BJR

KNEE

Computational wear prediction of insert conformity and material on mobile-bearing unicompartmental knee arthroplasty

Y-G. Koh,
J-A. Lee,
H-Y. Lee,
H-J. Kim,
K-T. Kang

Yonsei University, Seoul, South Korea

Objectives

Unicompartmental knee arthroplasty (UKA) is an alternative to total knee arthroplasty with isolated medial or lateral compartment osteoarthritis. However, polyethylene wear can significantly reduce the lifespan of UKA. Different bearing designs and materials for UKA have been developed to change the rate of polyethylene wear. Therefore, the objective of this study is to investigate the effect of insert conformity and material on the predicted wear in mobile-bearing UKA using a previously developed computational wear method.

Methods

Two different designs were tested with the same femoral component under identical kinematic input: anatomy mimetic design (AMD) and conforming design inserts with different conformity levels. The insert materials were standard or crosslinked ultra-high-molecular-weight polyethylene (UHMWPE). We evaluated the contact pressure, contact area, wear rate, wear depth, and volumetric wear under gait cycle loading conditions.

Results

Conforming design inserts had the lower contact pressure and larger contact area. However, they also had the higher wear rate and volumetric wear. The improved wear performance was found with AMD inserts. In addition, the computationally predicted volumetric wear of crosslinked UHMWPE inserts was less than half that of standard UHMWPE inserts.

Conclusion

Our results showed that increasing conformity may not be the sole predictor of wear performance; highly crosslinked mobile-bearing polyethylene inserts can also provide improvement in wear performance. These results provide improvements in design and materials to reduce wear in mobile-bearing UKA.

Cite this article: *Bone Joint Res* **2019;8:563–569.**

Keywords: Unicompartmental knee arthroplasty, Wear, UHMWPE

Article focus

- The influence of tibiofemoral conformity and tibial insert material on wear performance in mobile-bearing unicompartmental knee arthroplasty (UKA).

Key messages

- Increased tibiofemoral conformity showed greater wear rate than decreased conformity in mobile-bearing UKA.
- Predicted wear rate was lower in the crosslinked ultra-high-molecular-weight polyethylene (UHMWPE) insert than in the corresponding standard UHMWPE insert.

Strengths and limitations

- This study showed that tibiofemoral conformity and material have a significant impact on the wear performance in mobile-bearing UKA.
- This study did not compare actual clinical wear data.

Introduction

Unicompartmental knee arthroplasty (UKA) has become a popular surgical treatment for patients where only the medial or lateral compartment of the knee is treated.[1] In fact, UKA is a more effective treatment than total

Correspondence should be sent to K-T. Kang; email: tagi1024@gmail.com

doi: 10.1302/2046-3758.811.
BJR-2019-0036.R1

Bone Joint Res 2019;8:563–569.

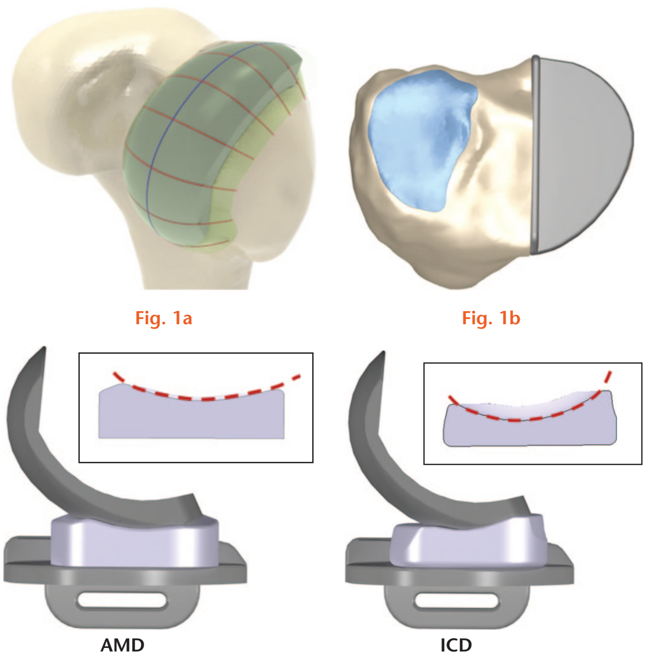

Fig. 1c

Development of unicompartmental knee arthroplasty (UKA) finite element (FE) models based on patient's CT and MRI images: a) femoral component; b) tibial component; and c) anatomy mimetic design (AMD) and increased conformity design (ICD) tibial inserts.

