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The risk of tibial eminence avulsion fracture with bi-unicondylar knee arthroplasty

A FINITE ELEMENT ANALYSIS

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Aims

The aim of this study was to determine the risk of tibial eminence avulsion intraoperatively for bi-unicondylar knee arthroplasty (Bi-UKA), with consideration of the effect of implant positioning, overstuffing, and sex, compared to the risk for isolated medial unicondylar knee arthroplasty (UKA-M) and bicruciate-retaining total knee arthroplasty (BCR-TKA).

Methods

Two experimentally validated finite element models of tibia were implanted with UKA-M, Bi-UKA, and BCR-TKA. Intraoperative loads were applied through the condyles, anterior cruciate ligament (ACL), medial collateral ligament (MCL), and lateral collateral ligament (LCL), and the risk of fracture (ROF) was evaluated in the spine as the ratio of the 95th percentile maximum principal elastic strains over the tensile yield strain of proximal tibial bone.

Results

Peak tensile strains occurred on the anterior portion of the medial sagittal cut in all simulations. Lateral translation of the medial implant in Bi-UKA had the largest increase in ROF of any of the implant positions (43%). Overstuffing the joint by 2 mm had a much larger effect, resulting in a six-fold increase in ROF. Bi-UKA had ~10% increased ROF compared to UKA-M for both the male and female models, although the smaller, less dense female model had a 1.4 times greater ROF compared to the male model. Removal of anterior bone akin to BCR-TKA doubled ROF compared to Bi-UKA.

Conclusion

Tibial eminence avulsion fracture has a similar risk associated with Bi-UKA to UKA-M. The risk is higher for smaller and less dense tibiae. To minimize risk, it is most important to avoid overstuffing the joint, followed by correctly positioning the medial implant, taking care not to narrow the bone island anteriorly.

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Article focus

- Finite element analysis assessing the risk of tibial eminence avulsion fracture during bi-unicondylar knee arthroplasty (Bi-UKA).
- Effect of overstuffing, variations to surgical cuts, and bony anatomy were investigated.
- Comparisons to avulsion risk in isolated medial unicondylar knee arthroplasty (UKA-M) and bicruciate-retaining total knee arthroplasty contextualize results.

Key messages

- There is a similar risk of tibial eminence avulsion fracture in Bi-UKA as in UKA-M. Risk is increased in smaller and less dense tibiae.
- Overstuffing the joint and cuts narrowing the bone island anteriorly should be avoided to reduce avulsion fracture risk.

Strengths and limitations

- The strengths of the study are the use of multiple specimen-specific experimentally validated tibia models, and a wide range of scenarios were investigated.
- The limitations of this study are that fracture propagation was not modelled, and the effect of relative femoral translation on anterior cruciate ligament (ACL) strain was not included.

Introduction

Knee osteoarthritis (OA) is a debilitating ailment that affects 16% of the global population.[1-3] One-third of people with knee OA have damage limited to just two compartments of the knee,[4] and as such there has been a renewed interest in combined partial knee arthroplasty (CPKA) to treat knee OA in a limited manner.[5-14] In particular, bi-unicondylar arthroplasty (Bi-UKA) is of interest for patients with a healthy patellofemoral compartment and functional cruciate ligaments, and either ipsilateral medial and lateral tibiofemoral OA,[4,5,11,12] or a well-functioning unicondylar arthroplasty (UKA) with subsequent degeneration in the other tibiofemoral compartment.[13]

Recent evidence suggests that Bi-UKA patients have superior outcomes and biomechanics compared to those with a similar disease pattern but treated with total knee arthroplasty (TKA).[11-13,15] However, a potential barrier to the wider use of this procedure is a perceived risk of compromising the anterior cruciate ligament (ACL) if the seemingly narrow bone island between the two tibial components fractures under ACL tension. Indeed, some authors have suggested that intraoperative tibial eminence avulsion fracture may occur in 4% to 9% of Bi-UKAs.[16,17] Bicruciate-retaining total knee arthroplasty (BCR-TKA) leaves behind a similar island to which the cruciates attach, although with bone also removed anteriorly. Intraoperative tibial island fractures with BCR-TKA also occurred at a rate of 9% in development.[18] There is little information available to delineate which factors increase or decrease the risk of ACL avulsion.

Finite element (FE) analysis has proved a valuable tool for assessing fracture risk,[19,20] bone mechanics,[21-24] joint kinematics,[25,26] and ligament mechanics[27] following unicompartmental arthroplasty. Therefore, the aim of this study was to investigate the risk of tibial eminence avulsion following Bi-UKA using FE analysis to determine the effects of implant positioning, overstuffing, and bony anatomy. To contextualize the findings, data were compared to tibiae implanted with isolated medial unicompartmental knee arthroplasty (UKA-M) and a bridged implant akin to BCR-TKA.

