



■ ARTHROPLASTY, KNEE

Metaphyseal cones in revision total knee arthroplasty

THE ROLE OF STEMS

**S. Xie,
N. Conlisk,
D. Hamilton,
C. Scott,
R. Burnett,
P. Pankaj**

*The University
of Edinburgh,
Edinburgh, UK*

Aims

Metaphyseal titanium cones can be used to manage the tibial bone loss commonly encountered at revision total knee arthroplasty (rTKA). Tibial stems provide additional fixation and are generally used in combination with cones. The aim of this study was to examine the role of the stems in the overall stability of tibial implants when metaphyseal cones are used for rTKA.

Methods

This computational study investigates whether stems are required to augment metaphyseal cones at rTKA. Three cemented stem scenarios (no stem, 50 mm stem, and 100 mm stem) were investigated with 10 mm-deep uncontained posterior and medial tibial defects using four loading scenarios designed to mimic activities of daily living.

Results

Small micromotions (mean < 12 μm) were found to occur at the bone-implant interface for all loading cases with or without a stem. Stem inclusion was associated with lower micromotion, however these reductions were too small to have any clinical significance. Peak interface micromotion, even when the cone is used without a stem, was too small to effect osseointegration. The maximum difference occurred with stair descent loading. Stress concentrations in the bone occurred around the inferior aspect of each implant, with the largest occurring at the end of the long stem; these may lead to end-of-stem pain. Stem use is also found to result in stress shielding in the bone along the stem.

Conclusion

When a metaphyseal cone is used at rTKA to manage uncontained posterior or medial defects of up to 10 mm depth, stem use may not be necessary.

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Keywords: Bone defect, Finite element analysis, Interfacial micromotion, End-of-stem pain, von Mises stress

Article focus

■ Investigate the role of the stem when cones are used at revision total knee arthroplasty (rTKA) for two commonly observed bone defects, with the joint subjected to four loading scenarios.

Key messages

- Stem inclusion was associated with lower micromotions, but their magnitude was too small to have any clinical significance.
- The use of stems caused a stress concentration at the tip of the stem and stress shielding in the bone along the stem.

- The stem is not necessary when a metaphyseal cone is used at rTKA to manage uncontained posterior or medial defects of up to 10 mm depth.

Strengths and limitations

- This is the first study that considers the role of the stem when the metaphyseal cone is used at rTKA.
- Time-dependent response of bone is not considered in this study.

Introduction

Bone loss is often encountered at revision total knee arthroplasty (rTKA)¹ and managing

Correspondence should be sent to P. Pankaj;
email: pankaj@ed.ac.uk

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large bone deficiencies remains a challenging problem.² There is little agreement on the optimal management of bone loss; bone grafts, metal or tantalum augments, metaphyseal sleeves, and porous cones have all been advocated.³ These techniques are generally used in combination with stems, which can be short or long, and cemented or press-fit.

Biomechanically, tibial stems assist tibial components by sharing loads⁴ and reducing tibial implant lift-off and micromotion at the bone-implant interface.⁵ Stem use can also assist implant alignment.⁶ The potential disadvantages of stems include stress shielding, periprosthetic fracture risk, and end-of-stem pain.⁴

Metaphyseal porous cones and sleeves have been designed to replace bone loss at rTKA.⁷ In principle, metaphyseal cones and stems have a similar function: to increase the contact area between the tibial bone and the implant, thus offloading the complex combination of loads and moments experienced at the interface. The large surface area optimizes stresses at the bone-implant interface, and the large friction coefficient at the porous coating and bone interface reduces micromotion.⁸ A number of clinical⁸⁻¹¹ and experimental^{5,7} studies have demonstrated metaphyseal cones to be a viable management solution for bone loss encountered during rTKA.

Where clinical studies have examined cones or sleeves in rTKA, a stem has generally been included as part of the construct.^{8,12} However, end-of-stem pain has been reported by a number of clinical studies.^{3,13,14} It has been suggested that sleeves or cones could potentially be used without a stem, thereby avoiding both end-of-stem pain and stress shielding.¹³ This has been investigated experimentally in a cadaveric tibia model where similar biomechanical conditions, in terms of implant stability and surface strain distribution, were found when a cone was used with or without a stem for a single defect type.⁵ The effect of different defect locations, varying loading scenarios, and cones without stems and with different stem lengths has not been previously investigated. Moreover, experimental studies are not equipped to examine stresses around the implants to evaluate the extent of stress shielding caused by their presence.

This computational study aims to investigate the biomechanical performance of metaphyseal cones used for rTKA with and without stems. Specifically, interface micromotion and cancellous bone stress were examined for two bone loss scenarios (medial and posterior defects) managed using metaphyseal cones both with stems (short and long) and without a stem. Our hypothesis was that the primary stability of the tibial implants is ensured if metaphyseal cones are used for rTKA even without a stem.

Methods

Geometry. A 3D computer-aided design (CAD) model of the tibia was obtained from a previous study.¹⁵ Resection

of the tibia model was performed for rTKA; the sectioning plane was a surface perpendicular to the mechanical axis of the tibia, located 8 mm below the medial articular surface. The choice of 8 mm was made to account for the primary TKA bone resection, subsequent removal of the tibial baseplate, and associated cement and conversion of 3° to 0° posterior tibial slope.

The tibial baseplate was aligned with the central axis of the diaphyseal canal, and the baseplate sizing was based on rotation oriented to the medial third of the tubercle and tibial plateau obtaining less than 1 mm of overhang. Universal Tibial Baseplate #3 (5521-B-300; Stryker Orthopaedics, Mahwah, New Jersey, USA) was chosen in this study and Triathlon Tritanium Symmetric Cone Augment Size A (5549-A-110; Stryker Orthopaedics) was considered as per the recommended surgical technique. Three implant constructs were modelled: no stem, short-cemented stem (50 mm length, 9 mm diameter), and long-cemented stem (100 mm length, 9 mm diameter) (Figure 1a). To avoid any direct contact between the baseplate and the cone, a 2 mm-thick cement layer was included. Cement was also filled in the medullary cavity up from 175 mm depth measured from the sectioning plane to the bottom of the cone.

