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Influence of tibiofemoral congruency design on the wear of patient-specific unicompartmental knee arthroplasty using finite element analysis

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Objectives

Unicompartmental knee arthroplasty (UKA) is an alternative to total knee arthroplasty for patients who require treatment of single-compartment osteoarthritis, especially for young patients. To satisfy this requirement, new patient-specific prosthetic designs have been introduced. The patient-specific UKA is designed on the basis of data from preoperative medical images. In general, knee implant design with increased conformity has been developed to provide lower contact stress and reduced wear on the tibial insert compared with flat knee designs. The different tibiofemoral conformity may provide designers the opportunity to address both wear and kinematic design goals simultaneously. The aim of this study was to evaluate wear prediction with respect to tibiofemoral conformity design in patient-specific UKA under gait loading conditions by using a previously validated computational wear method.

Methods

Three designs with different conformities were developed with the same femoral component: a flat design normally used in fixed-bearing UKA, a tibia plateau anatomy mimetic (AM) design, and an increased conforming design. We investigated the kinematics, contact stress, contact area, wear rate, and volumetric wear of the three different tibial insert designs.

Results

Conforming increased design showed a lower contact stress and increased contact area. In addition, increased conformity resulted in a reduction of the wear rate and volumetric wear. However, the increased conformity design showed limited kinematics.

Conclusion

Our results indicated that increased conformity provided improvements in wear but resulted in limited kinematics. Therefore, increased conformity should be avoided in fixed-bearing patient-specific UKA design. We recommend a flat or plateau AM tibial insert design in patient-specific UKA.

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Article focus

■ This current study uses a computational model to study the effect of tibiofemoral conformity on wear prediction in patient-specific unicompartmental knee arthroplasty (UKA).

Key messages

■ This finding indicates that tibiofemoral conformity design plays a more significant role in knee wear reduction.

■ There was a reduction in wear prediction with increasing tibiofemoral conformity in patient-specific UKA.

■ Increasing conformity design showed limited anteroposterior and internal-external kinematics.

Strengths and limitations

■ The computational wear model offers an alternative approach to experimental testing to allow for substantially reduced cost and time.

■ This study did not compare actual clinical wear data.

Introduction

For patients suffering from isolated medial gonarthrosis, unicompartmental knee arthroplasty (UKA) is a successful treatment method providing pain relief, fast recovery, and restoration of function.[1-3] This concept is based on the assumption that a less invasive approach with ligament preservation should lead to a more physiological function of the knee joint.[4] An increased range of movement has been reported after a patient undergoes UKA compared with total knee arthroplasty (TKA).[5-7] However, this is still controversial, and the survival rate of the UKA is inferior to that of TKA.[8,9]

Wear of a polyethylene tibial insert is a main cause of failure in fixed-bearing UKA.[10-12] Factors that influence wear damage include the thickness of the tibial insert, fabrication method of the polyethylene, conformity between the femoral and tibial articulating surfaces, positioning and alignment of the femoral and tibial components, and increased patient activity.[13-15] Reducing wear is a major issue in the longevity improvement of UKA.[16]

An *in vitro* wear simulation is a standard procedure to evaluate wear for different conditions in knee arthroplasty, and alternate materials or different designs have shown different amounts of wear in UKA.[16-18] Such tests are useful for the evaluation of new designs and comparisons of wear performance in different designs. However, the testing of a single design typically costs tens of thousands of dollars and requires several months to complete. Furthermore, for any particular design, the variability of motion and load inputs, as well as the positioning of the components in the machine, can have a considerable influence on the wear volume.[19] However, the computational wear model has offered an alternative approach to experimental testing to allow for substantially reduced cost and time.[20-22]