Methods

Bone model preparation. Two (one male, one female) experimentally validated specimen-specific FE models of right-sided proximal tibiae cut at mid-shaft were analyzed (Table I).[28] Bone volume meshes were created in 3-matic (Materialise NV, Belgium) with ten-noded tetrahedral elements of 2.4 mm global edge-length. The meshes were further refined locally at the resected bone surfaces to 0.95 mm edge-length, with a growth rate of 10% from these surfaces, to achieve mesh convergence within 5%. The bones were anatomically aligned with lateral x-axis, anterior y-axis, proximal z-axis, and origin at the midpoint between the condylar centres.[29] Distal cortical bone was modelled with type 127 ten-noded tetrahedral elements in MARC (MSC Software Corporation, USA). Proximally, the thin tibial cortex was modelled with type 22 one-side collapsed quadratic quadrilateral 0.2 mm thick shell elements to reduce partial volume effects arising from the bone material allocation method.

The tibiae were CT-scanned (Definition AS+, Siemens, Germany) with slice thickness of 0.6 mm, and cross-section voxels 0.5 × 0.5 mm, and a calibration phantom. Cancellous bone material properties were applied heterogeneously based on empirical measures relating Hounsfield units (HU) to density and elastic moduli from quantitative CT of each specimen using Mimics (Materialise NV).[20] All other materials were homogeneous, isotropic, and linear elastic (Table II). The stiffness of the thin cortex covering the proximal tibia (which is thinner than the resolution of the scan) was captured by applying shell elements proximally, which were assigned homogeneous material properties of 18 GPa (large, dense, male tibia) or 14 GPa (smaller, less denser, female tibia).

Implants. The Oxford medial and fixed lateral UKA implants were used (Zimmer Biomet, USA). For both UKA-M and Bi-UKA, implants were sized (Table I) and positioned using surgical planning software (Embody Orthopaedic, UK), following the senior surgical author's clinical practise (JPC). All interfaces were glued, with sensitivity studies confirming that this contact condition was acceptable for the static load cases applied.

Boundary conditions and loading. Tibiae were fixed distally and intraoperative loading at full extension was simulated, as the ACL is most strained in extension.[30] Sensitivity studies determined that force contributions from the ACL, medial collateral ligament (MCL), and lateral collateral ligament (LCL) should be simulated, with the corresponding joint reaction force. No single source could provide all data needed; loads were estimated from clinical data, intraoperative/in vitro measurements, and calculations (Table III).[30-35] Two loadcases (Figure 1) were investigated: 1) baseline loading for a balanced knee that replicated native knee ligament strain; and 2) an overstuffed knee. The latter was estimated by calculating the additional strain and load that would occur if

Table I. Bone model characteristics.

Model	Age, yrs	Height, cm	Weight, kg	Mean bone density, gcm^{-3}	Bone volume, cm^3	Medial implant size	Lateral implant size
Male	65	183	64	0.344	199	C	E
Female	81	152	91	0.296	154	B	D

Table II. Material properties and mesh size.

Material	Density, (ρ gcm^{-3})	Elastic Modulus, E (MPa)	Poisson's ratio	No. elements
Cancellous	ρ = 0.04 + 0.00092 HU	$E=\begin{cases} 311, & \rho < 0.1 \\ 26,480\rho^{1.93}, & 0.1 \le \rho \le 0.37 \\ 6,878.8\rho + 1351.9, & 0.37 < \rho \le 1.5 \\ 5,230\rho^{2.39} + 1000, & \rho > 1.5 \end{cases}$	0.3	685,667
Cortical	N/A	18,000	0.33	46,841
Cortex		18,000	0.33	4,595
CoCr implant		210,000	0.33	39,589
PE bearing		600	0.3	32,258
PMMA cement		1800	0.33	48,496

CoCr, cobalt-chromium; HU, Hounsfield unit; N/A, not applicable; PE, polyethylene; PMMA, polymethyl methacrylate.

