UC Davis
UC Davis Previously Published Works

Title
Posterior rim loading of a low-conforming tibial insert in unrestricted kinematic alignment is caused by rotational alignment of an asymmetric baseplate designed for mechanical alignment.

Permalink
https://escholarship.org/uc/item/1bh39703

Journal
Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 31(8)

ISSN
0942-2056

Authors
Hull, Maury L
Nicolet-Petersen, Stephanie
Saiz, Augustine
et al.

Publication Date
2023-08-01

DOI
10.1007/s00167-022-06994-5

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

Knee Surgery, Sports Traumatology, Arthroscopy
https://doi.org/10.1007/s00167-022-06994-5

KNEE

Posterior rim loading of a low-conforming tibial insert in unrestricted kinematic alignment is caused by rotational alignment of an asymmetric baseplate designed for mechanical alignment

Maury L. Hull[1,2,3] · Stephanie Nicolet-Petersen[1] · Augustine Saiz[3] · Connor Delman[3] · Stephen M. Howell[1]

Received: 17 January 2022 / Accepted: 22 April 2022
© The Author(s) under exclusive licence to European Society of Sports Traumatology, Knee Surgery, Arthroscopy (ESSKA) 2022

Abstract

Purpose Because different targets are used for internal–external rotation, an asymmetric baseplate designed for mechanical alignment may lead to under-coverage and concomitant posterior rim loading in the lateral compartment following unrestricted kinematic alignment (KA) TKA. Recognizing that such loading can lead to premature wear and/or subsidence, our aim was to determine the cause(s) so that occurrence could be remedied. Our hypothesis was that baseplate design features such as asymmetric shape when aligned in KA would consistently contribute to posterior rim loading in the lateral compartment.

Methods Based on analysis of fluoroscopic images of 50 patients performing dynamic, weight bearing deep knee bend and step up and of postoperative CT images, five possible causes were investigated. Causes included internal rotation of the baseplate when positioned in KA; posterior position of the lateral femoral condyle at extension; internal tibial rotation with flexion; internal rotational deviation of the baseplate from the KA rotation target; and posterior slope.

Results The incidence of posterior rim loading was 18% (9 of 50 patients). When positioned in KA, the asymmetric baseplate left 15% versus 10% of the AP depth of the lateral compartment uncovered posteriorly for posterior rim loading and non-posterior rim loading groups, respectively ($p = 0.009$). The lateral femoral condyle at extension was more posterior by 4 mm for the posterior rim loading group ($p = 0.003$).

Conclusions Posterior rim loading in the lateral compartment was caused in part by the asymmetric design of the tibial baseplate designed for mechanical alignment which was internally rotated when positioned in KA thus under-covering a substantial percentage of the posterior lateral tibia. This highlights the need for new, asymmetric baseplates designed to maximize coverage when used in KA.

Level of evidence III.

Keywords Total knee replacement · Total knee arthroplasty · Mechanical alignment · Tibiofemoral kinematics

Introduction

An important variable in the design of tibial baseplates is the shape (i.e. footprint) on the resected surface of the tibia. Since increased stress (i.e. patient weight/baseplate area) following TKA has been related to increased migration [4], which can lead to aseptic loosening and eventual revision surgery, the shape of the baseplate should cover maximum area [4, 5]. Recognizing that the tibial plateau is asymmetric, various studies have recommended anatomic baseplate shapes to achieve better coverage [14, 37].

Since rotational alignment of a tibial baseplate simultaneously affects coverage and knee joint function, design of an anatomic (i.e. asymmetric) baseplate should reflect the

✉ Maury L. Hull
mlhull@ucdavis.edu

1 Department of Biomedical Engineering, University of California Davis, Davis, CA 95616, USA

2 Department of Mechanical Engineering, University of California Davis, Davis, CA 95616, USA

3 Department of Orthopaedic Surgery, University of California Davis Medical Center, Sacramento, CA 95817, USA

Published online: 31 May 2022

intended alignment target in TKA. Two methods which differ in their targets for rotational alignment are mechanical alignment (MA) and kinematic alignment (KA). Mechanical alignment strives to align the anterior–posterior (AP) axis of the tibial baseplate perpendicular to the transepicondylar axis [18] whereas KA strives to align the AP axis parallel to the flexion–extension (FE) plane of the knee [16]. To achieve the desired rotational alignment in MA, a common alignment target is the medial third of the tibial tubercle [7, 33]. To achieve the desired alignment target in KA, templates have been developed [29] which generally position the AP axis more medial than MA. Thus, rotationally aligning an asymmetric baseplate designed for MA but used in KA requires internally rotating the baseplate relative to the alignment target in MA which may undercover the posterior lateral tibia (Fig. 1).

Under coverage of the posterior lateral tibia can lead to posterior rim loading on the tibial insert which is a concerning event (Fig. 2). Reported adverse consequences are early wear and/or fracture of the insert [13] and posterior subsidence caused by high repeated localized loading leading to eventual aseptic loosening [12, 27] (Fig. 3). For either consequence, costly revision surgery would be warranted. A previous study using asymmetric, fixed bearing, posterior cruciate-retaining (PCR), low-conforming components in unrestricted kinematically aligned (KA) TKA reported an incidence of posterior rim loading in the lateral compartment of 16% (4 of 25 patients) [26]. Hence, it is of interest to determine the causes of posterior rim loading so that remedial measures can be taken as appropriate.