Uncontained bone defects involving the medial and posterior tibia were considered. Each defect was 10 mm deep and commenced 9 mm away from the centre of the cone in a posterior or medial direction (Figures 1c and 1d). This resulted in six models for study with two bone defects (posterior and medial) examined for each of the three bone-implant constructs (cone without stem, cone with a short stem, and cone with a long stem).

Material definitions. All materials were assumed to be homogeneous, isotropic, and linear elastic (Table I). Young's moduli were obtained from previous studies and reports.^{1,16,17} Poisson's ratio of 0.3 was assumed for all materials.

Fully bonded interfaces were assumed where the bone or the implant was in contact with cement (i.e. baseplate and cement, cement and cone, and cement and bone); frictional contact was assumed at bone-implant interfaces. A standard Coulomb friction coefficient of 0.35¹⁸⁻²¹ was employed for baseplate-bone and tritanium cone-bone interfaces, while a coefficient of 1.01²² was assumed for the tritanium cone coating-bone interface (Figure 1b).

Loading and boundary condition. The force components +F_x, +F_y, and +F_z act in lateral, anterior, and inferior directions and positive moment components were defined accordingly, as shown in Figure 1. The forces and moments were applied to a reference point, which was at the centre of the baseplate and was constrained to the top surface of the baseplate using multipoint constraints. Standard mean loads for the knee joint in subjects with 75 kg body weight were chosen from OrthoLoad (Julius Wolff Institute, Berlin, Germany).²³ Four loading scenarios were

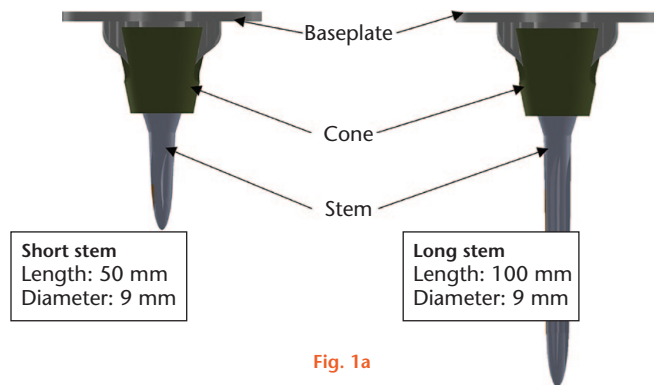


Fig. 1a

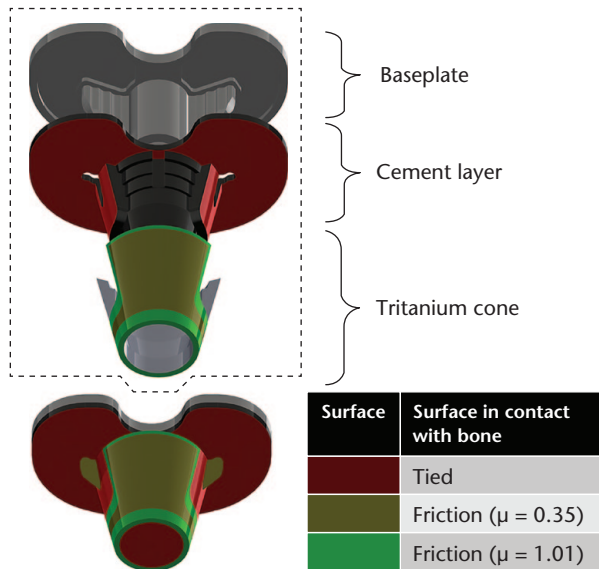
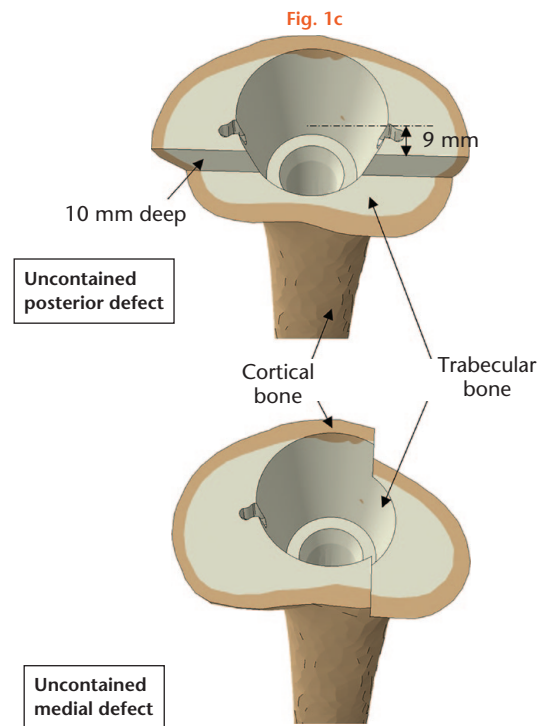


Fig. 1b



Uncontained medial defect

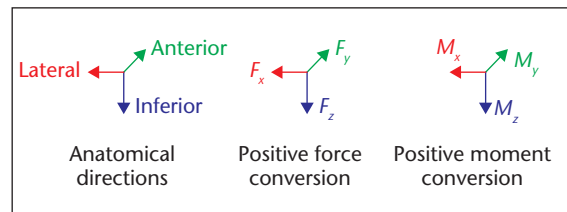


Fig. 1d

Illustration of two stems considered: a) short or long stems; b) the setup of metaphyseal tritanium cone together with illustration of contact properties; uncontained c) posterior and d) medial defects. The positive axes point to lateral, anterior, and inferior directions for F_x , F_y , and F_z , respectively, and for positive moments are defined accordingly.

Table 1. Young's modulus data for various materials. All materials were assumed to be linear elastic in this study.

Part	Young's modulus E, MPa
Cortical bone ¹⁶	15,250
Trabecular bone	449
Tibial baseplate	210,000
Bone cement ¹	2,280
Stem	117,000
Titanium cone ¹⁷	117,000
Tritanium cone coating ¹⁷	6,200

selected for the current study: knee bend (squatting), standing up, walking, and descending stairs (denoted as KB, SU, WA, and StaD, respectively), which cover the majority of the loading conditions encountered during activities of daily living. The timepoints with the largest superior-inferior forces (F_z) were chosen for WA and KB, and the timepoints having the largest M_x were considered for StaD and KB. Forces and moments for all loading

scenarios are illustrated in Figure 2. Similar to previous studies,^{24,25} the tibia was truncated and fixed in all degrees of freedom at a distance of 200 mm (measured from the sectioning plane Figure 1c).

