Biomechanical analysis of tibial insert under varus tilt after medial unicompartmental knee arthroplasy

Chen-Tung Yu
Department of Orthopaedic Surgery
Changhua Christian Hospital
Taipei, Taiwan
ortho.yu@msa.hinet.net

Chien-Wei Liu
Graduate Institute of Mechanical and Electrical Engineering
National Taipei University of Technology
Taipei, Taiwan
liu900927@pchome.com.tw

Wenlung Li
Graduate Institute of Mechanical and Electrical Engineering
National Taipei University of Technology
Taipei, Taiwan
wlli@ntut.edu.tw

Chia-Chi Lo
Mackay Medicine, Nursing and Management College
Taipei, Taiwan
s070@eip.mkc.edu.tw

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 clinical follow-ups, complications due to the wearing of polyethylene (PE) tibial components still exist. Therefore, the purpose of this study was to analyze the relation between insert wearing and components alignment in unicompartmental knee prostheses by finite element analysis. This study evaluates the angles after correction of varus deformity and posterior tibial slope (PTS), the results show that the varus tilt should be less than 10°, the excessive posterior tibial slope should be avoided, too. Otherwise the wear of the PE tibial components will increase and thus shorten the expectancy of joint protheses.**

Keywords-varus; tibial; wear; unicompartmental; FEA

I. Introduction

Unicompartmental knee arthroplasty (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 [1,4]. PE tibial component wear mainly comes from excess stress, mainly related to faulty component positioning [5, 6]. And, the main reason usually stems from the corrected angle in coronal plane and PTS [2,6,7]. Overcorrection may cause the damage of the opposite tibiofemoral cartilage, while undercorrection may cause the wear of PE tibial components. This implicitly signifies that the final angle corrected for knee deformity is a crucial factor of a successful UKA. Hernigou and Deschamps [8] further reported that the greater PTS would cause an increasing number of cases requiring secondary replacement due to PE tibial component damage.

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 alignment of the tibiofemoral joint 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 loading 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 the corrected angle and PTS on the PE tibial component scientifically. Therefore, this study plans to use finite element analysis (FEA), with its advantage of the accuracy of defined boundary conditions, to analyze object in order to study the effects of gait load on the PE tibial component when various alignments of the tibiofemoral joint in the coronal and sagittal planes. In other words, we can use the results from an analysis of stress and its distribution to determine the acceptable limit of alignment of the tibiofemoral joint, thus greatly reducing future surgical risks and difficulties.

II. Materials and Methods

Three different designs of UKP were chosen as the study samples in this investigation. They were from the Zimmer Unicompartmental Knee-High Flex (ZUK; Zimmer, Inc., Warsaw, IN), the Preservation Unicompartmental Knee (PUK; DePuy Orthopaedics, Inc., Warsaw, IN), and the Eius Unicompartmental Knee (EUK; Howmedica Osteonics, Inc., Mahwah, NJ), respectively. The selected the ZUK and EUK femoral component were anatomically designed, while that of PUK symmetrical one. All were flat nonconforming PE components. The solid models of these femoral and tibial components were built using a slit laser profilmeter and computer-aided design system; together with the FEA software (COSMOSWorks, SolidWorks, Inc., Concord, MA) that translated the models into the FE ones. Actually, it has been verified earlier[17] that the results of FEA were quite reliable in which the FE simulation of a patellar component was to compare with a worn out insert and found good consistence.

As it is commonly used [9], the femoral component was made of Co-Cr alloy, and the tibial component the Ultra High Molecular Weight Polyethylene (UHMWPE). The material properties were as follows: the Young's modulus and the Poisson's ratio for Co-Cr alloy were 220 GPa and 0.3, respectively; while 500 MPa and 0.4 for UHMWPE. The yield strength of the two PE components was 14.4 MPa. Moreover, the materials were isotropic and homogeneous..

