Journal of the mechanical behavior of biomedical materials 66 (2017) 181–186

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Strain shielding in trabecular bone at the tibial cement-bone interface

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ARTICLE INFO

Keywords:
Bone-cement interface
Strain shielding
Micromotion
Aseptic loosening
Finite element analysis

ABSTRACT

Aseptic loosening of the tibial component remains the leading cause for revision surgery in total knee arthroplasty (TKA). Understanding the mechanisms leading to loss of fixation can offer insight into preventative measures to ensure a longer survival rate. In cemented TKA, loosening occurs at the cement-trabecular interface probably due to a stress-shielding effect of the stiffer implant material in comparison with bone. Using finite element models of lab-prepared tibial cement-trabeculae interface specimens (n=4) based on micro-CT images, this study aims to investigate the micromechanics of the interlock between cement and trabecular bone. Finite element micromotion between cement and trabeculae and bone strain were compared in the interdigitated trabeculae as well as strain in the bone distal to the interface. Lab-prepared specimens and their FE models were assumed to represent the immediate post-operative situation. The cement layer was removed in the FE models while retaining the loading conditions, which resulted in FE models that represented the pre-operative situation. Results showed that micromotion and bone strain decrease when interdigitation depth increases. Bone-cement micromotion and bone strain at the distal interdigitated region showed a dependence on bone volume fraction. Comparing the immediate post-operative and pre-operative situations, trabeculae embedded deep within the cement generally showed the highest level of strain-shielding. Strain shielding of interdigitated bone, in terms of reduction in compressive strains, was found to be between 35 and 61 % for the four specimens. Strain adaptive remodeling could thus be a plausible mechanism responsible for loss of interdigitated bone.

1. Introduction

Total knee replacement (TKR) is currently a very successful treatment option for most patients with knee arthritis. The major cause for revision surgery in cemented total knee arthroplasty is aseptic loosening of the tibial component. The mechanisms leading to this aseptic loosening are multi-factorial in nature and are not yet fully understood. Both biological and mechanical factors have been recognized to contribute toward peri-prosthetic osteolysis and eventual loosening and failure of TKRs (Gallo et al., 2013). Mechanical aspects such as early migration of tibial trays have previously been related to aseptic loosening (Pijls et al., 2012). Tibial component malalignment has also been shown to contribute toward revision rate due to increased wear (Srivastava et al., 2012). Patient factors such as activity levels and poor muscle condition can potentially lead to overloading of the knee joint.

In cemented knee arthroplasty, the purpose of bone cement is to provide an interlock between trabecular bone and cement, providing initial fixation of the implant to bone. An experimental study with cement-bone interface specimens from post-mortem tibial retrievals has however demonstrated a significant loss of trabecular bone at the bone-cement interface, with large gaps and increased interface micromotion. Considerable bone remodeling was also observed in the bone distal to the cement layer in the form of pedestal-shaped bony supports (Miller et al., 2014). A possible cause of loss of interdigitation is osteolysis induced by fluid flow and fluid pressure (Johansson et al., 2009; Fahlgren et al., 2010) at the tibial cement-bone interface (Mann and Miller, 2014). Micromotion between trabeculae and interdigitated bone cement could result in a fluid pumping mechanism leading to further degradation of bone. The large stiffness gradient across the implant-cement and cement-bone interfaces means that stress shielding of bone in cemented TKA will always occur, which in turn may lead to a reduction in trabecular bone density. The extent of stress shielding can possibly be mitigated by implant design and material optimizations

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http://dx.doi.org/10.1016/j.jmbbm.2016.11.006
Received 23 June 2016; Received in revised form 12 October 2016; Accepted 1 November 2016

and accurate cementation. To this end, it is necessary to understand how micromotion and strain are distributed in the interdigitated and peri-prosthetic bone. Using bone-cement interface specimens obtained from lab-prepared cemented tibial bones, finite element (FE) models were created to study variations in micromotion and bone strain. The pattern of strain shielding can be obtained by comparing post-operative bone strain with those in the pre-operative situation. Finite element modeling can be used to obtain the pre-operative strain distribution by removing the cement layer while keeping the loading condition the same. The purpose of this research is to investigate what changes occur at the cement-bone interface in terms of micromotion and strain due to cementation of the implant. The following research questions were therefore proposed: (1) How do micromotion and strain vary within the interdigitated trabeculae at the cement-bone interface post-operatively? (2) Is the interdigitated trabecular bone strain-shielded compared to the bone distal to the interface? (3) What is the extent of strain shielding at the cement-bone interface in the directly post-operative scenario compared to the (pre-operative) intact bone?

2. Materials and methods

The cement-bone interface specimens and resulting FE models used in this study have been described in a previous study (Srinivasan et al., 2016). The four FE models were validated based on experimental micromotion and strain measurements using Digital Image Correlation. In the section below, a brief description of the specimen creation and FE model generation is provided.