knee arthroplasty (TKA) for more active patients because the mechanics of the knee are better preserved, and more functional anatomy is maintained.[2] The benefits of UKA include fewer complications, faster recovery, improved functional outcomes, and cost-effectiveness.[3-5] However, polyethylene wear is one of the main causes of failure in UKA. Revisions for polyethylene wear occur after a minimum of eight years, but some early catastrophic failures due to wear have been reported.[6,7] Excessive wear in the form of pitting and delamination may disrupt the surface geometry of the replaced plateau, altering joint alignment and stability.[8] The increased deformity from wear leads to increased load at the bone-implant interface and accelerates loosening.[9] Wear in the knee joint is a function of both the implant geometry and materials. More conforming designs have been favoured to reduce contact stress. The reduction of contact stress reduces polyethylene wear since adhesive and abrasive wear are due to the combined effect of contact stress and sliding conditions.[10] In addition, increased conformity has been reported to improve the stability of the implant.[11] However, other studies have reported that it may have little effect on polyethylene wear volume, because the decrease in contact stress is counteracted by an increase in the contact area subjected to sliding.[12,13] Furthermore, increased conformity has potential disadvantages such as increased contact stress if the components are misaligned, increased wear due to easier entrapment of wear particles between the articular surfaces, and increased component interface stresses.[14,15] Designs that conform less can reduce surface wear, provided that the contact stress does not exceed the fatigue limit of the material, in which case fatigue wear mechanisms such as delamination may occur.[16] However, the improvements in stability and mechanical properties also lead to an increase in the fatigue limit.[17] Crosslinking has been introduced to reduce wear of ultra-high-molecular-weight polyethylene (UHMWPE). Many in vitro and in vivo studies have demonstrated the advantages of crosslinked UHMWPE over standard UHMWPE.[18-20] Thus, one of the challenges of UKA design is to determine the conformity and material that strike a balance between these advantages and disadvantages. Testing of UKA designs with different degrees of conformity has been performed by knee simulator machines. However, testing a single design typically costs tens of thousands of dollars and takes several months.[21] For these reasons, recent studies have developed computational models of knee simulator machines to speed up and improve the implant design process.[22-24]

Therefore, the objective of this study is to investigate the effect of insert conformity and material on the predicted wear in mobile-bearing UKA using a previously developed computational wear method. Two different designs, anatomy mimetic design (AMD) and conforming design inserts with different conformity levels, were tested with the same femoral component under identical kinematic input. The insert materials were standard or crosslinked UHMWPE. We evaluated the contact pressure, contact area, wear rate, wear depth, and volumetric wear under gait cycle loading conditions. We hypothesized that increased conformity has advantages and disadvantages in wear in crosslinked UHMWPE.

Materials and Methods

The predicted wear of mobile-bearing UKA was evaluated using two different insert geometries: AMD and increased conformity design (ICD) of tibial inserts (Figure 1). In the natural knee, the medial and lateral tibial plateaus have asymmetrical geometries with a slightly dished medial plateau and a convex lateral plateau.[25,26] The dished medial plateau and greater stability of the medial meniscus restrict anteroposterior (AP) motion and posterior rollback of the medial femoral condyle. In contrast, the convex lateral plateau, combined with lateral meniscus mobility, allows greater range of AP motion with greater posterior rollback of the lateral femoral condyle. We used an existing subject-specific model and developed it further into a slightly dished AMD tibial insert design.[26-28] The wear prediction finite element (FE) method previously developed was used in this study.[26,29,30] A FE model of a Stanmore knee simulator machine was developed in the Abaqus 6.13 (Simulia, Providence, Rhode Island) dynamic simulation environment (Figure 2). The same loading and kinematic conditions used in the experimental studies were used in the computer simulation.

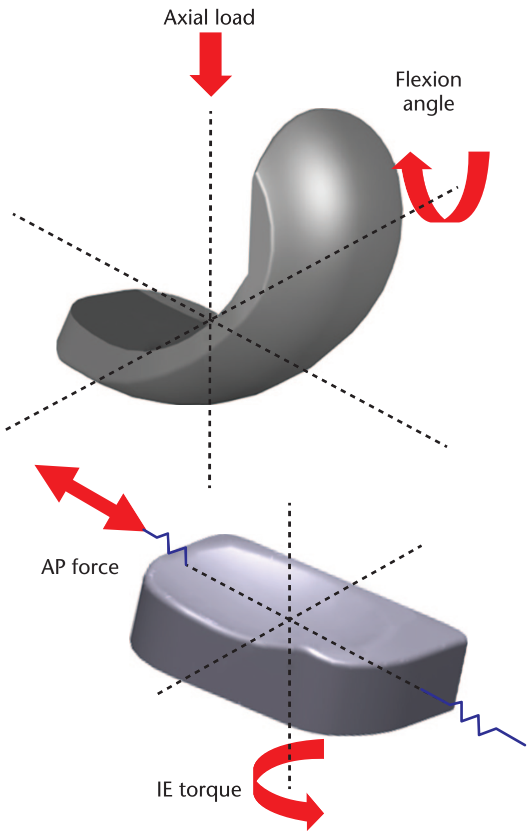

Fig. 2

Loading condition of the unicompartmental knee arthroplasty (UKA) finite element (FE) model for wear prediction in the study. AP, anteroposterior; IE, internal–external.