In simulating the unicompartmental knee prosthesis (UKP) positioning, the angle of the PE tibial component on the sagittal plane was to simulate the angle of the posterior slope resulting from the resection of the tibial plateau. The angle for posterior slope used in the study was set at 5° and 10°. In addition, the positioning angles of the femoral component in the coronal plane were simulated neutral position and various varus tilts (5°, 10°, 15° varus tilt) in the medial tibiofemoral joint (Fig 1). Some tilt ranges are fictitious and much larger than a normal UKA requires, however, the angles were modeled to mimic all possible corrections of the UKA. The main concern of the present study is the stress distributions under these circumstances.

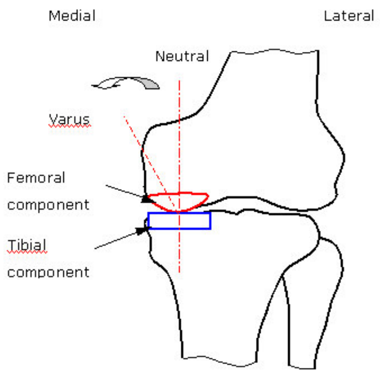

Figure 1. The simulation of varus tilt after medial unicompartmental knee arthroplasty

The original neutral position between the femoral and tibial components was set at the lowest point, at which the surfaces of the two components touch each other. The central axis of the femoral component on the coronal plane was set parallel to the mechanical axis, and perpendicular to the joint line (JL). Whereas, the bottom face of the PE tibial component was parallel to the JL. In the meantime, the PE tibial component was considered as a "fixed" boundary on its tibial bearing, while the required balancing load was provided by the relative displacement of the femoral component. The loading condition was defined as the maximal load on the tibiofemoral joint while walking with knee flexion 0°. Or, it is approximately three times of a person's body weight (BW) [10]. Thus, a person of 65 kg was chosen in this study and the load directly acting on the medial tibial condyle was defined as 75% BW [11]. In other words, the simulation load acting on the PE tibial component was 1435 N. Meanwhile, frictions and the relative displacement on PE were neglected in all models.

III. Results

During the analyses, the implanting angle of the tibial component is based on the angle of the posterior slope, which is produced by surgical excision of the tibial plateau. In addition, femoral components are simulated as the postoperative varus deformity with the angle 0° to 15° with increment 5°. The postoperative effects of PTS and varus tilt on tibial components are evaluated from both sagittal plane and coronal plane of these models.

Under the same gait loading condition, the maximal von Mises and contact stresses of the PE tibial components for ZUK, PUK and EUK for various posterior tibial slopes and varus tilts are shown in Table 1. As seen in Table 1, when PE tibial components increased with PTS and varus tilt, the von Mises stresses and contact stresses in all UKPs increases with increasing PTS and varus tilt most of the time. The above results reveal that when PTS is 5° or 10°, the rate of von Mises stress increase when varus tilt increases from 0° to 15° is more than 1.7 times as much as that from 0° to 10°. For all models, the von Mises stress exceeds the yield strength of the PE tibial components, and the value is highest at a 15° varus tilt. We also found that the maximal stress of PE components shifts laterally with the increasing varus tilt (Fig 2), suggesting that when varus tilt exceeds 10°, wear of the lateral side of PE tibial components is more likely to occur, and thus leads to dislocation of femoral components.

In summary, although PTS affects the stress of PE tibial component (the von Mises stress increase rate relative to the same varus tilt was < 3.2%), the effects of varus tilt is even more significant (the von Mises stress increase rate relative to the neutral position was approached 12.7%). In addition, Fig 3 shows that the maximal von Mises stress of PE tibial component occurs only beneath the contact surface of tibial component, suggesting that the flake of PE tibial component first takes place inside the tibial component from bottom to top and then results in cracks. Furthermore, our study suggests that the maximal von Mises stress occurs closer to the contact surface of PE tibial component while the maximal von Mises stress increases. This means the contact surface of PE tibial component is more likely subjected to stress damage.