In general, successful fixed-bearing UKA designs are based on a tibiofemoral articulation with low congruency to provide the individual patient's knee kinematics.[23,24] The characteristics of such a design were also applied to patient-specific UKA. Patient-specific UKA designs offer many theoretical advantages over traditional off-the-shelf UKA designs, such as improving bony coverage on the tibia as well as on the femoral side.[25] However, one of the potential limitations of a patient-specific UKA design is the variability in coronal curvature of the femoral component, which may lead to point loading in flexion when a curved tibial insert used is not well matched with femoral component conformity.[26,27] To address this problem, a flat polyethylene tibial insert is paired with a constant coronal curvature femoral component, which ensures constant loading conditions over a large area irrespective of flexion angle.[26,27] However, the comparatively low bearing congruency leads to high surface and subsurface
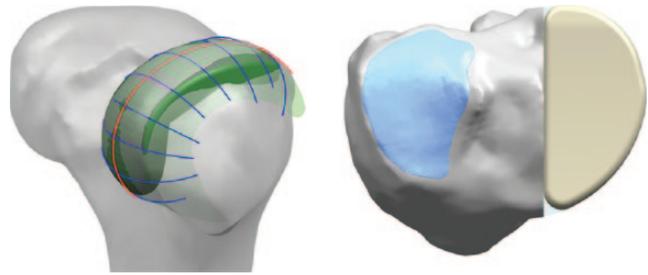
Development of the patient-specific unicompartmental knee arthroplasty (UKA) model based on using the patient's CT and MRI images: a) femoral component; b) tibial component.

stress concentrations in the polyethylene surfaces and increases the risk of abrasive wear, delamination, and structural fatigue failure.[17]

The purpose of this study was to evaluate the effects of varying the tibiofemoral conformity on tibial insert wear prediction using a validated computational method. Three different tibial insert designs were evaluated in a computational simulation under gait loading conditions. We investigated the kinematics, contact stress, contact area, wear rate, and volumetric wear. We hypothesized that an anatomy mimetic (AM) tibial insert design up to the tibial plateau showed the best wear performance.

Materials and Methods

Design procedure for patient-specific UKA. An existing 3D knee joint model was used to develop a patient-specific UKA model.[28,29] Anatomical modelling was based on using CT and MRI images to reconstruct the 3D model of the knee joint, which could guarantee the customized properties. The image data were imported into Mimics version 14.1 (Materialise, Leuven, Belgium) for editing and 3D reconstruction. Planes were introduced through the intersection of condyles in both the sagittal and coronal views. Intersection curves were used to extract the articulating surface geometry in both planes, which were imported into Unigraphics NX (Version 7.0; Siemens PLM Software, Torrance, California) and fitted with rational B-splines (Fig. 1).[29-31]

The patient's bone defines the sagittal geometry of the femoral component. Thus, the sagittal geometry is completely patient-specific, and the resultant sagittal implant radii vary along the anteroposterior (AP) dimension of the implant.[26,27,29-31] The coronal curvatures of the patient were measured at multiple positions along the length of the femoral condyle. A mean curvature was then derived for each patient. Using this approach, a patient-derived constant coronal curvature was achieved (Fig. 1). The tibial component was designed based on the CT and MRI data of the patient's tibia to ensure complete cortical rim coverage. In this method, the patient receives an implant with an optimized fit. Because the
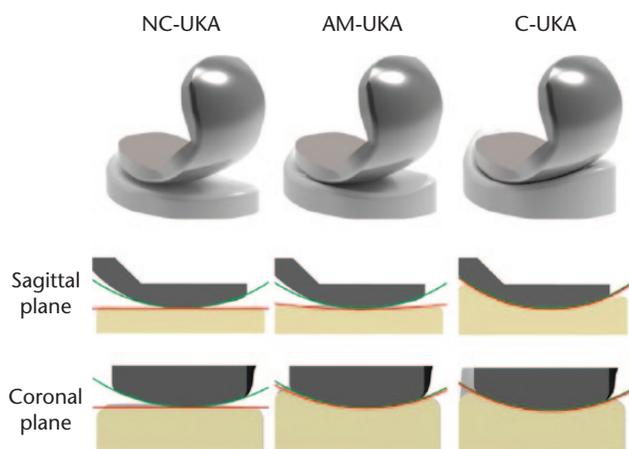
NC-UKA   AM-UKA   C-UKA

Sagittal plane

Coronal plane

Fig. 2

3D model and cross section of the three different tibial inserts: nonconforming (NC) unicompartmental knee arthroplasty (UKA), anatomy mimetic (AM)-UKA, and conforming (C)-UKA.
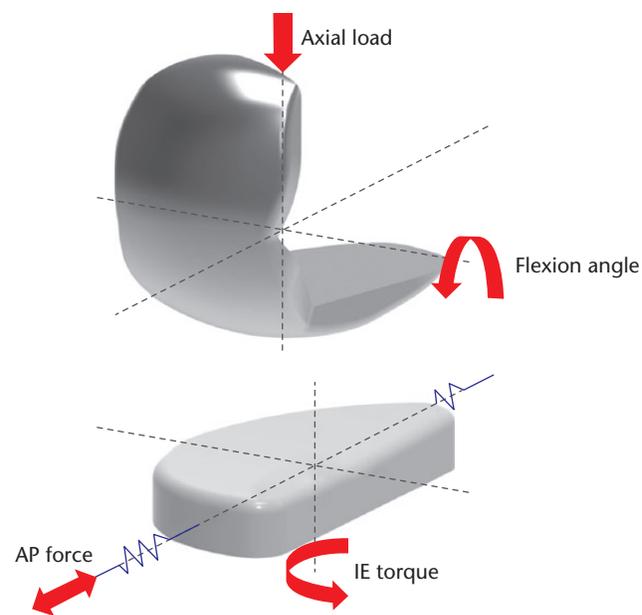

