



## ■ RESEARCH

# The effect of implant position on bone strain following lateral unicompartmental knee arthroplasty

A BIOMECHANICAL MODEL USING DIGITAL IMAGE CORRELATION

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## Objectives

Unicompartmental knee arthroplasty (UKA) is a demanding procedure, with tibial component subsidence or pain from high tibial strain being potential causes of revision. The optimal position in terms of load transfer has not been documented for lateral UKA. Our aim was to determine the effect of tibial component position on proximal tibial strain.

## Methods

A total of 16 composite tibias were implanted with an Oxford Domed Lateral Partial Knee implant using cutting guides to define tibial slope and resection depth. Four implant positions were assessed: standard (5° posterior slope); 10° posterior slope; 5° reverse tibial slope; and 4 mm increased tibial resection. Using an electrodynamic axial-torsional materials testing machine (Instron 5565), a compressive load of 1.5 kN was applied at 60 N/s on a meniscal bearing via a matching femoral component. Tibial strain beneath the implant was measured using a calibrated Digital Image Correlation system.

## Results

A 5° increase in tibial component posterior slope resulted in a 53% increase in mean major principal strain in the posterior tibial zone adjacent to the implant ( $p = 0.003$ ). The highest strains for all implant positions were recorded in the anterior cortex 2 cm to 3 cm distal to the implant. Posteriorly, strain tended to decrease with increasing distance from the implant. Lateral cortical strain showed no significant relationship with implant position.

## Conclusion

Relatively small changes in implant position and orientation may significantly affect tibial cortical strain. Avoidance of excessive posterior tibial slope may be advisable during lateral UKA.

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**Keywords:** Lateral unicompartmental knee arthroplasty, Digital image correlation, Bone strain, Tibial strain, Implant position

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## Article focus

- Investigation of the effect of lateral unicompartmental knee arthroplasty (UKA) tibial component position on proximal tibial strain.
- Increased and reversed sagittal slope and increased resection depth assessed.
- A biomechanical model using digital image correlation to measure strain.

## Key messages

- A 5° increase in posterior sagittal inclination results in a 53% increase in tibial strain adjacent to the implant posteriorly.
- The highest mean strains for all implant positions were generated in the

anterior cortex 2 cm to 3 cm distal to the implant.

- Avoidance of excessive posterior tibial slope may be advisable during lateral UKA.

## Strengths and limitations

- The first biomechanical study to assess the effect of lateral UKA implant position on proximal tibial cortical strain.
- Further studies are needed to assess the effect of coronal alignment and component rotation, and the effect of component position on cancellous bone.
- Clinical corroboration to determine the *in vivo* effects of implant position.

**Table 1.** Oxford Domed Lateral Partial Knee tibial implant position parameters for Digital Image Correlation experiment

	Resection depth (mm)	Posterior slope	Medial slope	Axial rotation	Implant size
Standard	4.5	5°	3°	0°	B
Increased resection	8.5	5°	3°	0°	B
Reversed slope	4.5	-5°	3°	0°	B
Increased slope	4.5	10°	3°	0°	B

Resection depth relative to lowest point on lateral tibial plateau. Rotational alignment relative to axes as defined using the two best-fit circle technique<sup>17</sup>

## Introduction

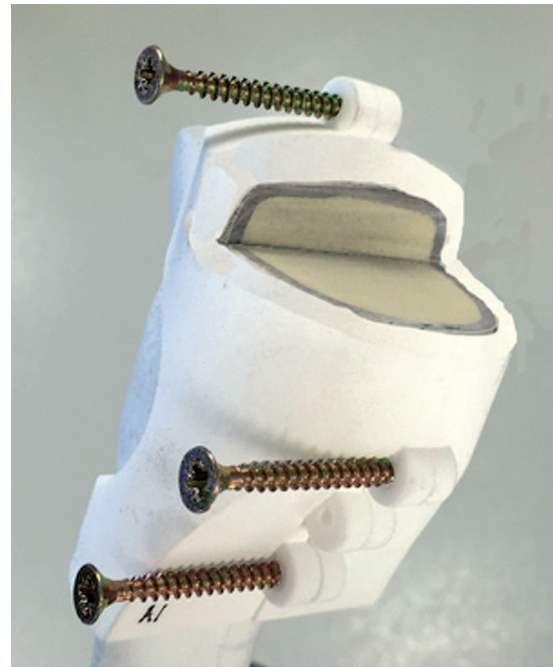
Unicompartmental knee arthroplasty (UKA) may be used for the treatment of osteoarthritis in patients with appropriate indications, offering improved functional outcome, faster recovery and reduced morbidity compared with total knee arthroplasty (TKA).<sup>1-3</sup> However, the use of UKA has been criticised for its comparatively high revision rate.<sup>3,4</sup> In the most recent report from the National Joint Registry for England and Wales, UKA accounted for just 9% of primary knee arthroplasties, despite evidence that almost 50% of patients may be suitable candidates for the procedure.<sup>4,5</sup>

