Biomechanical comparison of internal fixations in osteoporotic intertrochanteric fracture

A finite element analysis

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ABSTRACT

الأهداف : عمل مقارنة على أساس الخصائص الميكانيكية الحيوية بين برغي الورك الديناميكي والمسمار الفخذي الداني المضاد للدوران بهدف علاج 3 أنواع من الكسر الفخذي بين المدورين المخلخل للعظام بواسطة رسم نماذج، وعمل التقليل الحقيقي باستخدام تحليل العنصر المحدود. بالإضافة إلى إعطاء قواعد نظرية متعلقة باختيار التثبيت الداخلي الأمثل لعلاج مثل هذا المرض.

الطريقة : أُجريت هذه الدراسة في المعامل الميكانيكية الحيوية، مستشفى شانغهاي للإصابات الرضحية وتقويم العظام، جامعة شانغهاي جياتونغ للطب، شانغهاي، الصين وذلك خلال الفترة من فبراير إلى ديسمبر 2011م. لقد قمنا بتطبيق الأشعة المقطعية على 3 حالات تختلف فيها درجات الكسر الفخذي بين المدورين المخلخل للعظام (إيفانز–جينسين 2،3،4). وبعدها قمنا برسم نماذج الكسور للأنواع المختلفة من التثبيت من أجل محاكاة الوضع الطبيعي وتحليله وذلك بعد التحقق من الأمر. وفي حالة ظهور أنواع كثافة العظام السبعة، والأحمال المختلفة الثلاثة فإننا قمنا بحساب ضغط فون ميسيس ومعدل الفشل، وبعدها قمنا بمقارنة أنماط توزيع الضغط.

النتائج : أشارت نتائج الدراسة إلى أن التثبيت الداخلي باستخدام المسمار الفخذي الداني المضاد للدوران قد كان أفضل في توزيع الضغط من برغي الورك الديناميكي. ولقد كان أقصى ضغط فون ميسيس للأول على عظم الفخذ والتثبيت الداخلي أقل من الآخر، بالإضافة إلى أن معدل فشل العنصر الفخذي قد كان أقل أيضاً. وكان معدل سلامة هشاشة العظام باستخدام المسمار الفخذي الداني المضاد للدوران أعلى من برغي الورك الديناميكي.

خاتمة : لقد كانت نتائج هذه التجربة مختلفة عن الآراء الميكانيكية الحيوية وذلك من ناحية أنه يجب استخدام المسمار الفخذي الداني المضاد للدوران أولاً عند الإصابة بالكسر الفخذي بين المدورين المخلخل للعظام (إيفانز–جينسين 2،3،4).

Objectives: To compare the biomechanical characteristics of dynamic hip screw (DHS) and proximal femoral nail anti-rotation (PFNA) for the treatment of 3 types of osteoporotic femoral intertrochanteric fracture (OFIF) by modeling, and virtual reduction with finite element analysis, and to provide some theoretical basis and reference to select the best internal fixation for clinical treatment of OFIF.

Methods: The experiment was conducted at the Laboratory of Biomechanics, Shanghai Institute of Orthopedics and Traumatology, Shanghai Jiaotong University School of Medicine, Shanghai, People's Republic of China from February to December 2011. The CT scan was performed in 3 cases with different types of OFIF (Evans-Jensen II, III, and IV). Upon validation, fracture models with different internal fixations were developed to simulate and analyze. Under the conditions of 7 different apparent bone densities and 3 different loads, the Von Mises stresses, and the failure rates were calculated, and the stress distribution patterns were compared.

Results: The PFNA internal fixation system has better stress distribution than DHS. The former has smaller maximum Von Mises stress of femur and internal fixation, and the femoral element failure rate, as well. The safety range of osteoporosis in PFNA is wider than the DHS.

Conclusion: The experiment verifies, from the view of biomechanics, that PFNA should be taken into consideration firstly for OFIF (Evans-Jensen II, III, and IV).