Output variables. To evaluate micromotions, corresponding nodes between implants (tibial baseplate and two parts of the cone) and neighbouring bone were paired to produce implant-bone node-pairs by using a customized MATLAB code (The MathWorks, Natick, Massachusetts, USA). The micromotions between nodes were then evaluated as the relative displacement of the node-pairs after load application. Five sections along bone were selected to compare the differences in von Mises stresses in the bone for three different combinations of tibial components: cone alone, cone with short stem, and cone with long stem. Sections 1 and 2 are located around the cone mid-height and just below the cone, respectively. Sections 3 and 4 are located at the tip (distal end) of short and long stems, respectively. The choice of these sections

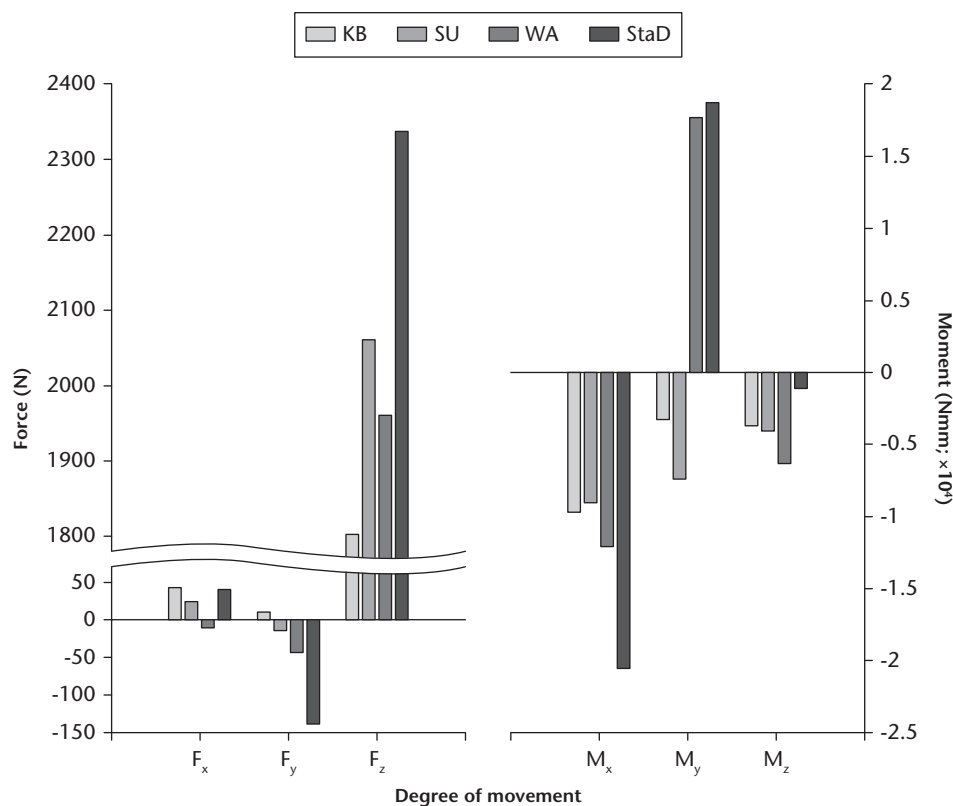


Fig. 2

Loadings applied. Six degrees of freedom were considered for load application, three forces (N), and three moments (Nmm). Four loading scenarios were considered: knee bend or squatting (KB), standing up (SU), walking (WA), and descending stairs (StaD).

is to determine the stresses around and at the bottom of each of the implant combinations. Section 5 is 50 mm away distally from the end of the long stem; all stresses at this section will be carried by the bone and are expected to be similar for all implant combinations.

Results

Micromotions. The typical micromotion patterns at the bone-implant interface for all four loading scenarios, including the mean and 95th percentile micromotions for each model, are shown in Figure 3. In general, it was found that micromotions at the interface were sensitive to the loading scenarios. Walking (WA) and stairs descending (StaD) resulted in higher micromotions compared to KB and SU. The mean micromotions are generally $\leq 12.0 \mu\text{m}$ for all the models considered in this study (Figure 3). Micromotions at the interface were grouped in ranges: $< 15 \mu\text{m}$, $15 \mu\text{m}$ to $25 \mu\text{m}$ (medium), and $25 \mu\text{m}$ to $40 \mu\text{m}$ (high). The percentage of surface areas within these ranges, relative to total areas of the bone-implant interface, were calculated and are shown in Figure 4 (micromotions $< 15 \mu\text{m}$ were excluded).

It was found that micromotions are small for KB and SU (Figure 3): $> 90\%$ of the area had micromotions $< 15 \mu\text{m}$ and they were $\leq 25 \mu\text{m}$ everywhere (Figures 4a and 4b).

A higher range of micromotions was found under WA and StaD loading scenarios, and higher micromotions were observed for bone with an uncontained medial defect compared to an uncontained posterior defect (Figure 3). The addition of a stem and increasing the length of the stem decreased both medium and high ranges of micromotions (Figure 4). The mean and 95th percentile micromotions were decreased with the addition of a stem and decreased further with increased stem length (Figure 3). However, this decrease in micromotions was small. For example, in the medial defect scenario with the StaD loading, the mean micromotions reduced from $12.0 \mu\text{m}$ (95th percentile: 29.0 ; no stem) to $11.6 \mu\text{m}$ (95th percentile: 26.3 ; short stem) and to $11.2 \mu\text{m}$ (95th percentile: 24.1 ; long stem) (Figure 3). The reductions in mean micromotions for bone with a medial defect were only 3.3% and 6.7% for short and long stems, respectively.

