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NUMERICAL ANALYSIS OF STRESS SHIELDING OF PLATEDHUMAN FEMUR USING 3-DIMENSIONAL FINITE ELEMENT METHOD

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Conventional compression bone fracture plates sometimes cause osteoporosis under the plate due to their high rigidity. In order to prevent the osteopenia, many researchers have attempted various types of bone plates. To meet the same purpose, a new concept bone plate which have a vicoelastic washer between plate and screw head is introduced. The washer is made of a biocompatible polymer(ultra high molecular weight polyethylene, UHMWPE). This research was performed first to establish a more realistic and detailed plated-bone system using finite element method and second to investigate the effect of the UHMWPE washer on the stress shielding comparing with the conventional plate model. Three-dinensional finite element meshes of the human femur with the conventional and new concept bone plate were generated and the comparative stress analysis of the stress shielding was performed with static half-stance loading condition. The results of analysis showed that the new and conventional bone plate transfer the stress through the bone average 15% and 10% that of the intact bone respecively. However, the local stress in the bone under the new bone plate have increased about 13~150% that of the conventional bone plate depending on the region. Earlier preliminary animal studies showed some promising results. It is suggested that the in vivo and FEM results support the feasibility of the new concept bone plate.

Key Words : Bone Plate, Osteoporosis, Osteopenia, Stress Shielding, *In-Vivo* Test

1. INTRODUCTION

The advantages of the compression-plating over non compression conventional plating are the achievement of the immediate stability of fracture fragments in an anatomical position and the early start of the active exercise and the use of the injured extremity(Rahn, Gallinaro, Baltensperger, Perren, 1971). The rigid internal fixation maintains alignment and promotes primary osseous union in the early stage of fracture healing. However, as healing progresses, the rigid fixation can cause significant loss of bone mass(osteoporosis)due to the stress protection of the healing bone. After plate and screw removal, therefore, the weakened bone stands the chance of possible refracture (Hidaka, Gustilo, 1984).

Many researchers attribute this problem mainly to the decreased stresses in the bone tissue as a substantial portion of the applied load is transferred to the plate and bypasses the bone(Unthoff, Dubuc, 1971, Akenson, Woo, Rutherford, Coutts, Gonsalves, Amiel, 1976, Carter, Vasu, 1981). In addition, another possibility can be the vascular insufficiency in the bone as the implants interferes with bone blood supply (Gunst, 1980).

In order to prevent the osteopenia, a new concept bone plate is devised to have the following two important characteristics. First, in the early stages of fracture repair, the new plate should immobilize the fracture fragments rigidiy. Second, in the later stages of fracture repair, however, it should allow to transfer a larger proportion of the functional load to the bone tissue to return to the normal physiologic loading.

The approach for the design of a new concept bone plate can be characterized as following. First, to develop a bone plate with less rigidity but sufficient mechanical strength. Woo et al. compared bone properties under the plate following the application of a plate made of graphite fiber methyl methacrylate resine composites(GFMM) which has less bending rigidity and rigid Co-Cr alloy(Vitallium)plate(Woo, Akeson, Coutts, Rutherford, Doty, Jemmott, Amiel, 1976). Significant bone loss was observed on the Co-Cr alloy plated bone. The mechanical properties of the bone tissue measured by ultimate bending strength and the flexural modulus of elasticity were similar, however, the structural properties represented by the maximum bending load and the maximum energy absorption were superior for the GFMM plated bone. Tonino et al. experimented a plastic poly-trifluoromonochloro-ethylene(PTFCE) plate to compare the healed bone properties with the 316L stainless steel plate (Tonino, Davidson, Klopper, Linclau, 1976). The results of three-pointbending test showed that the bone with the steel plate was significantly weaker than that from the PTFCE and the elastic modulus of the steel plated bone was less, suggesting that the porosity in the bone may have adverse effect on the material properties of the bone under the plates.