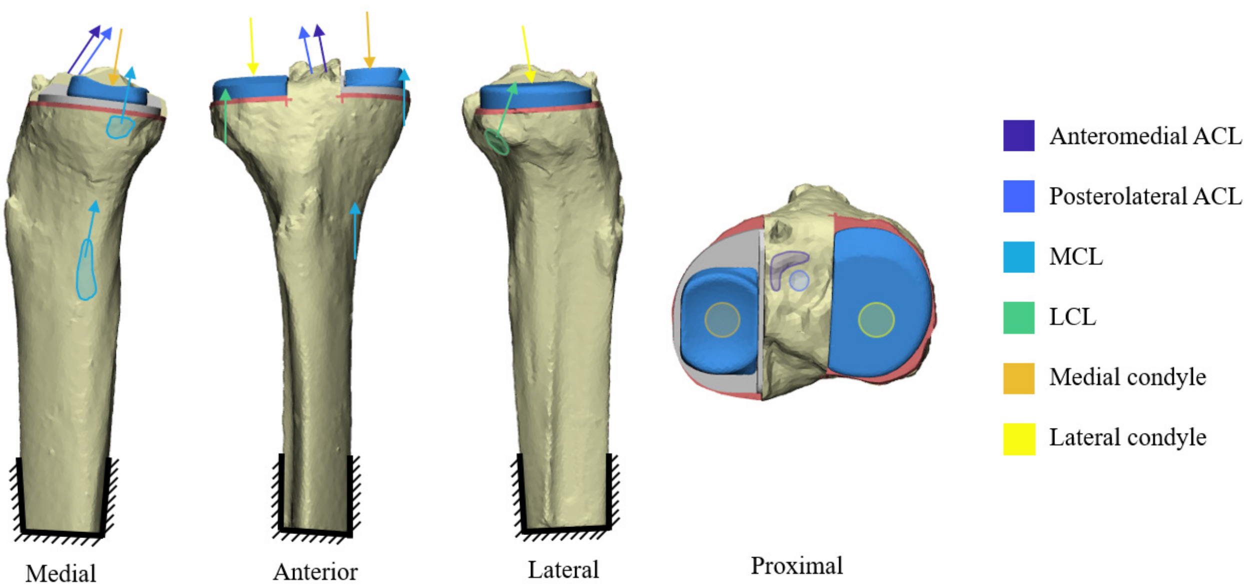

Fig. 1

Bi-unicondylar knee arthroplasty baseline with representation of loading. ACL, anterior cruciate ligament; LCL, lateral collateral ligament; MCL, medial collateral ligament.

2 mm oversized meniscal bearings were used (Table III). As both load cases were intraoperative, no muscle forces were simulated.

The effects of positioning. The typical variation associated with use of manual surgical instruments (Table IV)[36,37] was simulated. Either the medial implant was moved by two standard deviations (SD), the lateral implant by two SD, or both the medial and lateral implant moved by one SD simultaneously. Deviations that would make the bone island narrower and taller (and hence may increase risk of avulsion) were simulated. Bone overcuts were simulated, based on typical variation for manual instruments: 2 mm transversely, and 2.4 mm sagittally.[38] The overcuts were 1 mm wide,[19] corresponding to the width of sawblades used in surgery, and ran parallel to each implant.

Comparison to UKA-M and the effects of anterior bone cuts. The risk of fracture (ROF) following Bi-UKA was compared to other ACL-preserving arthroplasty procedures: isolated UKA-M, and a bridged implant akin to a BCR-TKA. For the UKA-M analyses, lateral condylar loading was distributed to simulate a healthy meniscus. Implant positioning was again varied by two SD of typical clinical

Table III. Boundary conditions and sources.

Boundary conditions	Balanced knee Magnitude, N	Direction i	j	k	Overstuffed by 2 mm Magnitude, N	Direction i	j	k	Reference
AM bundle ACL	38.0	0.16	-0.55	0.82	176.4	0.15	-0.53	0.84	30,32,35
PL bundle ACL	31.0	0.17	-0.56	0.81	216.4	0.16	-0.53	0.83	30,32,35
MCL	120.8	0	-0.19	0.98	304.0	0	-0.18	0.98	31,33-35
LCL	68.6	0	0-33	0.95	175.5	0	0.31	0.95	31,33-35
Medial condyle	145.9	-0.047	0.16	-0.99	493.2	-0.076	0.25	-0.96	31,35
Lateral condyle	97.3	-0.047	0.16	-0.99	328.8	-0.076	0.25	-0.96	31,35

ACL, anterior cruciate ligament; AM, anteromedial; LCL, lateral collateral ligament; MCL, medial collateral ligament; PL, posterolateral.

Table IV. Surgical errors simulated, measured from the baseline, planned positions.

Error type	Medial (2 SD)	Lateral (2 SD)	Compound (1 SD each) Medial	Compound (1 SD each) Lateral
Translations, mm				
Lateral	+2.9	-5.5	+2.2	-3.5
Proximal	-2.6	-2.6*	-0.6	-0.6*
Rotations, °				
Flexion	-11.4	-7.5	-8.1	-4.5
Varus	+1.1	+2.3	+2.05	+0.3
Internal	-7.4	+7.4	-1.7	+0.4

*Duplicated error from UKA-M reference, as no error acting in the detrimental direction measured for UKA-L was available.
SD, standard deviation; UKA-L, isolated lateral unicondylar knee arthroplasty; UKA-M, isolated medial unicondylar knee arthroplasty.

variation (Table IV).[36,37] The BCR-TKA analyses focused on the effects of the anterior bone removal as this is a key difference between Bi-UKA and BCR-TKA. To isolate the effects of anterior bone cuts from other variations in tray footprint specific to the implant manufacturer, a pseudo BCR-TKA implant was created by bridging the UKA-M and isolated lateral unicondylar knee arthroplasty (UKA-L) in their surgeon-planned positions. Two bridge sizes were analyzed, requiring removal of either 5 or 10 mm of anterior bone. A 7 mm radius was applied to the bridge to eliminate stress-concentrating sharp corners.