Bone stresses. The von Mises stresses in the tibial bone along the implant (with and without stems) were evaluated at five representative sections for all the loading scenarios considered in this study (Figures 5 and 6). Four points at anterior, lateral, medial, and posterior locations (A, L, M, and P) were selected from each section and the stresses were plotted. It is clear that the variation

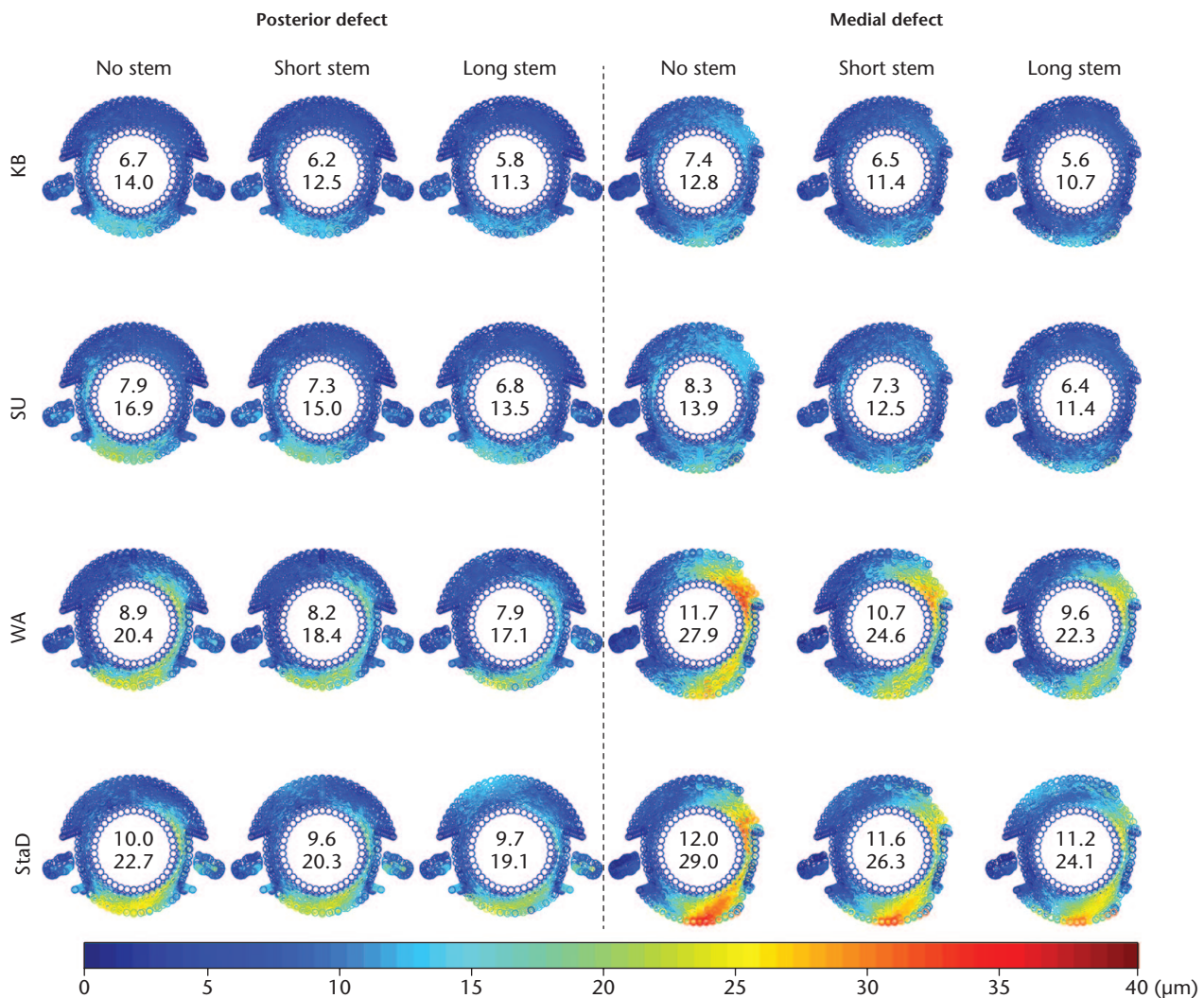


Fig. 3

Superior view of micromotion contours at the bone-implant interface for all loading scenarios for the two bone defects considered. The mean and 95th percentile of micromotions for each model are also shown (mean: upper number; 95th percentile: lower number). KB, knee bend or squatting; StaD, descending stairs; SU, standing up; WA, walking.

of stresses at each section is sensitive to the loading scenario (Figures 5 and 6). The percentage differences in von Mises stresses between no stem and short and long stem scenarios under StaD loading are given in Figure 7.

Stresses were examined at Section 1 (Figures 5 to 7) located just below the middle of the cone. When the cone was used without a stem, slightly higher stresses were observed for all loading scenarios, with the exception of the anterior region. Including a stem caused the applied forces and moments to bypass the cone and thus slightly smaller stresses were found, which were further reduced by the increase in stem length. The highest reduction of stresses with a short stem was 11% (for posterior defect) and 26% (for medial defect) in the StaD loading scenario; with the long stem these reductions were 19% and 28% (Figure 7).

Stresses were examined at Section 2 (Figures 5 to 7) located at the bottom of the cone. The stresses were reduced

by inclusion of a short stem and reduced further for the long stem. The largest reduction of stresses was 24% and 70% for posterior and medial defect scenarios, respectively (Figure 7). The highest reduction of stresses was observed in the anterior and lateral regions of the bone for posterior (Figure 5) and medial (Figure 6) defect scenarios, respectively, and this was true for all the loading scenarios.

Stresses were examined at Section 3 (Figures 5 to 7) located at the end of the short stem. Compared to the no stem construct, considerably higher stresses were found at all anatomical locations when a short stem was incorporated for both bone defects considered (Figures 5 and 6). The stress increment was more than 70% with the short stem, compared to cone being used alone (Figure 7). However, long stem use reduced the peri-bone stresses considerably, and these were more than 60% in the anterior region of the bone for both bone defects considered