Hutzschenreuter et al. have tested composite plates made of polyacetal with about the same rigidity as bone and incorporating a metal core inside the plate, in order to reduce the porosity of the plated bone(Hutzschenreuter, Mathys, Walk, Brummer, 1980). Claes et al. tried a plate using the carbon fibre-reinforced composites (Claes, Burri, Kinzl, Fitzer, Huttner, 1980). Pure carbon is an extremely biocompatible material, however, the experimental plate was required to improve the shear strength.

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Second approach is to develop a bone plate made of absorbable polymer which will have the similar property as the polymeric bone plate i.e. decreasing plate rigidity with time thus transfer load to the bone as the bone heals. Some designed partially absorbable bone plate made of carbon fibers(non absorbable) imbedded in a matrix of absorbable poly L(-) lactide(Cocoran, Koroluk,Parson,Alexander, Weiss,1980,Zimmerman,Parsons,Alexander,1987). The composite plates usually had a lower bending rigidity and modulus than 316L stainless steel plate. In *in vivo* test, however, the control of the absorption rate and uniformity as well as subsequent delamination of the plate have been encountered.

Tomita and Kutsuna approached differently from the previous research, devised a cushioned plate fixation using a silicone rubber placed between the steel plate and the bone (Tomita, Kutsuna, 1987). They compared the dynamic self-compression plate (DCP) with cushioned DCP. From the results of the rabbit experiments at nine and twelve weeks, they concluded that the extent of porosity of the cortex beneath the cushioned plate was smaller than that under the DCP only, and the cavity rate of the cortical bone directly beneath the cushioned plate was significantly lower($P<0.01$) then that directly beneath the DCP. However, no significant difference was seen in the porosity and the thickness of the cortical bone adjacent to the both plated site.

The main concept of the new device studied in this research is to increase the stress level on the bone beneath the plate using a viscoelastic biocompatible material, such as ultrahigh molecular weight polyethylene (UHMWPE). The new concept bone plate consists of 316L stainless steel compression plate and the UHMWPE washers inserted between the screw head and the screw hole of the plate.

The objective of the study is to establish a realistic and detailed bone plate system and to verify stress shielding problem using finite element method(FEM). In addition, it is to investigate the effectivity of the new plate on the stress shielding comparing with the conventional plate, and to discuss the feasibility of the new plate in connection with the earlier preliminary *in vivo* results in dogs(Park, Kuo, Rim, Choi, 1987).

Three dimensional finite element models of human femur with attached plate were developed and used to investigate the stress distribution of the conventional and new concept bone plate.

2. FINITE ELEMENT METHOD

The conventional compression bone plate made of 316L stainless steel having six screw holes is used. The plate is 103 mm long, 11 mm wide and 3.8 mm thick (Cat. No. 2362~06, Zimmer, Warsaw, Indiana).

The only difference between the conventional and new concept bone plate is the UHMWPE washer. In a new concept bone plate, one UHMWPE washer is inserted at each screw hole. Thus, the diameter of the screw hole is 2 mm larger than that of the conventional bone plate to accommodate the washer.

The stiffness and the fatigue life of the bone plate may be affected by the slightly larger screw holes, however, they are not going to be considered in this study since the main object of this study is the effect of UHMWPE washer on the stress distribution.