Common causes of UKA revision include component subsidence, tibial fracture and unexplained pain, with the latter accounting for 23% of revisions compared with 9% of revisions after TKA.<sup>6</sup> High strain concentrations in the proximal tibia have been implicated as a potential cause of these problems.<sup>7-9</sup> While previous biomechanical studies have shown that resection depth, component rotation and sagittal and coronal alignment of the tibial component can significantly affect proximal tibial strain after medial UKA, we are unaware of any published studies that evaluate the effect of implant position on tibial strain after lateral UKA.<sup>10,11</sup>

Digital Image Correlation (DIC) is a commonly used technique to measure full-field strain patterns in materials science and engineering. Through comparing digital images of an object at different stages of deformation and displacement, the surface strain can thus be calculated. DIC has been used in the assessment of both cadaveric and synthetic composite bones with and without implants to assess strain patterns under load.<sup>10,12-14</sup> The use of computer navigation and patient-specific instrumentation offer the potential for more accurate implant placement. However, at present there is no consensus on optimum positioning, nor on tolerances for the placement of lateral UKA components.<sup>15</sup> In this study, we used DIC to assess the effect of resection depth and sagittal inclination on proximal tibial strain after lateral UKA.

## Materials and Methods

A total of 16 fourth-generation synthetic composite bones were used for this study (Sawbones Europe AB, Malmö, Sweden). These comprise a short fibre-filled epoxy composite that simulates cortical bone (Young's modulus  $E = 16.7$  GPa) and rigid polyurethane foam that simulates cancellous bone ( $E = 0.155$  GPa). The bones

**Fig. 1**

Composite tibia post-osteotomy with a cutting guide *in situ*.

are reported to have < 10% interspecimen variability with material and mechanical properties similar to that of cadaveric bone.<sup>16</sup>

A CT scan of a representative bone was performed to obtain a Digital Imaging and Communications in Medicine (DICOM) file to facilitate surgical planning. Segmentation of the DICOM data was performed to produce a Stereolithography file (Acrobot Modeller; Acrobot, London, United Kingdom). Surgical plans for the Oxford Domed Lateral Partial Knee tibial component (Biomet, Bridgend, United Kingdom) were formulated using custom planning software (Acrobot Planner; Acrobot). Four tibial plans were generated (Table 1).<sup>17</sup> In all four plans, a size B tibia was the most appropriate of the four component sizes available.

Cutting guides were designed by Embody (Embodiy Orthopaedic Ltd., London, United Kingdom) using computer-aided design software (Solidworks, Waltham, Massachusetts and Rhinoceros, Barcelona, Spain). Guides encapsulated the proximal tibia to maximise accuracy (Fig. 1). Guides were produced using the Objet Eden250 3D Printing System (Objet Ltd., Rehovot, Israel) with a