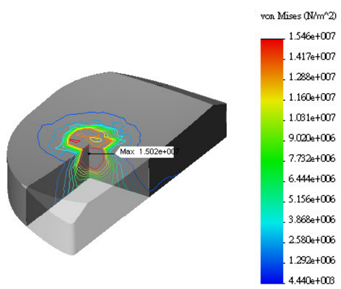

Figure 3. The max. von Mises stress is located at the center of contact area and occurs approximately 2 mm beneath the articulating surface.

TABLE 1. The maximal von Mises and contact stresses of the PE tibial components under various posterior tibial slopes and varus tilts (Unit：MPa)

	Maximum von Mises stress（Body）			Maximum contact stress			Maximum von Mises stress（Surface）		
	Zimmer	Preservation	Eius	Zimmer	Preservation	Eius	Zimmer	Preservation	Eius
5° Posterior slope									
Neutral position	15.46	15	15.08	35.43	32.13	33.5	14.87	13.92	14.59
Varus tilt 5°	15.56	15.13	15.54	34.57	32.66	38.84	14.96	14.47	14.83
Varus tilt 10°	16.09	15.57	15.87	34.97	34.83	37.06	15.77	14.95	15.56
Varus tilt 15°	16.73	16.69	16.4	44.68	38.8	45.66	16.05	16.42	15.43
10° Posterior slope									
Neutral position	15.32	15.4	15.21	35.01	33.73	33.94	14.93	14.65	14.75
Varus tilt 5°	15.55	15.4	15.8	34.97	33.93	38.01	14.91	14.83	14.94
Varus tilt 10°	16.4	15.58	15.95	46.2	34.88	39.82	15.08	15.15	15.75
Varus tilt 15°	17.27	16.59	16.53	47.5	36.94	51.11	16.75	16.1	16.17

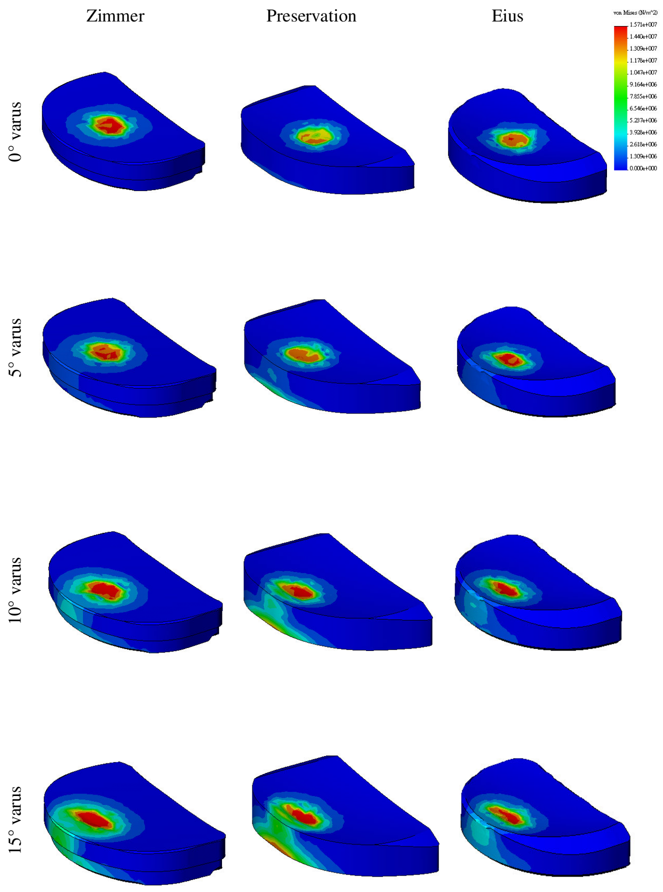

Figure 2. The contact patterns of the tibial PE components under various varus conditions for 5° posterior tibial slope.

IV. DISCUSSIONS

According to the stress simulation demonstrated above, although the PE tibial components of ZUK ,PUK and EUK differ in their geometric design and stress distribution under normal gait simulation, the stress both inside and on the contact surface of PE tibial components will exceed the yield strength of UHMWPE material and thus cause wear and delamination of PE components, regardless of the angle corrected for varus deformity. Therefore, accurate correction of varus deformity is is very important, because the von Mises stress and contact stress increased with increasing varus tilt.