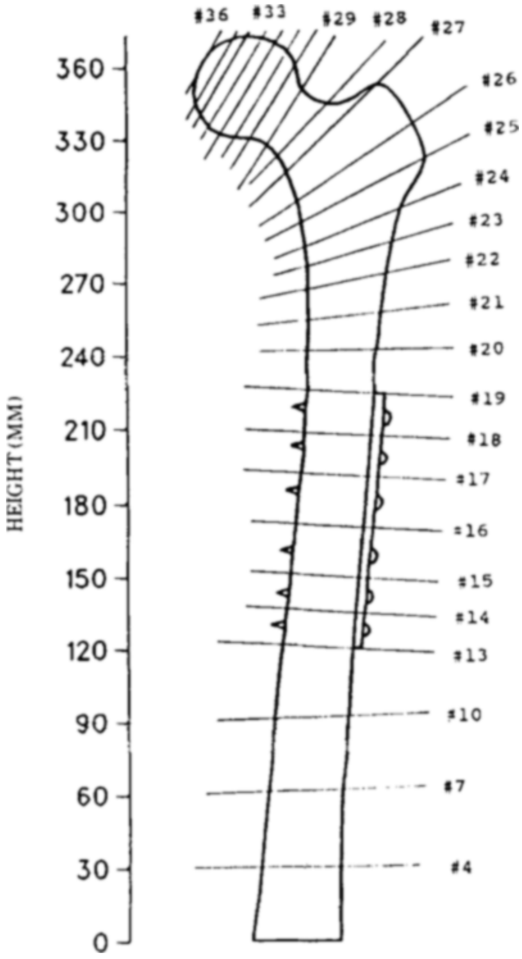


Fig 1 Section lines of the Implanted human femur

Three dimensional finite element models of the implanted human femur were generated and simulated for the study of the stress distribution before and after plate attachment.

The ANSYS finite element method package (Swanson Analysis Systems, Inc, Houston, Pennsylvania) implemented on an IBM computer was used to perform the finite element analysis.

The geometric data of a human femur were obtained from a cadaveric femur of 67 year-old man (right side). On the human cadaver femur, an artificial lead plate cast from a silicone rubber mold of the conventional plate was implanted.

Table 1 The material properties

	Cortical bone		Cancellous bone	UHMWPE	Plate & Screw
Young's modulus (GPa)	E1 E2 E3	11.5 11.5 17.0	0.325	1.24	200
Poisson's ratio	V12 V13 V23	0.3 0.35 0.35	0.29	0.3	0.3

The subscripts: 1 : Radial direction
2 : Circumferential direction
3 : Longitudinal direction