In addition to internal rotation of the asymmetric tibial baseplate when positioned in KA, four other possible contributing causes of posterior rim loading in the lateral compartment include (1) posterior position of the lateral femoral condyle at extension, which could predispose the joint to posterior rim loading with internal rotation of the tibia during flexion, (2) internal tibial rotation with flexion, (3) internal rotational deviation of the tibial baseplate

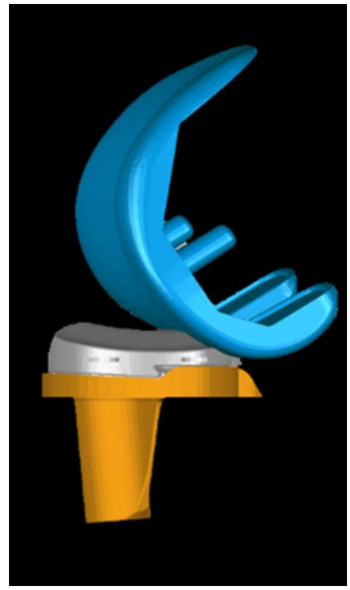

Fig. 2 Example of posterior rim loading in the lateral compartment of a left knee at 60° of flexion during a dynamic, weight bearing deep knee bend after unrestricted KA TKA. Posterior rim loading develops when the lateral femoral condyle is sufficiently posterior on the tibial insert such that the location of tibial contact is on the posterior rim of a concavity forming the articular surface of a compartment in the insert. The relative 3D position and orientation of the components were determined using single-plane fluoroscopy followed by 3D model-to-2D image registration

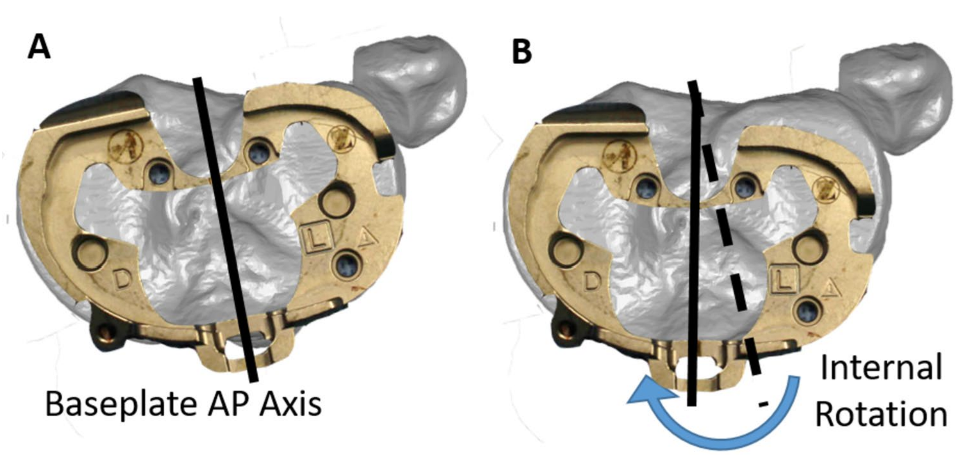

Fig. 1 Images showing an asymmetric tibial baseplate in mechanical alignment (**A**) and kinematic alignment (**B**). In mechanical alignment, a common rotational alignment target for the AP axis of the baseplate is the medial 1/3 of the tibial tubercle [7, 33]. In kinematic alignment, the target for the AP axis of the baseplate is parallel to the flexion–extension (FE) plane. To hit the target for kinematic alignment, the baseplate must be rotated internally leaving the posterior lateral tibia uncovered

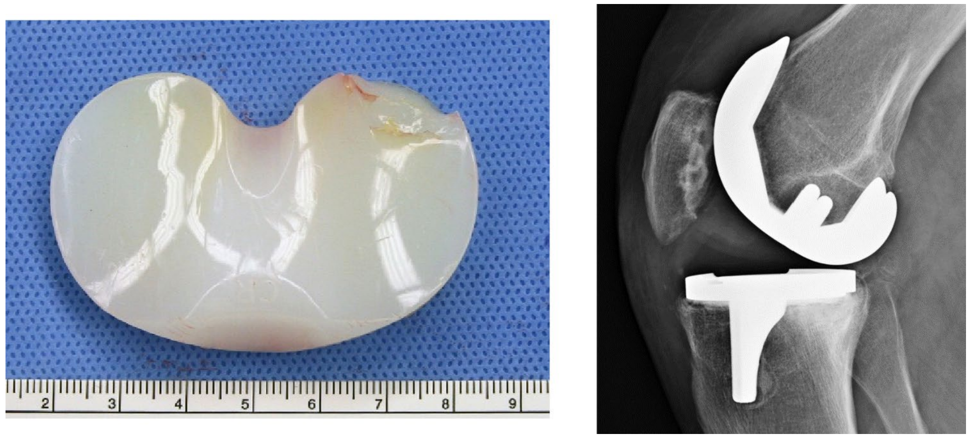

Fig. 3 Images showing adverse consequences of posterior rim loading. Left) fracture of the posterior rim; Right) subsidence of the posterior tibia, reactive sclerosis, and loosening of the tibial baseplate. Both consequences require revision surgery

from the KA rotation target which would uncover the posterior lateral tibia, and (4) posterior slope. Increased posterior slope would lead to an increased anterior component of the tibial contact force in weight bearing which would force the tibia anteriorly on the femur secondary to loss of the ACL [20].

The purposes of this study were to develop methods to quantify these five causes and to assess their respective contributions to the occurrence of posterior rim loading in the lateral compartment. If the occurrence was traced to the asymmetric shape of the baseplate and/or other design features of the insert (e.g. low-conformity), then this result would highlight the need for design modifications to limit the incidence of posterior rim loading in KA TKA. To determine whether patient-reported outcomes were adversely affected by posterior rim loading, this study also reported function scores. Our hypothesis was that asymmetric shape of a baseplate designed for MA would consistently contribute to posterior rim loading in the lateral compartment by under-covering the posterior lateral tibia when positioned in KA.