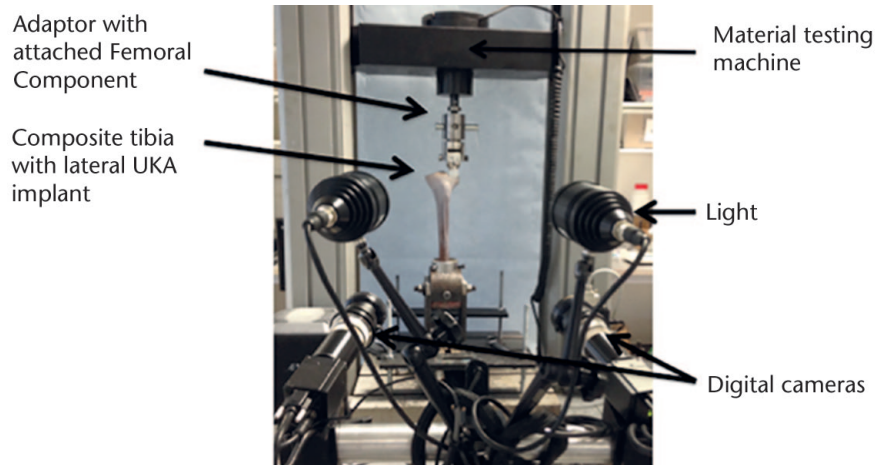


Fig. 2

Experimental setup for Digital Image Correlation (DIC) experiment. The speckle-painted composite tibia with tibial implant *in situ* is positioned vertically under the materials testing machine load cell. The load cell is fitted with an adaptor for a femoral unicompartmental knee arthroplasty component. The DIC apparatus includes two halogen lamps and two digital cameras set up at a 60° angle to each other.

medical-grade polymer (Objet MED610). The bones were prepared using the bone-specific guides and standard Oxford Domed Lateral Partial Knee instrumentation. The tibial components were cemented *in situ* with polymethylmethacrylate (PMMA) (Simplex Rapid; Austenal Dental Products Ltd., Swindon, United Kingdom), with care taken to ensure an even 1 mm cement mantle as measured by digital micrometer. Bones were speckled with a thin layer of white and black matt paint (Plastikote; Valspar Paint UK, Wokingham, United Kingdom) to produce sufficient contrast for DIC.

The distal 8 cm of the bone was removed and the remaining bone placed within a steel cylinder and set in PMMA to a depth of 10 cm. Bones were positioned vertically in a screw-driven materials testing machine with a 5 kN load cell (Instron 5565; Instron Co., High Wycombe, United Kingdom). A medium Oxford UKA femoral component was cemented to an adaptor that was fitted to the load cell of the materials testing machine. A 5 mm Oxford Domed Lateral Partial Knee bearing was used for the study, with the tibia positioned to ensure that the bearing was centred on the tibial implant in the coronal plane and the midpoint of the bearing was 18 mm from the anterior margin of the implant, consistent with the loading position in full knee extension.

A 3DDIC system (GOM 5M; GOM GmbH, Braunschweig, Germany) with a strain measuring accuracy of up to 0.005% was used (Fig. 2). The system was calibrated prior to use with a calibration block. A preload of 5 N was applied and three images acquired before loading at 60 N/s to a maximum load of 1.5 kN. To image the entire lateral tibial plateau, three projections were obtained for each bone: anterior; lateral; and posterior. For each projection, each bone was loaded five times. Images were acquired at two-second intervals during loading. The final

image, acquired ten seconds after the maximum load had been reached, was used for analysis.

DIC analysis was conducted using Aramis software (GOM GmbH). An identical DIC facet size (15 pixels) was used in each analysis. Major principal strain data were obtained for each projection, with the lateral projection divided into anterior and posterior sections. The medial border of the implant marked the medial limit of the analysis for the anterior and posterior projections. Three 1 cm bands relative to the position of the inferior surface of the tibial implant at the midpoint of each of the four sections were defined (zone 1: 0 cm to 1 cm distal to inferior surface of implant; zone 2: 1 cm to 2 cm distal to inferior surface of implant; zone 3: 2 cm to 3 cm distal to inferior surface of implant, Fig. 3). Consequently, 12 zones extending to a distance 3 cm distal to the tibial implant (three anteriorly, three posteriorly and six laterally) were produced for analysis in a manner similar to that performed by Small et al<sup>18</sup> for the medial proximal tibia.