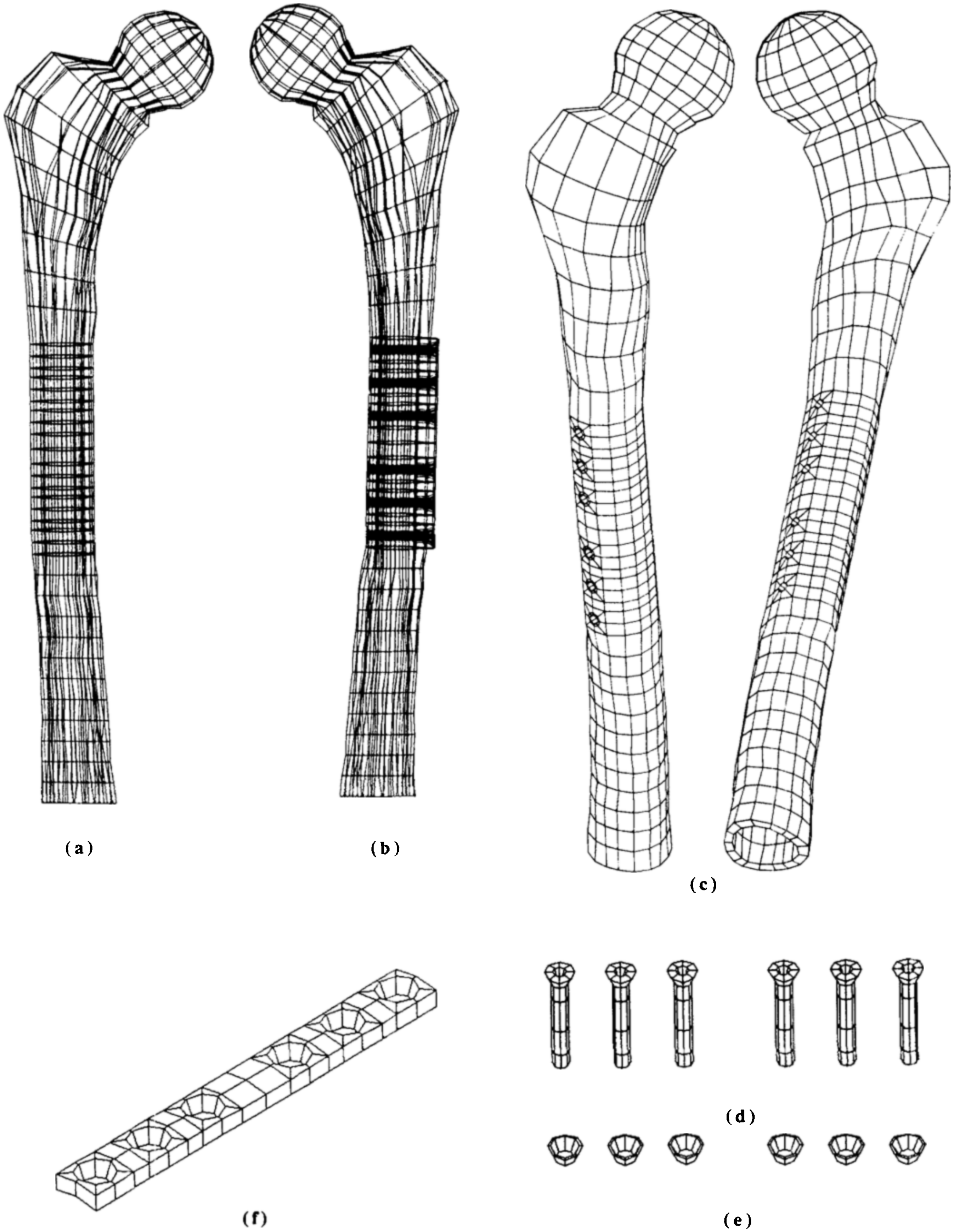


Fig 2 The finite element models: (a) intact femur (b) implanted femur (c) femur (d) bone screw (e) UHMWPE washer (f) bone plate (oblique view)

Table 2 The number of nodes and elements of the finite element models

Model	Nodes	Elements
I.F	1453	752
CCV	2224	1196
CNEW	2224	1196
OCV	2323	1196
ONEW	2323	1196

where

I.F	: intact femur model
CCV	: contact model with conventional B.P.
CNEW	: contact model with new concept B.P.
OCV	: non-contact model with conventional B.P.
ONEW	: non-contact model with new concept B.P.

Then, it was cast in a box with a plaster of paris and cut into serial sections and digitized each section for the finite element model construction. The sectional lines are shown in Fig.1.

The model was represented with 8-node isoparametric solid elements, and each node had three degrees of freedom

The material properties are given in Table 1. The bone is assumed transversely isotropic, and the elastic constants determined by Ashman et al. using a continuous wave technique are adopted for the material property of the cortical bone (Ashman, Cowin, Van Buskirk, Rice, 1984).

In physical situation, the interface between bone and plate is discontinuous. However, the frictional effect in the interface cannot be neglected. Thus, two different types of plate-bone interface were considered in each model to approach this clinical situation. They are named as contact and non-contact model. The contact model means that the plate-bone interface in continuous, while for the non-contact model, it is discontinuous. The finite element models are shown in Fig.2.

The numbers of node and element of each model are shown in Table 2.

For the loading conditions, the analysis by McLeish and Charnley has been adopted (Mcleish, Charnley, 1970). In Fig. 3, the lines of action of muscle groups and the forces are shown. M is the total abduction force and T is the force in the ilio-tibial tract. J is the head load and assumed to be distributed over the femoral head.

The following data would be expected for the size of femur and body weight considered as 70.3kg (Valliapan, Svenssin, Wood, 1977).

M=1061 N,J=1620 N,J=172 N,

Φ=24.4°, θ=29.5°

The boundary condition applied in this analysis is that the lowest section of the model is rigidly fixed.

3. RESULTS

In order to examine the question of the effectiveness of the new concept bone plate on the stress distribution of the bone, the von Mises stresses of the lateral and medial side of the femur are plotted (Fig. 4 and Fig. 5). Included are the results of von Mises stress for the intact and for the plated bone as predicted by the contact and non-contact finite element model. It is obvious that the plate application reduced the magnitude of the stress, especially in the region directly beneath the plate.