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Bone strength decreases, and fragility increases because of osteoporosis, which is a kind of systemic metabolic bone disease that leads to osteopenia and regression of the bone microstructure. It is a slight damage in daily life that can cause osteoporotic fracture in patients with osteoporosis. Owing to accidental fall mostly,[1,2] femoral intertrochanteric fracture is common in clinic,[3] which will be a serious public health crisis with the trend of population senility worldwide.[4] Operation is the most common treatment at present, while dynamic hip screw (DHS) and proximal femoral nail anti-rotation (PFNA) are the most popular surgical methods. However, poor bone microstructure and quality lead to limited clinical effect of internal fixation, such as cutoff or looseness, which will interfere with fracture healing and limb function. In previous research,[5,6] DHS was considered as an effective method to treat stable intertrochanteric fracture, while in others,[7-9] the outcome of PFNA was better than DHS, especially in reducing blood loss and failure rate, and allowing early weight bearing. Consequently, the question still remains unresolved, how to choose the best internal fixation method for osteoporotic femoral intertrochanteric fracture (OFIF) before the operation to avoid failure and enhance the treatment effect. This study aimed to compare the biomechanical characteristics of DHS and PFNA for the treatment of 3 types of OFIF so as to offer some theoretical basis and reference to select the best internal fixation for clinical treatment.

Methods. The experiment was conducted at the Laboratory of Biomechanics, Shanghai Institute of Orthopedics and Traumatology, Shanghai Jiaotong University School of Medicine, Shanghai, China from February to December 2011. A 64-slice CT (GE Medical System, New Braunfels, Texas, USA) scan was performed in 3 cases with different types of OFIF (Evans-Jensen II, III, and IV). All of them were not suffering pathological fracture, tumor, infection, malformations, or coxitis. A series of images (slice thickness, 0.625 mm) of the upper and middle femur were obtained. This study was carried out according to the principles of Helsinki Declaration and ethical approval was provided with permission from the Ethics Committee of Ruijin Hospital.

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Fracture models. Bone and soft tissue can be distinguished by threshold method and erase operation according to their difference of CT value through the use of Mimics (Materialise HQ Technologielaan, Leuven, Belgium). Then, based on the distribution of fracture line, all parts of fracture models such as femoral head, shaft of femur, greater trochanter, and the fragment are constructed. Next, surface grids of these models are exported and saved as .inp file. Finally, it was imported back to Mimics (Materialise HQ Technologielaan, Leuven, Belgium) after 3D elements meshing in Hypermesh (Altair HyperWorks, Detroit, Michigan, USA).

Material properties. Two hundred and fifty-six material properties are given to each part of fracture models in Mimics by calculating the CT value (Hounsfield unit [Hu]). According to Rice's research,[10] apparent bone density ρ_{app} can be calculated by the following formulas: ρ_{app} =1.9x10^{-3}xHu+0.105 (Hu≤816); ρ_{app} =7.69x10^{-4}+1.028 (Hu>816). According to Carter's research,[11] elastic moduli (E) can be calculated by the formula: E=2875xρ^3_{app}, with megaPascals (MPa) as the unit. The Poisson ratio is 0.3.

According to statistical analysis, the mean apparent bone density in this study is: Evans-Jensen II - 0.544 ± 0.430; III - 0.844 ± 0.616; and IV - 0.795 ± 0.467 g/cm^3. The aim of this study is to research the stability of internal fixation in various degrees of osteoporosis, so different levels can be simulated by increasing or decreasing every apparent bone density by 10% based on the mean value. There are 7 levels in all from 70-130%. The elastic moduli can be changed on the same principle. It is more closer to the reality in clinic by this method, simulating the biomechanical characteristics in different osteoporotic levels.

Reposition and assembly. The fracture model can be replaced and assembled with internal fixation in Hypermesh. The DHS and PFNA used in this study are supplied by Synthes USA Sales (West Chester, Philadelphia, USA), and it is impossible to gain the structure, material property, or component due to the protection of intellectual property. So with the help of XL3DS-S 3D laser scanner (Shining 3D, Hangzhou, China), their precise structures can be obtained. The elastic moduli is set at 110 gigapascals (GPa), and Poisson ratio is set at 0.35 based on some relevant literatures.[12,13]

Load and boundary. According to a research,[14] the joint-contact force equals the weight when standing on 2 legs, while 2.1 times body weight (BW) when on one leg, and 2.6-2.8 times BW when walking. Based on this and others,[15] 3 kinds of load are set: 50%; 100%; and

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300% BW, while the angle of load and femoral shaft is 20. The constraint is imposed on distal femur to restrict the displacement along X, Y, Z directions.