The axial load was force-controlled, while the flexion, AP translation, and internal–external (IE) rotation were displacement-controlled. The femoral axis loading (peak load of 2.6 kN) and flexion–extension (0° to 58°) input were referred to ISO 14243-3 for all studies (Figure 3).[31] The IE tibial rotation was ± 5° based on the natural kinematics of the knee according to Lafortune et al.[32] This study evaluated mobile-bearing UKA, which relies in vivo on natural tissues, and thus has no intrinsic stability owing to implant geometry.[33] Therefore, displacement-controlled studies were performed to replicate the constraint provided by soft tissue in vivo. A high kinematic condition was used for all studies, with an AP displacement of 0 mm to 10 mm.[34] These experiments typically feature springs to represent soft-tissue constraints that are normally present in the knee. In order to include these effects, a translational spring, with a stiffness of 30 N/mm against the relative AP motion of the components, and a torsional spring, with a stiffness of 0.6 Nm/° against the relative IE rotation of the components, were included (Fig. 3).[35] The standard UHMWPE was modelled with the isotropic elastic–plastic reported by Godest et al[36] with a modulus of elasticity of 463 MPa and Poisson's ratio of 0.46. The crosslinked UHMWPE was modelled using stress-strain data with a modulus of elasticity of 673 MPa and Poisson's ratio of 0.46.[16] Contact was simulated on articular surfaces between the femoral component and insert, and the insert and tibial tray with coefficient of friction of 0.04.[36] A convergence test was performed for the optimum mesh density in the tibial insert. Convergence of the analytical solutions with 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. Based on the convergence study, the mesh density used for the tibial insert was appropriate.[36,37]

Wear prediction of two tibial insert designs with different conformity and two different materials. 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 wear coefficient *k*, is

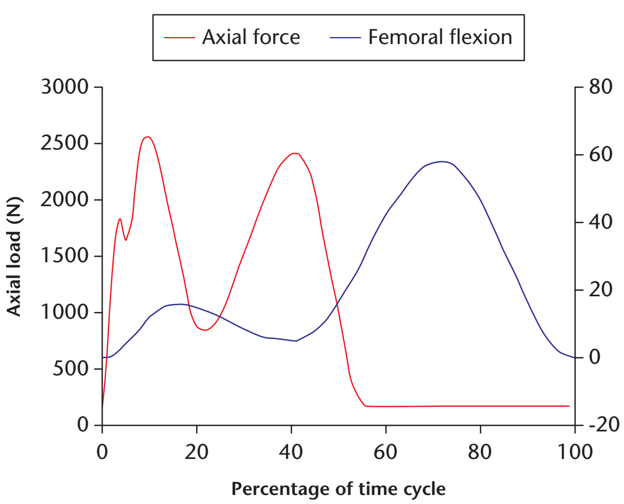

Fig. 3a

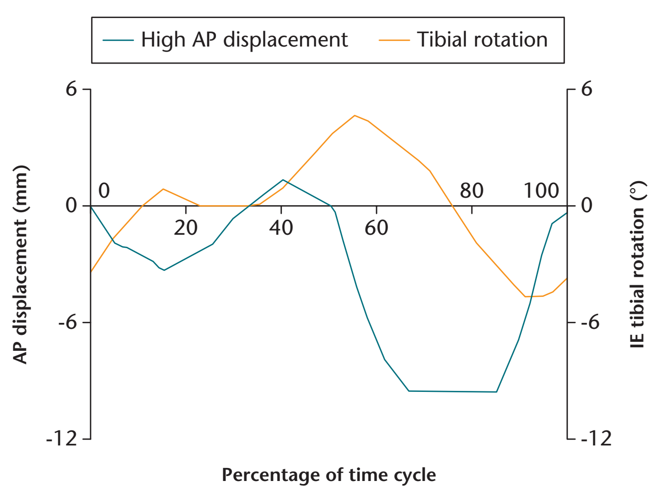

Fig. 3b

Profiles of: a) axial force and femoral flexion inputs; and b) tibial displacement and rotation inputs. AP, anteroposterior; IE, internal–external.