Methods

A total of 50 patients were involved by combining two cohorts of 25 patients each from previously published studies [8, 26]. Both previous studies were approved by the Institutional Review Board (IRB# 954288 and IRB# 1385598-6). Since the methods of patient recruitment were described previously, the interested reader is referred to those publications. Worthy of note is that patients were selected with no restriction on preoperative varus-valgus or flexion-contracture deformity. Demographics of patients who developed posterior rim loading and those who did not develop posterior rim loading are given in Table 1.

Surgical technique

In brief, a single surgeon performed unrestricted, calliper-verified KA TKA using manual instruments through a mid-vastus approach and intraoperatively recorded a series of verification checks using a previously described technique [17]. For the femoral component, the internal–external axial (IE) and varus-valgus (VV) rotations and the AP and proximal–distal (PD) positions were set coincident with the native distal and posterior joint lines by adjusting the caliper-measured thicknesses of the distal and posterior femoral resections to within 0 ± 0.5 mm of those of the femoral component condyles after compensating for cartilage wear and kerf of the saw blade. These steps set the distal lateral femoral angle within $\pm 3°$ of the healthy contralateral limb in 97% of patients [24] and the IE rotation of the femoral component with a deviation of $0.3° \pm 1.1°$ external from the FE plane which is the KA target [23, 25].

For the tibial component, the VV rotation and posterior slope of the resection were set coincident with the native proximal tibial joint line and native posterior slope of the medial compartment, respectively. The proportion of patients with a proximal medial tibial angle within $\pm 3°$ of the native contralateral healthy limb is 97% [24] and the mean difference between the posterior slope of the tibial component and the native posterior slope is $0° \pm 2.4°$ [19].

Kinematic tibial templates were used to set IE rotation to the KA target which is the FE plane. The largest of seven kinematic templates was best fit within the cortical edge of the tibial resection. The accuracy of localizing the FE plane by a best fit of the kinematic tibial template on the tibial resection is $0° \pm 4°$ [29]. The largest trial tibial baseplate that maximized the tibial resection coverage without cortical overhang and set the AP axis of the component parallel to the slot was selected. There was no up- or downsizing of the tibial component based on the femoral component size.

Table 1 Demographic data for posterior rim loading patients and all other patients

	Posterior rim loading patients (N=9) (mean ± SD)	All other patients (N=41) (mean ± SD)	p value
Age (years)	68 ± 9	65 ± 7	0.244
Sex	6 Females	18 Females	
	3 Male	23 Males	
BMI (kg/m^2)	32 ± 5	28 ± 5	**0.034***
Preoperative weight bearing deformity (degrees) [− Varus, + Valgus]	4 ± 8	0 ± 7	0.158
Type of deformity	Varus, N=4	Varus, N=29	
	Valgus, N=4	Valgus, N=9	
	Neutral, N=1	Patellofemoral, N=1	
Kellgren–Lawrence classification	III, N=2	II, N=1	
	IV, N=7	III, N=12	
		IV, N=28	
Passive extension, KA TKA (degrees)	0 ± 2	0 ± 0	0.077
Passive flexion, KA TKA (degrees)	118 ± 9	121 ± 10	0.325

Statistical significance was set at p < 0.05. Significant p-values are bolded and starred.

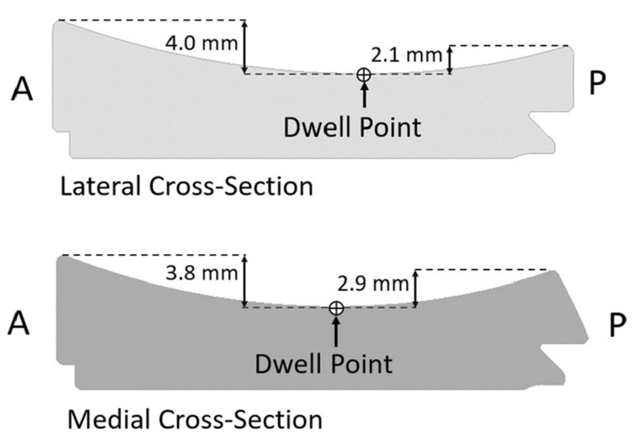

Fig. 4 Cross-sections of the tibial insert in the medial and lateral compartments. Cross-sections are in the AP direction and pass through the respective dwell points

The implants used were Persona posterior cruciate retaining (CR) components (Zimmer-Biomet, Warsaw, IN). These components consist of an asymmetric tibial baseplate (Fig. 1) interfaced with an insert which offers low conforming articular surfaces in the form of shallow concavities in both the medial and lateral compartments. In both compartments the height above the dwell point is higher anterior than posterior (Fig. 4).

Data collection

Fluoroscopic images (OEC 9900 Elite, General Electric, Boston, MA) were recorded for each patient's KA TKA knee in an oblique sagittal orientation of approximately 10°–15° at 15 frames per second while they performed a dynamic, weight-bearing deep knee bend from full extension to maximum flexion, and again while they performed a step-up. For the deep knee bend, patients staggered their stance in the AP direction to prevent the contralateral knee from impeding the view of the knee under study, and to keep both feet planted on the platform. For the step-up, patients placed the foot of the limb under study on a 22 cm high step and lifted themselves as though they were climbing a set of stairs, but did not follow through with the contralateral limb, again to prevent obstructing the view of the knee under study. Patients performed the activities over 5–7 s to reduce motion blur. Handrails were provided to aid in stability. Passive limits of extension and flexion were measured. Patient-reported outcome scores were obtained at the time of imaging (Table 2).