Groups. Every type of fracture model can be divided into 2 groups: DHS model; and PFNA model. For each group, there are 7 kinds of apparent bone densities and 3 kinds of loads. In this way, with different internal fixations, different apparent bone densities, and different fracture types, 126 models are created in this study.

Failure criterion. The failure of element can be calculated by max strain criterion,[16] max stress criterion and Von Mises criterion. With the help of literature,[17-21] this study adopted the following criterion: $S=137x\rho_{ash}^{1.88}$ ($\rho_{ash}<0.317$); $S=114x\rho_{ash}^{1.72}$ ($\rho_{ash}\geq 0.317$), where ρ_{ash} is ash density, approximate 0.6 time apparent bone density according to the literature.[22] The element is damaged when the actual stress is beyond the strength. The failure rate is defined as the ratio of the damaged element number to the total.

Statistical analysis. The Statistical Package for Social Sciences version 13 software (IBM SPSS Inc, Chicago, IL, USA) was used for data analysis. The difference was compared with the analysis of variance. Correlational analysis was used to find out the relationship between apparent bone density and Von Mises stress. For both statistical analyses, $p<0.05$ was considered significant.

The clinical interpretation of our results with our finite element analyses for proximal femur was carried out according to the suggestions of Viceconti et al.[23]

Results.

Von Mises stress distribution nephrogram. The following image shows the stress distribution of DHS and PFNA in 3 types of fracture model in the condition of 100% BW, and 100% apparent bone density (**Figures 1a, 1b, and 1c**). Although the stress values are different because of the various conditions, the distributions are similar. The results reveal that the Von Mises stress of DHS is concentrated at the bottom