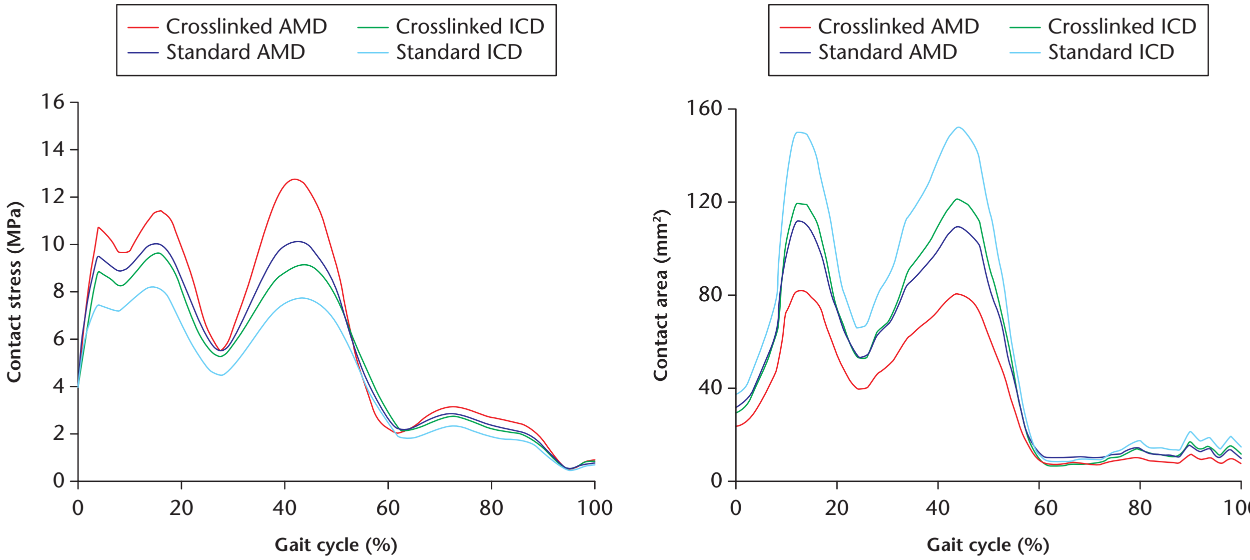

Fig. 4a Fig. 4b

Comparison of a) contact stress and b) contact area for the two different tibial insert designs with two different materials during gait cycle. AMD, anatomy mimetic design; ICD, increased conformity design.

known to be able to predict wear with reasonable accuracy if a proper value of k is found experimentally.[38-41] The modified Archard's wear model states the following, 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:

$$W_{vol} = \iint k\sigma dsdA$$

Each cycle was divided into 100 increments, and wear was computed for each increment and summed up during the cycle. The surface nodes influenced by wear were moved in a direction perpendicular 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. Adaptive wear simulation was carried out using Python scripts (Stichting Mathematisch Centrum, Amsterdam, The Netherlands) to interface with the Abaqus output database. The model for 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 after five million cycles. This update interval was shorter than those used in previous FE analysis studies on TKA wear.[24,42,43] The computed volumetric wear was converted to gravimetric wear using a polyethylene density of 0.93 mm^3/mg. The wear factor used in this study was estimated using the mean wear factors from TKA and balloon-flat wear tests in a previous study.[44]

We evaluated the wear performance of two tibial insert designs and two different materials of mobile-bearing UKA. In addition, the contact stress, contact area, wear rate, wear depth, and volumetric wear were compared for the two tibial insert designs and two different materials of mobile-bearing UKA.

Results

Figure 4 shows the contact stress and area for the two tibial insert designs and two different materials under gait cycle loading conditions. The ICD UKA had a larger contact area than the AMD UKA. Contrasting trends were observed for contact stress. The ICD UKA had a lower contact stress than the AMD UKA. Both contact area and stress were large in the stance phase. Crosslinked UHMWPE showed greater contact stress and smaller contact area than standard UHMWPE regardless of insert design (Figure 4). The standard UHMWPE computational wear rates for the AMD and ICD inserts were 8.3 mm^3/million cycles and 10.9 mm^3/million cycles, respectively. The corresponding predicted values for the crosslinked UHMWPE inserts were 4.1 mm^3/million cycles and 5.3 mm^3/million cycles, respectively. The standard UHMWPE computational volumetric wear for the AMD and ICD inserts were 38.9 mg and 50.6 mg, respectively, after five million cycles. The corresponding predicted values for crosslinked UHMWPE inserts were 19.0 mg and 24.6 mg, respectively, after five million cycles. The maximum wear depths in the standard UHMWPE insert corresponded to 0.14 mm and 0.17 mm in AMD and ICD, respectively, after five million cycles. In addition, the maximum wear depths in the crosslinked UHMWPE insert corresponded to 0.06 mm and 0.09 mm in AMD and ICD, respectively, after five million cycles. The computationally predicted wear contours for different inserts with standard and crosslinked UHMWPE materials under gait cycle loading