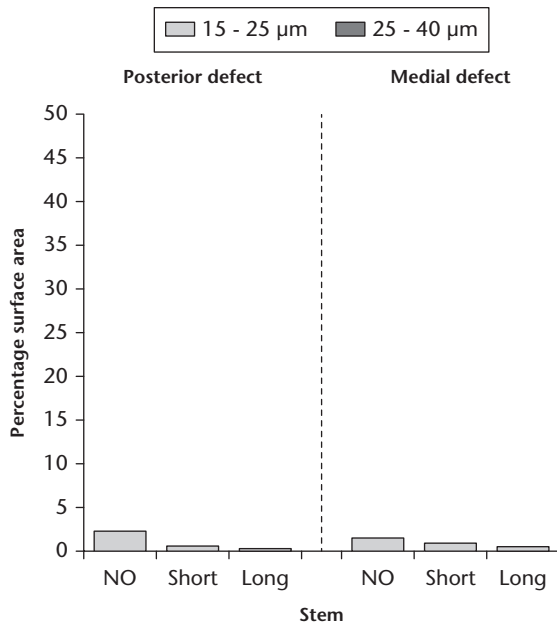


Fig. 4a

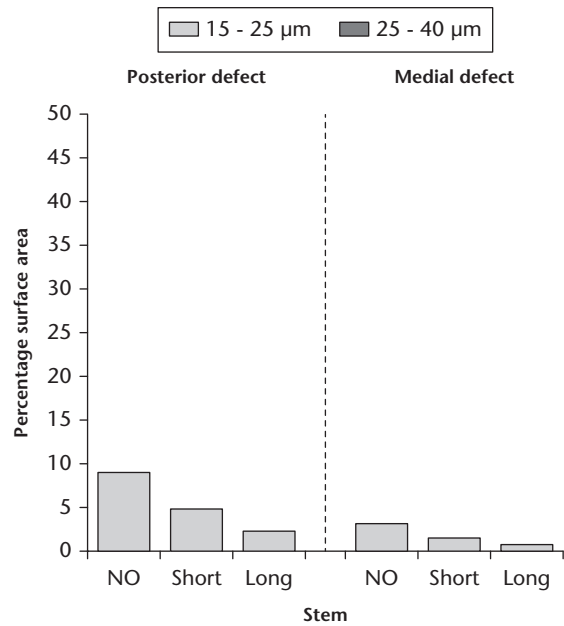


Fig. 4b

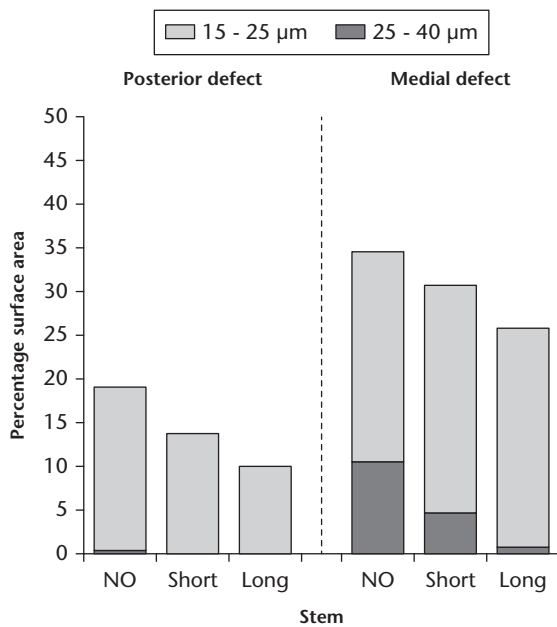


Fig. 4c

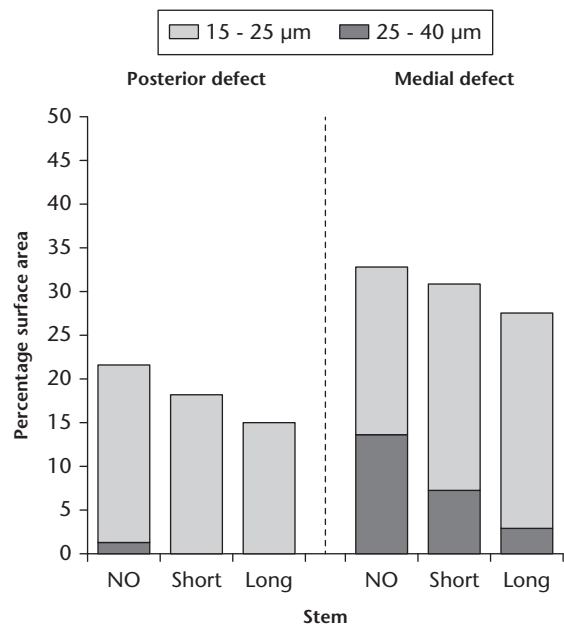


Fig. 4d

Comparison of the predicted micromotions occurring at the bone-implant interface by range for: a) knee bend; b) standing up; c) walking; d) descending stairs.

(Figure 7). Essentially this means that a considerable amount of load, or stress, bypassed the cone and was carried by the stem.

Stresses were examined at Section 4 (Figures 5 to 7) located at the end of the long stem. Similarly, for the long stem construct higher stresses were found at all four locations compared to the short stem and no stem cases, again coincident with the stem tip (Figures 5 and 6). The elevated stresses found at the end of the long stem were more than three times the stresses observed for a cone

used alone (Figure 7). At this section, almost no difference in stresses was found when a cone was used without a stem or with a short stem (Figure 7).

Stresses were examined at Section 5 (Figures 5 to 7) located 50 mm away from the end of the long stem. The von Mises stresses were similar for all the implant constructs (i.e. cone with or without stem) with differences of less than 1% (Figure 7) for both posterior (Figure 5) and medial (Figure 6) defects. This was true for all the loading scenarios considered.