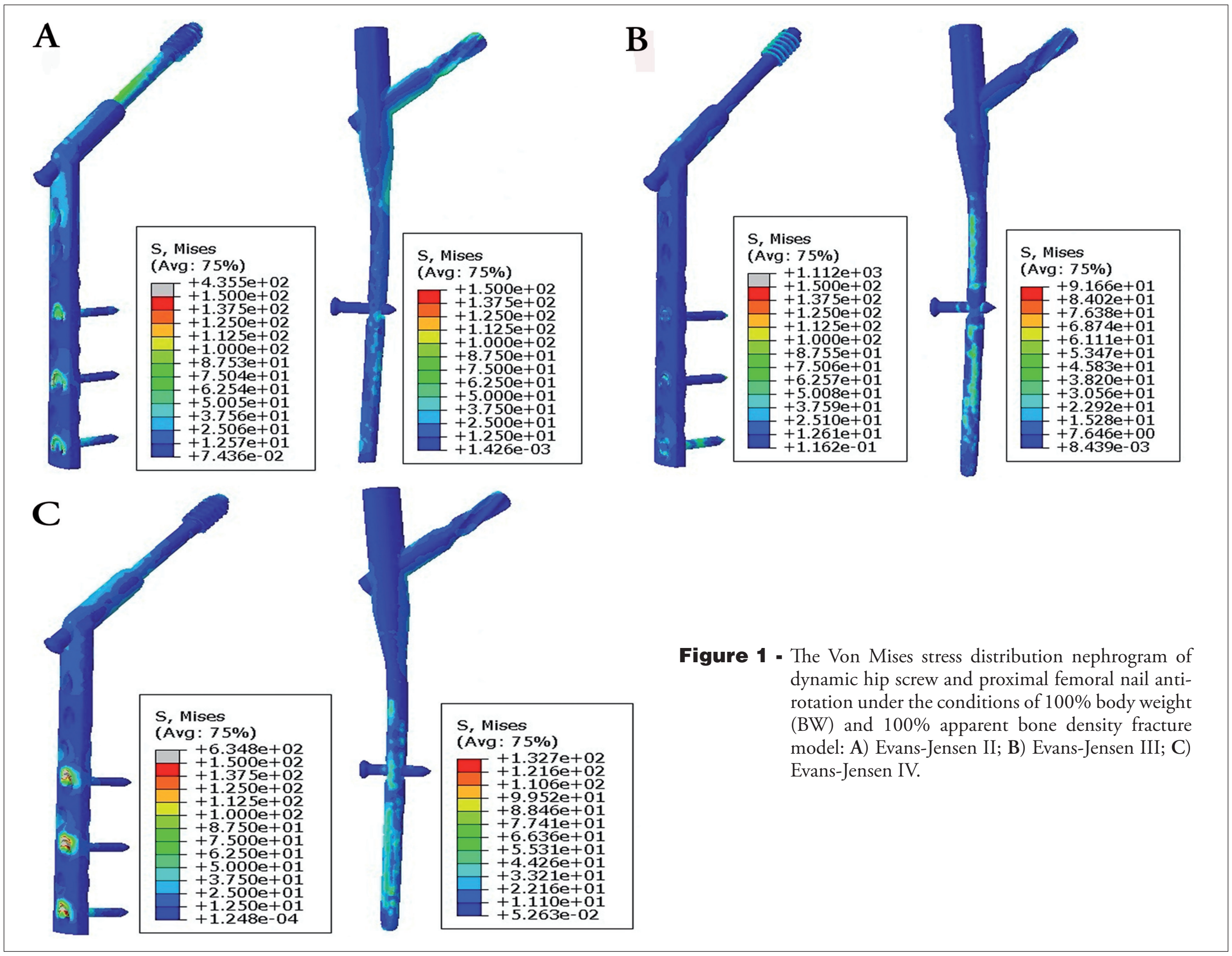

Figure 1 - The Von Mises stress distribution nephrogram of dynamic hip screw and proximal femoral nail anti-rotation under the conditions of 100% body weight (BW) and 100% apparent bone density fracture model: **A**) Evans-Jensen II; **B**) Evans-Jensen III; **C**) Evans-Jensen IV.

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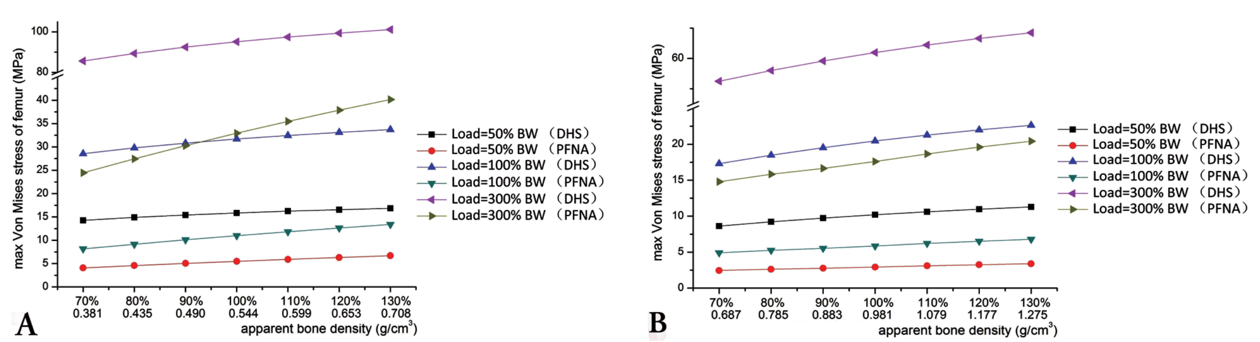
of third screw, while at the top of anti-rotation blade in PFNA. Without obvious stress concentration, PFNA is better distributed than DHS.

Maximum value of Von Mises stress of femur. The following image (**Figures 2a, 2b, and 2c**) is the curves of femoral max Von Mises stress in 3 types of fracture model. The trends of these curves are similar, increasing with the increase of apparent bone density (all Pearson correlation coefficients ≥0.99, all p=0.00). The femoral max Von Mises stress of DHS model is larger than that of PFNA in all conditions (F=134.11, p=0.00). These results reveal that DHS has less stress shielding than PFNA, which is conducive to bone growth, but on the other hand, the possibility of microstructure damage is larger simultaneously.