Axial load

Flexion angle

AP force

IE torque

Fig. 3

Wear prediction finite element (FE) model of unicompartmental knee arthroplasty (UKA) and loading condition used in this study. AP, anteroposterior; IE, internal-external.

implant is patient-specific, it provides the potential for complete cortical rim coverage that cannot be achieved with a conventional implant.[32]

We designed three different tibial insert conformities (Fig. 2). In general, a flat design is used for a tibial insert in fixed-bearing UKA,[23,24] which is similar to patient-specific fixed-bearing UKA. In addition, patient-specific designs have variability in the coronal curvature of the femoral component, leading to point loading in select flexion angles when a curved tibial insert is used.[26,29] To address this problem, a flat tibial insert is paired with a constant coronal curvature femoral component, which provides constant loading conditions over a large area irrespective of the flexion angle.[26,29] We therefore developed tibial insert conformity in nonconforming patient-specific UKA as the initial design. For the second design, the real medial geometry was measured, and a medial AM patient-specific UKA was developed. This implant is used in patient-specific UKA and can be applied with various tibial insert designs. For the third design (increased conformity in conforming patient-specific UKA), tibiofemoral conformity between femoral component and tibial insert were perfectly matched. As the femoral component designs were all the same in patient-specific UKA, we could evaluate the effect of tibial insert conformity corresponding to the femoral component.

Computational wear simulation of three different conformity tibial insert designs. An existing wear prediction finite element (FE) method was used in this study.[22,33] We analyzed the wear of patient-specific UKA according to tibiofemoral conformity. These included three patient-specific designs: nonconforming (NC)-UKA, AM-UKA, and conforming (C)-UKA. The cobalt chromium molybdenum femoral and tibial components were modelled as a rigid surface. The tibial insert was modelled as an elastic-plastic material with a modulus of elasticity.[33] The

material of the tibia insert was conventional ultra-high-molecular-weight polyethylene (UHMWPE). Linear hexahedral elements were used to model the tibial insert. A penalty-based contact condition was specified at the femoral component and tibial insert interface with a friction coefficient of 0.04.[33] Solid modelling and meshing were performed by using Hypermesh 11.0 (Altair Engineering, Inc., Troy, Michigan), and analysis and post-processing were performed by using Abaqus 6.13 (Simulia, Providence, Rhode Island).

