The effect of malalignment on stresses in polyethylene component of total knee prostheses – a finite element analysis

Jiann-Jong Liau a, Cheng-Kung Cheng a,*, Chun-Hsiung Huang a,b, Wai-Hee Lo c

a Orthopaedic Biomechanics Laboratory, Institute of Biomedical Engineering, National Yang Ming University,
No. 155, Sec. 2, Li-Nung St., Shih-Pai, Taipei 11221, Taiwan, ROC
b Department of Orthopaedic Surgery, Mackay Memorial Hospital, Taipei, Taiwan, ROC
c Department of Orthopaedic and Traumatology, Veterans General Hospital, Taipei, Taiwan, ROC

Received 20 March 2001; accepted 1 November 2001

Abstract

Objective. To investigate the effects of malalignment on stresses in tibial polyethylene component of total knee prostheses.

Design. A three-dimensional finite element analysis was used to calculate the contact stress and von Mises stress in the tibial polyethylene component subjected to a compressive load, and the malalignment situations were simulated.

Background. Many biomechanical studies to investigate the stresses in tibial polyethylene component were assumed at the ideal contact alignment. The effect of malalignment on stresses in tibial polyethylene component was not investigated extensively.

Methods. Three-dimensional finite element models of the tibiofemoral joint of knee prostheses for three different designs were constructed. Three malalignment conditions including the medial translation (0.25, 0.5 and 1.0 mm), internal rotation (1°, 3° and 5°), and varus tilt (1°, 3° and 5°) of the femoral component relative to the tibial component were simulated. A compression load of 3000 N was applied to the tibiofemoral joint at 0° of flexion. The maximum contact stress and von Mises stress in the tibial component were compared to investigate the effects of malalignment.

Results. In comparing with the neutral position, the greatest increase of maximum contact stress were 67.6%, 14.3% and 145.9% and the greatest increase of maximum von Mises stress were 92.5%, 22.7% and 120.6% in maltranslation, internal rotation and varus tilt simulations, respectively.

Conclusion. The greatest increase of contact stress and von Mises stress was occurred in the high conformity flat-on-flat design of knee prosthesis under the severest malalignment condition. The high conformity curve-on-curve design of knee prosthesis has the minimal risk of polyethylene wear under the malalignment conditions.

Relevance

This study revealed the importance of malalignment effect on stresses in tibial polyethylene component. Polyethylene wear in surface replacement total knee will be minimal when a high conformity curve-on-curve knee design is used and the rotational line between the femoral and tibial components has the least effect on polyethylene wear but varus/valgus malalignment, even with the best designed prosthesis will still accelerate wear. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Tibiofemoral joint; Malalignment; Finite element analysis; Knee prosthesis

1. Introduction

Alignment is an important consideration in many clinical situations, such as fracture reduction, deformity correction and total knee arthroplasty. Significant changes in the axial alignment of the femur and tibia may alter the loading distribution in the knee joint. These changes can also alter the stress distribution on the contact surface and the soft tissue tension at knee joint. Excessive medial or lateral displacement of the femur relative to the tibia may be associated with osteoarthritis, especially when there is a combination of axial malalignment and loss of joint line horizontality [1].

Polyethylene wear of the articular surface is a well-known complication of total knee arthroplasty (TKA) [2–4]. In many retrieval analyses, an asymmetric wear beginning at the posteroomedial part of tibial insert was the common pattern [4]. The progressive femoral-tibial
subluxation, which resulted in polyethylene failure, was also demonstrated to be associated with post-operative extremity malalignment and excessive varus positioning of the tibial component [2]. Therefore, the role of extremity and implant alignment in wear of the tibial polyethylene component caught more attention recently.