Maximum value of Von Mises stress of internal fixation. The following image (**Figures 3a, 3b, and 3c**) is the curves of max Von Mises stress of internal fixation in 3 types of fracture model. The trends of these curves are similar, decreasing with the increase of apparent bone density (all Pearson correlation coefficients ≤0.99, all p= 0.00). All values of DHS are larger than those of PFNA (F=62.12, p=0.00). The higher stress of internal fixation will lead to higher possibility to implant failure. These results show that DHS model has larger probability of internal fixation failure than PFNA.

Femoral element failure rate. **Table 1** shows the element failure rate of femur in different fracture types and apparent bone densities, with the conditions of 300% BW. The ratios increase with the decreasing apparent bone density (all Pearson correlation coefficients ≤-0.81, all p≤0.03), and all values of DHS are larger than those of PFNA (F=33.37, p=0.00). In the condition of 300% BW and 70% apparent bone density, the ratios of DHS model and PFNA model reach: 180.13×10^{-2}% and 49.96×10^{-2}% in Evans-Jensen II; 226.68×10^{-2}%, and 0.17×10^{-2}% in Evans-Jensen III; and 261.67×10^{-2}% and 15.28×10^{-2}% in Evans-Jensen IV.

Discussion. The stress distribution can be solved from the known load through the use of finite element analysis by simulating the origin tissue by discretized finite elements, setting parameters according to the actual material properties and load conditions, and calculating by computer. The requirement of biomechanical quantitative analysis can be met by simulating the bone structure accurately, and assigning different parameters based on the experiment task. The finite element analysis has been widely used in the biomechanics research.[24-26] With more comparability and authenticity, the finite element models assembled with different internal fixations can reveal the global



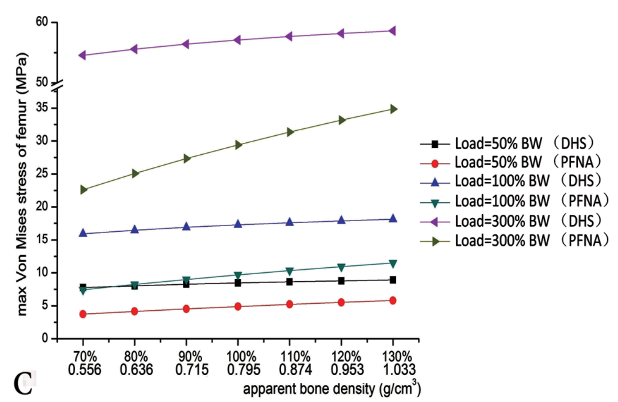


Figure 2 - Curves of femoral max Von Mises stress of dynamic hip screw (DHS) model and proximal femoral nail anti-rotation (PFNA) model under the conditions of 3 kinds of loads and 7 kinds of apparent bone densities in: **A**) Evans-Jensen II; **B**) Evans-Jensen III; **C**) Evans-Jensen IV. MPa - megaPascals, BW - body weight.