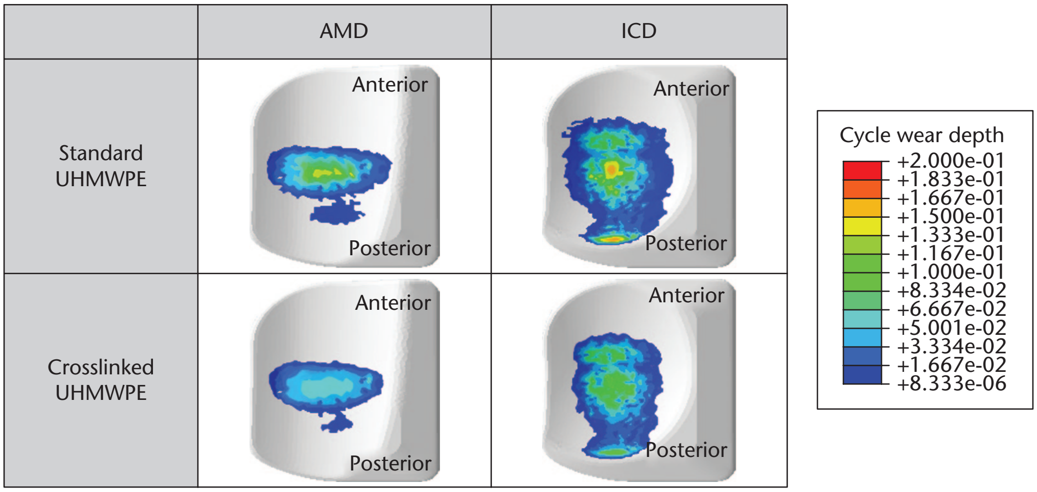

Fig. 5

Predicted wear contour for the two different tibial insert designs with two different materials during gait cycle. AMD, anatomy mimetic design; ICD, increased conformity design; UHMWPE, ultra-high-molecular-weight polyethylene.

conditions are shown in Figure 5. For AMD UKA, by changing the tibial insert from an ICD (decreased conformity), the conformity decreased the wear contour under gait cycle loading conditions. The same trend was observed in standard UHMWPE with changes in crosslinked UHMWPE material.

Discussion

The most important finding of this study is that increased conformity and material are the important factors influencing wear in mobile-bearing UKA. We found that ICD UKA with increased conformity has a worse wear performance than AMD UKA with decreased conformity. In addition, crosslinked UHMWPE has a better wear performance than standard UHMWPE. Our results suggest that the enhanced mechanical properties of polyethylene through advanced manufacturing and sterilization processes enable the consideration of lower-conformity implants with higher contact pressure to reduce surface wear.[45] The computer model made it possible to isolate the effects of crosslinking from the mobile-bearing UKA. We evaluated the wear rates and volumetric wear for two different designs using the material properties and wear factors obtained for low and highly crosslinked polyethylene. In general, the wear behaviour of UKA is influenced by a number of parameters, including articular bearing design, contact stresses, kinematics, implant material, and surface finish.[46] The ICD UKA is highly conforming and has an increased contact area and reduced contact stress. Increased contact stress and reduced contact area were found to reduce polyethylene wear not only in simple configuration laboratory testing but also in total hip arthroplasty and TKA designs.[47-49] Although motion decouplement was shown to reduce wear for highly conforming designs, this study confirmed that the positive effects of a reduced contact area are more dominant in the predicted wear rates of non-conforming UKA than the potentially negative effects of only femoral interface motion.

Overall, the general trends of FE results compare favourably with the previously published computational literature for the mobile-bearing UKA.[50,51] Over the last two decades, the design of knee arthroplasty devices has focused on increased conformity in order to maximize contact areas, reduce contact stress at the articulating interface, and prevent fatigue-related polyethylene failure.[52] The availability of stabilized, oxidation- and fatigue-resistant polyethylene now provides the opportunity for less-conforming designs with the potential to reduce device wear by reducing contact areas.[49] The results of this study clearly demonstrate that significant reductions in polyethylene wear are achievable with low-conformity devices. Such a trend was shown in recent studies.[16,53] Abdelgaied et al[16] showed that a potential method for increasing the lifespan of a TKA can be to introduce less-conforming knee arthroplasties using computational studies. Brockett et al[53] showed that under in vitro kinematic conditions, decreasing conformity significantly reduced wear rate, and this was demonstrated more clearly when combined with previously reported data under comparable conditions. There is a current deficiency in the knee arthroplasty market for devices with low-conformity geometries. However, it is the authors' view that orthopaedic device manufacturers should consider low conformity in order to reduce insert wear and osteolytic potential, and, ultimately, to provide longevity in partial knee arthroplasty when patients have good soft-tissue function. Essner et al[54] indicated that implant design plays a more significant role in knee wear reduction than insert material. However, our results showed that the material is also important. The reduction in wear rate with the change in bearing material is attributed to changes in experimental wear parameters, contact area, and wear factor. The crosslinked UHMWPE experimentally measured wear parameters were lower than those of standard UHMWPE material. In addition, changing the insert bearing material from soft (standard UHMWPE) to hard (crosslinked UHMWPE) reduced the contact area during articulation. According to Archard's law, the contact pressure, contact area, and sliding distance are all important factors. There are two knee simulation strategies: force control and displacement control. In the displacement control strategy, the AP displacement and IE rotation are closed-loop controlled by displacement and closely follow the displacement command profiles.[55] The advantage of displacement control is a consistent path, displacement, surface velocity, and phasing, relative to the femoral rotation (flexion) and axial load, which results in consistent force per velocity.[55] The wear coefficient-based computational wear model is dependent on contact area and wear rate. The directly proportional relationship between volumetric wear and contact area in the current model means that the smaller the contact area, the less wear under controlled kinematic inputs. Increasing the conformity between the femoral component and insert increases the contact radius with higher IE and AP motion. As a result of the improved material properties, and recognizing the importance of wear and the function of contact area, wear can be reduced using less-conforming bearing surfaces because of the reduction in contact area.