Data processing

Fluoroscopic images were corrected for distortion after which images at 0°, 30°, 60°, 90°, and maximum flexion were identified for the deep knee bend and images at 0°, 15°, 30°, 45°, and 60° were identified for the step-up. The in vivo 3D position and orientation of the manufacturer-supplied component models were determined using 3D model-to-2D image registration techniques [2] and open-source software (https://sourceforge.net/projects/jointtrack/). The femoral component was translated in the out-of-plane direction until it was centred on top of the tibial component. This step was necessary given that the out-of-plane translation errors encountered in registration using single-plane images can result in the reconstruction of physiologically impossible poses [11, 30]. Coordinate systems were established on the

Table 2 Patient-reported outcome scores for the posterior rim loading patients and all other patients

	Posterior rim loading patients ($N=9$) (mean ± SD)	All other patients ($N=41$) (mean ± SD)	p value
Oxford Knee Score (48 best, 0 worst)	44 ± 3	45 ± 5	0.858
WOMAC Score (0 best, 96 worst)	10 ± 10	9 ± 13	0.832
Forgotten Joint Score (100 best, 0 worst)	77 ± 13	73 ± 28	0.684
Knee Society Score (150 best, − 20 worst)	136 ± 13	134 ± 22	0.835
UCLA Score (10 best, 1 worst)	7 ± 2	7 ± 1	0.779

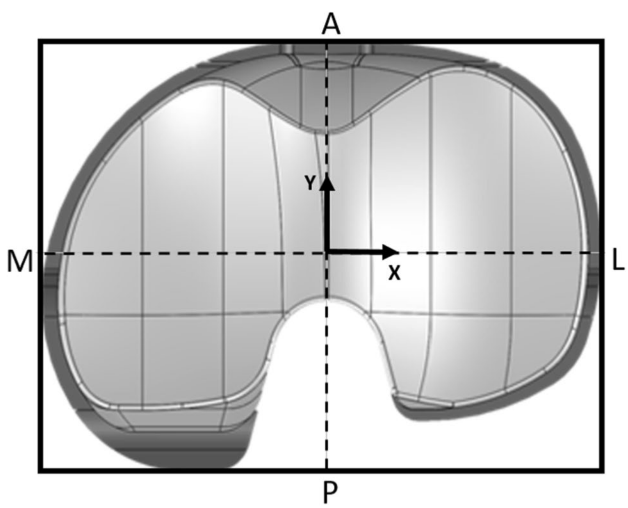

Fig. 5 Axial view of a right tibial component shows the tibial coordinate system used to report AP positions of the medial and lateral femoral condyles. The centre of the bounding box around the component defined the origin of the coordinate system. Directions of axes coincided with those of the manufacturer's CAD model.

tibial baseplate for the TKA knee to report the AP positions of the femoral condyles (Fig. 5).

The AP positions of the medial and lateral femoral condyles for the TKA knees were indicated by the lowest (i.e. closest) points of the femoral condyles with respect to the transverse plane of the tibial baseplate. Because this method references only the transverse plane of the baseplate and does not take into account the AP dimensions of the baseplate and insert, it is possible that the lowest point is more posterior than the most posterior point of the insert. Accordingly, a lowest point beyond the most posterior point of the insert was evidence of posterior rim loading. Further, because the method does not account for curvature of the articular surface of the insert, the femoral condyle can be contacting (and hence loading) the posterior rim even if the posterior position of the femoral condyle is inside the insert [34]. To correct the AP position of a femoral condyle to a location of contact by a femoral condyle on the tibial insert (i.e. tibial insert contact location), lowest points lying within 4 mm of the most posterior point on the insert [31] also were evidence of posterior rim loading. All AP positions were standardized to the 53 mm AP depth of the mid-sized tibial baseplate (Size F, Persona CR, Zimmer-Biomet). I–E rotation was determined as the angle between the line connecting the actual (i.e. non-standardized) A–P positions of the lowest points in each compartment at extension and the line connecting the actual A-P positions of the lowest points in each compartment at a particular flexion angle.

Five potential contributing causes of posterior rim loading were evaluated. One was tibial component rotation required to kinematically align the baseplate causing the posterior lateral tibial to become uncovered and was computed as a percentage of the AP depth of the baseplate (Fig. 6, Images 3a–c). A second was internal rotational deviation of the tibial baseplate from the KA rotation target (Fig. 5, Image 2) which required that the AP axis of the baseplate be parallel to the FE plane of the knee. Internal rotation deviation would cause a larger portion of the posterior lateral tibia to be uncovered. A third was increased posterior slope of the tibial component (Fig. 6, Image 4). A fourth was posterior position of the lateral femoral condyle at full extension. Internal rotation of the tibia on the femur with flexion, as indicated by the external rotation of the AP positions of the femoral condyles, was a fifth potential contributing cause. Internal rotation was determined based on the true AP positions rather than standardized AP positions.

Statistical analysis

Demographic variables (Table 1), patient-reported outcome scores (Table 2), and the five contributing causes (Table 3) were analyzed for differences between the patients with posterior rim loading and the remaining patients without posterior rim loading using a one-way analysis of variance (ANOVA). An intraclass correlation coefficient (ICC) analysis was performed to determine the repeatability and reproducibility of the registration method. The methods and results of the ICC analysis were described previously [26].