In order to investigate the stress protection effect, a stress shielding ratio is defined as following.

stress shieding ratio= $s_{int} - s_{imp})/s_{int}$
where s_{int} :stress of the intact bone
S_{imp}:stress of the implanted bone

The data for stress shielding ratio were obtained from six locations on the bone between screw holes. This "stress

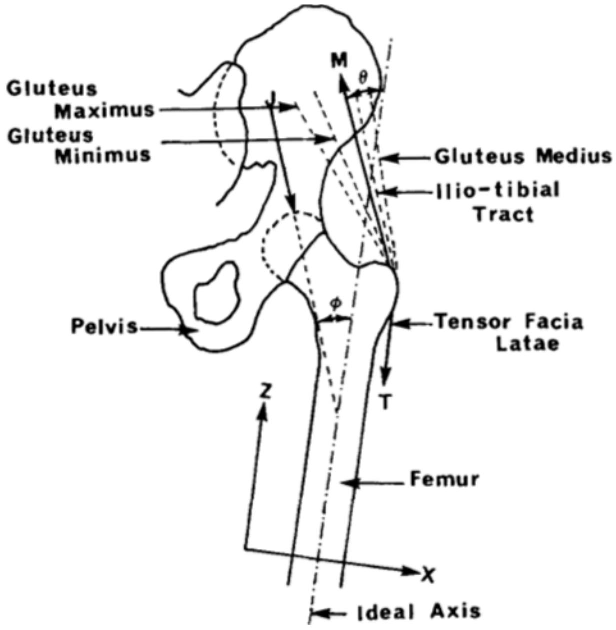


Fig 3 The lines of muscle groups and forces in the human femur (from Valliapnan, 1977)