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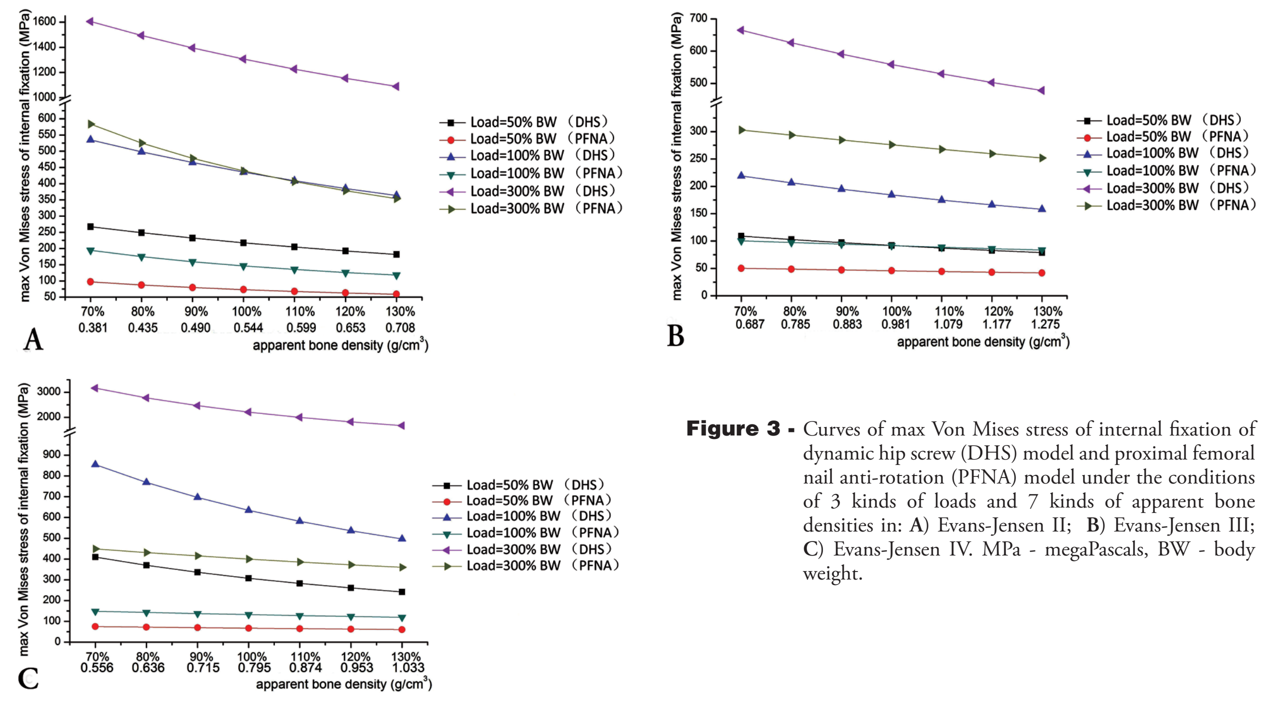

Figure 3 - Curves of max Von Mises stress of internal fixation of dynamic hip screw (DHS) model and proximal femoral nail anti-rotation (PFNA) model under the conditions of 3 kinds of loads and 7 kinds of apparent bone densities in: **A**) Evans-Jensen II; **B**) Evans-Jensen III; **C**) Evans-Jensen IV. MPa - megaPascals, BW - body weight.

Table 1 - The element failure rate of femur in dynamic hip screw (DHS) model and proximal femoral nail anti-rotation (PFNA) model under the conditions of 300% body weight (x0.01%).

Evans-Jensen II				Evans-Jensen III				Evans-Jensen IV			
Apparent bone density		DHS	PFNA	Apparent bone density		DHS	PFNA	Apparent bone density		DHS	PFNA
(%)	g/cm³			(%)	g/cm³			(%)	g/cm³		
(70)	0.381	180.13	49.96	(70)	0.687	226.68	0.17	(70)	0.556	261.67	15.28
(80)	0.435	82.74	21.91	(80)	0.785	164.17	0.11	(80)	0.636	140.58	7.53
(90)	0.490	34.04	4.89	(90)	0.883	123.98	0.11	(90)	0.715	72.39	3.98
(100)	0.544	15.60	0.63	(100)	0.981	95.46	0.06	(100)	0.795	35.64	2.21
(110)	0.599	7.72	0.16	(110)	1.079	75.60	0.06	(110)	0.874	17.05	1.77
(120)	0.653	2.52	0	(120)	1.177	59.85	0.06	(120)	0.953	13.50	1.11
(130)	0.708	1.42	0	(130)	1.275	47.42	0.06	(130)	1.033	8.19	0.44
Pearson		-0.85	-0.81			-0.96	-0.87			-0.89	-0.87
P-value		0.02	0.03			0.00	0.01			0.01	0.01

and local stress distribution, without worrying about the biomechanical characteristic change of bone and instrument because of the reduplicative tests. So it is possible to choose the best surgery method for OFIF before operation.