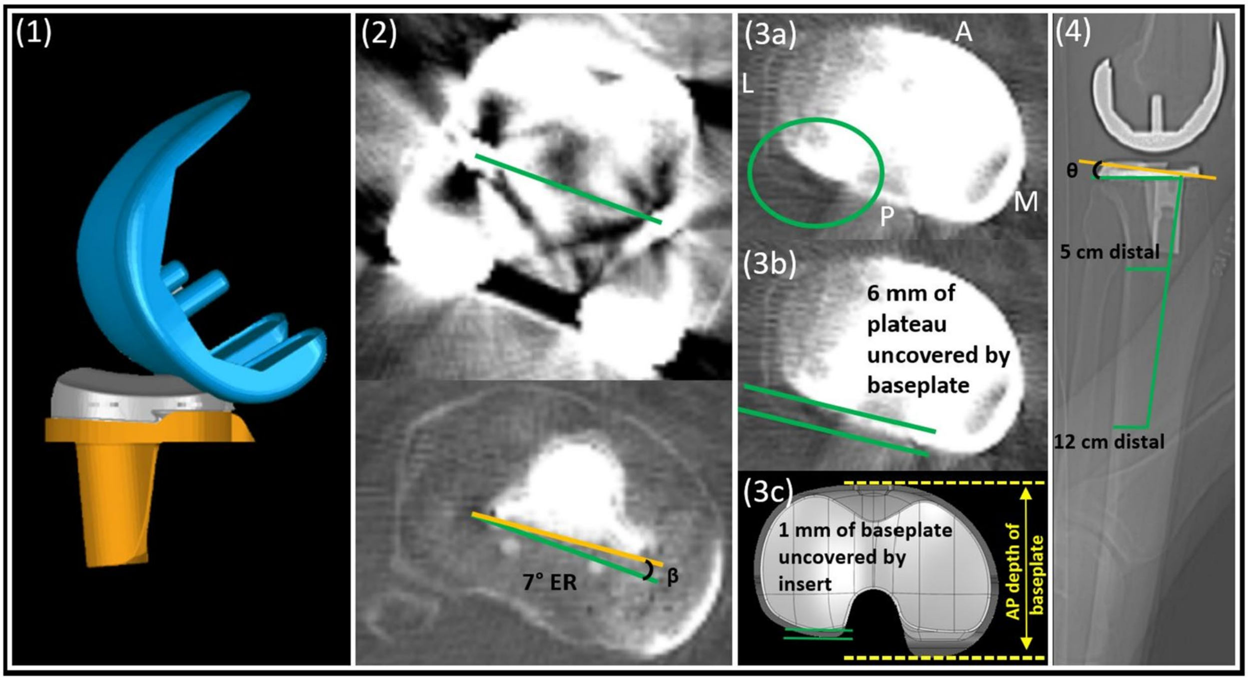

Fig. 6 Composite shows a lateral view of the femoral and tibial components for Patient 15 at 60° of flexion where posterior rim loading occurred in the medial and lateral compartments (**1**). Internal–external rotational deviation (β) of the tibial component from the IE rotation target was measured on a postoperative axial CT scan for each patient as the angle between a line connecting the femoral lugs and a line connecting the posterior tips of the proximal tibial keel (**2**). The percentage of the posterior lateral tibia left uncovered (**3a**) was measured as the distance from the posterior edge of the tibia to the posterior rim of the tibial insert, divided by the AP depth of the tibial baseplate. The distance from the posterior edge of the tibia to the posterior rim of the tibial insert was the sum of the distance from the posterior edge of the tibia to the posterior edge of the baseplate (**3b**) plus the distance from the posterior edge of the baseplate to the posterior rim of the tibial insert (**3c**). Here, the percentage uncovered was 16% (**3a**–**c**). The posterior slope of the tibial component (θ) was measured relative to a line perpendicular (orange line) to the proximal tibial anatomic axis, which was defined as a line connecting the midpoints of two lines drawn across the tibia 5 cm and 12 cm distal to the joint line (**4**)

Table 3 Five potential contributing causes for posterior rim loading patients and all other non-posterior rim loading patients

	Posterior rim loading patients ($N=9$) (mean ± SD)	All other patients ($N=41$) (mean ± SD)	*p* value
AP percentage of posterior lateral tibia uncovered	15% ± 7%	10% ± 5%	**0.009***
Deviation in rotation of tibial component from KA target [+ Internal, − External]	3° ± 7°	0° ± 3°	0.207
Posterior slope of tibial component	7° ± 4°	6° ± 3°	0.637
AP position of lateral femoral condyle at full extension deep knee bend [+ Anterior, − Posterior]	− 8 mm ± 3 mm	− 4 mm ± 4 mm	**0.003***
Approximate IE rotation of tibia on femur from full extension to maximum flexion, deep knee bend [+ Internal, − External]	7° ± 6°	6° ± 4°	0.546

*Outlier omitted in analysis

Results

Posterior rim loading occurred for eight patients in the deep knee bend and for one additional patient in the step up who did not develop posterior rim loading in the deep knee bend. Flexion angles at which the position of the lateral femoral condyle was most posterior differed among patients.

The mean AP percentage of the posterior lateral tibia uncovered was 5% greater for the posterior rim loading patients than all other patients without posterior rim loading ($p = 0.009$) (Table 3). Also the mean AP position of the lateral femoral condyle was 4 mm more posterior for the posterior rim loading patients ($p = 0.003$).

Notwithstanding the occurrence of posterior rim loading, patient-reported outcome scores for patients with posterior rim loading were relatively high with mean values being virtually identical to all other patients without posterior rim loading) (Table 2).

Discussion

This study quantified contributing causes of posterior rim loading in the lateral compartment following unrestricted, calliper-verified KA TKA using manual instruments and asymmetric, fixed bearing, PCR, low-conforming components. The most important findings were that (1) internal rotation of the asymmetric tibial baseplate when used in KA was a consistent contributing cause and the posterior position of the lateral femoral condyle at extension also was a consistent contributing cause, and (2) patient-reported outcome scores were relatively high for all patients who developed posterior rim loading with mean values being virtually identical to those scores of all other patients who did not develop posterior rim loading.