In terms of clinical relevance, the AMD UKA showed improved wear performance compared with the ICD UKA. The AMD UKA has dished geometry in the medial tibial plateau so it would reduce the risk of dislocation in mobile-bearing UKA. As previously mentioned, in the native knee, the medial and lateral tibial plateaus have asymmetrical geometries, with a slightly dished medial plateau and a convex lateral plateau.[25,26] Therefore, our results showed that making changes to slightly dished designs could resolve the problem of wear in conforming design in medial mobile-bearing UKA.

The study had three limitations. First, our model included a constant wear factor that did not change with respect to contact stress or sliding direction. However, previous studies showed good agreement in wear experiments using contact wear factors. Second, we compared in vitro experimental wear and measured the wear in a computational simulation, but we did not compare actual clinical wear data. The loading condition in which five million cycles represented a clinical wear situation was not completely realistic and exhibited limited applicability. Since UKA can also be used for younger patients, a greater number of cycles may be required for further study. Third, we evaluated wear only in a gait cycle condition. In future work, highly demanding daily activities for knee wear simulation are required. These activities include stair ascent, stair descent, rising from a chair, and deep squatting. However, despite the limitations outlined above, the simulations are much more time-saving and cost-efficient than physical wear testing, allowing the investigation of a wider variety of design parameters than was previously feasible.

In conclusion, the very low wear rates found with low-conformity design and crosslinked UHMWPE UKA show the potential for reducing conformity in order to reduce knee arthroplasty wear. Increasing conformity may not be the sole predictor of wear performance; highly crosslinked mobile-bearing polyethylene inserts can also provide high wear performance. These results provide improvements in design and materials to reduce wear in mobile-bearing UKA.

References

1. **Berger RA, Meneghini RM, Jacobs JJ, et al.** Results of unicompartmental knee arthroplasty at a minimum of ten years of follow-up. *J Bone Joint Surg [Am]* 2005;87-A:999-1006.
2. **Goodfellow J, O'Connor J, Dodd C, Murray D.** *Unicompartmental arthroplasty with the Oxford knee*. Oxford: Oxford University Press, 2006.
3. **Siman H, Kamath AF, Carrillo N, et al.** Unicompartmental knee arthroplasty vs total knee arthroplasty for medial compartment arthritis in patients older than 75 years: comparable reoperation, revision, and complication rates. *J Arthroplasty* 2017;32:1792-1797.
4. **Liddle AD, Judge A, Pandit H, Murray DW.** Adverse outcomes after total and unicompartmental knee replacement in 101,330 matched patients: a study of data from the National Joint Registry for England and Wales. *Lancet* 2014;384:1437-1445.
5. **Shankar S, Tetreault MW, Jegier BJ, Andersson GB, Della Valle CJ.** A cost comparison of unicompartmental and total knee arthroplasty. *Knee* 2016;23: 1016-1019.
6. **Deshmukh RV, Scott RD.** Unicompartmental knee arthroplasty: long-term results. *Clin Orthop Relat Res* 2001;392:272-278.
7. **Palmer SH, Morrison PJ, Ross AC.** Early catastrophic tibial component wear after unicompartmental knee arthroplasty. *Clin Orthop Relat Res* 1998;350:143-148.
8. **Wright TM.** Polyethylene in knee arthroplasty: what is the future? 2005;440:141-148.
9. **Wright TM, Rimnac CM, Faris PM, Bansal M.** Analysis of surface damage in retrieved carbon fiber-reinforced and plain polyethylene tibial components from posterior stabilized total knee replacements. *J Bone Joint Surg [Am]* 1988;70-A: 1312-1319.
10. **Kuster MS, Stachowiak GW.** Factors affecting polyethylene wear in total knee arthroplasty. *Orthopedics* 2002;25(2 Suppl):s235-s242E.
11. **Luger E, Sathasivam S, Walker PS.** Inherent differences in the laxity and stability between the intact knee and total knee replacements. *Knee* 1997;4:7-14.
12. **Bei Y, Fregly BJ, Sawyer WG, Banks SA, Kim NH.** The relationship between contact pressure, insert thickness, and mild wear in total knee replacements. *CMES* 2004;6:145-152.
13. **Essner A, Klein R, Bushelow M, et al.** The effect of sagittal conformity on knee wear. *J Wear* 2003;255:1085-1092.
14. **D'Lima DD, Chen PC, Colwell CW Jr.** Polyethylene contact stresses, articular congruity, and knee alignment. *J Clin Orthop Relat Res* 2001;392:232-238.
15. **Sathasivam S, Walker PS.** Optimization of the bearing surface geometry of total knees. *J Biomech* 1994;27:255-264.
16. **Abdelgaied A, Brockett CL, Liu F, et al.** The effect of insert conformity and material on total knee replacement wear. *Proc Inst Mech Eng H* 2014;228:98-106.
17. **Fisher J, Jennings LM, Galvin AL, et al.** 2009 Knee society presidential guest lecture: polyethylene wear in total knees. *Clin Orthop Relat Res* 2010;468:12-18.
18. **Kobayashi K, Kakinoki T, Sakamoto M, Tanabe Y.** The effects of strain rate and low-gamma irradiation on the compressive properties of UHMWPE. *Biomed Mater Eng* 2007;17:87-95.
19. **Glyn-Jones S, Isaac S, Hauptfleisch J, et al.** Does highly cross-linked polyethylene wear less than conventional polyethylene in total hip arthroplasty? A double-blind, randomized, and controlled trial using roentgen stereophotogrammetric analysis. *J Arthroplasty* 2008;23:337-343.