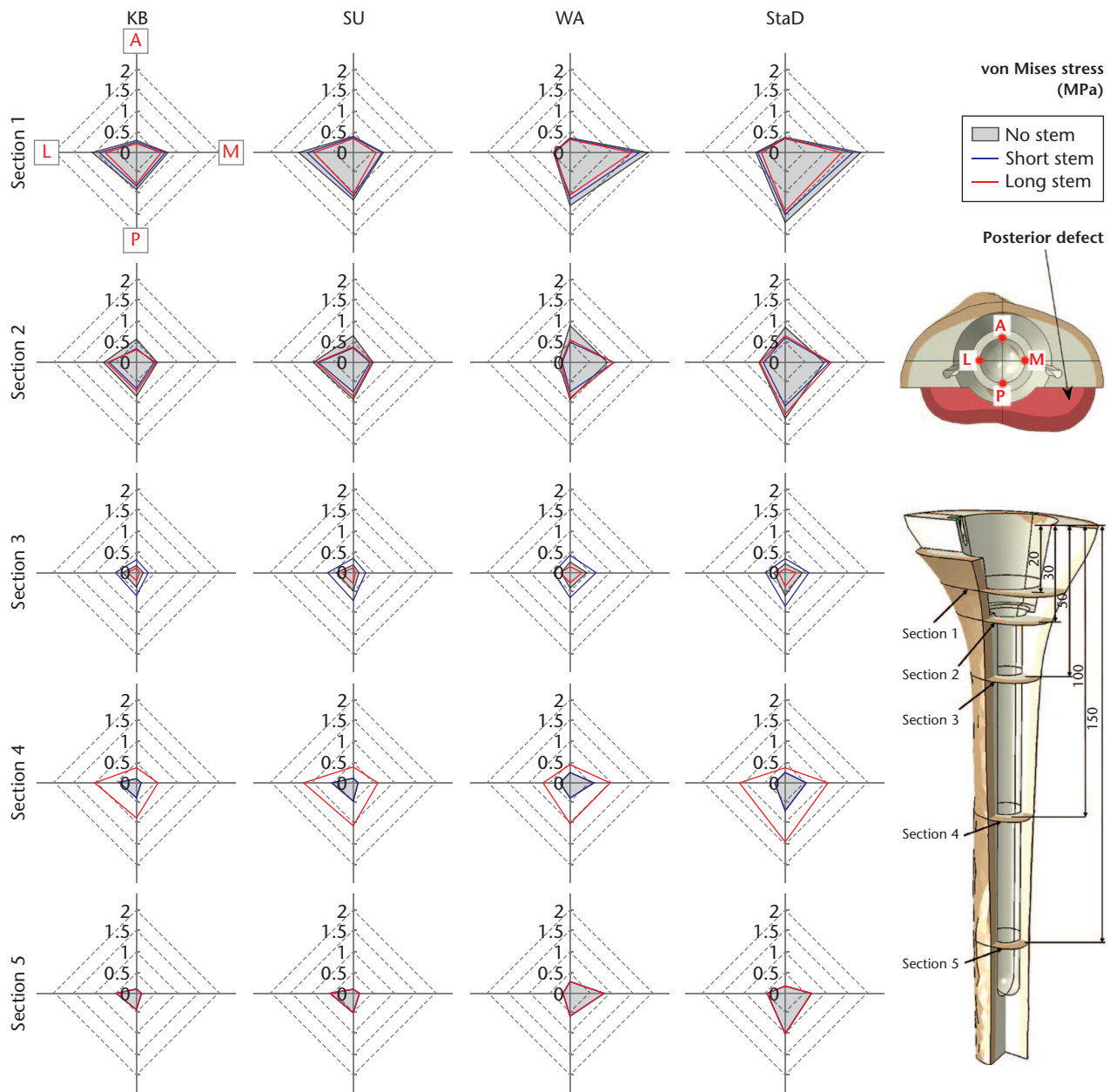


Fig. 5

von Mises stress of posterior defected bone from four anatomical points (anterior: A, lateral: L, medial: M, and posterior: P) when the cone was used for revision total knee arthroplasty with no stem, a short stem, or a long stem. Four loading scenarios were considered: knee bend (KB), standing up (SU), walking (WA), and descending stairs (StaD).

Discussion

Metaphyseal cones are designed to replace large bone defects at rTKA, and have been shown to have comparable or superior fixation compared to existing systems in clinical⁸⁻¹¹ and experimental^{5,7} studies. A stem is generally considered as additional fixation and is typically used to augment cones. The present study demonstrates that when cones are used to manage uncontained posterior or medial defects in the tibia, compromised primary stability leads to some micromotions at the implant-bone interface that occur with or without a stem. Micromotions

at the interface are found to decrease with the inclusion of a stem and decrease further with increasing stem length, however micromotions are small in all cases, with or without stems. Inclusion of a stem reduces the stresses in the bone around it and at the bottom of the cone. Stress concentrations occur at the tip of both short and long stems, and much larger stress concentrations are found in the tibial bone at the tip of the long stem.

Interfacial micromotion is an important indicator in the evaluation of the mechanical stability of bone-implant constructs. The bone-implant construct experiences large