**Statistical analysis.** The mean major principal strain for DIC facets within each zone was obtained for each bone. Normal distribution of data was assumed and groups compared by one-way analysis of variance (ANOVA) with *post hoc* Dunnett's correction (taking the standard implant position as the control group). To determine the relative importance of implant position and zone, a two-way repeated measures ANOVA (implant position/zone, with zone as the repeated measure) was performed for the anterior and posterior surfaces. For the lateral surface, a three-way repeated measures ANOVA was performed (implant position/zone/anterior or posterior position on lateral surface). Analysis was performed using the SPSS statistical programme (Version 24; IBM Corp., Armonk, New York). A *p*-value < 0.05 was taken as statistically significant throughout.

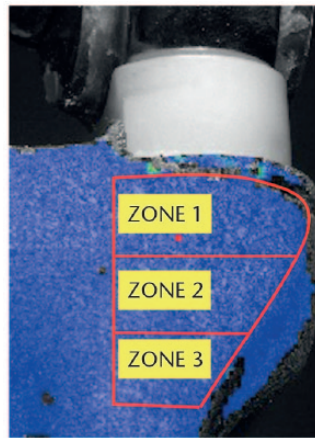


Fig. 3a

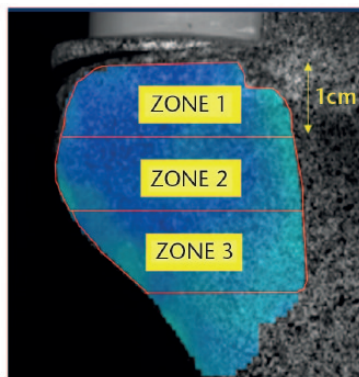


Fig. 3b

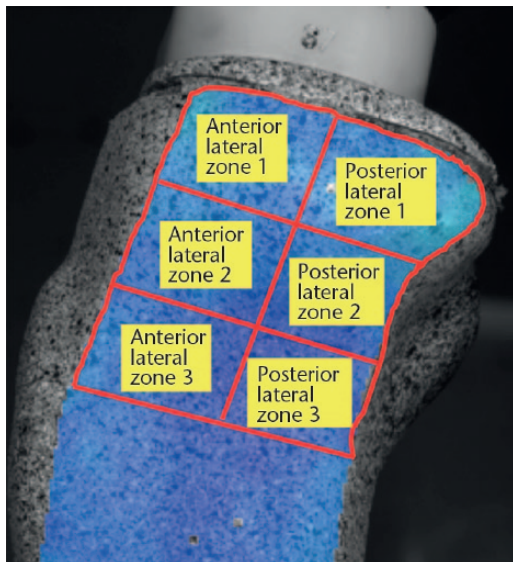


Fig. 3c

Images showing the mean major principal strain calculated in a) three anterior zones; b) three posterior zones; and c) six lateral zones

## Results

The mean major principal strain results for each of the 12 zones (three anterior, three posterior and six lateral) across all samples is displayed in Figures 4 to 6.

In the anterior zones, mean strain was lower with the standard implant position than with increased resection,

reverse slope or increased slope positions, although this difference was not statistically significant (Fig. 4). For all implant positions, the mean anterior strain increased with distance from the implant and was significantly higher in zone 3 than in zones 1 or 2. However, when zone 3 mean strain was compared between implant positions there was no significant difference (for the effect of zone,  $F = 43.2$  ( $p < 0.001$ ) and for the effect of implant position,  $F = 0.534$  ( $p = 0.670$ ) with no significant interaction between the two variables ( $F = 0.888$ ,  $p = 0.524$ )).

In the posterior region, the highest mean strains were observed in zone 1 (i.e. closest to the implant) for all positions (Fig. 5), in contrast to the trend observed anteriorly. Increased posterior slope was associated with the highest posterior cortical strains, with a 53% increase in strain in the zone adjacent to the implant when compared with the standard implant position (mean principal strain = 0.280 versus 0.183,  $p = 0.003$ ) (Fig. 7).

There were no significant differences between the four implant positions with respect to lateral cortical strain and, as with posterior zones, mean lateral strains were significantly lower with increasing distance from the implant (for the effect of zone,  $F = 9.408$  ( $p = 0.031$ ), for the effect of implant position,  $F = 0.297$  ( $p = 0.827$ ) and for the effect of anterior or posterior position on the lateral surface,  $F = 7.316$  ( $p = 0.114$ ), with no significant interactions between any of the variables ( $F = 1.571$ ,  $p = 0.238$ )).