20. **Brown TS, Van Citters DW, Berry DJ, Abdel MP.** The use of highly crosslinked polyethylene in total knee arthroplasty. *Bone Joint J* 2017;99-B:996-1002.
21. **Fregly BJ, Marquez-Barrientos C, Banks SA, DesJardins JD.** Increased conformity offers diminishing returns for reducing total knee replacement wear. *J Biomech Eng* 2010;132:021007.
22. **Zhao D, Sakoda H, Sawyer WG, Banks SA, Fregly BJ.** Predicting knee replacement damage in a simulator machine using a computational model with a consistent wear factor. *J Biomech Eng* 2008;130:011004.
23. **Knight LA, Pal S, Coleman JC, et al.** Comparison of long-term numerical and experimental total knee replacement wear during simulated gait loading. *J Biomech* 2007;40:1550-1558.
24. **Zhao D, Sawyer WG, Fregly BJ.** Computational wear prediction of UHMWPE in knee replacements. In: Brown SA, Gilbertson LN, Good VD, eds. *Wear of articulating surfaces: understanding joint simulation.* West Conshohocken: ASTM International, 2006:45-52.
25. **Freeman MA, Pinskerova V.** The movement of the normal tibio-femoral joint. *J Biomech* 2005;38:197-208.
26. **Kang KT, Son J, Kim HJ, et al.** Wear predictions for UHMWPE material with various surface properties used on the femoral component in total knee arthroplasty: a computational simulation study. *J Mater Sci Mater Med* 2017;28:105.
27. **Kang KT, Son J, Suh DS, et al.** Patient-specific medial unicompartmental knee arthroplasty has a greater protective effect on articular cartilage in the lateral compartment: a finite element analysis. *Bone Joint Res* 2018;7:20-27.
28. **Kang KT, Koh YG, Son J, et al.** Finite element analysis of the biomechanical effects of 3 posterolateral corner reconstruction techniques for the knee joint. *Arthroscopy* 2017;33:1537-1550.
29. **Koh YG, Son J, Kwon OR, Kwon SK, Kang KT.** Tibiofemoral conformity variation offers changed kinematics and wear performance of customized posterior-stabilized total knee arthroplasty. *Knee Surg Sports Traumatol Arthrosc* 2019;27:1213-1223.
30. **Koh YG, Park KM, Lee HY, Kang KT.** Influence of tibiofemoral congruency design on the wear of patient-specific unicompartmental knee arthroplasty using finite element analysis. *Bone Joint Res* 2019;8:156-164.
31. **No authors listed.** ISO 14243-3: 2014. Implants for surgery–wear of total knee-joint prostheses–part 3: loading and displacement parameters for wear-testing machines with displacement control and corresponding environmental conditions for test. International Organization for Standardization (ISO), 2014. https://www.iso.org/standard/56649.html (date last accessed 20 September 2019).
32. **Lafortune MA, Cavanagh PR, Sommer HJ III, Kalenak A.** Three-dimensional kinematics of the human knee during walking. *J Biomech* 1992;25:347-357.
33. **Barnett PI, Fisher J, Auger DD, Stone MH, Ingham E.** Comparison of wear in a total knee replacement under different kinematic conditions. *J Mater Sci Mater Med* 2001;12:1039-1042.
34. **McEwen HM, Barnett PI, Bell CJ, et al.** The influence of design, materials and kinematics on the in vitro wear of total knee replacements. *J Biomech* 2005;38:357-365.
35. **Kretzer JP, Jakubowitz E, Reinders J, et al.** Wear analysis of unicondylar mobile bearing and fixed bearing knee systems: a knee simulator study. *Acta Biomater* 2011;7:710-715.
36. **Godest AC, Beaugonin M, Haug E, Taylor M, Gregson PJ.** Simulation of a knee joint replacement during a gait cycle using explicit finite element analysis. *J Biomech* 2002;35:267-275.
37. **Halloran JP, Easley SK, Petrella AJ, Rullkoetter PJ.** Comparison of deformable and elastic foundation finite element simulations for predicting knee replacement mechanics. *J Biomech Eng* 2005;127:813-818.
38. **Archard J, Hirst W.** The wear of metals under unlubricated conditions. *Proc R Soc Lond* 1956;236:397-410.
39. **Marshek K, Chen H.** Discretization pressure-wear theory for bodies in sliding contact. *J Tribol* 1989;111:95-100.
40. **Maxian TA, Brown TD, Pedersen DR, Callaghan JJ.** The Frank Stinchfield Award. 3-dimensional sliding/contact computational simulation of total hip wear. *Clin Orthop Relat Res* 1996;333:41-50.