A convergence test was performed for the optimum mesh density in the tibial insert. Convergence of the analytical solutions for the measurements of the maximum contact stresses within 5% was achieved with a mesh density using elements with a mean edge length of 1.2 mm (0.8 to 1.6). Based on a convergence study, the mesh density used for the tibial insert was appropriate.[34,35] The loading and kinematic conditions in the experimental knee simulator studies were used in the FE simulation, and the force was controlled.[17,36] The kinematics, contact mechanics, and wear performance were evaluated using a computational model based on a Stanmore knee simulator.[17,22,33,36] These experiments typically feature springs to represent soft-tissue constraints that are normally present at the knee. In order to include these effects, a translational spring with a stiffness of 30 N/mm against the AP relative motion of the components was included, as well as a torsional spring with a stiffness of 0.6 Nm/° against the internal-external (IE) relative rotation of the components (Fig. 3). The following test parameters were employed: a maximum load of 2600 N, flexion angle of
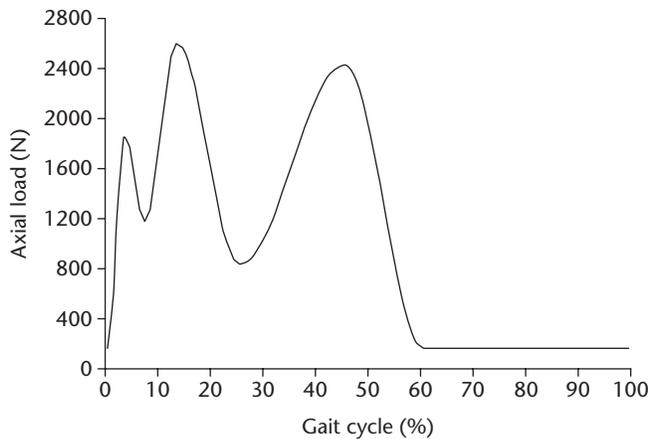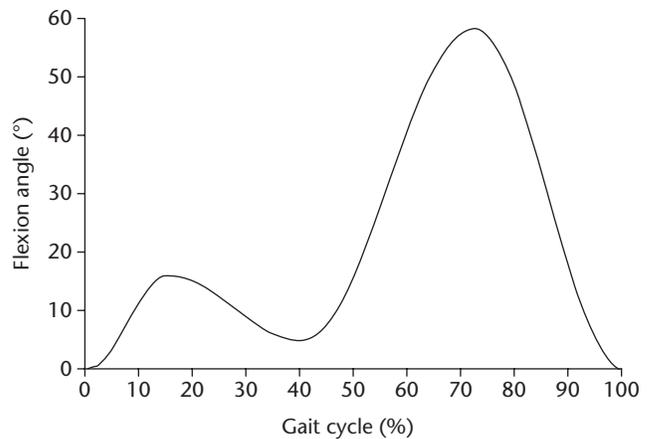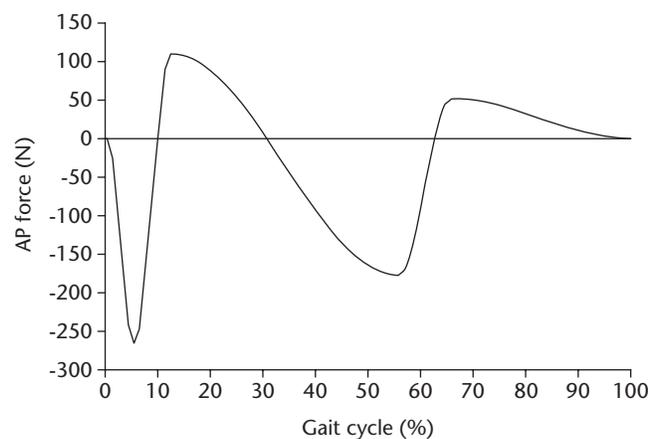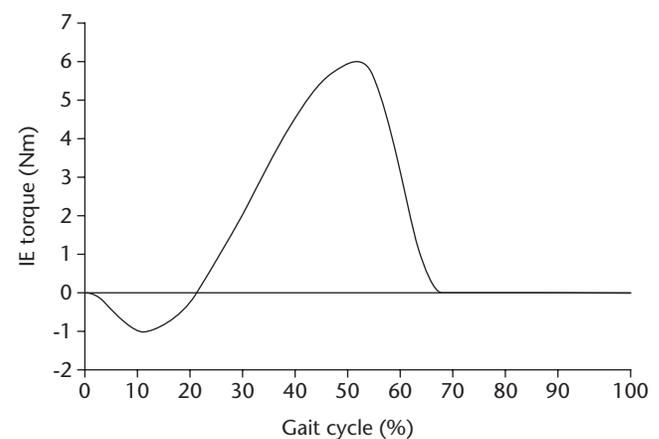
Input function for finite element (FE) model based on the ISO gait cycle: a) axial load; b) flexion angle; c) anteroposterior (AP) force; and d) internal-external (IE) torque.

0° to 58°, AP force of -265 N to 110 N, and IE rotational torque of -1 to 6 Nm (Fig. 4). The femoral component and tibial insert were used under testing conditions wherein the input profiles of an AP load and IE torque were applied to the insert, and a flexion-extension angle and axial force were applied to the femoral component. The axial load, AP translation, and IE rotation were force controlled, and the flexion was displacement controlled. The femoral component was constrained in IE, mediolateral (ML), and AP directions. It was free to translate in the inferior-superior (IS) direction and to rotate about the frontal and transverse axes to represent varus-valgus (VV) rotation and flexion extension, respectively. The tibial insert was allowed to translate in the AP direction and rotate about a fixed vertical axis located in the centre of the tibial condyles to simulate the IE rotation. The distal surface of the tibial insert was supported in the IS direction, the tibial insert tilt was constrained, and the VV and ML degrees of freedom were unconstrained.

