Evaluation of UHMWPE Component under Various Positions for UKA

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Total number of pages: 6
Total number of tables: 0
Total number of figures: 4
Total number of words: 1,900
Rev.1: August 14, 2007

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Key words: unicompartmental; finite element analysis; tibial; knee; position

Evaluation of UHMWPE Component under Various Positions for UKA

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Abstract. The development of artificial joints is now considered to be quite mature, and is the main treatment for osteoarthritis. However, in recent unicompartmental knee arthroplasty (UKA) clinical follow-ups, complications due to the wearing of polyethylene (PE) tibial components still exist. Therefore, this study is focused on avoiding and minimizing damage to the PE tibial component. Currently, the most common problem in the application of UKA is the malresection of the tibial plateau, often resulting in malpositioning of the tibial implant. This malpositioning may be the main reason for advanced wear and dislocation of the PE tibial component. In this study, finite element analysis (FEA) was used to study the stress change of malpositioned PE tibial components in order to better understand the damaging actions on PE tibial components. From FEA, it was found that anatomically designed unicompartmental knee prostheses (UKP) allowed more positional error in varus tilt than symmetrically designed UKP, and both should avoid any positional error greater than 10° valgus tilt. Otherwise, increased wear of PE tibial components would result in shortened lifetime of the artificial joint.

Introduction

UKA has been developing since the early 1970s. Much early literature indicates that results were not ideal. The main reasons inlcuded poorly designed implant, inappropriate patient selection, and doctors' misconceptions regarding the surgery [1-3]. UKA results and evaluations have greatly improved, thanks to improved implant design, precise patient selection, refined surgical techniques, and accumulated expertise in related techniques. However, recent reports of UKA clinical follow-ups continue to show failed operations due to wearing PE tibial components [4, 1]. PE tibial component wear mainly comes from excess stress, mainly related to faulty component positioning [5, 6]. Among the many reasons for a component to be malpositioned, malresection of the tibial plateau's coronal plane is the most common [7]. This error in the operation often leads to unsatisfactory joint stability, mobility, and fixation [8].

Therefore, the issue of how to avoid and minimize damage on the PE tibial component due to stress has become the main focus of research regarding UKA. However, existing studies of UKA which deal with damage of the PE tibial component due to malpositioning of the joint component are mostly limited to statistical reports of clinical follow-ups. These studies involve many unseen factors which could affect the data: weight of the examined patient, condition of the soft tissue of the knee joint, precise positioning of the joint component, and stress condition between the joints, among others. These uncontrolled factors often lead to statistical errors. In addition, under the condition that no in vitro or in vivo biomechanical studies have been done on UKA, it would be necessary to study the effects of malresection on the PE tibial component scientifically. Therefore, this study plans to use FEA, with its advantage of accuracy, to analyze object and boundary conditions in order to study the effects of gait load on the PE tibial component when malresection of the tibial plateau's coronal plane occurs. In other words, we can use the results from an analysis of stress and its distribution to determine the acceptable limit of varus/valgus tilt of the PE tibial component, thus greatly reducing future surgical risks and difficulties.

Materials and Methods

We chose Zimmer Unicompartmental Knee (ZUK; Zimmer, Inc., Warsaw, IN) and Depuy Unicompartmental Knee (DUK; DePuy Orthopaedics, Inc., Warsaw, IN) brands as our samples. The femoral component in ZUK is anatomically designed and it is symmetrically designed in DUK. Both use flat nonconforming components for PE tibial components. Before this study, 3D solid models of ZUK and DUK femoral and tibial components were built using a computer-aided design system, and FEA software (COSMOSWorks, SolidWorks, Inc., Concord, MA) translated the 3D models into 3D finite element models. The femoral component was made of Co-Cr alloy, and the tibial component was made of Ultra High Molecular Weight Polyethylene (UHMWPE). The settings for each component's material properties were as follows: Young's modulus for Co-Cr alloy was 220 GPa with Poisson's ratio of 0.3; Young's modulus for UHMWPE was 500 MPa with Poisson's ratio of 0.4 and a yield strength of 14.4 MPa. The above materials were hypothesized to be isotropic and homogeneous.