Biomechanical studies have demonstrated that the stress in polyethylene component of artificial tibiofemoral joint is closely related to polyethylene wear [5,6]. The analytical approach [7,8], finite element method [9,10] and experimental measurement [11–13] have been widely used to investigate the stress distribution of tibial polyethylene component of knee prostheses. Most studies assumed the femoral and tibial components were at ideal contact alignment. Under this situation, the external load can be equally distributed on the medial and lateral parts of tibial component, which can reduce the stress concentration on the tibial insert. Only a few researchers had investigated the contact characteristics under malalignment conditions. Liau et al. [11] used the Fuji pressure sensitive film to study the influence of contact alignment of the tibiofemoral joint of knee prostheses in in vitro biomechanical testing. Matsuda et al. [14] utilized the digital electronic pressure sensor to measure contact stresses on upper- and undersurface of the tibial polyethylene components with the neutral and malrotated tibial tray of three mobile bearing designs and one fixed design of knee prostheses. They also used the electronic pressure sensor to investigate the effect of varus tilt on contact stresses in total knee prostheses [15]. However, using those pressure sensors can only measure the contact stress on the contact surface of the tibial polyethylene component. Bartel et al. [16] had described the dominant mode of surface damage in total knee prostheses is delamination. Delamination is caused when subsurface cracks continue to propagate tangent to the surface. The maximum shear stress is a measure of the distortion of the material, as is the von Mises stress, which is used often as an alternative measure of distortion. The experimental measurement cannot predict the stress distributions within tibial polyethylene component. These limitations can be solved by finite element analysis. Therefore, the objective of this study was using three-dimensional finite element analysis to investigate the effect of malalignment on stresses in polyethylene component of total knee prostheses.

2. Methods

Three-dimensional finite element models of the femoral and tibial polyethylene components for three different designs were constructed. Because the maximum contact stress was found to be most sensitive to change in the frontal radii of the femoral and tibial components [9], the sagittal radii of the femoral and tibial components were identical in those three knee prostheses. The conventional parameters used in knee design [17] of those three knee prostheses were summarized in Table 1. In the sagittal plane (Fig. 1(a)), these three models have the same femoral and tibial radii with a radius of 34.5 and 90 mm, respectively. In the frontal plane (Fig. 1(b)), the high conformity flat-on-flat design (HFF model) of one knee prosthesis (U-knee, United Orthopaedic, Taipei, Taiwan) has the same curvatures in femoral and tibial components with a radius of 120 mm. The high conformity curve-on-curve design (HCC model) has a smaller curvature in femoral and tibial components with a radius of 70 and 72 mm, respectively. The medium conformity curve-on-curve design (MCC model) has a curvature in femoral and tibial components with a radius of 70 and 80 mm, respectively. The curvatures in the frontal plane of HCC and MCC models were adopted from the literature [10].

The bearing surface of femoral component was modeled with rigid body elements because the elastic modulus of femoral component was much larger than the ultra high molecular weight polyethylene (UHMWPE) tibial component’s. A total of 11,232 eight-node solid block elements were used to model the tibial component. The material properties reported in the literature were employed in this study. The UHMWPE tibial component was assumed as an elastic-plastic material; the elastic modulus was 1016 MPa, the yield stress was 14.07 MPa and the Poisson’s ratio was 0.46 [16]. The thinnest thickness of the UHMWPE tibial component in these three models was all 6 mm.

When the femoral and tibial components were at the neutral position, these two components were contact at the deepest point on the tibial bearing surface. In this situation, all models have a symmetric contact characteristic in the medial and lateral parts of the tibial component because of a symmetric design of these three knee models and the applied load also passed through

<table>
<thead>
<tr>
<th>Model</th>
<th>Femoral frontal radius (mm)</th>
<th>Tibial frontal radius (mm)</th>
<th>Femoral sagittal radius (mm)</th>
<th>Tibial sagittal radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFF</td>
<td>120</td>
<td>120</td>
<td>34.5</td>
<td>90</td>
</tr>
<tr>
<td>HCC</td>
<td>70</td>
<td>72</td>
<td>34.5</td>
<td>90</td>
</tr>
<tr>
<td>MCC</td>
<td>70</td>
<td>80</td>
<td>34.5</td>
<td>90</td>
</tr>
</tbody>
</table>