With most of the strain at this level being delivered onto the anterior cortex, 2 cm to 3 cm distally, the strain was similar laterally and posteriorly (Fig. 8).

## Discussion

This is the first study to evaluate the effect of lateral UKA implant position on proximal tibial cortical strains. Increased posterior slope resulted in significantly higher posterior strain adjacent to the implant and non-significant increases in other posterior regions relative to the standard implant position. Although no studies exist for comparison with lateral UKA, our results are in keeping with a number of studies that assess the effect of increased posterior slope in medial UKA.<sup>10,19,20</sup> Small et al<sup>10</sup> found that a change from 5° to 10° in posterior slope for the Oxford medial UKA gave a significant increase in strain response in the proximal, posterior region as measured by DIC and strain gauges. In a series of 32 UKAs that required revision, Aleto et al<sup>20</sup> found that 15 tibial components failed by medial collapse. For these 15, the tibial slope predicted the aspect of medial collapse, with those that collapsed posteriorly having a mean posterior slope of 12° and those that collapsed anteriorly having a mean slope of 4.8°. Gulati et al<sup>21</sup> found no difference in clinical outcome using the Oxford UKA among all patients in their study when sagittal tilt was within standard deviation 5° of a neutral 7° slope, and a finite element analysis from the same centre found that sagittal alignment was a

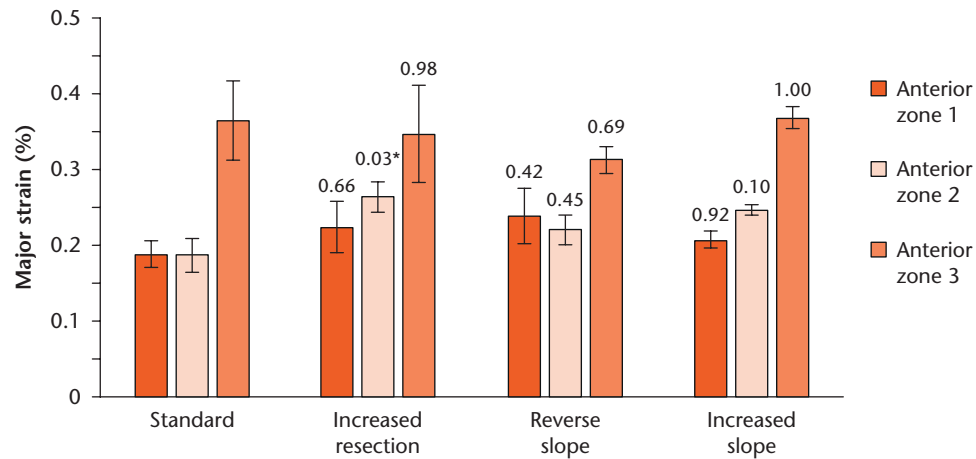


Fig. 4

Graph showing the mean (standard error) major principal strain (%) for the anterior three zones with each implant position. Above the bar for each zone is shown the p-value for comparison with the equivalent zone using the standard implant position. \*indicates  $p < 0.05$ .

