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Full and surface tibial cementation in total knee arthroplasty: A biomechanical investigation of stress distribution and remodeling in the tibia

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ABSTRACT

Background: Aseptic tibial component loosening remains a major cause of total knee arthroplasty failure. The cementation technique used to achieve fixation may play a major role in loosening. Despite this, the optimum technique remains unanswered. This study aims to investigate stress and strain distributions in the proximal tibia for full cementation and surface cementation of the Genesis II tibial component.
Methods: Principal cortical bone strains were measured experimentally in intact, surface cemented and fully cemented synthetic tibiae using strain gauges. Both axial and 15° flexion loading were considered. Finite element models were used to assess both cortical and cancellous bone stresses and strains. Using a bone remodeling algorithm potential sites of bone formation and resorption were identified post-implantation.
Findings: Principal cortical bone strain results demonstrate strong correlations between the experimental and finite element analyses ($R^2 \geq 0.81$, RMSE(%)$\leq$17.5%). Higher cortical strains are measured for surface cementation, as full cementation creates a stiffer proximal tibial structure. Simulations reveal that both cementation techniques result in lower cancellous stresses under the baseplate compared to the intact tibia, with greater reductions being computed for full cementation. The surface cementation model displays the closest cancellous stress distribution to the intact model. In addition, bone remodeling simulations predict more extensive bone resorption under the baseplate for full cementation (43%) than for surface cementation (29%).
Interpretation: Full cementation results in greater stress reduction under the tibial baseplate than surface cementation, suggesting that surface cementation will result in less proximal bone resorption, thus reducing the possibility of aseptic loosening.

1. Introduction

Total knee arthroplasty (TKA) is an established treatment option for end-stage degenerative knee joint disease. With revision or loosening as the endpoint, survivorship of greater than 93.7% at 15 years has been reported for cemented implants (Ito et al., 2003; Keating et al., 2002). Successive arthroplasty registers have noted aseptic loosening as the most common cause of failure (38%–44%) (CJRR, 2003; Graves et al., 2004; Robertsson et al., 2001). Demand in the US for TKA revision surgery is set to increase by 601% between 2005 and 2030 (Kurtz et al., 2007). Cementless implants have not demonstrated superior survivorship to cemented TKA (Baker et al., 2007; Gandhi et al., 2009). The underlying mechanisms of aseptic loosening are not known and are considered to have a multi-factorial etiology. Due to component implantation, tibial load transfer is altered and may result in peri-prosthetic bone remodeling and subsequent stress shielding. Aseptic tibial component loosening may be attributed to such changes in bone morphology post-implantation.

Implant fixation is paramount in achieving long-term stability and is still a major issue concerning primary TKA. Tibial cementation techniques include full cementation (FC) and surface cementation (SC). FC involves cementing the tibial cut surface and stem. SC implies the application of cement across the tibial cut surface leaving the stem uncemented. FC and SC tibial component cementation techniques in primary TKA have widely been debated however no optimum technique has been determined. Advocates of SC claim sufficient component stability and maintenance of the underlying BMD thus leaving the bone less vulnerable to stress shielding (Hofmann et al., 2006; Kolisek et al., 2009; Seki et al., 1997; Skwara et al., 2009). Advocates of FC claim better fixation as well as a lower potential for early micromotion thus creating a stronger construct for long-term stability (Bert and McShane, 1998; Luring et al., 2006).

Micromotion, assessed clinically through roentgen stereophotogrammetric analysis (RSA), has not shown significant differences between the two techniques (Saari et al., 2008). Experimentally, only

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micromotion has been evaluated via cyclic point loading as an end-point for comparing SC and FC and has shown conflicting results between the two techniques (Bert and McShane, 1998; Luring et al., 2006; Peters et al., 2003; Seki et al., 1997; Skwara et al., 2009). Cement penetration has been highlighted as playing a key role in implant stability between the two techniques (Bert and McShane, 1998; Hofmann et al., 2006; Peters et al., 2003). The extent to which the tibial cut surface is cemented is dependent on the operator, bone and implant. Cortical bone strains have also been used to assess cementation technique in primary (Seki et al., 1997) and revision TKA (Completo et al., 2007a, 2008; Seki et al., 1997). However the role of the stem in revision TKA is different to primary TKA. Revision TKA is frequently complicated by poor quality proximal tibial bone, requiring diaphseyeal stem fixation, in which the stem used to stabilize the tibial component is considerably longer than that used in primary TKA implants. Regardless of cementation technique the revision stem engages the cortices of the more distal tibial diaphysis. Therefore due to the key differences in bone quality, stem length, cortical contact and load transfer, investigation of primary and revision TKA cementation techniques must be considered separately. Clinical cohorts have not provided conclusive direction on the optimal cementation method (Hofmann et al., 2006; Ito et al., 2003; Kolisek et al., 2009; Schai et al., 1998; Sharkey et al., 2002). Only Schai et al. (1998) compared clinical survivorship for FC and SC in primary TKA.