In simulating UKP positioning, the angle of placement of the PE tibial component on the sagittal plane simulated that of the angle of posterior slope resulting from the resection of the tibial plane.[8] The angle for posterior slope used in the study was set at 5°. In addition, the angle of positioning of the PE tibial component's coronal plane simulated the neutral, varus, and valgus positions resulting from the resections of the tibial plateau, shown in（Fig. 1）. The various angles of position in the simulation included 0° neutral position; 5°, 10°, 15° varus tilt; and 5°, 10°, 15° valgus tilt. Thus we can observe the stress changes in the two brands' PE tibial components resulting from malresections of the tibial plateau in the seven variation models.

The lowest point at which the PE tibial component touches the surface was chosen as the original neutral position between the femoral and tibial components. The central axis of the coronal plane of the femoral component was parallel to the mechanical axis, and perpendicular to the joint line (JL), whereas the bottom face of the PE tibial component was parallel to JL. In the meantime, the PE tibial component was defined as “fixed”, while the relative displacement of the femoral component provides the required load. The loading condition was defined as the maximal loading on tibiofemoral joint walking with knee flexion 0°, which was approximately three times of a person’s body weight (BW) [9], we chose a person’s BW of 65 kg in this study. In addition, the load was defined 75% on the medial unicompartmental knee [10]. Therefore, the load on the medial tibial tibial component was 1435 N. Meanwhile, frictions and the relative displacement are neglected in all models.

Results

Gait load simulations showed that the maximum von Mises stress and maximum contact stress of the PE tibial components of the two brands varied according to varus and valgus tilt criteria, as shown in（Fig. 2）and（Fig. 3）respectively.

As seen in（Fig. 2）, when PE tibial components increased with varus/valgus tilt, the von Mises stresses in both brands increases with increasing varus/valgus tilt most of the time. However, the ZUK model did not exhibit this trend in varus tilt, and its amount of stress change exceeded the norm. Stress change was 15.45 - 15.57 MPa, and the stress increase rate relative to the neutral position (15.46 MPa) was <0.71%. The stress change for valgus tilt was 15.58 - 16.56 MPa, and the stress increase rate was 0.78% (5°), 4.01% (10°), and 7.12% (15°). The varus tilt in the DUK model exhibited stress change 15.11 - 16.34 MPa (where neutral position stress value = 15.02 MPa), and stress increase rates were 0.6% (5°), 4.73% (10°), and 8.79% (15°). The stress change for valgus tilt was between 15.11 and 16.57 MPa, and stress increase rates were 0.6% (5°), 3.86% (10°), and 10.32% (15°).

Despite the type of vagus and valgus tilts of PE tibial components, the maximum von Mises stress did not occur on the contact surface for either ZUK or DUK model, but below the contact surface. The closest point to the contact surface was at 15° valgus tilt in the ZUK model (1.72 mm) and 15° valgus tilt in the DUK model (1 mm), as shown in（Fig. 4）.

Analyzed results of the ZUK model show that no correlation exists between maximum contact stress and change in varus/valgus tilt. Changes in stress increase rates of vagus tilt relative to neutral position (35.43 MPa) were all under 2.31%, and the stress change was between 35.21 and 36.25 MPa. The stress change was between 34.62 and 46.38 MPa for valgus tilt, where the maximum stress increase rate occurred at 15° valgus tilt (30.91%). Maximum contact stress and varus/valgus tilt changes were correlated in the DUK model, increasing with increasing tilt angle. Changes in stress increase rate are described as follows: stress increase rates were 0.96% (5°), 11.11% (10°), and 15.15% (15°) for varus tilt and stress change was between 32.45 and 37.01 MPa; stress increase rates were 1.31% (5°), 6.53% (10°), and 23.4 % (15°) for valgus tilt and stress change was between 32.56 and 39.66 MPa.