Data analysis. Strains were observed qualitatively throughout the model and peak strains quantified. The 95th and 99th percentile maximum principal elastic strains (MPES) were quantified in the region of interest. For the Bi-UKA implant positioning analyses, this region included the bone island and adjacent cuts: it extended 10 mm distal to the transverse bone cuts, 5 mm medially/laterally of the medial/lateral sagittal cuts, respectively, and included all bone elements in the anteroposterior (AP) direction. These analyses found that in all cases the strain was largest around the medial implant bone cuts. Thus, when comparing Bi-UKA and UKA-M the region of interest was narrowed to capture only the medial half of the spine providing two benefits: 1) a more focused region of interest; and 2) a similar number of nodes for the Bi-UKA and UKA-M models in the region of interest; an important factor when comparing 95th and 99th percentile strains.

Bone failure is related to a yield strain criterion;[39] in proximal tibial bone, tensile yield strain has been measured to be + 6500με.[40] Hence, ROF[19,41] was calculated as follows:

$$ROF = \frac{MPES_{95}}{6500}$$

ROFs are reported in the main text, with MPES-95, MPES-99, and peak strains tabulated in the Supplementary Material.

Sensitivity analyses. The sensitivity of the model to key modelling decisions was evaluated: firstly the sensitivity to material assignment, and secondly the effects of ACL load distribution.

Results

In all cases simulated, the highest tensile strains occurred on the anterior portion of the face of the medial sagittal cut, just proximal to the junction between the medial sagittal and transverse cuts, and distal to the ACL attachment (Figure 2). Strain concentrations were also observed on the anterior portion of the face of the lateral sagittal cut, but these were 44% to 84% lower than that on the medial cut.

Effect of surgical positioning. For all variations in surgical positioning, except varus/valgus which had negligible effect, a 2 SD variation in positioning the medial implant had a greater effect on ROF than a 2 SD variation in positioning the lateral implant in Bi-UKA (Figure 3). Varying the position of the lateral implant alone had little effect on ROF for all cases except medial translation, which resulted in a 21% increase in ROF. In general, variation that narrowed the bone island medially and anteriorly had the largest effect: lateral translation of the UKA-M in isolation, or combined with medial translation of the UKA-L, had the greatest effect, increasing ROF by 43%. The next largest

