Evaluation of Implant Positioning Alignment in Medial Unicompartmental Knee Arthroplasty

Chien-Wei Liu
Department of Orthopaedic Surgery
Changhua Christian Hospital
Taipei, Taiwan

Chen-Tung Yu
Department of Orthopaedic Surgery
Changhua Christian Hospital
Taipei, Taiwan

Wenlung Li
Graduate Institute of Mechanical and Electrical Engineering
National Taipei University of Technology
Taipei, Taiwan

Chia-Chi Lo
Department of Orthopaedic Surgery
Changhua Christian Hospital
Taipei, Taiwan

***Abstract*—Unicompartmental knee arthroplasty (UKA) is a kind of minimally invasive surgery (MIS), which has relatively small scarring, short recovery time, and greater postoperative range of motion. UKA has therefore become the trend of arthroplasty in recent years, and it has been widely accepted by patients with unilateral joint damage. However, there are problems under the surging demands for UKA, such as the selection of patients, knee prostheses and surgical method. Because these factors have great impacts on the surgical outcomes, it is critical to explore the influence of unicompartmental knee prostheses (UKP) in various alignments. This study employs the finite element analysis (FEA) to evaluate the effects of UKP on the polyethylene (PE) components in various implant alignments, and thus provides further information for clinical practices. The results show that UKP has considerable impact upon the wear of the PE tibial components under conditions such as joints overuse, overweight or undercorrection of varus deformity. In addition, this study evaluates the angle after correction of the varus deformity, and results show that the angle should be less than 10°, otherwise the wear of the lateral side of the PE tibial components will increase and thus shorten the expectancy of joint protheses.**

Keywords-varus deformity; implant; alignment; FEA; unicompartmental knee arthroplasty

I. INTRODUCTION

UKA was developed in the early 1970's [1]. According to documents, the outcomes were undesirable at that time due to poor design, inappropriate patient selection and misconception of the surgeons [2,3]. In recent years, however, the surgical outcome of UKA has greatly improved due to the advancement of prostheses design and material, as well as accumulation of surgical experience and appropriate patient selection.

The principle of UKA technique is similar to total knee arthroplasty (TKA); however, they are not exactly the same. UKA preserves the anterior cruciate ligaments (ACL), the posterior cruciate ligaments (PCL), the medial/lateral meniscus and the undamaged joint surfaces while TKA removes all joint surfaces, ACL and PCL (according to the type of prosthesis) regardless of whether they are worn or not and completely reconstructs knee mobility and the surrounding tissue. Because TKA cannot completely restore the range of motion (ROM) of knee joint, UKA is superior with its more comprehensive ROM restoration [4,5]. However, the accuracy of UKA implantation is very critical for the balance of knee joint ligaments and the surrounding soft tissue.

Because UKA is a kind of MIS, it is technically more difficult than TKA and there are more potential problems during the procedure [6], such as internal/external rotation, translation, varus/valgus tilt and tibial malresection. These problems may cause undesired outcomes in stability, mobility, wear and fixation of components. The excellent long-term results of UKA require coordination of multiple factors, including appropriate selection of patient and prostheses, as well as refined surgical techniques. Vardi and Strover [7] analyzed reports of cases that failed within one year after UKA and suggested that inappropriate patient selection and technical errors were the major causes of failure.

Failure cases of UKA also show that the wear of PE components is the most common problem [3,7,8] and it is usually due to inappropriate correction of angle [5,6,9] and posterior tibial slope (PTS) [5,6]: overcorrection may cause wear of opposite tibiofemoral cartilage, while undercorrection may cause wear of PE tibial components. This indicates that the final angle corrected for knee deformity is the crucial factor of a successful UKA. Hernigou and Deschamps [6] further reported that the greater PTS would cause an increasing number of cases requiring secondary replacement due to PE tibial component damage.

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According to literatures, inappropriate the varus tilt angle (VTA) and the PTS are both factors which may cause the tibial component failure or aseptic loosening, either directly or indirectly. To date, however, there is no evidence to support this observation. In this study, we employ the FEA to evaluate the effects of these two factors on UKP, especially the changes of stress on the PE components caused by UKP alignment. Therefore, the major implantation processes that cause the PE component damage can be established.