In previous studies,[15,17,20,25] researchers reconstructed the normal cadaver femur models, and then induced to fracture artificially to simulate the femoral intertrochanteric fracture. However in this study, the objects are the patients with OFIF (Evans-Jensen II, III, and IV). With smaller grids and more elements, the models are more accurate so that it can reflect the actual situation of the fracture. These results can be used to guide the clinical treatment directly. Zauel et al[27] indicates that bone can be considered as linear elastic and isotropy in the condition of quasi-static, which is this study based on, as well as the previous research.[20,25,26]

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The Von Mises stress is a kind of yield criterion that is used in the finite element analysis most frequently,[28,29] and its value equals equivalent stress, calculated by the principle stress of X, Y, and Z axis. So it is a kind of stress without direction, following the 4th strength law. In this study, comparing the actual stress with the element strength according to the failure criterion is another characteristic. The element failure rate is used to indicate the damage of bone microstructure. By comparing the failure rates, the stability in different bone quality and strength can be compared.

When components with different elastic moduli bear load together, the lower one bears less stress, which is called stress shielding. The internal fixation induces this effect to femur while using DHS and PFNA for the treatment of OFIF because of the difference between the elastic moduli. Based on Wolff's theory, the bone is absorbed where it is not required, while it grows where it is needed. The stress stimulus decreases due to less stress that the bone bears, which is due to stress shielding. As a result, the bone will grow slowly and even be absorbed. It is revealed that the maximum value of femoral Von Mises stress increases with the increasing apparent bone density (Figures 2a, 2b & 2c). Bone elastic moduli increases in virtue of the increasing apparent bone density, which can narrow the gap between bone and internal fixation. In this way, the decreasing stress shielding leads to the increasing stress that the bone bears. The better the bone quality is, the more stress the bone bears. The increasing stress stimulus results in bone growth and a decrease of failure rate, which does not mean the larger stress is better. If the stress is too large, the element will be damaged, and the bone microstructure will be destroyed. The femoral max Von Mises stress of DHS model is larger than that of PFNA model in all conditions. It shows that DHS has less stress shielding than PFNA, which is conducive to bone growth, but on the other hand, the possibility of microstructure damage is larger simultaneously. Both Evans-Jensen III and IV femoral intertrochanteric fracture are unstable. The fracture involves femoral calcar, damaging the intertrochanteric frame structure, and impairs the functions of bearing load, transmitting load, and dispersing load. As a result, the local shearing force increases. The latter calls comminuted intertrochanteric femoral fracture also, which has more segments and worse contraposition.

In this research, the max Von Mises stress of DHS is larger than that of PFNA in the condition of same density and load. The results reveal that the Von Mises stress of DHS is concentrated at the bottom of the third screw, while at the top of anti-rotation blade in PFNA. Without obvious stress concentration, PFNA is better distributed than DHS. The value of DHS in Evan-Jensen III in the condition of 300% BW and 70% apparent bone density is 664.67 MPa and 302.90 MPa of PFNA. The yield strength of medical titanium alloy is 850-900 MPa,[30] so these values are still in the safety range. But with higher stress, DHS will be easier to fatigue fracture resulting from long-term use. In Evan-Jensen IV, in the same condition, the value reaches at 3164.44 MPa for DHS, exceeding the security range of medical titanium alloy. The internal fixation will be broken where the stress concentrated. In clinical cases, the fracture often affects the bottom of the third screw mostly. Meanwhile, the value of PFNA is 448.59 MPa, just only 14.18% of DHS. It is less than the yield strength, and the stress distribution is better, so the failure risk is lower.

Evans-Jensen II femoral intertrochanteric fracture is stable. The fracture does not involve femoral calcar. The max Von Mises stress of DHS in the condition of 300% BW and 70% apparent bone density is 1604.39 MPa and 583.38 MPa of PFNA. The former is beyond the safety range, and the stress concentrated at the same place. Because of the serious osteoporosis, the 70% apparent bone density is only 0.381 g/cm^3. The stress shielding is so obvious that the value of DHS is greater. It also reveals that the maximum Von Mises stress of DHS and PFNA decreases with the increasing of apparent bone density, and the former has more extensive range (Figures 3a, 3b & 3c). In other words, the influence of density on the maximum Von Mises stress of DHS is bigger than PFNA, which is to say, the safety osteoporosis range of PFNA is wider than DHS.