Wear prediction of three different conformity tibial insert designs. There is currently no analytical model that can accurately predict wear. However, a modified version of Archard's wear model, which states that wear is a function of contact pressure, contact area, sliding distance, and a wear coefficient k, is known to be able to predict wear with reasonable accuracy if a proper value of k is found experimentally.[37-40] The modified Archard's wear model states that:

$$W_{vol} = \iint k\sigma \, ds \, dA$$

This is where W_{vol} is the volumetric wear, k is the wear coefficient, σ is the contact pressure, s is the sliding distance, and A is the contact area. Each cycle was divided into 100 increments, and wear was computed for each increment and summed during the cycle. The surface nodes influenced by wear were moved in a direction normal to the articular surface based on the computed material loss at the end of each increment. An adaptive remeshing procedure was introduced to simulate the surface wear progression.

An adaptive wear simulation was carried out using Python scripts (Stichting Mathematisch Centrum, Amsterdam, The Netherlands) to interface with the
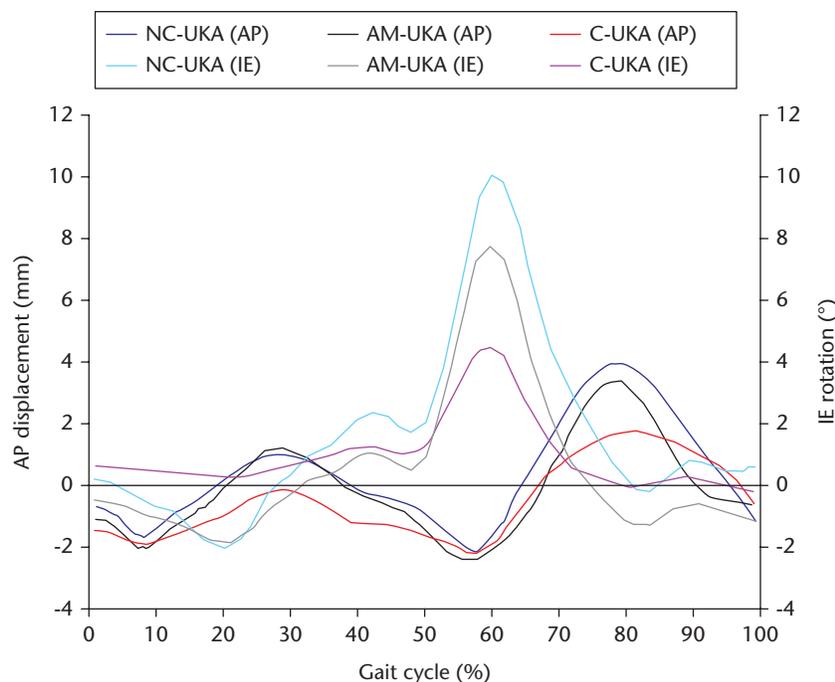
Fig. 5

Kinematic ranges of anteroposterior (AP) displacement and internal-external (IE) rotation for the three different tibial insert designs under the gait cycle over five million cycles. NC, nonconforming; AM, anatomy mimetic; C, conforming; UKA, unicompartmental knee arthroplasty.

Abaqus output database. The model for the wear calculation of the tibial insert was incorporated into the user subroutine VFRICTION, which was developed using FORTRAN code. The simulation was iterated, and the wear was multiplied by the size of each step (50 000 cycles per step) to evaluate the total wear during five million cycles. This update interval was shorter than those used in previous FE analysis studies on TKA wear.[20,41] The computed volumetric wear was converted to gravimetric wear by using a polyethylene density of 0.93 mm³/mg. The wear factor used in this study was estimated using a mean of wear factors from TKA and ball-on-flat wear tests in a previous study.[42]

We evaluated the wear performances of three different UKA tibial insert designs. Additionally, the AP and IE kinematics, contact stress, contact area, wear rate, and volumetric wear were compared between the three different UKA tibial insert designs. Kinematic evaluates of tibial component AP displacement and IE rotation with respect to a fixed femoral component flexion were calculated, in order to investigate the effect of tibial insert design. The AP translation of the tibiofibular (TF) joint was calculated based on the definition of the joint coordinate system by Grood and Suntay.[43]

Results

The gait cycle loading data were applied to each tibial insert design UKA in a FE simulation, and the resultant kinematics and contact mechanics were computed. Figure 5 shows the AP and IE kinematics for the three different tibial insert designs of UKA. During the wear simulation, the kinematic ranges of AP displacement and IE rotation decreased for the three different tibial insert designs over five million cycles. The AP kinematics and IE rotation of the NC-UKA varied between -2.2 mm and 4.0 mm, and -2.0° and 10.0°, respectively, while those of the AM-UKA varied between -2.4 mm and 3.4 mm, and -1.8° and 7.8°, respectively. However, the C-UKA showed a lower variability of -2.2 mm to 1.7 mm in AP kinematics, and -0.1° to 4.4° in IE rotation.