II. Materials and Methods

There are two common UKP products are chosen as the samples in this investigation. They are respectively from Zimmer unicompartmental knee (ZUK) and Depuy unicompartmental knee (DUK) (Fig. 1). The tibial components are all fixed components.

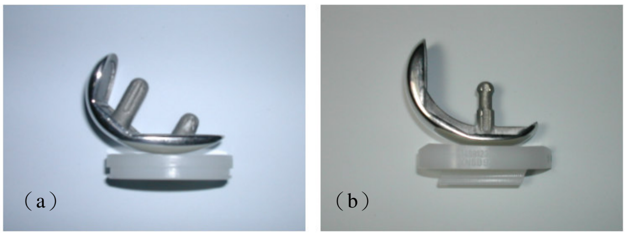

Figure. 1. Unicompartmental knee prostheses system (a) Zimmer and (b) Depuy

The 3D solid models of the femoral and tibial components of ZUK and DUK are established using CAD system before the FEA of UKP, followed by conversion into 3D finite element models using finite element software. The femoral components are made of Co-Cr alloy and the tibial components are made of ultra high molecular weight polyethylene (UHMWPE). The material properties of each component are listed below: for Co-Cr alloy, the Young's modulus is 220 GPa and the Poisson's ratio is 0.3; for UHMWPE, the Young's modulus and the yield strength are 500 MPa and 14.4 MPa, while the Poisson's ratio is 0.4 [10,11]. Both materials are assumed to be isotropic and homogeneous.

In UKP, the implanting angle of tibial component is based on the angle of posterior slope, which is produced by surgical excision of tibial plateau. According to documents, the angle of tibial plateau ranges from 5° to 10° [5], so we simulate the posterior slope as 5° and 10° . In addition, femoral components are simulated as the postoperative varus deformity with the angle 0° , 5° , 10° and 15° after correction. The postoperative effects of PTS and VTA on tibial components will be evaluated from both coronal plane and sagittal plane of these 8 models.

The commercial package COSMOS (COSMOSWorks, SolidWorks, Co., US) is the finite element analysis software used in our study, with tetrahedral solid elements as the element type. After processing by mesh, ZUK model has 10,918 elements and 16,732 nodes, while DUK model has 10,186 elements and 15,522 nodes. The contact surface of the PE tibial component is defined as "source" and the contact surface of the femoral component is defined as "target". During simulation, the original alignment baseline between the tibial and femoral component is defined as follows: the lowest point of contact surface of the tibial component is defined as the neutral position; the neutral axis of femoral component's coronal plane will be parallel to it's mechanical axis (MA) and MA will be perpendicular to the joint line (JL) with the bottom surface of femoral component parallel to JL.

Regarding the boundary and loading conditions in our study, the femoral component is defined as "fixed", and the relative displacement of the PE tibial component provides the required contact force (loading). The simulated loading conditions are defined as the maximal loading on tibiofemoral joint while walking with knee flexion 0° [12-14], which is approximately 2895 N or 4 times the body weight for a person of 74 kg [15,16]. The assumed loading in this study is thus 2895 N. In addition, our study analyzes unilateral condyle and assumes that the loading is equally distributed over the medial / lateral condyle. Therefore the force over unilateral condyle is only half of the total loading. Friction and relative displacement are ignored in all models.

III. Results

Under the same gait loading in UKP, the changes of the maximal von Mises stress and the maximal contact stress on the PE tibial components of ZUK and DUK in response to various PTS and VTA are analyzed by finite element analysis and are shown in Figs. 2 , and 3.