Considering first internal rotation of the asymmetric tibial baseplate, it should be noted that the AP percentage of the posterior lateral tibia uncovered in Table 3 could be due either to internal rotation of the asymmetric tibial baseplate when positioned in KA and/or to internal rotational deviation of the asymmetric tibial baseplate from the KA target. For those patients with posterior rim loading however, the small average internal rotational deviation of 3° in conjunction with large variability of ± 7° (Table 3) excluded consistent internal rotational deviation from the IE rotation target as a primary cause for under-coverage. Consequently, under-coverage was due primarily to internal rotation of the asymmetric tibial baseplate when positioned in KA.

Although the tibial baseplate was neither upsized nor downsized based on the femoral component size, a feature of this particular component set had the potential to affect the under coverage of the posterior lateral tibia. Namely, the same size insert could be used with two different sized baseplates. Thus, if the larger of the two sizes was used, then although the baseplate per se would offer greater coverage of the resected surface of the tibia, use of the same sized insert that fit the smaller baseplate in the pair would lead to under coverage. To assess whether the proportion of larger sized baseplates differed between the posterior rim loading patients and all other patients, a post hoc Fisher's exact test was performed. This test revealed no statistically significant difference ($p = 0.2814$) indicating that the baseplate size/insert combination likely did not affect our results.

A second consistent contributing cause was the posterior position of the lateral femoral condyle at full extension likely due in part to anterior movement of the tibia secondary to loss of the ACL. Loss of the ACL generally results in increased anterior laxity but the increase varies widely between knees [32]. Although anterior laxity was not measured in the present study, possibly the patients who developed posterior rim loading in the lateral compartment had greater increases in anterior laxity following loss of the ACL than the patients who did not develop posterior rim loading. Regardless, patients who developed posterior rim loading are representative of the patient population.

The design of the tibial insert also likely plays a role in the posterior position of the lateral femoral condyle at extension. For this particular insert design, both compartments feature an asymmetric shallow (i.e. low-conforming) concavity where the height of the rim is considerably greater anterior than posterior (Fig. 4). Hence, the femur is able to displace posteriorly on the tibia with little resistance provided by the posterior articular surfaces of the shallow concavities which is secondary to the loss of the ACL. Further, the dwell points of the concavities are posterior on the insert surface as intended for this insert design [29] which exacerbates the tendency for the positions of the femoral condyles at extension to be posterior.

It is unlikely that variation in tension of the posterior cruciate ligament (PCL) influenced the occurrence of posterior rim loading. During unrestricted, calliper-verified KA TKA, one verification check performed with trial components at 90º of flexion determines whether the AP offset, which is the distance from the anterior tibia to the distal surface of the medial femoral condyle, is restored to that of the knee at the time of exposure. When the offset is larger than at exposure, the PCL is too tight. When the offset is smaller, the PCL is too loose. Intraoperatively, the verification check above restores posterior laxity to that of the native knee over the full range of flexion [32] indicating that PCL tension is restored to native as well.

It is also unlikely that a large size differential between the femoral and tibial components played a role in the occurrence of posterior rim loading. For the nine patients who developed posterior rim loading, only one baseplate and femur size combination was at the low and high limits, respectively, of compatibility as recommended by the manufacturer [1].

Comparison of our results to those previously published is necessarily limited. This is because few studies report patient-specific results of the AP position of the lateral femoral condyle but rather report descriptive statistics (e.g. mean and standard deviation). However, two previous studies are relevant. One study reported the absence of posterior rim loading following unrestricted KA TKA in contrast to the results herein [15]. This may have occurred because the activities of daily living studied differed, because the implant designed differed, and/or because the AP position of the lateral femoral condyle was not corrected to indicate the tibial insert contact location since the 4 mm posterior correction was unknown at that time [31]. The other study, which also preceded the publication of the posterior correction, reported a much higher incidence of posterior rim loading [22]. Using mechanically aligned TKA and a bi-surface implant design which allowed high flexion past 120° in 25 of 43 knees, the incidence of posterior rim loading (termed posterior subluxation in their paper) was 64% (16 of 25 high flexion knees) during a deep knee bend. The four times higher incidence than that reported herein was evidently due in part to the greater flexion angle as well as differences in the implant design and surgical alignment method.

To limit the incidence of posterior rim loading in the lateral compartment, design modifications should be considered. One modification for reducing under-coverage of the posterior lateral tibia is an asymmetric tibial baseplate that more fully covers the tibial resection when the IE rotation is set parallel to the FE plane of the native knee. Making this modification would minimize under-coverage due to internally rotating a baseplate designed for MA. This modification could easily be realized by having the baseplate match the shape of the template used to set the IE rotation of the baseplate in KA [29]. Another modification is a tibial insert with more conformity particularly in the medial compartment to mimic that of the native knee [6, 10] in conjunction with a dwell point(s) which is further anterior.

Even if the asymmetric baseplate was redesigned to reflect the KA alignment target in IE rotation, the wide variability in the asymmetry of the tibial plateau present challenges to the designer in maximizing coverage for all patients. In a study of some 2200 tibias, tibial asymmetry was 3.7 mm on average with the AP depth of the medial tibial plateau being greater than that of the lateral tibial plateau [21]. However, asymmetry in more than 20% of patients exceeded 5 mm. Accordingly, some compromise would be necessary. To limit the risk of posterior rim loading in the lateral compartment, it would seem prudent to maximize coverage of the lateral tibial plateau at the expense of under-coverage of the medial tibial plateau.