2.1. Specimen creation and FE model generation

Two fresh-frozen tibias obtained from the SUNY Anatomical Gift Program were prepared for cementation of tibial component as in TKR. Radiolucent surgical bone cement was vacuum mixed. After the cement reached a state of “does not stick to glove”, cement was applied to the proximal tibia and pressurized with a cement mixing spatula. Surgical bone cement (Radiolucent Simplex P, Stryker Orthopedics, Mawah, NJ) was vacuum mixed and applied to the proximal tibia once the cement had reached a state of *does not stick to glove*. Pressurization of cement into the trabecular bone was performed with a mixing spatula. Varying levels of cement interdigitation depth were obtained by applying twice as much cement to one half of the tibial plateau. The cemented tibias were sectioned into ~4×4×15 mm cement-bone interface specimens following a previously described method (Mann et al., 2008). From each donor, two specimens were chosen from tibial regions with different interdigitation depth (1.1–5.2 mm). These lab-prepared cement-bone specimens are representative of the immediate post-operative bone-cement interface.

Micro-CT scans of all specimens were made at 12 µm isotropic resolution (Scanco Inc. Media, PA, USA). The four cement-bone interface specimens were modelled using these micro-CT images. The images were segmented based on an image greyscale ranging from −1024 to −769 using Mimics 14.0 (Materialise, Leuven, Belgium). A threshold between −880 and −769 was applied for bone and between −1024 to −940 for cement. The segmentation mask of the cement layer was used to identify the interdigitated bone mask using the procedure described by Mann et al. (2012). Supporting bone was defined as bone distal to the cement layer (Fig. 1a) and was obtained by subtracting the interdigitated mask from the total bone mask. Segmentation masks of the cement, interdigitated bone and supporting bone were used to create corresponding surface and then 4-node tetrahedral solid meshes (3-matic 5.1 and Patran Mesher in Mentat 2012, MSC Software Corporation, Santa Ana, CA, USA). Due to the variation in cement interdigitation depth, the total number of elements ranged from 4 to 8 million with 1 to 2 million nodes. Specimen 1 had the least interdigitation depth and Specimen 4, the highest. The bone volume fraction (BV/TV) varied from 0.12 to 0.24 over the four specimens (Fig. 1a), which fall into the normal range for proximal tibial trabecular bone (Ding et al., 1999; Liu et al., 2008).

Linear elastic and isotropic material properties were assumed in the FE models. Young’s modulus for the cement and bone was set to 3 GPa (Lewis 1997) and 14 GPa, respectively. A Poisson’s ratio of 0.3 was applied for both materials. The cement-bone contact interface was modelled as unbonded (Waanders et al., 2010) and a double-sided segment-to-segment contact algorithm without friction was used (MSC Marc 2012). No influence of friction was seen in pilot studies.

The four (post-operative) models were loaded in compression at 1 MPa (which equated to 1 body weight) axially and constrained at both long ends, allowing only vertical movement (y-direction). Cement-trabecular micromotion was calculated using pairs of cement-bone contact nodes as described previously in the validation study. Each node pair was followed throughout the simulation, during which the total and incremental micromotion was calculated.

2.2. Pre-operative bone models

In order to obtain the change in strains once the implant has been cemented, it was needed to first recreate the pre-operative situation. This was done by cutting through the surface mesh of the cement (Rhinoceros 5.0) with a cutting plane; thereby effectively removing the cement layer. In each of the four models, the cut was performed such that just enough of the interdigitated cement geometry was preserved to form a pressure plate for the trabecular bone below (Fig. 1b). This ensured similar load distribution as in the post-operative situation. The surface mesh of the cement pressure plate was then converted to a solid tetrahedral mesh. The four new models - without interdigitated cement - represent the pre-operative situation. The same boundary conditions as in the post-operative models were applied to these models. The element sets and numbering for the bone was retained from the post-operative models so that change in strains could be obtained easily.

2.3. Definition ROI interdigitated bone

The main goal of this paper is to understand how micromotion and strain are distributed in the interdigitated bone post-surgery. To facilitate post-processing of relevant output variables, the elements and nodes of the interdigitated bone were divided into four regions of interest (ROI) having equal thickness (Fig. 2). The thickness of the regions between models was different due to the variation in depth of cement penetration. Regions were numbered 1–4, from most proximal to distal. Elemental strains and micromotion data were outputted using a subroutine. Median micromotion and strain were determined in each region and also as a function of interdigitation depth. Interdigitation depth is zero at the cement border and maximum at the deepest part within the cement mantle. The cement border is the distal border of the cement enclosing the interdigitated bone as shown in Fig. 2. Interdigitated bone strain (all four ROIs together) was also compared with supporting bone strain. The same ROIs were retained for the pre-operative models.

3. Results

3.1. Distribution of micromotion in interdigitated bone

Cement-trabecular micromotion was found to decrease from the distal to proximal interdigitated bone as shown in the FE contour plot for specimen 3 (Fig. 3). The contour plot shows the interdigitated bone without interdigitated cement layer for clarity. Maximum micromotion predicted by the four FE models was between 3 and 14 micrometers. Median micromotion in each region of interest as a function of the interdigitation depth showed that lower micromotion occurred deeper within the cement layer (Fig. 4). At the cement-bone contact interface