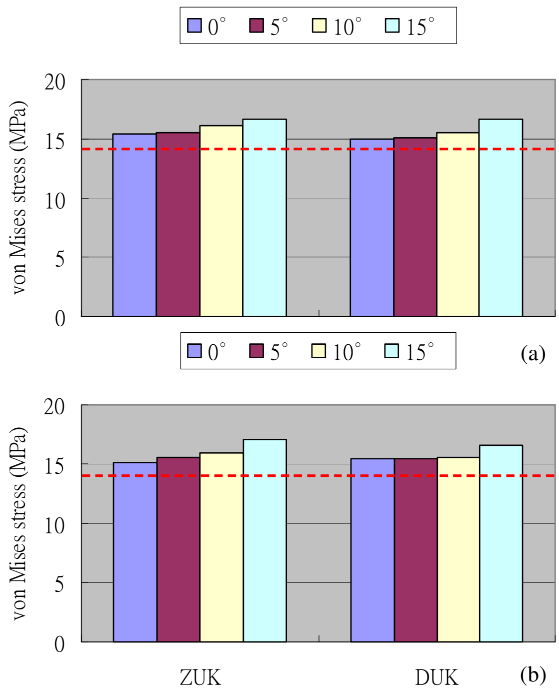

Figure 2. The max. von Mises stress in the PE tibial components of the two designs under the different varus tilt conditions for: (a) 5° and (b) 10° posterior tibial slopes.

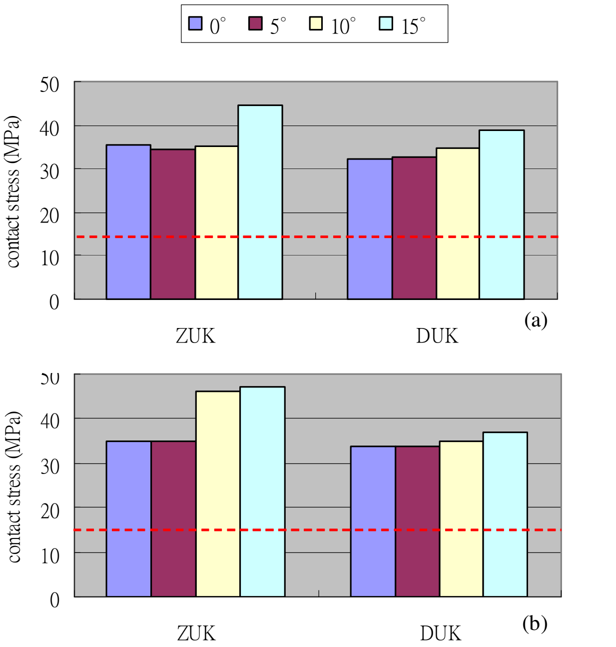

Figure 3. The max. contact stress on the PE tibial components of the two designs under the different varus tilt conditions for : (a) 5° and (b) 10° posterior tibial slopes.

Fig. 2 reveals that under the same PTS, both brands' the von Mises stress increases slightly with increasing VTA, and the effect of PTS is not significant. When PTS is 5° or 10°, the increase of the maximal von Mises stress when VTA increases from 0° to 10° is as follows: 4 % (PTS 5°) and 5.78 % (PTS 10°) in ZUK; 3.8 % (PTS 5°) and 1.17 % (PTS 10°) in DUK. The rate of increase in stress is still mild. When VTA increases from 0° to 15°, the increase of the maximal von Mises stress is as follows: 8.2 % (PTS 5°) and 13.3 % (PTS 10°) in ZUK; 11.3 % (PTS 5°) and 7.3 % (PTS 10°) in DUK. The above results reveal that when PTS is 5° or 10°, the rate of stress increase when VTA increases from 0° to 15° is more than twice as much as that from 0° to 10°. For both brands, the von Mises stress slightly exceeds the yield strength of the PE tibial components, and the value is higher at a 15° varus tilt.

Fig. 3 reveals that the maximal contact stress generally increases with the increasing VTA, similar to those results in the study of the maximal von Mises stress. When varus tilt increases from 0° to 15°, VTA increases 26.1 % (PTS 5°) and 34.3 % (PTS 10°) in ZUK, while 20.8 % (PTS 5°) and 9.5 % (PTS 10°) in DUK. The maximal contact stress of ZUK is higher than that of DUK, especially when varus tilt is 15°. Furthermore, the contact stress of ZUK is quite sensitive to changes of PTS: there is an interaction between PTS and VTA when PTS is 10° and VTA is 10° or 15°. In other words, VTA should be controlled under 10° when PTS is 10°; otherwise the maximal contact stress will increase significantly. DUK, however, doesn't have the same phenomenon.