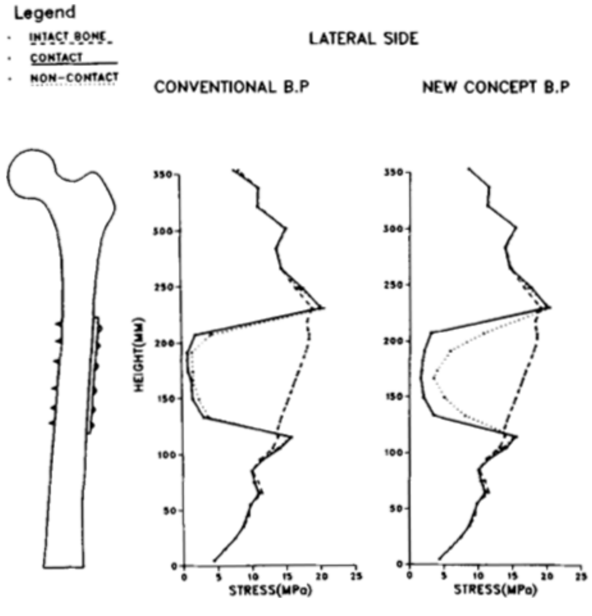


Fig 4 Von mises stress of the lateral side for contact and non-contact model

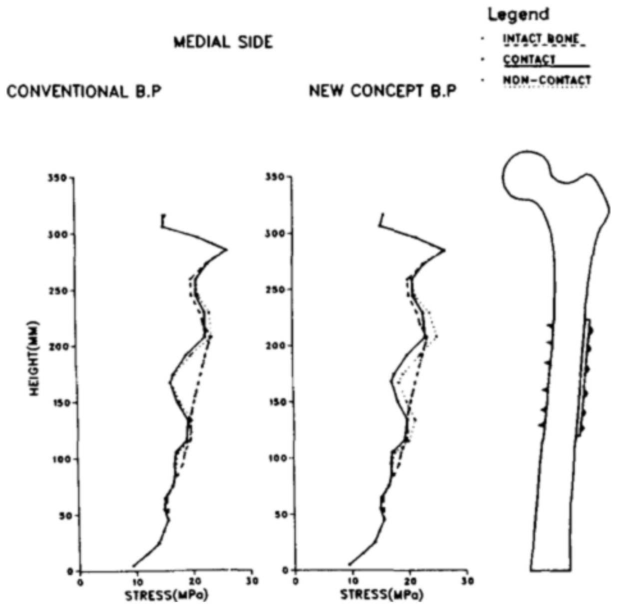


Fig 5 von Mises stress of the medial side for contact and non-contact model

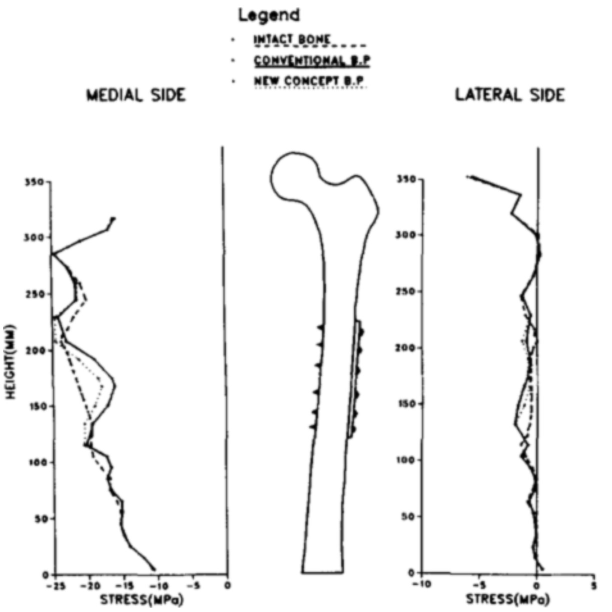


Fig 7 Minimum stress for non-contact model

shielding", calculated as an average percentage of the stress level generated by the same load case applied to the intact bone, represented about 89.9% decrease in conventional model(CCV) and 85.6% in new concept plate model (CNEW) in contact cases. It also represents 88.4% decrease in model OCV and 62.6% in model ONEW in noncontact FE analyses. Note that the stress shielding is reduced in both contact and non-contact model by the application of the new concept bone plate. In addition, the results for the non contact model is less than that for the contact model. We could also see the similar trend in the medial side as shown in Fig. 5.

In order to identify the characteristic of the stress in the lateral and medial side, the maximum and minimum stresses are plotted. The maximum and minimum stresses indicate the algebraic largest and smallest stress in numbers. The results show that the tensile stress is dominant in the lateral side while the compressive stress in the medial side(Fig. 6 and Fig 7).

To further examine the plate-induced stress shielding effect, the normal stress distribution on the middle section(#16) is drawn as shown in Fig. 8. The application of plate shifted and rotated the neutral axis toward the plate-bone interface as shown in Fig. 8(c,d.) This effectively reduces the magnitude of the longitudinal stresses, especially in the region directly beneath the plate. Note that the application of the new concept bone plate prevents the neutral axis move-