Figure 6 shows the contact stress and contact area in the three different tibial insert designs of UKA during a gait cycle. The contact stress increased and decreased during the stance and swing phases, respectively, in all three different tibial insert designs. The contact stress was greatest in the NC-UKA, followed by the AM-UKA and C-UKA. As expected, the opposite trend was found in the contact area. The UKA design with low contact stress showed a high contact area during the gait cycle.

The C-UKA showed the lowest wear rate and volumetric wear. By contrast, the NC-UKA showed the highest wear rate and volumetric wear. The predicted wear rates were 9.2 mm³/million, 6.8 mm³/million, and 4.3 mm³/million for NC-UKA, AM-UKA, and C-UKA, respectively (Table I). The predicted volumetric wear values were 42.7 mg, 31.6 mg, and 19.9 mg for NC-UKA, AM-UKA, and C-UKA, respectively, after five million cycles (Table I). The computationally predicted wear contour for the different tibial insert designs under gait cycle loading is shown in Figure 7. Decreasing the conformity by changing the
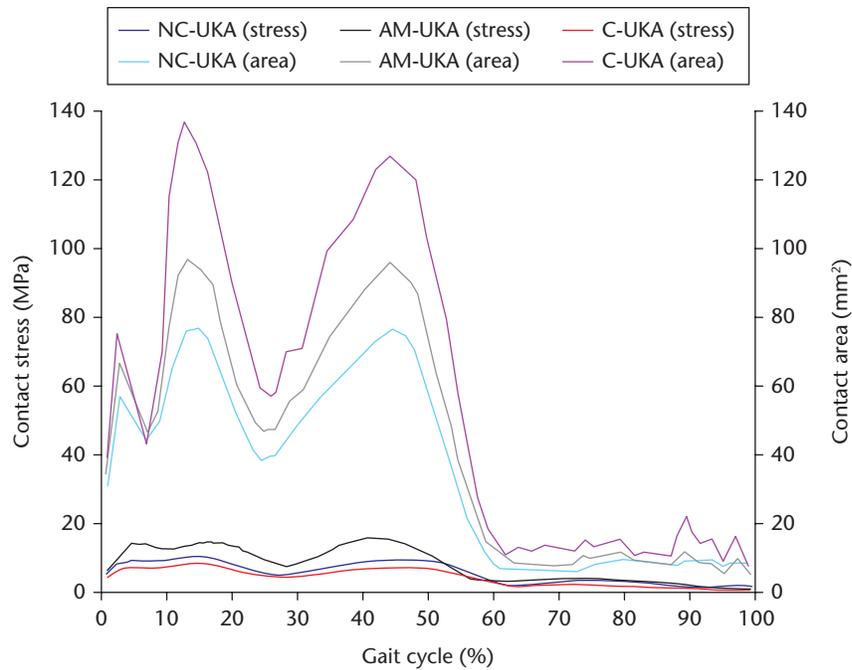
Fig. 6

Comparison of the contact stress and contact area for the three different tibial insert designs under the gait cycle over five million cycles. NC, nonconforming; AM, anatomy mimetic; C, conforming; UKA, unicompartmental knee arthroplasty.

Table I. Comparison of the wear rate and volumetric wear according to the three different unicompartmental knee arthroplasty (UKA) tibial insert designs

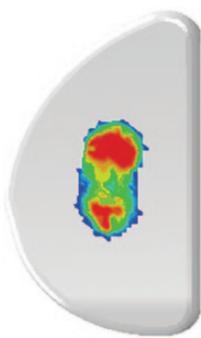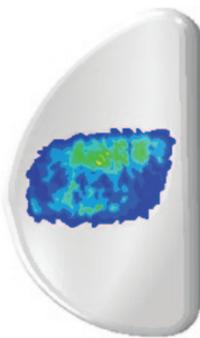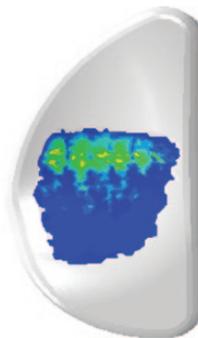| Measurement	Nonconforming UKA	Anatomy mimetic UKA	Conforming UKA
Wear rate, mm³/million	9.2	6.8	4.3
Volumetric wear, mg	42.7	31.6	19.9