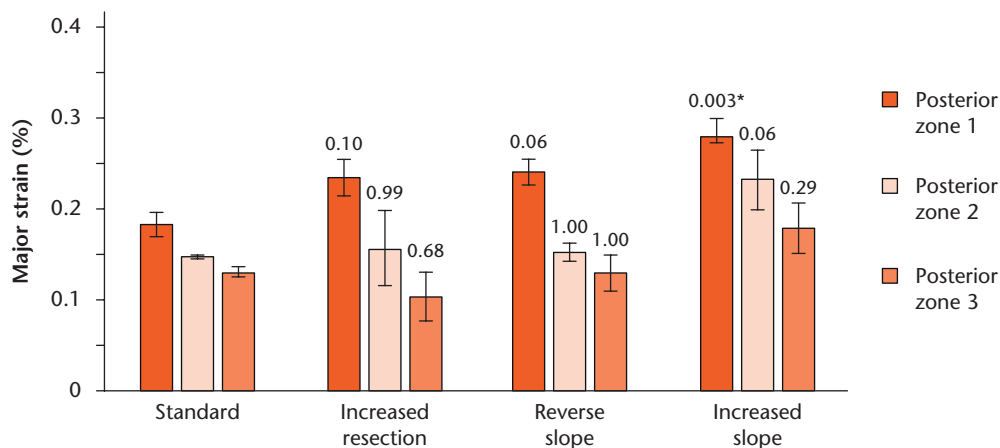


Fig. 5

Graph showing the mean (standard error) major principal strain (%) for the posterior three zones with each implant position. Above the bar for each zone is shown the p-value for comparison with the equivalent zone using the standard implant position. \*indicates  $p < 0.05$ .

less important determinant of proximal tibial strain than varus malalignment, increased tibial resection or component overhang.<sup>22</sup> The differences in morphology of the medial and lateral tibiofemoral compartments make comparison between them difficult. Our results support the view that excessive posterior slope can produce significant increases in strain. This increased strain seen in the bone close to the prosthesis may add to the risk of microfracture, resorption and early loosening, at least contributing an objective metric to this discussion. Whether this affects clinical outcomes for the lateral compartment was not addressed in this study.

Several studies assessing medial UKA have shown that increased resection depth increases strain.<sup>10,22</sup> However, in our study the effect of increased resection depth was inconsistent and dependent upon distance from the implant. Adjacent to the implant, mean strains were higher for the increased resection group than for the standard position group, although this trend was

reversed with increased distance from the implant. Most strain was delivered onto the anterior cortex 2 cm to 3 cm distal to the implant, and this was true regardless of implant position.

Our study has a number of limitations. Whilst fourth-generation composite bone models have been shown to exhibit similar geometric and mechanical properties to cadaveric tissue,<sup>23,24</sup> our model nonetheless overlooks the contribution from soft tissues and dynamic forces around the knee, including the load-distributing effects of the meniscus. The *in vivo* effect of increased strain is also unclear. While higher strains may, in the short term, be associated with pain or fracture, controlled microdamage to bone acts as a stimulus for remodelling that may then reduce strain to a normal level.<sup>25,26</sup> However, strains above a threshold level may induce bone degeneration.<sup>26</sup> The impact of tibial implant malpositioning with respect to cancellous bone strain was not considered and may be an area for further study, potentially through acoustic