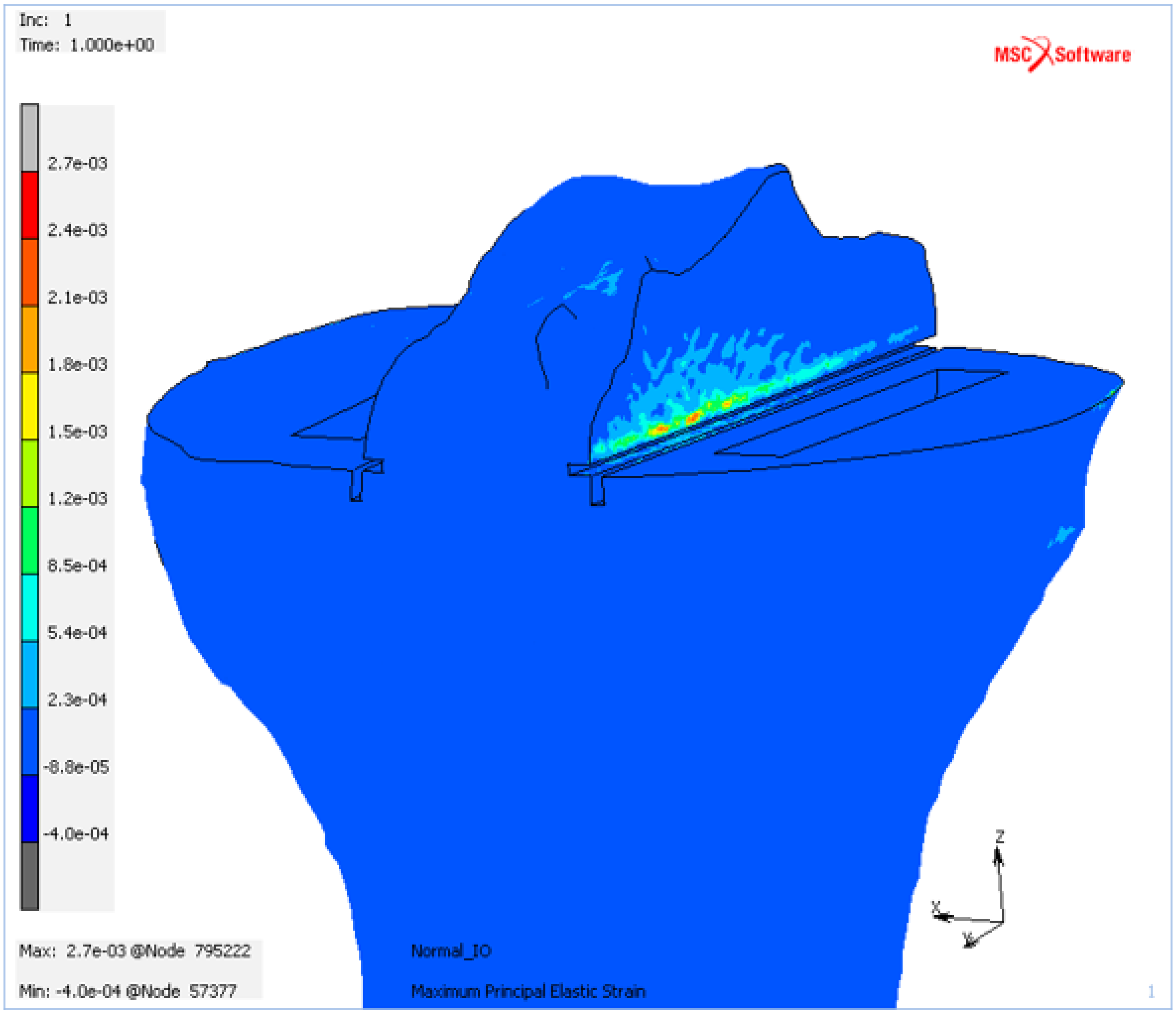

Fig. 2

Maximum principal elastic strain in the male baseline bi-unicondylar knee arthroplasty model for the balanced loadcase. Blue indicates low/compressive strains and red indicates the highest predicted tensile strains.

effect was external rotation of the UKA-M, increasing ROF by 22%. Distal translation of the UKA-M increased ROF by 12%. All other variations resulted in changes in ROF < 10%.

Effect of overstuffing. Overstuffing the joint with bearings two sizes larger resulted in ~600% increases in ROF regardless of implant positioning. The worst case was the combination of overstuffing with lateral translation of the UKA-M (Figure 4).

Sensitivity to anatomy. Following Bi-UKA, the ROF predicted for the smaller, less dense female model was 43% higher than the male model (Figure 5).

Comparison to UKA-M and the effect of anterior bone cuts for BCR-TKA. For both the male and female tibiae, ROF in Bi-UKA was predicted to be 9% to 13% higher than in UKA-M for the planned positions and all variations simulated (Figures 5 and 6). Anterior bone cuts for BCR-TKA increased ROF (Figure 7): 55% for a 5 mm cut, and 105% for a 10 mm cut.

Sensitivity analyses. The conclusions drawn from the model were found to be insensitive to the material property assignment, and choice of ACL load distribution (Supplementary Material).

Discussion

The most important finding from this study was that there was only a small increase in the risk of tibial eminence avulsion fracture in Bi-UKA compared to UKA-M for both the larger, denser male tibia (Figure 6) and the female tibia (Figure 5). The predicted strains were an order of magnitude below the 6,500 με fracture limit, and thus this FE analysis supports the use of Bi-UKA. For all experiments, the highest strains in the tibia were seen on the anterior portion of the face of the medial sagittal cut, distal to the ACL attachment (Figure 2). The initiation of failure at this point is intuitive, correlating with the anatomy of the ACL, which pulls posteriorly and laterally on the tibial eminence.

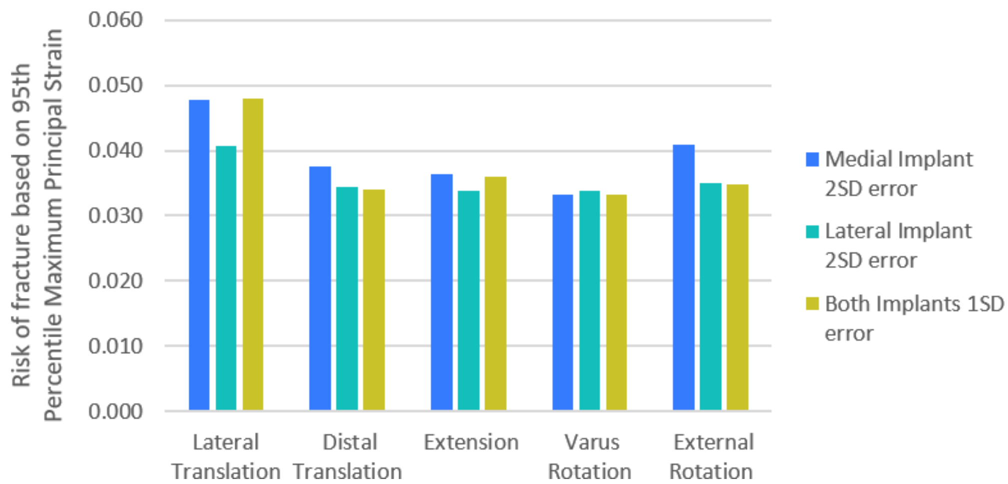

Fig. 3

Bar graph showing the percentage difference in risk of fracture as the positions of the isolated medial unicondylar knee arthroplasty (UKA-M) and isolated lateral unicondylar knee arthroplasty (UKA-L) components were varied from the planned bi-unicondylar knee arthroplasty based on the typical accuracy achieved with manual instruments. A 2 standard deviation (SD) variation of the UKA-M implant only (blue), 2 SD variation in the UKA-L only (green), and 1 SD variation of both implants (yellow) are shown. In all cases the variation acts to narrow the bone island and/or make it taller.