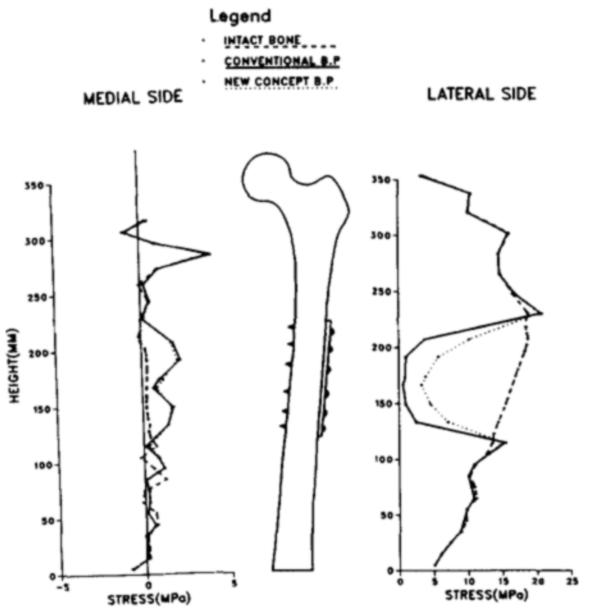
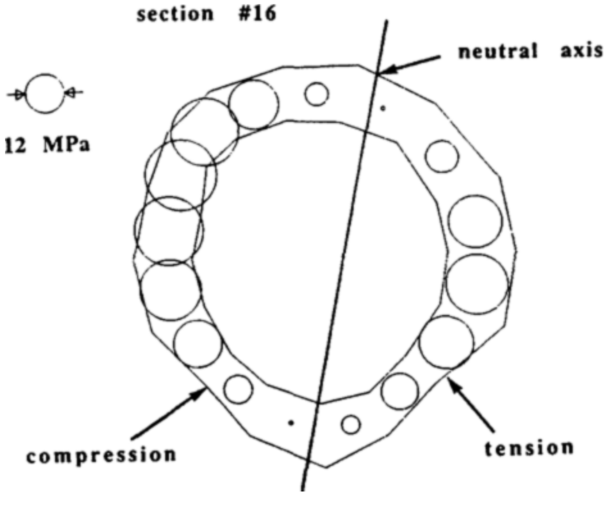
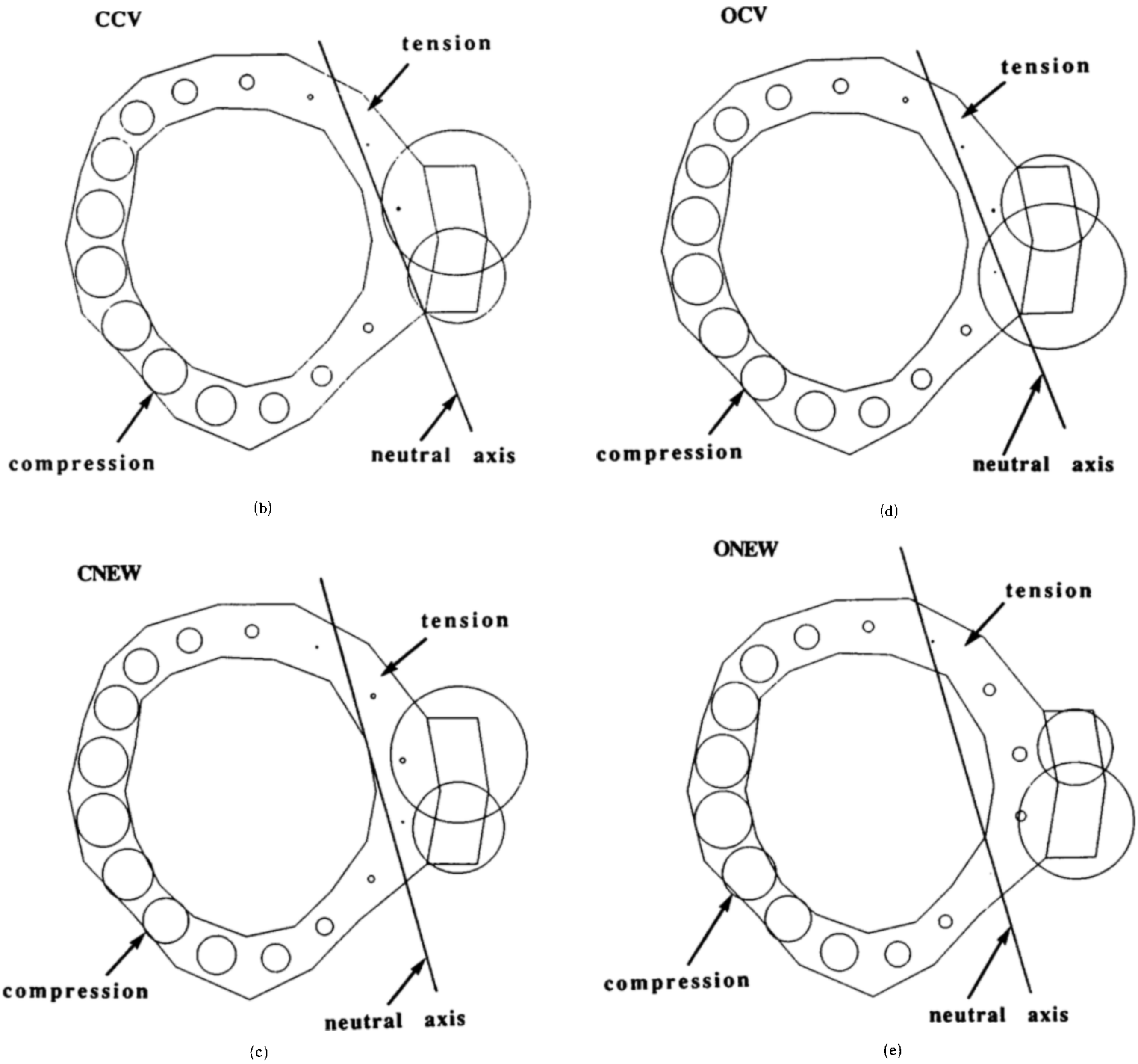