Fig. 7a   Fig. 7b   Fig. 7c

Predicted wear contour of the three different tibial insert designs under gait cycle loading: a) nonconforming unicompartmental knee arthroplasty (UKA); b) anatomy mimetic UKA; and c) conforming UKA.

tibial insert from a curved insert (increased conformity) decreased the wear contour under the gait cycle loading conditions.

Discussion

The most important finding of this study was that C-UKA with increased conformity design decreased the wear rate and volumetric wear. However, we do not recommend increased conformity design in terms of patient-specific UKA because the increased conformity design showed limited AP and IE kinematics. In addition, the study hypothesis was rejected.

Long-term outcome studies for UKA have shown the improvement of survival rates by up to 98% over ten years.[9,44] For appropriate cases, this can provide better physiological function, a better range of movement, and quicker recovery. This is more cost-effective than TKA.[45] Proper selection of patients and implants in order to give the best fit to the resected surface plays an important role in the long-term outcome of UKA.[46]

When performing UKA, the geometry of the tibial component should match the resected surface as closely as possible to provide the best stability and load transfer. Asians tend to have a smaller build and stature compared with their Western counterparts.[47] However, a majority of conventional UKA prostheses are designed to match the build of Caucasians.[44] A patient-specific approach has therefore become popular, but this new technique needs an additional medical image with slices through the hip and ankle.[25] Another disadvantage is its manufacturing time of six weeks.[25] However, Koeck et al[48] showed that patient-specific fixed-bearing UKA can restore the leg axis

reliably to obtain a medial proximal tibial angle of 90°, avoid implant malpositioning, and ensure maximal tibial coverage. In addition, Kang et al[29] showed that patient-specific UKA provided mechanics that were closer to those of a normal knee joint. Therefore, the decreased contact stress on the opposite compartment may reduce the overall risk of progressive osteoarthritis.[29]

All previous patient-specific UKA studies selected the flat tibial insert design.[29,48] In addition, in a native knee, the medial and lateral tibial plateaus have asymmetrical geometries with a slightly dished medial and a convex lateral plateau.[48] The biomechanics of the medial and lateral meniscus are substantially different.[49] The medial meniscus is significantly less mobile than the lateral meniscus because of its attachment to the medial collateral ligament (MCL) and larger insertion areas.[49] Therefore, the medial meniscus contributes more to joint stability than the lateral meniscus, which closely follows the AP excursion of the femur.[49] The dished medial plateau and greater stability of the medial meniscus restricts the AP motion and posterior rollback of the medial femoral condyle.[49] Therefore, various tibial insert conformity designs should be considered in patient-specific UKA design.

Overall, the general trends of the FE results showed good agreement with previously published experimental and computational studies. Although the UKA geometry is different, the contact area had a two-peak shape during the stance phase under a gait cycle in a fixed-bearing condition.[50] In addition, the AP kinematics and IE rotation varied in a range of a few millimetres and a few degrees.[51,52] In general, we believe that low contact stress produced low wear. Therefore, increased congruency is preferable in a joint arthroplasty design since it leads to low contact stress owing to a high-contact area. Small contact areas with high contact stresses generate higher linear penetration than volumetric wear, while large contact areas with low contact stresses can increase volumetric wear with lower linear penetration. This distinction can be important since a tendency toward greater linear penetration is more likely to result in localized damage to the insert (or even wear-through), while a tendency toward greater volumetric wear (with low linear penetration) is more likely to generate a greater volume of wear debris and can result in an osteolytic reaction.

Grupp et al[53] proved that increased congruency in conjunction with decreased surface contact stresses significantly contributes to reducing wear in fixed-bearing knee arthroplasty. In addition, Fregly et al[54] showed that increased sagittal conformity was found to decrease the predicted wear volume in a nonlinear pattern, with reductions gradually diminishing as conformity increased. The researchers suggested that a TKA design aimed at reducing wear should focus on sagittal rather than coronal conformity, and that at least moderate sagittal conformity is desirable in both compartments.[54] However,

recent *in vitro* results showed that the increased conforming design often used in mobile-bearing UKA design showed higher wear than flat NC design.[18,21,36] This trend was found in fixed-bearing TKA.