Note: HFF: high conformity flat-on-flat design. HCC: high conformity curve-on-curve design. MCC: medium conformity curve-on-curve design.
the medial line of tibial component in the frontal plane. The convergence test on the solution of maximum contact stress has been conducted to ensure an adequate mesh model for knee prosthesis. To investigate the effect of malalignment on stresses in tibial polyethylene component, three malalignment conditions were simulated. The femoral component was moved 0.25, 0.5, and 1.0 mm linearly along medial direction relative to the tibial component to simulate the maltranslation condition. In rotation malalignment condition, the femoral component was rotated 1°, 3°, and 5° internally relative to the tibial component. In varus malalignment condition, the femoral component was simulated as varus tilt of 1°, 3°, and 5° relative to the neutral tibial component (Fig. 2). The origin of the coordinate used to simulate the translation, rotation and varus tilt of the femoral component was at the intersection of the line of the flexion radius in the sagittal plane and the center plane of the intra-condylar notch in the frontal plane of the femoral component.

The fixed boundary condition was specified on the base of the tibial component. The femoral component was constrained to move vertically only. The initial contact was to obtain point or line contact between tibial and femoral components. Then a compression load of 3000 N, which was usually used to evaluate the contact characteristics in tibiofemoral joint of knee prostheses, was applied to the tibiofemoral joint at 0° of flexion. The interface frictional characteristic between the polyethylene insert and femoral component was assumed frictionless. The I-DEAS Master series 6.0
(Structural Dynamics Research, Milford, Ohio, USA) was used to create the three-dimensional finite element models. The finite element code ABAQUS 5.8-10 (Hibbit, Karlsson and Sorenson, Pawtucket, RI, USA) was used to carry out the contact analysis and the Exceed 3D 6.1.1 (Hummingbird Communications, North York, Ontario, Canada) was using to display the final result.

3. Results

When these knee prostheses were at the ideal contact alignment, the HFF model has a rectangular contact area and the high or medium conformity curve-on-curve model (HCC/MCC models) has an elliptic contact area (Fig. 3). The contact patterns of these two models under the normal contact alignment were in agreement with the theoretical approach. The most nonconforming design (MCC model) had the greatest maximum contact stress and von Mises stress (Table 2). The maximum contact stress and von Mises stress in HCC model were 15.8% and 20.6% smaller than that in MCC model, respectively. The maximum contact stress and von Mises stress in HFF model was approximately equal to that in HCC model. The contact area in HFF, HCC and MCC models were 167.8, 162.2 and 147.4 mm², respectively.

When the femoral component was simulated as a maltranslation in the medial direction relative to the tibial component, the maximum contact stress and von Mises stress in the tibial component significantly increased in comparing with the neutral position (Table 2). The greatest contact stress and von Mises stress in

Fig. 3. The contact patterns on the tibial polyethylene component for: (a) high conformity flat-on-flat; (b) high conformity curve-on-curve design of knee prostheses under a compression load of 3000 N at the neutral position. The contact pattern for medium conformity curve-on-curve design was similar with high conformity one.
the tibial component were at the condition when the femoral component was moved to the longest displacement (1.0 mm). In comparing with the neutral position, the greatest increases of contact stress was 67.6% in HCC model and of von Mises stress was 92.5% in HFF model. The greater the displacement of the femoral component moved medially, the greater the increase in maximum contact stress and von Mises stress except the contact stress in MCC model.

When the femoral component was rotated internally relative to the tibial component, the changes in maximum contact stress and von Mises stress were significantly smaller than the maltranslation conditions (Table 2). In maximum contact stress, the greatest increase was 14.3% at 1° of internal rotation of femoral component in HFF model and the greatest decrease was 13.6% at 5° of rotation in MCC model. In maximum von Mises stress, the greatest increase was also at 1° of rotation in HFF model (22.7%) and the greatest decrease was also at 5° of rotation in MCC model (5.5%).