To date no biomechanical study has considered the cancellous bone stresses/strains or bone remodeling due to FC or SC of primary TKA, despite the clinical evidence of stress shielding in the proximal cancellous bone (Lonner et al., 2001). The aim of this study is to experimentally and computationally investigate primary tibial component TKA cementation techniques; FC and SC. This study hypothesizes that SC of the tibial component in primary TKA results in less stress shielding directly under the baseplate than FC. To test this hypothesis cortical bone strains are experimentally measured in intact, FC and SC tibiae at axial and 15° flexion loading. Experimental results are then used to validate finite element (FE) simulations, which offer an insight into the cancellous stress and strain distributions for FC and SC. Using an established bone remodeling algorithm (Huiskes et al., 1992; Ong et al., 2009) regions of bone resorption and formation are computed for both FC and SC.

2. Methods

2.1. Experimental testing

Six pairs of 4th generation synthetic composite tibiae (#3402, 10pcf cellular rigid, Sawbones, Malmö, Sweden) were implanted with the Genesis II Total Knee System (Smith & Nephew, Memphis, USA). Six models per group each tested 4 times provided statistical significance, which is greater than previous sawbone arthroplasty studies (Bert and McShane, 1998; Completo et al., 2007a; Luring et al., 2006). All stages of tibial preparation were performed by an orthopedic resident (DTC) under the supervision of a consultant orthopedic surgeon (FJS). Cutting, drilling and punching were standardized to ensure identical preparation was achieved with all tibiae. The tibiae were cemented at room temperature with PMMA bone cement (SimplexP, Stryker-Howmedica, NJ, USA), 6 FC and 6 SC. The polyethylene insert and femoral component were used to load the tibiae. Eight tri-axial strain gauge rosettes (KFG-3-120-D17-11L3M2S, Kyowa Electronic Instruments, Tokyo, Japan) were applied to each tibia at the antero-medial (AM), lateral (L) and posterior (P) aspects at 5 mm, 30 mm and 50 mm below the proximal tibial cut surface (Fig. 1). Gauge positions are referred to as AM5 (antero-medial gauge at 5 mm), L5, P50 etc. P5 gauges were not considered due to cement overspill at this location during implantation. In order to obtain consistent strain gauge placement a vernier height gauge (Mitutoyo Corporation, Tokyo, Japan) was used. A reference axis was marked on the cortex and each gauge was aligned and positioned accordingly. The middle strain gauge was aligned with the vertical axis of the tibia.

The tibia was rigidly fixed at the distal end and placed in a universal testing machine (Model 4467, Instron, MA, USA). The femoral component was constrained so that a 60:40 medial:lateral (Completo et al., 2007a; Halloran et al., 2005) load distribution was implemented. A load of 2060 N (3 × 70 kg BW) was applied. Both axial and 15° flexion loading of the tibia were implemented. An intact tibia was also tested to 2060 N for comparison with the implanted tibiae (Fig. 1C). A pressure pad was used at the joint line to monitor contact stresses so that native joint loading contact conditions could be replicated. Maximum principal (ε_{max}) and minimum principal (ε_{min}) cortical strains were calculated based on three strains measured with tri-axial rosettes using a data acquisition system (National Instruments, TX, USA) at the eight gauge locations, with four test replicates. Null calibration was performed at the outset, and shunt calibration was performed with each adjustment of position (standard of error < 0.2%). One-way analysis of variance (ANoVA) was applied to test for the effect of cement on the measured variable strain using statistical software (v.15, Minitab Inc., State College, PA, USA). Pairwise post-hoc analyses were performed using the General Linear Model with a Tukey significant difference test. Significance was determined at $\alpha < 0.05$.

2.2. Finite element modeling

One-millimeter CT images of a sawbone tibia (#3402, 10pcf) were utilized to create solid computational models of intact and implanted

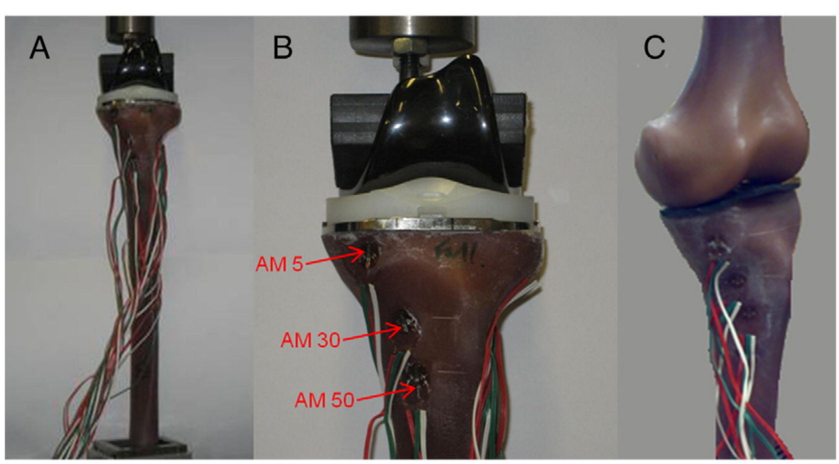

Fig. 1. Experimental loading setup. A: implanted tibia with femoral component articulation proximally and rigid constraint distally. B: proximal implanted tibia with strain gauges placed at 3 levels (5 mm, 30 mm and 50 mm) from the tibial cut surface. C: intact loading configuration.