We also found that the maximal stress of the PE tibial components shifts laterally with the increasing VTA, suggesting that when VTA exceeds 10° or when it is undercorrected, wear of the lateral side of the PE tibial components is more likely to occur, and thus leads to dislocation of the femoral components. This result is consistent with the revision case presented by Hernigou and Deschamps [17].

In summary, although PTS angle affects the stress of the PE tibial component, the effects of varus tilt is even more significant. Fig. 4 shows that the maximal von Mises stress of the PE tibial component occurs only beneath the contact surface of the tibial component, suggesting that the deformity of the PE tibial component first takes place inside the tibial component from bottom to top and then results in cracks or flakes. Furthermore, our study suggests that the maximal von Mises stress occurs closer to the contact surface of the PE tibial component while the maximal von Mises stress increases. This means the contact surface of the PE tibial component is more likely subjected to stress damage.

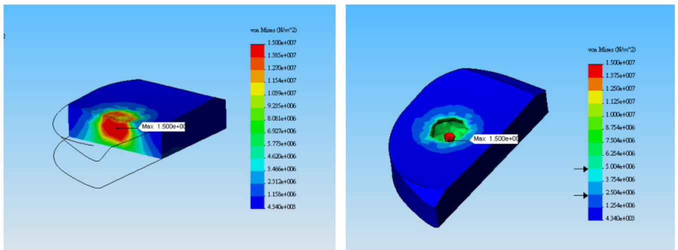

Figure 4. The max. von Mises stresses are located at the center of contact and occur approximately 2 mm beneath the articulating surface.

IV. Discussions

According to the contact stress simulation demonstrated above, although the PE tibial components of DUK and ZUK 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 indentation, wear or tear of the PE components, regardless of the angle corrected for varus deformity. Therefore, accurate correction of varus deformity is as important as patient selection, such as body weight, for a successful surgery: to extend the expectancy of joint implants, avoid damage and dislocation of implant components, and reduce the need for a secondary replacement surgery.

Generally speaking, the maximal von Mises stress and contact stress of the 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 the PE components in UKP; in other words, when the PTS angle gets larger, better conformity can be made between UKP components in order to reduce wear and damage of the PE tibial components. Nevertheless, a large PTS angle still causes increased stress on the PE tibial component. Hernigou and Deschamps [17] have reported that the patient with larger PTS angle has a higher probability of the 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 the PE tibial component will increase. Our study therefore suggests that the PTS angle should be taken into account as a criterion for patient selection.

One other positive point of view, if larger PTS angle has been produced by excision of tibial plateau in UKA, besides the conformity of the PE tibial components and the femoral component, both brands can be corrected by using smaller VTA so as to reduce the problem of high stress and shortened expectancy of the PE tibial components resulting from large postoperative PTS, as summarized in figure 1 and figure 2.

Furthermore, requiring secondary replacement surgery after the initial UKA is mostly due to damage of the opposite tibiofemoral cartilage, which is much more often than overcorrection resulting from wear of the PE tibial components [3]. This suggests that accurate VTA correction during UKA can effectively extend the expectancy of UKP. According to Cartier et al. [18], there are favorable outcomes during postoperative follow-ups in cases with slight undercorrection on the coronal plane of knee joints.

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 the 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 the 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 the 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 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. Besides appropriate patient selection and precise surgical techniques, improvement of PE material, geometric design of implants, and ROM between components should be incorporated to reduce damage of the tibial components.

To date, 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°.

To further enhance the precision of UKA alignment and subsequently reduce the wear of the tibial component caused by alignment errors, applying a navigation-enhanced computer assisted surgery system to increase the success rate of surgery will be the trend of the future [19].

