the stress distribution regularity in axial is analyzed quantitatively when the thermal effect is mainly taken into account, therefore, the model of forcing can be simplified to some extent. Prosthesis, bone cement, femur are supposed as linear elastic and isotropic materials and they consist of a completely united concentric cylinder. Based on the hypothesis above mentioned, stress variation of other surfaces are the same as this surface.

Assume the radius of the prosthesis is a, the radius of bone cement is b, the radius of femur is c, the axis of the prosthesis stem is the same as Z axis, the length of prosthesis stem which is inserted in femur is L, the inserting end z=0, the loading end z=L, the value of each parameter is a=5mm,b=10mm,c=17mm,L=150mm[15].

Assume an adult weighs 60kg and the hip joint bears 6-7 times weight than avoirdupois, so, about 2000N is applied to each hip joint. The pressure stress is expressed as $\sigma = p/(\pi a^2) = 25.5Mpa$. Constrain the femur end when the pressure is applied with the thermal effect considered under the condition of the prosthetic material is at 20℃,and the body temperature is at 37℃.

RESULTS AND DISCUSION

The Fig.1 shows the distribution of shear stress changes along with Z axis of prosthesis/bone cement. From the picture we can see the maximum of is at the prosthetic terminal and it decreases rapidly then maintains relative stability. The possibility of distal failure is happened because of the highly stress of distal interface. It can be observed that the interface stress of prosthesis stem /bone cement when cobalt-chromium alloy is used as prosthesis is larger than which is made by titanium alloy. Therefore, the prosthesis made by cobalt-chromium alloy leads to the distal failure easier.

It's shown in Fig.2 that the distribution of shear stress changes along with τ_F the axis z of bone cement/ femur. is maximize at the distal terminal and then decrease to a certain value, at τ_F last, maintains relative stability. From the Fig.2 we can see that the existence of thermal stress enlarges the value of τ_P, although the stress transferred to femur is increased and the possibility of interface τ_P failing of bone cement/femur is also increased. Thus, the thermal stress accelerates the distal failure by analyzing the shear stress of bone cement/femur.

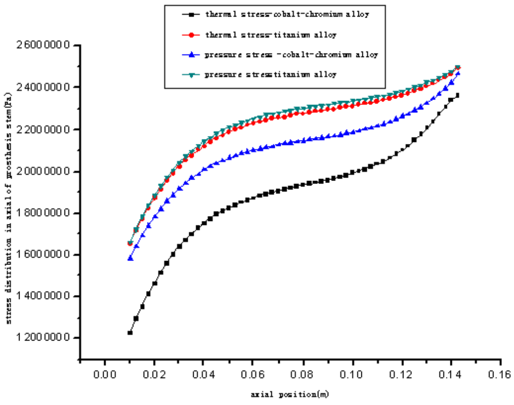

Figure1. The shear stress distribution in axial of prosthesis stem/bone cement

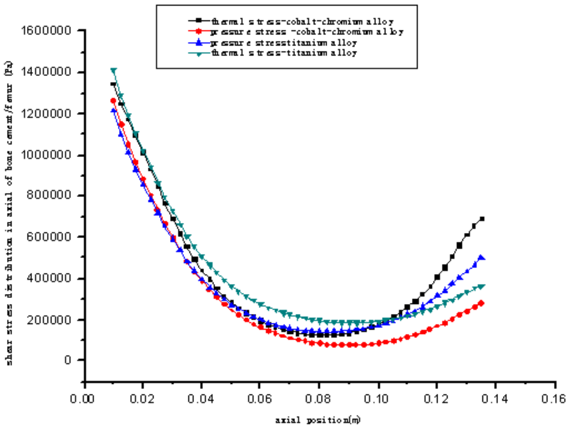

Figure2. The shear stress distribution in axial of bone cement/femur

From the Fig.1and Fig.2, the interface stress distribution of prosthesis stem/ bone cement is the same as the bone cement/femur along with the axial position. The maximum of stress is found at the terminal of the contact surface where is prone to interface failing most easily. The interface stress is enlarged because of the thermal effect which accelerates the interface failing. In addition, owing to the elastic module and thermal expansion coefficient of titanium alloy which used as prostatic material is smaller than Cobalt-chromium alloy. Therefore, the prosthesis which made by titanium alloy could reduce the probability of interface failing in some degree.

Fig.3 is shown that axial stress of bone cement changes along with axial position when the prosthesis made by titanium alloy and Cobalt-chromium alloy. If the room temperature increases from 20℃ to 37℃, the curve got from cobalt-chromium alloy is almost the same as titanium alloy. They're both from the minimum to the maximum rapidly and then remain constant, and the maximum is found at the loading end. That's because the tensile and compressive strength of bone cement material(PMMA) are usually about 50～77 MPa. In Fig.3,When the temperature difference is-17℃, the axial average stress of bone cement is about 5 MPa ,so, it won't damage the bone cement. Thus, it is an advantage of using the polymethylmethacrylate as bone cement material.

From the Fig.1 to Fig.3, due to the thermal expansion coefficient of bone cement is much higher than prosthesis and femur, the thermal effect accelerates the damage of the interfaces of prosthesis stem/bone cement and bone cement/femur, which also aggravates the distal failure.