Discussion

FEA simulated analysis showed that differently designed femoral components resulted in different stress expressions on PE tibial components, and these differences were especially prominent when PE tibial components were at various varus positions. Anatomically designed ZUK, with varus tilt from 0° to 15°, had a steady change in maximum von Mises stress and maximum contact stress. On the other hand, the symmetrically designed DUK exhibited sudden increases in stress at 10° varus tilt, and at 15° varus tilt the stress increase rate was 1.86 times (maximum von Mises stress) and 1.36 times (maximum contact stress) that of 10° varus tilt. In the valgus positions, both ZUK's and DUK's maximum von Mises stress and maximum contact stress increased with increasing valgus tilt. Also, sudden stress increased when ZUK and DUK were at 10° valgus tilt.

Therefore, change of varus tilt had limited effect on the anatomically designed femoral component, which was also better able to handle deformity. In other words, the anatomical femoral component allowed for more errors in varus malresection. However, it needs to avoid errors greater than and including 10° valgus tilt. When using symmetrical femoral components, the operation should avoid varus/valgus malresection of 10° or greater, or edge contact could easily happen. This would cause the contact surface to deteriorate, leading to excess stress on the PE tibial components, and advanced damage. Results from analysis of the simulation were very similar to those of the clinical statistical analysis from Collier et al [7].

As shown, even though anatomical femoral components had better stress performance at varus tilts than symmetrical femoral components, they had poorer stress performance within 5° varus tilt. This is because the warp rates of the coronal surface of anatomical femoral components were greater than that of symmetrical femoral components.

In conclusion, either anatomically or symmetrically designed UKP at neutral position resulted in early plastic deformation of PE tibial components when UHMWPE yield strength was exceeded. Also, the location of damage due to maximum von Mises stress moved from the interior to the contact surface with increasing maximum von Mises stress and maximum contact stress. Damage was especially prominent at 15° varus/valgus tilt. Looking at the overall expression of stress of varus/valgus tilt, even though anatomically components' stress values were higher than those of symmetrically designed components, it allowed for more error in varus malresection. Therefore, when better performance and longer length of usage are expected of anatomically UKP, patient's weight and activity must be factored in to a greater extent than when using symmetrically designed UKP.

Overall, for UKA to have excellent long-term results, patient selection, prosthesis choice, and most importantly excellent UKA surgical techniques will all be required. More accurate positioning and better surgery success rates will also require a computer assisted surgery navigation system.

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Legends

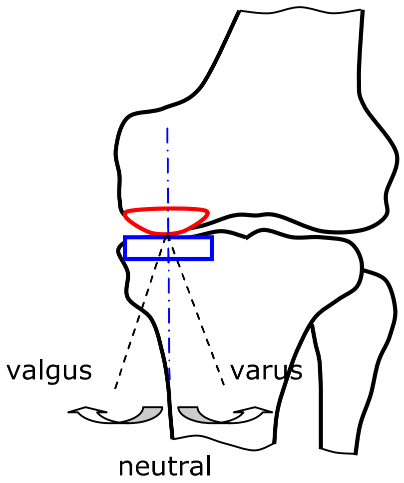

Fig. 1. The tibial component was placed on the medial tibial plateau at various tilt conditions in the coronal plane.

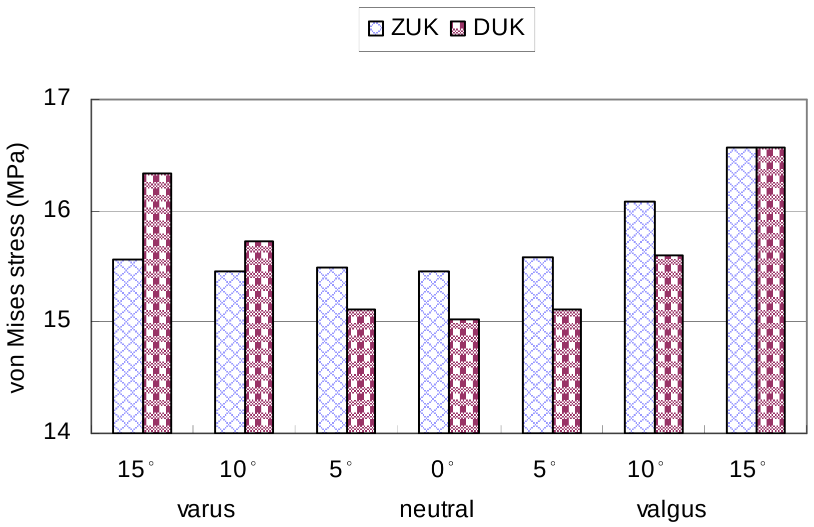

Fig. 2. The max. von Mises stresses of the PE tibial components under varus/valgus tilt conditions