The femur element failure is not obvious in low loads (50% and 100% BW), while in high load (300% BW) with the osteoporosis stage progresses, 2 groups of failure rates in all 3 types of fracture are increasing. The rates of DHS model are larger than those of PFNA, with more extensive range. It shows the damage of microstructure is more through the use of DHS, compared with PFNA. In the other words, the influence of osteoporosis on the femur element failure rate is slight, which is to say, the safety osteoporosis range of PFNA is wider than DHS. The advantage of PFNA is of much more significance especially for severe osteoporosis, which can be also explained by stress shielding theory. Some clinical research[31-33] indicate that the intramedullary fixation is much better than decentered fixation. The stress of intramedullary fixation is less than that of decentered fixation, especially for instable femoral intertrochanteric fracture. The main nail of PFNA is in the medullary cavity, which can reconstruct the force line, decreasing the moment of force, and increasing

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the stability of fixation. Compared with the dynamic screw of DHS, the decentered internal fixation, the anti-rotation blade of PFNA is shorter. With the shorter force arm, the blade has less moment of force, inducing the stronger bending resistance. Meanwhile, the stress of blade can be transmitted and dispersed to the main nail expeditiously, and to the cortical by the locking screw. The stress and strain of the main nail are minor because of the small influence of tension and compression from shaft of femur. In DHS model, the bottom of distal screw will be failed due to the enormous shearing stress and tensile stress, produced by the trend that the proximal fragment of intertrochanteric fracture moves downwards and outside, and the distal fragment moves upwards and inside. The stress increases with the decreasing apparent bone density. So, for patients with osteoporosis, the failure possibility of DHS increases with the progression.

The innovation of this research covers 3 aspects: first, in a previous research,[24] the fracture models were reconstructed by the normal femur with Boolean operation, or the cadaveric fracture specimen through the use of material testing machine, but the objects of this study are patients with osteoporosis. Based on the actual fracture, loads (weight) and material properties (osteoporosis), the results of the study can be used to guide the clinical treatment. Second, in previous research,[13,26] the internal fixation models are created by measuring the structure and reconstructing in computer-aided design (CAD) software. However, the XL3DS-S 3D laser scanner is used in this study to obtain the precise geometric information. Third, 3 kinds of loads, 7 kinds of apparent bone densities, and failure rates calculated by failure criterion are adopted in each model of this study.

However, there are some limitations in this study. First, only the models of the same fracture type with different loads and apparent bone densities can be compared. Those models of different fracture types cannot be compared because the primary apparent bone density and load are different. Second, the force environment of proximate femur is so complicated that the main loads femur bears are considered as the concentrated force. And patient-specific measures of soft tissue thickness, or muscle function were not taken into calculation. The study is based on the static status, not the actual biomechanical situation. Third, the apparent bone densities in this research are calculated by the formula from CT value, not by the dual energy x-ray, which is used mostly in the clinics. The relationship between them still needs further studies.

This study indicated PFNA is superior to DHS in stress distribution and decreasing the stress of femur and internal fixation from the biomechanical aspect. The authors believe that PFNA system is better than DHS in treating osteoporotic intertrochanteric fracture, but the differences of clinical outcomes is still to be proven by further clinical experiments.

In conclusion, the PFNA system has better stress distribution rather than DHS for the treatment of osteoporotic intertrochanteric fracture (Evans-Jensen II, III and IV) from the aspect of biomechanics by using finite element method. The former has less maximum Von Mises stress of femur and internal fixation than the latter, as well as the femoral element failure rate. The safety osteoporosis range of PFNA is wider than DHS. From the perspective of biomechanics, PFNA system should be taken into consideration preferentially for the treatment of osteoporotic intertrochanteric fracture (Evans-Jensen II, III and IV).

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