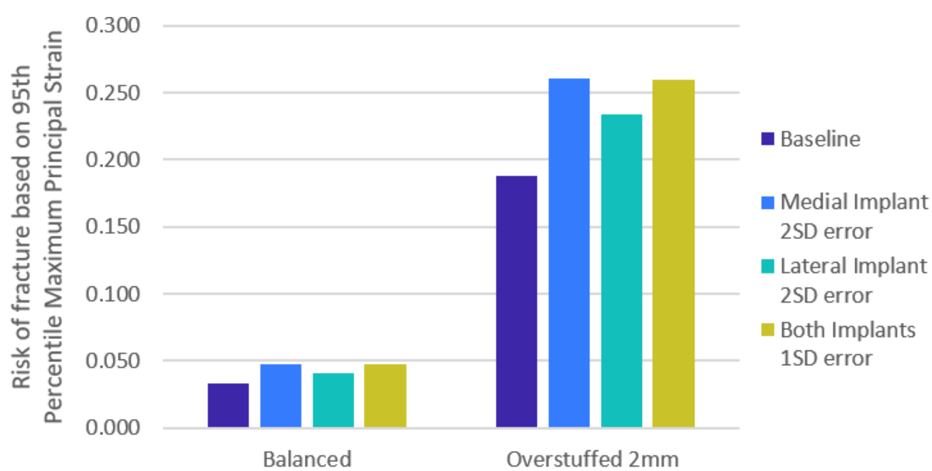

Fig. 4

Bar graph showing the risk of fracture in bi-unicondylar knee arthroplasty (Bi-UKA) when the knee is balanced, and overstuffed by 2 mm. Dark blue bars show risk of fracture with Bi-UKA in the planned positions, while the variations displayed are of mediolateral translation of each implant. This is representative of all the directions of surgical variations.

Overstuffing increased ROF the most: a 2 mm distraction of the joint led to strains six times higher than when native joint laxity was restored (Figure 4). Trial meniscal bearings should be chosen conservatively, working upwards in thickness to minimize likelihood of overstuffing. Slow extension of the knee when trialling bearings, and close attention to resistance to extension, may also help to avoid these higher joint loads. Moving the UKA-M away from the planned position led to higher ROF than the same degree of variation of the UKA-L. Furthermore, variations that narrowed the island anteromedially resulted in the largest increase (i.e. UKA-M external rotation and lateral translation) due to the posterolateral directed ACL tension. Positional variation that made the bone island taller also increased fracture risk, but to a lesser extent (i.e. extension and distal translation), a finding that is likely a consequence of bone stiffness decreasing distally from the joint line. These results highlight the need to position the medial implant correctly. The removal of anterior bone also acted to increase ROF in comparison to Bi-UKA, with 10 mm of bone removed more than doubling the tensile strains in the spine. This demonstrated that BCR-TKA and Bi-UKA are fundamentally different, with Bi-UKA a lower-risk procedure for maintaining ACL function, as the anterior bone is not compromised. The peak tensile strains in the smaller, less dense female tibia were approximately 1.5 times higher than in the male specimen. The increase in fracture risk

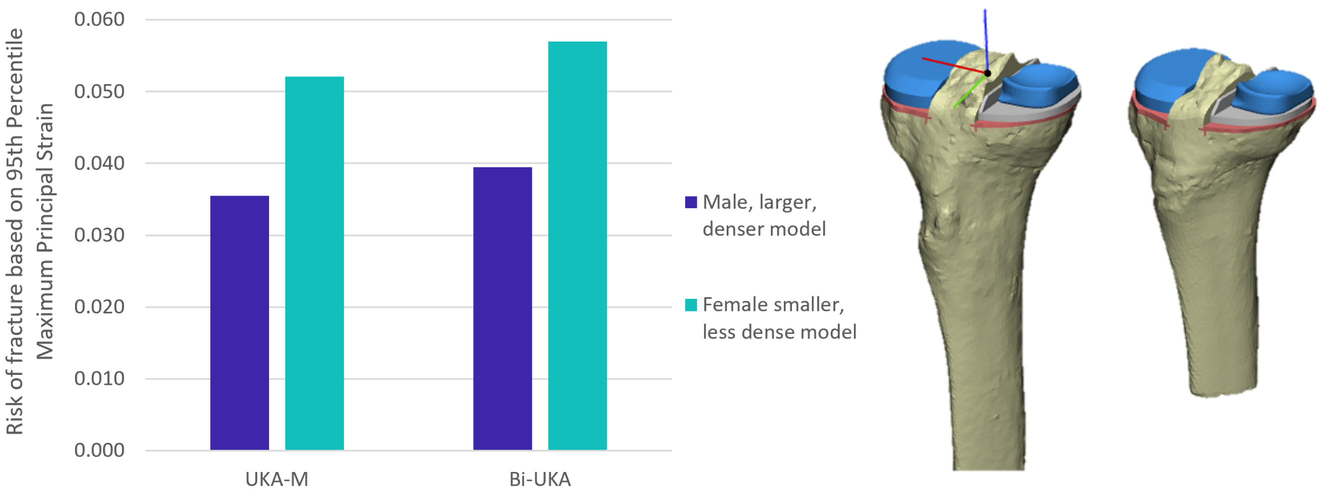

Fig. 5

Bar graph showing the risk of fracture in isolated medial unicondylar knee arthroplasty (UKA-M) and bi-unicondylar knee arthroplasty (Bi-UKA) when the knee is balanced in the male (dark blue) and female (turquoise) tibiae.