41. **Hamilton MA.** Development of a computational tool to predict wear in UHMWPE tibial bearings: STLE scholarship award winner. Department of Mechanical and Materials Engineering, University of Florida, 2001. https://blog.xuite.net/aa371010a/twblog/200979045-%E4%BA%BA%E5%B7%A5%E8%86%9D%E9%97%9C%E7%AF%80UHMWPE+Tibial+Bearings%5BArchard+wear+law%3A%3A%E7%A3%A8%E8%80%97%E7%90%86%E8%AB%96%5D (date last accessed 14 November 2019).
42. **Knight LA, Pal S, Coleman JC, et al.** Comparison of long-term numerical and experimental total knee replacement wear during simulated gait loading. *J Biomech* 2007;40:1550-1558.
43. **Abdelgaied A, Liu F, Brockett C, et al.** Computational wear prediction of artificial knee joints based on a new wear law and formulation. *J Biomech* 2011;44:1108-1116.
44. **McGloughlin TM, Murphy DM, Kavanagh AG.** A machine for the preliminary investigation of design features influencing the wear behaviour of knee prostheses. *Proc Inst Mech Eng H* 2004;218:51-62.
45. **Kurtz SM, Muratoglu OK, Evans M, Edidin AA.** Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. *Biomaterials* 1999;20:1659-1688.
46. **Burton A, Williams S, Brockett CL, Fisher J.** In vitro comparison of fixed- and mobile meniscal-bearing unicondylar knee arthroplasties: effect of design, kinematics, and condylar liftoff. *J Arthroplasty* 2012;27:1452-1459.
47. **Barbour PS, Barton DC, Fisher J.** The influence of stress conditions on the wear of UHMWPE for total joint replacements. *J Mater Sci Mater Med* 1997;8:603-611.
48. **Wang A, Essner A, Klein R.** Effect of contact stress on friction and wear of ultra-high molecular weight polyethylene in total hip replacement. *Proc Inst Mech Eng H* 2001;215:133-139.
49. **Galvin AL, Kang L, Udofia I, et al.** Effect of conformity and contact stress on wear in fixed-bearing total knee prostheses. *J Biomech* 2009;42:1898-1902.
50. **Netter J, Hermida J, Flores-Hernandez C, et al.** Prediction of wear in crosslinked polyethylene unicompartmental knee arthroplasty. *Lubricants* 2015;3:381-393.
51. **Netter J, Hermida JC, D'Alessio J, Kester M, D'Lima DD.** Effect of polyethylene crosslinking and bearing design on wear of unicompartmental arthroplasty. *J Arthroplasty* 2015;30:1430-1433.
52. **Kurtz SM.** The clinical performance of UHMWPE in knee replacements. In: Kurtz SM, ed. *UHMWPE biomaterials handbook.* Second ed. Cambridge, Massachusetts: Academic Press, 2009:97-116.
53. **Brockett CL, Carbfigone S, Fisher J, Jennings LM.** Influence of conformity on the wear of total knee replacement: an experimental study. *Proc Inst Mech Eng H* 2018;232:127-134.
54. **Essner A, Herrera L, Hughes P, Kester M.** The influence of material and design on total knee replacement wear. *J Knee Surg* 2011;24:9-17.
55. **Affatato S, Leardini W, Rocchi M, Toni A, Viceconti M.** Investigation on wear of knee prostheses under fixed kinematic conditions. *Artif Organs* 2008;32:13-18.

Author information
- Y-G. Koh, MD, Orthopaedic surgeon, Joint Reconstruction Center, Department of Orthopaedic Surgery, Yonsei Sarang Hospital, Seoul, South Korea.
- J-A. Lee, MS, Senior researcher, Department of Mechanical Engineering, Yonsei University, Seoul, South Korea.
- H-Y. Lee, MS, Senior researcher, Department of Mechanical Engineering, Yonsei University, Seoul, South Korea.
- H-J. Kim, PhD, Professor, Department of Sport and Healthy Aging, Korea National Sport University, Seoul, South Korea.
- K-T. Kang, PhD, Professor, Department of Mechanical Engineering, Yonsei University, Seoul, South Korea.

Author contributions
- Y-G. Koh: Designed the study, Evaluated the results using finite element analysis, Wrote the manuscript.
- J-A. Lee: Developed the 3D model.
- H-Y. Lee: Evaluated the results using finite element analysis.
- H-J. Kim: Evaluated the results using finite element analysis.
- K-T. Kang: Supervised the study, Analyzed the data.
- Y-G. Koh and J-A. Lee contributed equally to this study.

Funding statement
- No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.