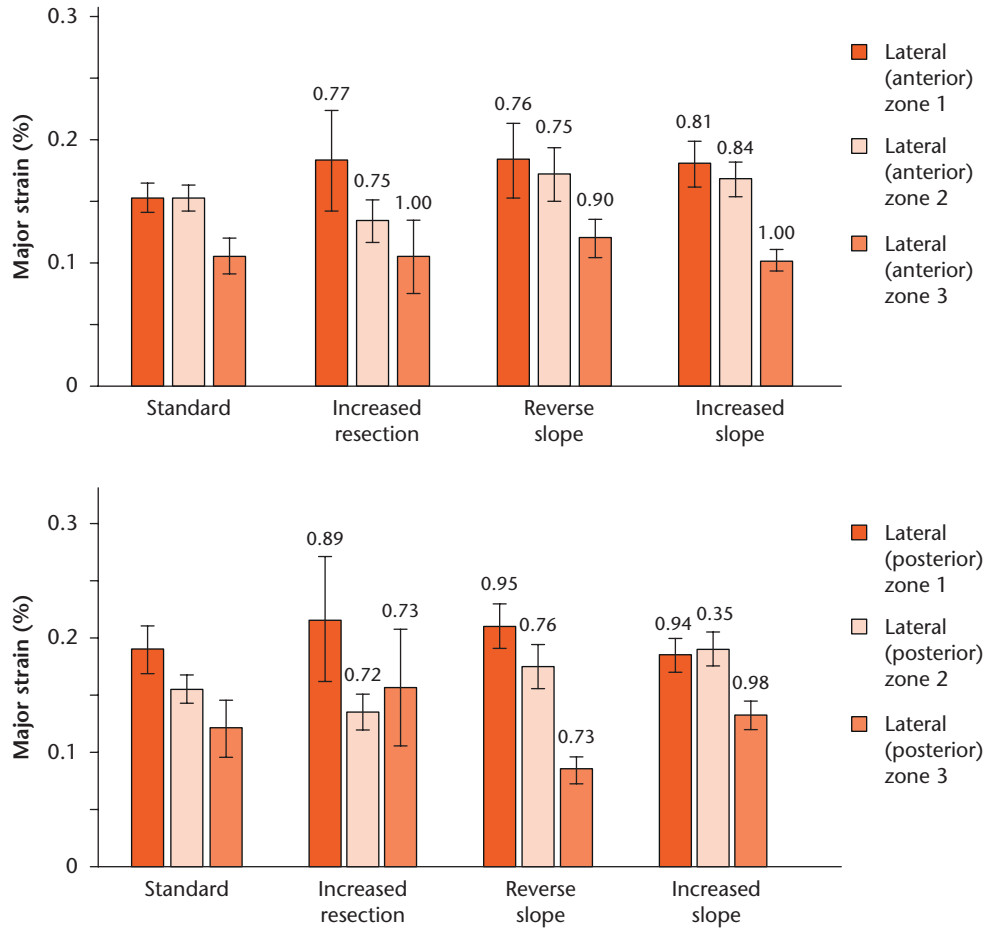


Fig. 6

Graphs showing the mean (standard error) major principal strain (%) for the six lateral zones with each implant position. Above the bar for each zone is shown the p-value for comparison with the equivalent zone using the standard implant position.

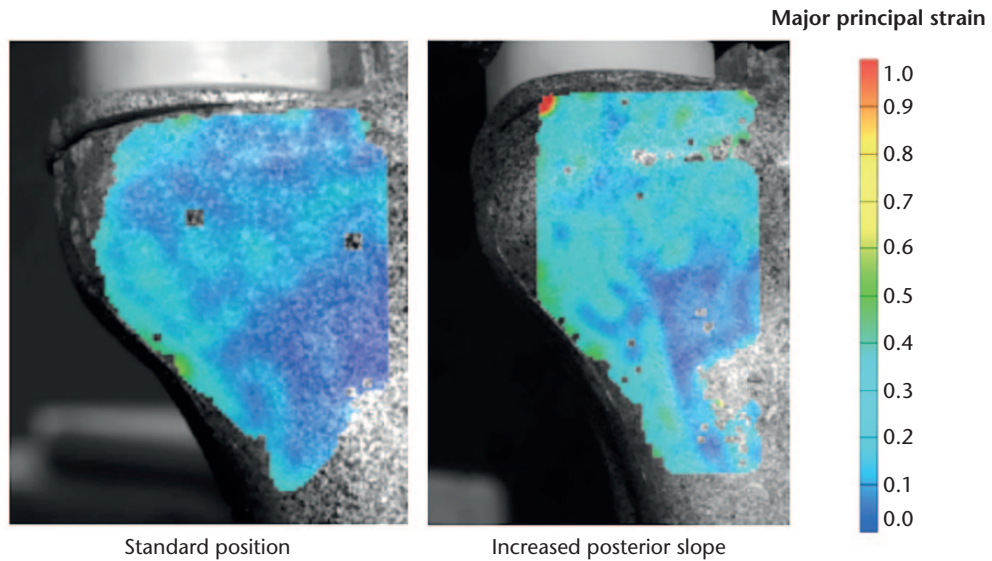
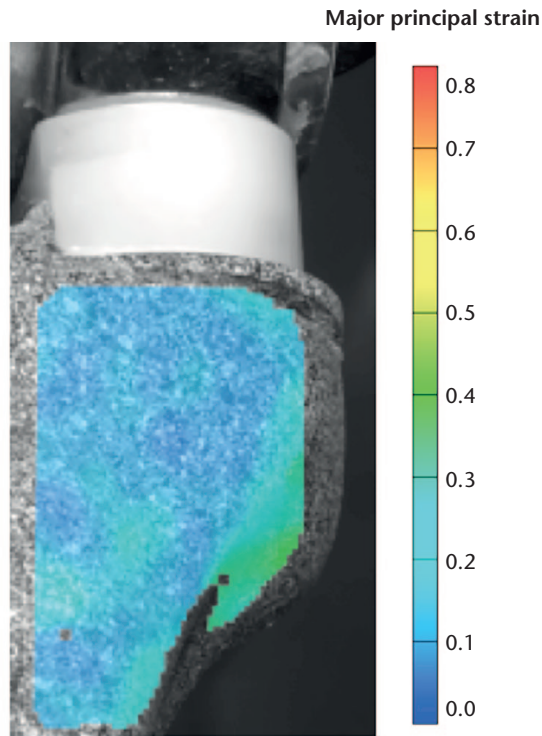