Despite the occurrence of posterior rim loading, mean patient-reported outcome scores for these nine patients were relatively high being virtually identical to all other patients without posterior rim loading (Table 2). This may be because the deep knee bend is an infrequent activity of daily living and/or because posterior rim loading does not compromise tibiofemoral joint function. In any case, it will be of interest to follow these patients into the future to determine whether the occurrence of posterior rim loading leads to long term complications.

Some limitations merit discussion. First, this study considered one asymmetric, fixed-bearing, PCR, low-conforming component design (Persona CR, Zimmer Biomet, Warsaw, IN). It is well-documented that component design and the presence or absence of the posterior cruciate ligament (PCL) are important independent variables which affect tibiofemoral kinematics [3, 9, 28, 35, 36] so that these results may not be generalizable to KA TKAs performed with different component designs. Nevertheless, our results alert manufacturers of asymmetric baseplate designs that coverage may be compromised when used in KA in which case coverage for both MA and KA should be evaluated as part of the design process. If the coverage is compromised as for the baseplate used herein, then a KA-specific baseplate design is warranted. Next, although the sample size was not sufficiently large to confidently conclude that small differences in means were not significantly different from zero, the issue is moot because the posterior slope and approximate IE rotation differed by only 1° in their mean values (Table 3), which is not clinically important, and the means of the patient-reported outcomes were virtually identical (Table 2).

Conclusions

Internal rotation of the asymmetric tibial baseplate designed for MA left on average 15% of the posterior lateral tibia uncovered when used in KA and was a consistent contributing cause of posterior rim loading in the lateral compartment following unrestricted, caliper-verified KA TKA. Also, posterior position of the lateral femoral condyle at extension of 8 mm on average posterior of the centreline of the tibial baseplate was a consistent contributing cause. These results highlight the need for new, asymmetric baseplate designs which maximize coverage based on the KA rotational alignment target.

Acknowledgements We acknowledge the financial support provided by Zimmer-Biomet, Award Number IRU2016-101K: Knees, by the Orthopeadic Research and Education Foundation, and by Medacta USA, Inc. We also acknowledge Alexander Simileysky who provided valuable technical support. Finally we thank the patients who participated in this study for their contribution to the advancement of education and research.

Author contributions SNP and CD contacted and enrolled patients, processed images, performed statistical analyses, and drafted sections of manuscript; AS and CD obtained license to operate fluoroscopy system, trained patients in performing activities of daily living, and used fluoroscopy system to collect images; SMH provided patients, co-supervised the project, and contributed to data analysis; MLH obtained funding for the project, co-supervised the project, conceived methods of data analysis, and wrote sections of manuscript including the revision.

Funding This article was funded by Orthopaedic Research and Education Foundation, Zimmer-Biomet, IRU2016-101K: Knees, and Medacta USA, Inc.

Declarations

Conflict of interest S. M. Howell is a paid consultant for Medacta USA, Inc. M. L. Hull received research support for this study from Zimmer-Biomet, the Orthopeadic Research and Education Foundation, and Medacta USA, Inc. M. L. Hull currently receives corporate research support from Medacta USA, Inc.

Ethical approval The previous studies which generated the images used for analysis in the present study were approved by theInstitutional Review Board (IRB) at the University of California Davis (IRB #954288, IRB#1385598-6).