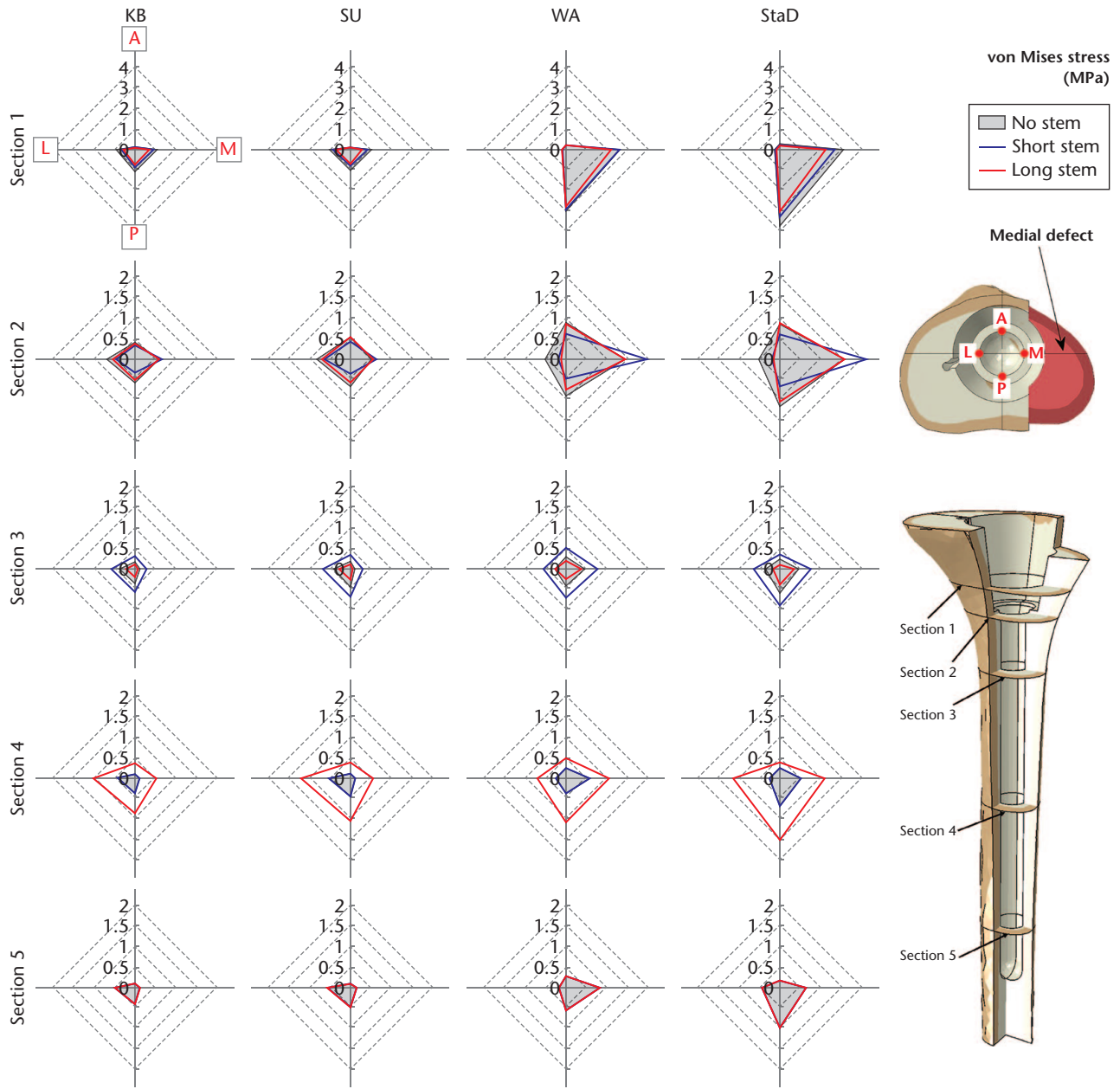


Fig. 6

von Mises stress of medial defected bone from four anatomical points (anterior: A, lateral: L, medial: M, and posterior: P) when the cone was used for revision total knee arthroplasty with no stem, a short stem, or a long stem. Four loading scenarios were considered: knee bend (KB), standing up (SU), walking (WA), and stairs descending (StaD).

moments during WA and StaD (Figure 2), therefore these loading scenarios resulted in higher micromotions compared to KB and SU cases. A previous computational investigation for a primary TKA showed that the mean micromotions between cement and bone were reduced by 19% and 23% for press-fit and cemented stems, respectively.¹ An experimental study also reported that if the stem is used in combination with a metaphyseal sleeve for rTKA, the micromotions will be reduced.²⁵ The reduction of micromotions at the sleeve region has also been previously reported computationally, however this reduction was small: around 10% with a stem length of 60 mm.²⁶ In

the current study, we found that stem inclusion was associated with smaller micromotions. However, the reduction is only 3.3% and 6.7% for short and long stems, respectively, used in conjunction with cones for medial bone defect considered and subjected to descending stairs loading (worst case scenario). This reduction in micromotions is too small to affect overall tibial construct stability, and of doubtful clinical significance. Moreover, micromotions found in this study, for both tibial defects considered, were small in all cases. Previous research has shown that bone ingrowth is achieved if interface micromotions are < 50 μm .^{27,28} The micromotions observed in the current study

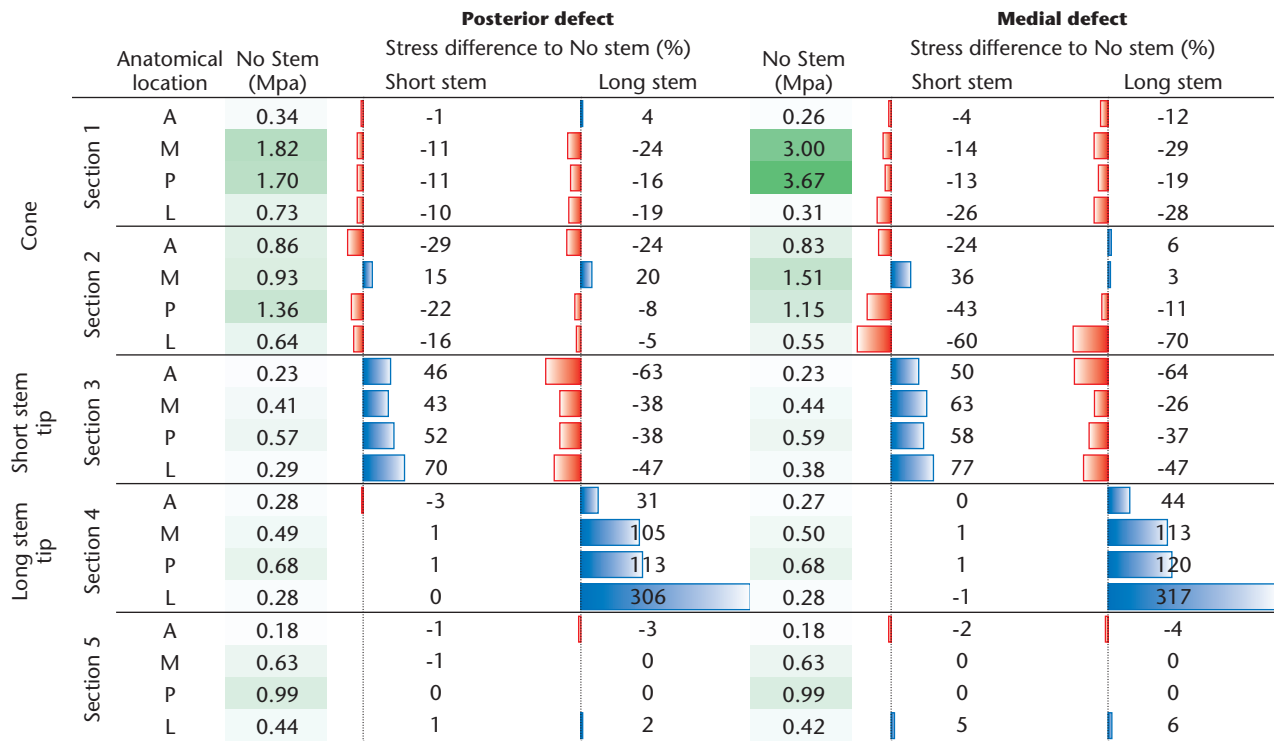


Fig. 7

von Mises stresses of bone at five representative sections for the three implant constructs under the loading scenario stair descent. For comparison, the stresses displayed when a short or long stem was added are represented as percentage differences compared to no stem. Negative and positive differences simply imply that the stresses observed in the bone are smaller or larger, respectively, than those found for the cone used without a stem. A, anterior; L, lateral; M, medial; P, posterior.