Fig. 7

Digital Image Correlation images demonstrating the posterior cortices of a standard implant position bone (left) and an increased implant posterior slope bone (right), both loaded at 1.5 kN. Higher strain values (major principal strain, %) are seen with increased posterior slope, particularly immediately adjacent to the implant.



**Fig. 8**

Anterior Digital Image Correlation image of a standard implant position bone loaded at 1.5 kN, demonstrating that the highest strains are being delivered onto the anterior cortex 2 cm to 3 cm distal to the implant.

emission monitoring or digital volume correlation techniques.<sup>27,28</sup> Additional factors that have been shown to affect strain in medial UKA that we did not assess include component rotation, coronal alignment and bonded contact between the vertical wall and adjacent bone.<sup>10,19,22</sup>

In normal coronal alignment, it has been estimated that 60% of load through the knee is transmitted through its medial compartment, with a total force through the knee of at least four-times body weight during stair ascent.<sup>29</sup> During single-leg stance, the force through the lateral compartment for a 75 kg adult would therefore be 294 N, increasing with activity and being expected to reach more than 1.2 kN during stair ascent, other strenuous activity and in patients of greater weight. In our study, the load applied was 1.5 kN. The importance of implant position at different loads is beyond the scope of this study, but, given the potential significance of peak strain, 1.5 kN is a clinically meaningful value for lateral compartment load.<sup>22</sup> Our study does not, however, account for the *in vivo* effects of loading purely through the lateral compartment which is a non-physiological state and may affect the pattern of lateral load distribution and thereby the effect of implant position. For example, increased resection depth may affect the proportion of load transmitted through the medial compartment, and *in vivo* compensatory mechanisms may influence the relationship between total load through the knee and lateral cortical strain. Moreover, we simulated the effect of

tibial loading with the knee in extension but the sagittal plane kinematics of the lateral tibiofemoral compartment may result in significantly higher posterior strain as the knee flexes, and thus the strains exhibited here may be an underestimate of *in vivo* values.

The lack of published studies on the outcome of lateral UKA, in particular with regard to modes of failure, makes it difficult to infer the direct clinical relevance of our findings. The most commonly reported reasons for failure of lateral UKA include progression of osteoarthritis, aseptic loosening, bearing dislocation and unexplained pain.<sup>30</sup> The importance of increased cortical strain in each of these scenarios has not been established. It has been postulated that if strain values in cortical bone exceed 4000 microstrains, bone remodelling will lead to degeneration and thus implant failure.<sup>7,25</sup> The strain values observed in our study were below this threshold and so it is possible that, while they may be associated with pain, bone remodelling could compensate for this over time and reduce strain values observed *in vivo*.

In conclusion, this is the first study to assess the effect of component orientation and position on bone strains associated with lateral UKA. Despite limitations, it provides evidence of the impact of even moderate changes in implant position and orientation on proximal tibial strain. Errors in both slope and resection depth can cause excessive strain and thus should be avoided. Clinical studies are needed to confirm the significance of these findings. Any assistive technologies which enable greater precision in implant positioning and orientation may help in avoiding these errors, as may the use of pre-operative planning.<sup>31,32</sup>

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#### Author Contributions

- A. M. Ali: Study planning, execution and analysis, Composing manuscript.
- S. D. S. Newman: Study planning, execution and analysis, Composing manuscript.
- P. A. Hooper: Study planning, execution and analysis, Composing manuscript.
- C. M. Davies: Study planning, execution and analysis, Composing manuscript.
- J. P. Cobb: Study planning, execution and analysis, Composing manuscript.

#### Conflicts of Interest Statement

None declared

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