When the femoral component was simulated at malalignment conditions, the femoral component was in contact with both medial and lateral parts of the tibial component. However, when the femoral component was simulated as varus tilt, the worst case, the femoral component was only in contact with the medial part of tibial component, which induce the greatest increase of stresses in the tibial component in those three malalignment simulations (Table 2). The greatest and smallest increase in contact pressure were 145.9% at 5° of varus tilt of the femoral component in HFF model and 39.4% at 1° of varus tilt in MCC model. The greatest increase in maximum von Mises stress was also at 5° of varus tilt in HFF model (120.6%) and the smallest increase was 70.0% at 1° of varus tilt in MCC model. The greater the varus angle of the femoral component tilted, the greater the increase in maximum contact stress and von Mises stress in the tibial component of those three knee models.

4. Discussion

In many retrieval studies, the post-operative radiographic data had shown that the polyethylene wear in the tibial component was almost accompanied with the varus tilt of knee joint and/or excessive femoral-tibial component subluxation [2,3]. Therefore the stress distribution in the tibial polyethylene component under a malalignment condition could approach to a more actually clinical situation. However, most studies to evaluate the different designs of knee prostheses were carried out when the knee prosthesis was at the neutral position. The effects of malalignment on stresses in the tibial polyethylene component have not been investigated extensively.

Bartel et al. [16] used finite element analysis to determine the stress caused by contact for eight knee prostheses when these knee prostheses were at the neutral position. Their results showed that nonconforming design of knee prostheses had larger contact stress and von Mises stress than the conforming one. In our study, the medium conformity curve-on-curve design has larger contact stress and von Mises stress than both high conformity flat-on-flat and curve-on-curve designs of knee prostheses at the neutral position (Table 2). Our result was consistent with Bartel’s study.

The effect of malrotation on contact stress in polyethylene component of knee prostheses had been investigated in our previous study by in vitro biomechanical testing [11]. The contact stress was measured when the tibial component was normally aligned and at the malrotation conditions (internal or external rotation of 1°, 3° and 5°). We found that in the internal–external malrotation, the ratios of contact stress under the malrotation conditions relative to the normal contact alignment ranged from 0.97 to 1.11. In this study, the greatest change in contact stress was 14.3% under the malrotation simulation, which was similar with our previous study. However, when the tibial component was at 15° internal and 15° external

---

Table 2

<table>
<thead>
<tr>
<th>Maximum contact stress</th>
<th>Maximum von Mises stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFF</td>
<td>HCC</td>
</tr>
<tr>
<td>Neutral position</td>
<td>32.6</td>
</tr>
<tr>
<td>Med. Trans. 0.25 mm</td>
<td>40.1</td>
</tr>
<tr>
<td>Med. Trans. 0.50 mm</td>
<td>40.7</td>
</tr>
<tr>
<td>Med. Trans. 1.00 mm</td>
<td>43.4</td>
</tr>
<tr>
<td>Int. Rotation 1°</td>
<td>37.3</td>
</tr>
<tr>
<td>Int. Rotation 3°</td>
<td>34.9</td>
</tr>
<tr>
<td>Int. Rotation 5°</td>
<td>34.1</td>
</tr>
<tr>
<td>Varus Tilt 1°</td>
<td>56.6</td>
</tr>
<tr>
<td>Varus Tilt 3°</td>
<td>71.3</td>
</tr>
<tr>
<td>Varus Tilt 5°</td>
<td>80.2</td>
</tr>
</tbody>
</table>

Note: HFF: high conformity flat-on-flat design. HCC: high conformity curve-on-curve design. MCC: medium conformity curve-on-curve design.
rotation, the marked increase in peak and mean contact stress was found on the articular surface with malalignment of the tibial component [14]. The greater malrotation angle of the tibial component would increase the risk of edge contact.

Matsuda et al. [15] used an experimental setup to investigate the effect of varus tilt on contact stresses in five total knee prostheses. They divided those knee prostheses into two groups, the curve-on-curve group and the flat-on-flat group. Their results showed that the maximum contact stress increased greater for flat-on-flat design than curve-oncurve one when the tibial component was 5° of varus tilt at 15° of flexion. In our study, the increase of maximum contact pressure was greater in high conformity flat-on-flat design than both high and medium conformity curve-on-curve designs of knee prostheses when the femoral component was 5° of varus tilt at 0° of flexion (Table 2). Our results showed the same tendency with Matsuda’s study.