are far below 50 μm for both considered defects using cones with or without stems. Therefore, successful cone osseointegration would be expected even where cones are used without stems for rTKA.²⁹

Inclusion of a stem in TKA, primary or revision, may improve mechanical stability, but comes at the cost of stress shielding along the length of the stem and has been discussed in a number of studies and reviews.^{3,4,9} Computational²⁶ and experimental³⁰ studies have reported that the inclusion of a stem results in a decrease in proximal tibial strain. The reduction of the strain within the bone (or strain shielding) was observed in a computational study when a stem was used in combination with a metaphyseal sleeve for rTKA.²⁶ A previous experimental study found that tantalum cones produced very similar biomechanical conditions for rTKA with or without a stem by examining the strain distribution at the outer surface of the tibia.⁵ However, the strain or stress distribution in the bone at the interface is a better indicator of stability and stress shielding in the bone-implant system. In this computational study, we considered the stress distributions in the bone at the interface. We found that stem inclusion reduced the stresses at the inferior aspect of the cone by up to 29% and 60% for posterior and medial defects, respectively. Inclusion of a stem offloads forces from the proximal bone defect region and, therefore, appears desirable. However, stress shielding at the base

of the cone (section 2) and in the bone along the stem is not desirable and may result in bone resorption. Some clinical studies have reported metaphyseal bone resorption after knee reconstructions when a stem is included, suggesting stress shielding.^{31,32} Consistent with a previous clinical study,³³ we also observed that the longer the stem, the greater the bone stress shielding.

The stresses generated within the tibial bone due to bending moments are largely carried by the stem, therefore the stresses in the bone are reduced at the proximal region of the stem but elevated at the tip of the stems. The stress concentration at the tip of the stem has been previously reported in experimental and computational studies. An experimental study observed the strain concentration at the stem tip for both cemented and press-fit stems for primary TKA.³⁰ A computational study compared stresses at the tip of the stem with those in an intact tibia and reported that the former were four times and seven times the stresses in the intact tibia for stem lengths of 50 mm and 100 mm, respectively.³⁴ We too observed stress concentration at the tip of the stem and found larger tip stresses with increased stem length. The stresses observed at the tip of the stem here increased up to 77% and 317% for short and long stems, respectively, compared to cone used alone for rTKA. Stress concentration at the stem tip can be associated with end-of-stem pain and could potentially put periprosthetic bone at risk of fracture.⁴ End-of-stem pain is a recognized clinical issue and has been

reported by a number of clinical studies.^{14,31} Our study shows that inclusion of stems with cones for rTKA does not offer any benefits.

There are a number of limitations in this study. Material non-linearity was not considered and might influence the stress/strain distributions in the bone.^{16,35,36} Bone properties vary with age and disease and this variation is not included in the current study. Bone is considered an isotropic homogeneous material. This assumption simplifies modelling and has been commonly used in almost all previous studies, for example Scott et al,¹⁵ Danese et al,³⁷ and Conlisk et al.³⁸ This assumption is unlikely to alter the interfacial micromotions and stress trends observed. Bone is known to be a time-dependent material,^{39–41} and this time-dependent response accentuates implant loosening when cyclic loading is applied.⁴² The interfacial micromotions are also related to loading frequencies.⁴³ The biomechanical performances of the bone-implant construct used for rTKA with increased gait cycles need further investigation by the inclusion of the time-dependent response of bone.

This study investigated the role of stems in conjunction with tritanium cones in the management of posterior and medial defects at rTKA. It was found that although a stem used in combination with the cone did reduce micromotions at the bone-implant interface, these reductions in micromotions were too small to have clinical significance. Peak interface micromotions were small and would not be expected to affect osseointegration even when the cone is used alone without a stem. Although bone stresses near the defect were reduced by stem inclusion, which may help protect defected bone, undesirable stress shielding occurs at the base of the cone and in the bone surrounding the stem. Moreover, stress concentrations are observed at the end of the stem, resulting in stresses that are up to three times those without a stem; these may be associated with end-of-stem pain and periprosthetic fracture. Although stemmed tibial components assist in restoring implant alignment, a stemless construct is more bone-preserving. Therefore, for the scenarios examined, this computational study shows that when a metaphyseal cone is used for rTKA, biomechanically the stems may not be necessary. Before stems are abandoned altogether, further clinical assessment may help to confirm the findings of this computational study.

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Author information

- S. Xie, PhD, Post-doctoral Research Associate,
- N. Conlisk, PhD, Post-doctoral Research Associate,
- P. Pankaj, PhD, Professor of Computational Biomechanics, School of Engineering, Institute for Bioengineering, The University of Edinburgh, Edinburgh, UK.
- D. Hamilton, PhD, Research Fellow, Department of Orthopaedics and Trauma, The University of Edinburgh, Edinburgh, UK.

- C. Scott, MD, MSc, FRCSEd(Tr&Orth), MFSTEd, Consultant Orthopaedic Surgeon, Department of Orthopaedics, Royal Infirmary of Edinburgh, Edinburgh, UK.
- R. Burnett, MB ChB, FRCS (Ed), FRCS (Orth), Consultant Orthopaedic Surgeon, Department of Orthopaedics, Royal Infirmary of Edinburgh, Edinburgh, UK.

Author contributions

- S. Xie: Initialized the research method, Prepared the computational models, Analyzed the data, Wrote the manuscript.
- N. Conlisk: Revised the manuscript, Discussed the results.
- D. Hamilton: Participated in the conceptualization of the research study.
- C. Scott: Revised the manuscript, Carried out the critical discussion of the results.
- R. Burnett: Participated in the conceptualization of the research study.
- P. Pankaj: Participated in the conceptualization of the research study, Revised the manuscript, Carried out the critical evaluation of the results.

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Ethical review statement

- This study did not require ethical approval.

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