Fig.4 shows axial stress of the prosthesis stem made by 2 different prosthetic materials when the thermal effect is considered. Using titanium alloy and cobalt-chromium alloy as prosthesis, the axial stress distribution regularity of prosthesis stem are the same. Their minimum both at the distal end, and increases rapidly, then, grows slowly, finally, the maximum comes out at the loading end. The 2 prosthesis bear most load of the hip joint after the replacement which may lead the stress shielding. Considering the thermal effect, the influence when using cobalt-chromium alloy bears much more than using the titanium alloy as the prosthetic material. Because the elastic module and the thermal expansion coefficient of titanium alloy are smaller than the cobalt-chromium alloy, the effect of heat is weak.

The mean stress of femur changes along with the position of axis z is shown in Fig.5. We can get that the axial distribution of femoral average stress and the axial stress distribution of prosthesis stem appears the opposite result. The reason is that femur and prosthesis share the load. The analytical correctness of is proved by Fig.4 and Fig.5. Without the thermal effect, the load which femur bearing accounts for 30% of the same condition when using the prosthesis stem. Thus, the axial stress decreases greatly after the prosthesis is implanted and cause stress shielding. In the condition that the thermal effect exists, the stress shielding is eased somewhat, but the effect is not obvious which is the same as Fig.1 and Fig.2 indicate.

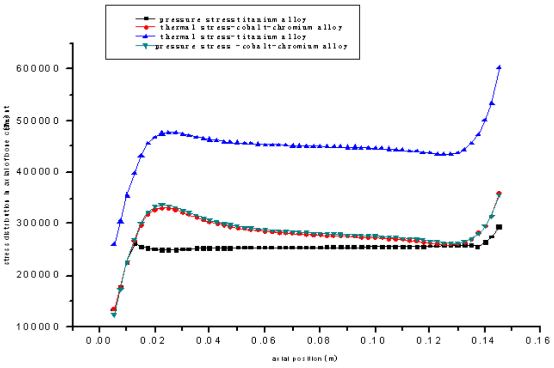

Figure3. The stress distribution in axial of bone cement

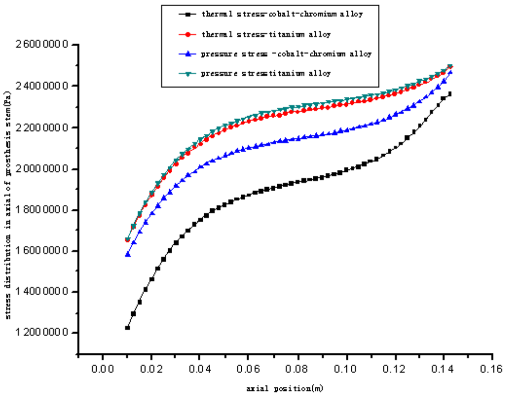

Figure4. The stress distribution in axial of prosthesis stem

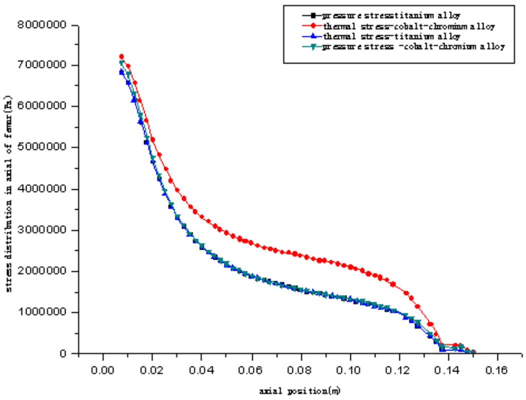

Figure5. The stress distribution in axial of femur

Compare Fig.4 to Fig.5, we can obtain most of the load is undertaken by the prosthesis after the hip joint replacement, so the load of femur decreases greatly than before. These phenomena cause the stress shielding. When the thermal effect exists, cobalt-chromium alloy is a better choice to ease the stress shielding than titanium alloy, however, the effect is not obvious.

CONCLUSION

Considering the thermal effect, the stress distribution regularity in axial is acquired by the analysis and solving above when the cobalt-chromium alloy and titanium alloy are used as prosthesis stem. In order to provide the reference for the choice of prosthetic materials ,the axial stress of prosthesis stem, bone cement and femur, the shear stress of the interface among the prosthesis stem/bone cement, bone/femur are compared and analyzed to conclude the influence on the femur- prosthesis system. The conclusions are summarized as follow:

(1) When thermal effect exists, with the change of axial position, regularities of interface stress distribution of prosthesis stem/bone cement and bone cement/femur are the same considering the fore-and-aft thermal effect. But regularities of axial stress distribution of prosthesis, bone cement and femur are different.
(2) The interfaces of prosthesis stem/bone cement and bone cement/femur lose efficacy. Especially, remote failure is the main failure mode after replacement of hip joint under press. Under the effect of thermal stress, the interface is prone to be mixed but not only the failure mode of pure shear.
(3) Because the thermal expansion coefficient of bone cement is much higher than the prosthesis, the existence of thermal effect speeds up remote failure and the damage of interfaces of prosthesis stem/bone cement and bone cement/femur.
(4) When thermal effect exists, the thermal expansion coefficient and elastic module of titanium alloy are smaller than cobalt-chromium alloy. So prosthesis stem of titanium alloy eases the interface failing to a certain degree.

Acknowledgment
The authors would like to thank for the financial support of the national nature science foundation of China (61272387), new century excellent talents in university and distinguished young scientists funds of Heilongjang province(JC201302).

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