Our results show that the maximal von Mises stress of PE tibial components demonstrates no significant difference in response to changes of PTS. This may be because our study assumes that both ACL and PCL will reach a state of stable balance, and there is no friction between joint components. In other words, if the soft tissue and ligaments surrounding the knee joint are robust and balanced postoperatively, the effects of PTS on PE tibial components can be ignored.

Generally speaking, the maximal von Mises stress and contact stress of PE tibial components increase accordingly to the increasing PTS. However, when comparing different PTS under the same VTA, a larger PTS angle does not necessarily produce a higher stress value. This may arise from the conformity of PE components in UKP. Nevertheless, a large PTS angle still causes increased stress on PE tibial component. Hernigou et al. [8] have reported that the patient with larger PTS angle has a higher probability of PE tibial component damage. UKA usually removes tibial plateau following its original PTS and this is the only way to restore balance of the surrounding soft tissue and ligaments. However, if the bone is excised from its original large PTS, the risk of wear on PE tibial component will increase. Our study therefore suggests that the PTS angle should be taken into account as a criterion for patient selection, in other words, the excessive PTS angle should be avoided.

In conclusion, the expectancy of UKA can be lengthened effectively by proper control of corrected angle and patient selection, especially body weight. However, most clinical reports lack body weight information. According to previous UKA studies, wear of PE tibial component cannot be totally spared even with a precise alignment. This may suggest that patients' body weight is one of the major factors that causes wear of PE tibial component. In addition, patients' activity is one of the major factors which affects the contact stress between joint components, and its effect even multiples the effect of body weight. Therefore the activity should also be considered in UKA, given that the bearing of PE tibial component is limited. The contact stress of joint components is also associated with the geometric design of implants; a larger contact surface can effectively reduce the stress by scattering it. However, a large contact surface means a more restricted range of motion (ROM). For example, when the contact surface between joint components is reduced into a line or a point, there is minimal ROM restriction, rendering the activity similar to the natural knee joint while the stress between joint components becomes relatively higher.

Some researchers suggested that increasing the thickness of tibial component may reduce the damage caused by stress [12, 13]. According to documents, while increasing thickness of PE tibial components prolongs their expectancy, the risk of tibial plateau fracture will increase as well. Tibial plateau fracture is not caused by a single factor; it may also be associated with, for example, the position of tibial peg implantation [14], especially in patients with low bone density. Therefore, in order to prevent stress damage to the PE tibial component as well as the complications, effective control of corrected angle is the better choice. By the in-depth study results, shown in Fig. 4, increasing the PE tibial thickness is not a good way to minimize the stress damage, it has been found that the stresses are all limited within the ranges between 14.82 and 15.05 MPa, or reducing less than 0.28 MPa (1.8%), even with almost double the thickness.

Therefore, indications of UKA for correcting varus deformity are not fully developed and controversies still exist. Our study reveals that besides considering the patient's body weight, excess activity loading to the postoperative knee joint should be avoided and the angle after correction of varus deformity should not exceed 10°, or edge contact could easily happen.

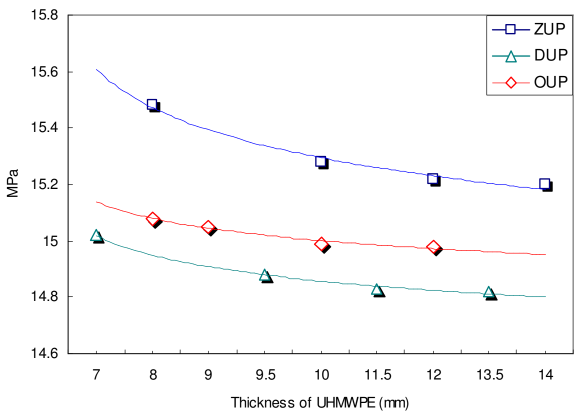

Figure 4. The max. von Mises stress on the PE tibial components of three different UKPs under various thicknesses.

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