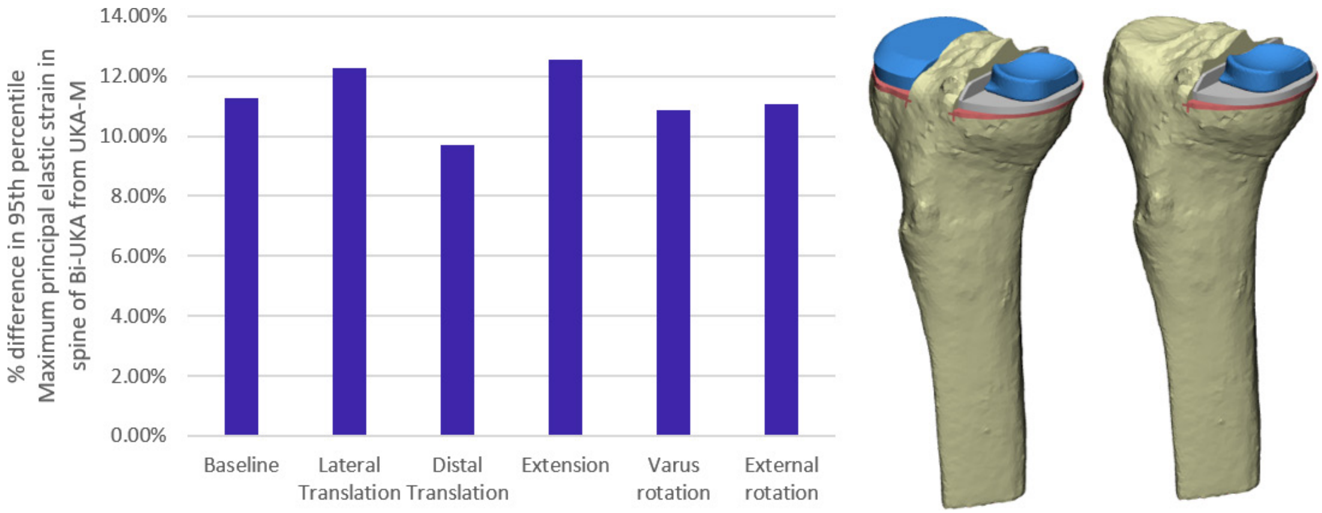

Fig. 6

Bar graph showing the percentage difference in maximum principal elastic strain (MPES)-95 measured in the medial portion of the spine of bi-unicondylar knee arthroplasty (Bi-UKA) from isolated medial unicondylar knee arthroplasty (UKA-M), when the implants are positioned as planned, and with typical surgical variation applied to the medial implant.

was similar for both the larger, denser male (11.3%) and smaller, less dense female (9.3%) models with Bi-UKA compared to UKA-M. While all ROFs measured in this study were less than 1, only two bones were analyzed; this finding indicates that a combination of a smaller tibia and less dense bone may lead to an appreciable risk for some patients, particularly if the joint was overstuffed intraoperatively. Hence, additional care may be needed in planning Bi-UKA for osteoporotic, small females, as well as intraoperatively.

To the authors' knowledge, this is the first study to examine tibial eminence avulsion fracture risk following arthroplasty, so there are no studies that provide a direct comparison. The modelling methods employed are similar to those used in recent FE studies focused on tibial strains following UKA-M. Pegg et al[19] investigated similar surgical cut parameters in their probabilistic FE study looking at condylar fracture risk post-UKA. They considered gait-loading rather than intraoperative loads, and so saw larger condylar loads as well as muscle-loading leading to a generally compressive strain field, rather than the tensile field induced in the spine intraoperatively. Despite this, they also found that the corner where the transverse and sagittal cuts met was at high risk of fracture. Danese et al[42] looked at the effect of malalignment on proximal tibial strains for UKA-M, using a similar number of models and similar modelling parameters to this study, and found that varus/valgus alignment had a greater effect on compressive overstraining under UKA-M compared to internal/external rotation. Thus, it appears