When the femoral component was simulated as medial maltranslational, the increase of maximum contact pressure was greater in curve-on-curve design than the flat-on-flat one. The wear rate of polyethylene increases exponentially when the contact pressure increases [18]. Therefore, curve-on-curve design of knee prosthesis has a higher polyethylene wear rate than flat-on-flat design when the medially–lateral maltranslational of knee prosthesis occurred. However, the maximum von Mises stress was greater in flat-on-flat design (Table 2). When the von Mises stress was greater than the yield stress of UHMWPE (14.07 MPa), a local plastic deformation would occur. The onset of those plastic deformations was usually at 1 mm beneath the contacting surface. As the applied load increases, those plastic deformations may propagate upward into the contacting surface. The geometry of the contact surface would become more conforming then reduce the maximum contact pressure. This is why the HFF model has the greatest von Mises stress but has the smallest contact pressure. The flat-on-flat design increases the risk of delamination wear than the curve-on-curve design when the medial maltranslational of the femoral component occurs.

The most severe situation which significantly increases the risk of polyethylene wear was varus tilt of the femoral component. The maximum contact stress and von Mises stress significantly increased in all three knee models (Table 2). The high conformity curve-on-curve design had the smallest contact stress and von Mises stress. This design of knee prostheses has a less risk of polyethylene wear than other two designs. From these results, the varus–valgus alignment of the knee joint should be the most important consideration during TKA.

Comparing the malrotation to the maltranslational and varus tilt of the femoral component, the increase of stress in the tibial component was the smallest in malrotation condition. The malrotation of the femoral component would slightly increase the risk of polyethylene wear in tibial component. However, the malrotation of the femoral component would significantly increase the risk of patellofemoral complication after TKA [19].

If we evaluate the different designs of knee prostheses only under the ideal contact alignment, we would conclude that the high conformity design of knee prostheses has a less risk of polyethylene wear, and the high conformity flat-on-flat design has almost equal risk with the curve-on-curve one. However, if we consider the malalignment of the knee prostheses, the flat-on-flat design has a higher risk for polyethylene wear than the curve-on-curve design. To approach the actual condition of knee prostheses in vivo and be more objective to evaluate the different designs of knee prostheses, the malalignment conditions should be taken into consideration.

Several limitations in these finite element models of the current study were considered. First, polyethylene wear is a dynamic process affected by many factors, including contact stress, sliding distance, frictional behavior, and the cyclic load. In this study, only a vertical compression load was applied to the tibiofemoral joint of knee prostheses at 0° of flexion. The knee’s kinematics and the cyclic nature of load were also important factors, which were not considered in the present study. Secondly, the stresses in the tibial component were used only to predict the polyethylene. Delamination or fatigue wear of polyethylene is a function related to the strain/damage accumulation [20]. A further finite element analysis with those damage functions will be the subject of future study. Thirdly, the analysis considered conformity changes in one plane, however, a total knee prosthesis design may show varying conformities in the coronal and sagittal planes. Finally, the maximum medial maltranslation distance was 1 mm, and the maximum rotation and varus tilt’s angle was 5°. To approach the actual condition in vivo, the larger translation distance, and larger rotation angle need to be further investigated. Furthermore, the effect of malalignment simulation including maltranslation, malrotation, and varus tilt of the femoral component was separately investigated. In actual situation of knee prosthesis in vivo, it would be a combination of these malalignment conditions. These effects need to be further investigated.

5. Conclusion

The greatest increases of contact stress and von Mises stress occurred in the high conformity flat-on-flat design of knee prosthesis under the severest malalignment condition. Therefore, the high conformity curve-on-curve design of knee prosthesis had the minimal risk of polyethylene wear under malalignment conditions.
Acknowledgements

The authors are honored to acknowledge the financial support of the National Science Council (NSC-89-2213-E-010-007), ROC.

References