Fig 6 Maximum stress for non-contact model



(a)



(b) (d) (c) (e)

Fig 8 The longitudinal stress of section #16 : (a) intact bone (b) CCV model (c) CNEW model (d) OCV model (e) ONEW model

ment toward the plate-bone interface. Thus, it causes to increase the stress level beneath the plate and to decrease the stress of the plate. This result is most obvious for the model ONEW in Fig. 8(e).

4. DISCUSSION

The finite element analyses of human femur implanted with the conventional and new concept bone plate show that the application of new concept bone plate increased the stress level on the bone, especially for the non-contact model. It is inferred that the UHMWPE washer of the new concept bone plate enables to increase the stress level in the bone, reducing the load transfer through the plate. Furthermore, it is also suggested that relative motion at the plate-bone interface may enhance the effectiveness of the new concept plate.

The characteristic of the plate-bone interface has significant effects on the mechanics of the plate-bone system. For the contact model, the load transfer from the bone to the plate occurs very rapidly, resulting in high magnitude stresses in the bone at the end of the plate. In addition, it tends to overestimate the bending stiffness of the plated bone. For the non-contact model, however, the load is transferred only through the bone screws. Thus, the transfer of load is somewhat gradual and as a result, it causes to reduce stress in the region under the plate(Cheal, Hayes, White, Perren, 1983). For the clinical situation, the slipping motion in the plate-bone interface cannot be eliminated at all, and the friction between the bone and plate cannot be neglected either. Thus, the contact and non-contact models may represent extreme cases in the physiological condition of the plated bone.

The preliminary *in vivo* test of the new concept bone plate was performed by Park et al. (Park, Kuo, Rim, Choi, 1987). The new concept bone plate for the test was 4-hole 316L stainless steel plate with two UHMWPE washers in the canine femur. The test showed some promising results for preventing osteopenia. The flexural modulus was generally higher for the bone specimen from the experimental side and the fracture load was also significantly higher ($p < 0.05$) than that from the control side. No difference in the ultimate flexural strength between them was measured, however, the cortical thickness was much higher ($p < 0.05$) for the experimental side. The result is similar to the results of Woo et al. (Woo, Akeson, Coutts, Rutherford, Doty, Jemmott, Amiel, 1976, Woo, 1981), wherein GFMM plates were tested. Finally, it is suggested from the results of the preliminary *in vivo* test and the finite element analysis that the idea of the new device can contribute to diminish the plate-induced osteopenia. In addition, another advantage of the new plate is that the washer may prevent fretting corrosion between the plate and screw (Syrett, Charya, 1979).

5. CONCLUSIONS

Based on the present study, the following preliminary conclusions can be made.

(1) The stress transfer ratio for the lateral side of human femur is ranged from 10.1% to 37.4%, while for the medial side 86.5%~97.2% depending on the finite element models.

(2) The stress shielding in the lateral side is decreased by the new concept bone plate approximately 4,8% and 29% in contact and non-contact model respectively, while in the medial side, 23% and 74.5%.

(3) The stress shielding of non-contact model is effectively decreased compared with that of contact model. For the non-contact model, it is decreased approximately 16,7% and 26.9% in the lateral side, while in the medial side, 18.5% and 72.9% implanted with the conventional and new plate respectively.

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