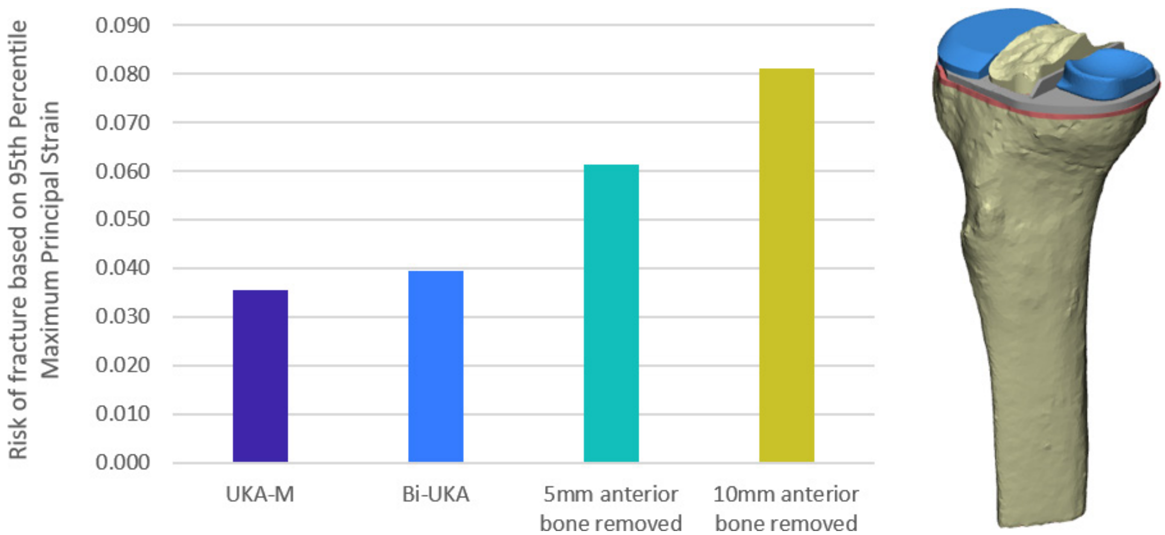

Fig. 7

Bar graph showing the risk of fracture in isolated medial unicondylar knee arthroplasty (UKA-M) and bi-unicondylar knee arthroplasty (Bi-UKA) when the knee is balanced, and when 5 mm and 10 mm of bone is removed anteriorly.

that the varus/valgus positioning is important to avoid postoperative fractures during functional activity, and rotational positioning is important to avoid avulsion fractures intraoperatively. A recent study determined that surgical cut errors in UKA-M were effected by limb posture.[43] They found similar errors to those used in this study, however they found significantly higher errors in the internal rotation of the medial component when the traditional supine leg position was used, rather than the manufacturer-recommended hanging leg position. The extreme of the internal rotation error associated with the supine position was greater than the error assessed in this study. The magnitude of the errors used in this study was representative of traditional surgical techniques, however both compound translational and compound rotational errors have been shown to be reduced with robot-assisted surgery.[36] As such, the results of this study may overestimate the risk of ACL avulsion compared to that which might be expected in robot-assisted Bi-UKA, for which there has been a growing interest.[14,44]

The models used for this research were originally developed and validated for UKA-M under compressive loading, for medial cortical strains distal to the implant and bone-implant micromotions. It was assumed that the utility of this model could be extended to also include UKA-L, with an additional tensile ACL load applied, and examining regions of interest closer to the implants. Other researchers have made similar assumptions, using cortical strain measurements as a basis for validation of bone FE models investigating fracture.[19,45-48] While direct data to validate peri-implant bone strains were not available, the internal stress distribution predicted by the model was found to be similar to recently published experimental measurements,[49] verifying that the predicted peri-implant cancellous bone stresses were representative of reality (Supplementary Figure b). This research did not study fracture propagation,[50] with MPES-95 used as a surrogate measure to determine whether fracture would occur. None of the simulations resulted in MPES-95 that exceeded the tensile yield strain of proximal tibial bone, although the absolute peak tensile strains in overstuffed Bi-UKA did exceed this threshold (Supplementary Material), and hence such a fracture could propagate with the progressive deactivation of overstrained elements and may explain the clinical observation that ACL avulsion can occur intraoperatively. Gait load cases were not simulated, as there have been no reports of avulsion postoperatively. Further, postoperative condylar fracture during gait was not studied, as this has been analyzed with the FE method by others for UKA-M. One limitation was that the femur was not modelled; a steeper posterior slope (flexed implant) can lead to anterior tibial translation and consequently increased ACL strain.[51] Omitting the femur and a continuum model of the ACL allowed for a computationally cheaper model, and so more simulations could be run; the effect of relative femoral translations may be a topic of future work. The magnitude of the typical variations in implant positions simulated were taken from two Sawbones studies, one looking at UKA-M and the other UKA-L. There have been no studies quantifying the variations in Bi-UKA and so it was assumed that the errors from each of the unicompartmental procedures would be the same in bicompartmental surgery. The authors of these studies suggested that surgeons would take greater care in positioning the implants in a real surgery, and so expected the errors to be smaller than those measured.[38] However, the limited exposure intraoperatively may also serve to increase errors compared to the synthetic bone, capsule, and four-ligament model.[37] Finally, ligament loading necessitated the combination of multiple studies, and hence is a representative model of intraoperative loading, rather than an exact model for the two tibiae simulated.

In conclusion, the risk of tibial eminence avulsion fracture associated with Bi-UKA is similar to UKA-M, suggesting that any perceived risk of avulsion should not weigh heavily in decision-making regarding knee arthroplasty procedures. The risk was higher for a smaller and less dense female tibia. To minimize risk, it is most important to avoid overstuffing of the joint, followed by correctly positioning the medial implant, taking care not to narrow the bone island anteriorly.

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Supplementary material

Numerical results for each experiment are presented for different percentiles of the maximum principal elastic strain. Sensitivity studies referred to in the main text are explained further.

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