References

1. (2013) Persona Product Profiler. Zimmer-Biomet, Warsaw, IN
2. Banks SA, Hodge WA (1996) Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Trans Biomed Eng 43:638–649
3. Banks SA, Hodge WA (2004) Design and activity dependence of kinematics in fixed and mobile-bearing knee arthroplasties. J Arthroplasty 19:809–816
4. Berend ME, Ritter MA, Hyldahl HC, Meding JB, Redelman R (2008) Implant migration and failure in total knee arthroplasty is related to body mass index and tibial component size. J Arthroplasty 23:104–109
5. Bourne RB, Finlay JB (1986) The influence of tibial component intramedullary stems and implant-cortex contact on the strain distribution of the proximal tibia following total knee arthroplasty. An in vitro study. Clin Orthop Relat Res:95–99
6. Churchill DL, Incavo SJ, Johnson CC, Beynnon BD (1998) The transepicondylar axis approximates the optimal flexion axis of the knee. Clin Orthop Relat Res 356:111–118
7. Dai Y, Scuderi GR, Bischoff JE, Bertin K, Tarabichi S, Rajgopal A (2014) Anatomic tibial component design can increase tibial coverage and rotational alignment accuracy: a comparison of six contemporary designs. Knee Surg Sports Traumatol Arthrosc 22:2911–2923
8. Delman CM, Ridenour D, Howell SM, Hull ML (2021) The posterolateral upslope of a low-conforming insert blocks the medial pivot during a deep knee bend in TKA: a comparative analysis of two implants with different insert conformities. Knee Surg Sports Traumatol Arthrosc. https://doi.org/10.1007/s00167-021-06668-8
9. Dennis DA, Komistek RD, Mahfouz MR, Haas BD, Stiehl JB (2003) Multicenter determination of in vivo kinematics after total knee arthroplasty. Clin Orthop Relat Res 416:37–57
10. Freeman MA, Pinskerova V (2005) The movement of the normal tibio-femoral joint. J Biomech 38:197–208
11. Fregly BJ, Rahman HA, Banks SA (2005) Theoretical accuracy of model-based shape matching for measuring natural knee kinematics with single-plane fluoroscopy. J Biomech Eng 127:692–699
12. Gudnason A, Adalberth G, Nilsson KG, Hailer NP (2017) Tibial component rotation around the transverse axis measured by radiostereometry predicts aseptic loosening better than maximal total point motion. Acta Orthop 88:282–287
13. Harman MK, Banks SA, Hodge WA (2001) Polyethylene damage and knee kinematics after total knee arthroplasty. Clin Orthop Relat Res 392:383–393
14. Hartel MJ, Loosli Y, Delfosse D, Diel P, Thali M, Ross S et al (2014) The influence of tibial morphology on the design of an anatomical tibial baseplate for TKA. Knee 21:415–419
15. Howell SM, Hodapp EE, Vernace JV, Hull ML, Meade TD (2013) Are undesirable contact kinematics minimized after kinematically aligned total knee arthroplasty? An intersurgeon analysis of consecutive patients. Knee Surg Sports Traumatol Arthrosc 21:2281–2287
16. Howell SM, Papadopoulos S, Kuznik KT, Hull ML (2013) Accurate alignment and high function after kinematically aligned TKA performed with generic instruments. Knee Surg Sports Traumatol Arthrosc 21:2271–2280
17. Howell SM, Shelton TJ, Gill M, Hull ML (2021) A cruciate-retaining implant can treat both knees of most windswept deformities when performed with calipered kinematically aligned TKA. Knee Surg Sports Traumatol Arthrosc 29:437–445
18. Indelli PF, Graceffa A, Marcucci M, Baldini A (2016) Rotational alignment of the tibial component in total knee arthroplasty. Ann Transl Med 4:3
19. Johnson JM, Mahfouz MR, Midillioglu MR, Nedopil AJ, Howell SM (2017) Three-dimensional analysis of the tibial resection plane relative to the arthritic tibial plateau in total knee arthroplasty. J Exp Orthop 4:27
20. Markolf KL, Jackson SR, Foster B, McAllister DR (2014) ACL forces and knee kinematics produced by axial tibial compression during a passive flexion-extension cycle. J Orthop Res 32:89–95
21. Meier M, Zingde S, Best R, Schroeder L, Beckmann J, Steinert AF (2020) High variability of proximal tibial asymmetry and slope: a CT data analysis of 15,807 osteoarthritic knees before TKA. Knee Surg Sports Traumatol Arthrosc 28:1105–1112
22. Nakamura S, Sharma A, Ito H, Nakamura K, Zingde SM, Komistek RD (2015) Kinematic difference between various geometric centers and contact points for tri-condylar bi-surface knee system. J Arthroplasty 30:701–705
23. Nedopil AJ, Howell SM, Hull ML (2016) Does malrotation of the tibial and femoral components compromise function in kinematically aligned total knee arthroplasty? Orthop Clin North Am 47:41–50
24. Nedopil AJ, Singh AK, Howell SM, Hull ML (2018) Does calipered kinematically aligned TKA restore native left to right symmetry of the lower limb and improve function? J Arthroplasty 33:398–406
25. Nedopil AJ, Zamora T, Delman C, Howell SM, Hull ML (2021) Which asymmetric tibial component is optimally designed for calipered kinematically aligned total knee arthroplasty? J Knee Surg. https://doi.org/10.1055/s-0041-1728815
26. Nicolet-Petersen S, Saiz A, Shelton T, Howell SM, Hull ML (2020) Small differences in tibial contact locations following kinematically aligned TKA from the native contralateral knee. Knee Surg Sports Traumatol Arthrosc 28:2893–2904
27. Nilsson KG, Karrholm J, Ekelund L, Magnusson P (1991) Evaluation of micromotion in cemented vs uncemented knee arthroplasty in osteoarthrosis and rheumatoid arthritis. Randomized study using roentgen stereophotogrammetric analysis. J Arthroplasty 6:265–278
28. Okamoto N, Breslauer L, Hedley AK, Mizuta H, Banks SA (2011) In vivo knee kinematics in patients with bilateral total knee arthroplasty of 2 designs. J Arthroplasty 26:914–918
29. Paschos NK, Howell SM, Johnson JM, Mahfouz MR (2017) Can kinematic tibial templates assist the surgeon locating the flexion and extension plane of the knee? Knee 24:1006–1015
30. Prins AH, Kaptein BL, Stoel BC, Reiber JHC, Valstar ER (2010) Detecting femur–insert collisions to improve precision of fluoroscopic knee arthroplasty analysis. J Biomech 43:694–700

31. Ross DS, Howell SM, Hull ML (2017) Errors in calculating anterior–posterior tibial contact locations in total knee arthroplasty using three-dimensional model to two-dimensional image registration in radiographs: an in vitro study of two methods. J Biomech Eng 139:121003.121001-121003.121010
32. Roth JD, Howell SM, Hull ML (2019) Analysis of differences in laxities and neutral positions from native after kinematically aligned TKA using cruciate retaining implants. J Orthop Res 37:358–369
33. Saffarini M, Nover L, Tandogan R, Becker R, Moser LB, Hirschmann MT et al (2019) The original Akagi line is the most reliable: a systematic review of landmarks for rotational alignment of the tibial component in TKA. Knee Surg Sports Traumatol Arthrosc 27:1018–1027
34. Simileysky A, Ridenour D, Hull ML (2021) Circle-based model to estimate error in using the lowest points to indicate locations ofcontact developed by the femoral condyles on the tibial insert in total knee arthroplasty by the tibia. J Biomech 120:110365
35. Victor J, Banks S, Bellemans J (2005) Kinematics of posterior cruciate ligament-retaining and-substituting total knee arthroplasty: a prospective randomized outcome study. J Bone Joint Surg 87-B:646–655
36. Watanabe T, Ishizuki M, Muneta T, Banks SA (2013) Knee kinematics in anterior cruciate ligament-substituting arthroplasty with or without the posterior cruciate ligament. J Arthroplasty 28:548–552
37. Wevers HW, Simurda M, Griffin M, Tarrel J (1994) Improved fit by asymmetric tibial prosthesis for total knee arthroplasty. Med Eng Phys 16:297–300

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.