REFERENCES

[1] A.F. David, W. Melanie, and E.D. Kenneth, "Implant position in knee surgery: a comparison of minimally invasive, open unicompartmental, and total knee arthroplasty," J Arthroplasty, vol. 18, 2003, pp. 2-8

[2] I. Richard, L.H.William, "Current concepts review unicompartmental arthritis of the knee," J Bone Joint Surg, vol. 85, 2003, pp. 1351-1364.

[3] J.G. Terence, K.K. Kathleen, P.H. Daniel, M.B. Jack, K.C. Thomas, S. Karen, M. Susan, G. Vardi, and A.E. Strover, "Early complications of unicompartmental knee replacement: the Droitwich experience," The Knee, vol. 11, 2004, pp. 389- 394.

[4] R.C. Eric, R.M. Richard, R.A. Thomas, and G.R. Aaron, "Functional analysis of cemented medial unicompartmental knee arthroplasty," J Arthroplasty, vol. 11, 1996, pp. 553-559.

[5] P. Hernigou and G. Deschamps, "Alignment influences wear in the knee after medial unicompartmental arthroplasty," Clin Orthop Relat Res, vol. 423, 2004, pp.161–165.

[6] P.A. Keblish, "Surgical techniques in the performance of unicompartmental arthroplasties," Operative Tech Orthop, vol.8, 1998, pp. 134-145.

[7] G. Vardi, A.E. Strover, "Early complications of unicompartmental knee replacement : The Droitwich experience," The Knee, vol. 11, 2004, pp. 389-394.

[8] Hans B. Porous-coated anatomic unicompartmental knee arthroplasty in osteoarthritis: a 3- to 9-year follow-up study. J Arthroplasty 1995; 10: 8-13.

[9] R. Iorio and W. Healy, "Current concepts review unicompartmental arthritis of the knee," J Bone Joint Surg, vol. 85, 2003, pp. 1351-1364.

[10] T.Q. Lee, J.E. Budoff, and F.E. Glaser, "Patellar Component Positioning in Total Knee Arthroplasty," Clin Orthop Relat Res, vol. 366, 1999, pp. 274-281.

[11] J.H. Heegaard, P.F. Leyvraz, and C.B. Hovey, "A computer model to simulate patellar biomechanics following total knee replacement: the effects of femoral component alignment," Clin Biomech, vol. 16, 2001, pp. 415-423.

[12] J.B. Morrison, "Function of the knee joint in various activities," Biomed Eng, vol. 4, 1969, pp. 573-580.

[13] J.B. Morrison, "The mechanics of the knee joint in relation to normal walking," J Biomech, vol. 3, 1970, pp. 51-61.

[14] A. Seireg and R.J. Arkivar, "The prediction of the muscular load sharing and joint forces in the lower extremities during walking," J Biomech, vol. 8, 1975, pp. 89-102.

[15] T.P. Andriacchi, G.B.J. Andersson, R.W. Fermier, D. Stern, and J.O. Galante, "A study of lower-limb mechanics during stair-climbing," J Bone Joint Surg, vol. 62, 1980, pp. 749-757.

[16] M.P. Kadaba, H.K. Ramakrishnan, and M.E. Wootten, "Measurement of lower extremity kinematics during level walking," J Orthop Res, vol. 8, 1990, pp. 383-392.

[17] P. Hernigou and G. Deschamps, "Posterior slope of the tibial implant and the outcome of unicompartmental knee arthroplasty," J Bone Joint Surg, vol.86, 2004, pp. 506-511.

[18] P. Cartier, J.L. Sanouiller, and R.R. Grelsamer, "Unicompartmental knee arthroplasty surgery 10-year minimum follow-up period," J Arthroplasty, vol. 11, 1996, pp. 782-788.

[19] M. Marcacci, F. Iacono, S. Zaffagnini, L. Nofrini, M.P. Neri, and A, "Russo Minimally invasive unicompartmental knee arthroplasty in varus knee," Tech Knee Surg, vol. 3, 2004, pp. 259-266.