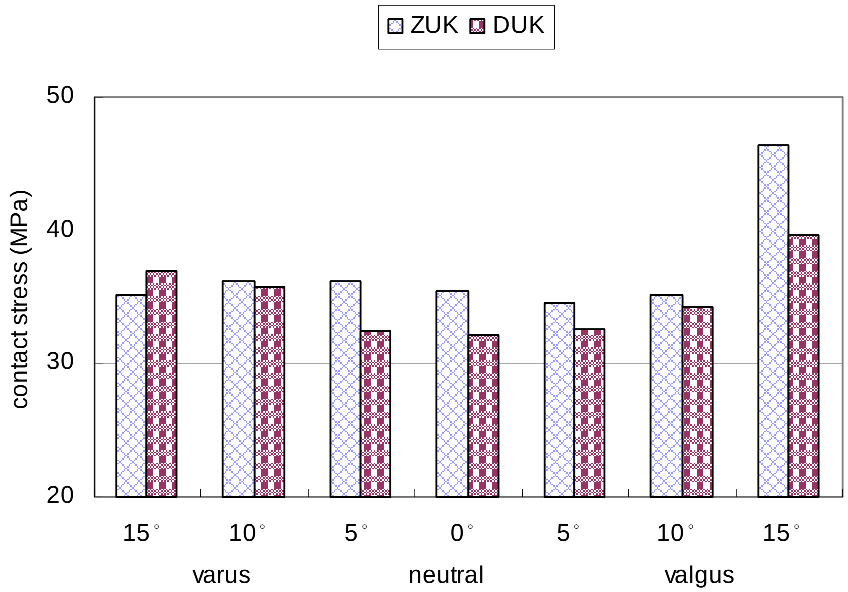

Fig. 3. The max. contact stresses of the PE tibial components under varus/valgus tilt conditions

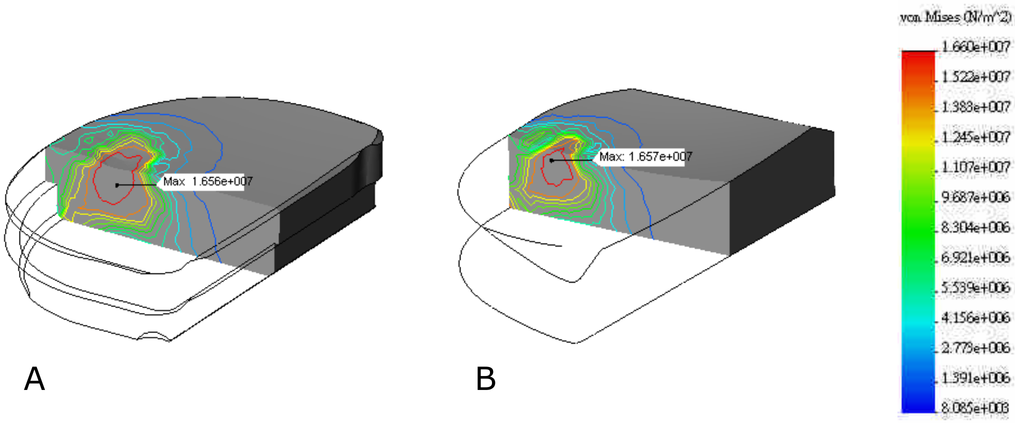

Fig. 4A-B. The max. von Mises stresses are located at the center of contact and occur beneath the articulating surface from a coronal cross-section view for（A）ZUK and （B）DUK.