Abdelgaied et al[55] predicted that wear rates for a curved tibial insert were more than three times those for a flat tibial insert. In addition, Brockett et al[56] proved that reduction in wear occurred when the implant conformity was reduced. This study demonstrated that bearing conformity has a significant impact on the wear performance of a fixed-bearing TKA.[56] These studies showed the opposite results because our results showed reduced wear in conformity design; this difference may be a result of the loading conditions. While Abdelgaied et al[55] and Brockett et al[56] used AP and IE displacement control, this study used force control. In short, movement is different owing to conformity in our study, but movement is always the same in displacement control leading to high wear. However, a displacement control simulation has the advantage of providing a consistent path, displacement, surface velocity, and phasing relative to the femoral flexion and axial load, resulting in a consistent force velocity.[57]

One of the problems with defining motion profiles is the inconsistent motion in patients after TKA.[58] The *in vivo* motion of identical TKA approaches using the same surgical procedure results in different motions in patients. This demonstrates that the interface and external forces are not consistent, and that the interface forces are not dominant.[58] As previously mentioned, a curved design with increased conformity is widely used in mobile bearings.[18,21,36] In addition, recent sensitivity indices demonstrated that femoral and tibial distal radii, femoral and tibial posterior radii, and the femoral frontal radius are the main parameters that simultaneously affect the contact mechanics and kinematics. In other words, our study showed that increased conformity design in C-UKA provided low wear because of kinematic reduction. This finding indicates that implant design plays a more significant role in knee wear reduction. However, kinematics should be considered in designing patient-specific UKA. This is because C-UKA showed limited AP and IE kinematics compared with conventional UKA in knee simulator studies.[51,52,59] UKA performance can be evaluated through different criteria including kinematics, contact mechanics, and functional outcome tribological behaviour.

Clearly, the aforementioned criteria are linked to each other. For example, the underlying contact mechanics and kinematics have an impact on the tribological behaviours that all produce an overall impact on the functional outcome, which in turn impacts the clinical scores.[59] However, each group of the aforementioned performance criteria is most suitable for a special direction of investigation. Therefore, the basic contact mechanics such as contact area and pressure on one side and basic kinematic data such as AP displacement and IE rotation

were chosen as performance criteria in this study. Our results indicate that tibiofemoral articular surface conformity is important to patient-specific fixed-bearing UKA. However, it should be noted that our result was evaluated using only traditional off-the-shelf UKA. Although it was designed with anatomy dished medial plateau, a single patient's anatomy was used to develop a patient-specific fixed-bearing UKA. Future studies using the femoral components of off-the-shelf UKA are necessary in order for results to be directly applicable to traditional off-the-shelf UKA.

In terms of clinical relevance, we recommend an AM or flat tibial insert design for patient-specific fixed-bearing UKA. A flat design can avoid edge loading, but the AM design showed better results in wear reduction and kinematics.

This study is not without limitations. First, our model included a constant wear factor that did not change with respect to the contact stress or with the sliding direction. However, previous studies showed that there was good agreement in wear experiments using contact wear factors. Second, we compared *in vitro* experimental wear and measured the wear in a computational simulation, although we did not compare actual clinical wear data. However, the loading condition in which five million cycles represented a clinical wear situation was not completely realistic and exhibited limited applicability. Third, we only performed simulation for conventional polyethylene. According to a previous study,[55] tibiofemoral conformity and the type of ultra-high-molecular-weight polyethylene, such as conventional or moderately crosslinked, are important factors in wear performance. Fourth, we evaluated wear only in a gait cycle condition. In future research, highly demanding daily activities on a knee-wear simulation are required. These activities include stair ascent, stair descent, chair raising, and deep squatting. However, despite the limitations outlined above, the simulations are also much more time- and cost-efficient than physical wear testing, allowing for a wider variety of design parameters to be investigated than was previously feasible.

This study investigated the influence of tibiofemoral conformity on the computational wear prediction of patient-specific UKA under gait cycle conditions. Our results demonstrate that increased congruency, in conjunction with decreased contact stresses, substantially contributes to wear in patient-specific UKA. However, increased conforming design showed limited activity in AP kinematic and IE rotation. Therefore, it should be avoided in fixed-bearing patient-specific UKA design. We recommend a flat or AM tibial insert design in patient-specific UKA.

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