ARTICLE IN PRESS

Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Validation of model-predicted tibial tray-synthetic bone relative motion in cementless total knee replacement during activities of daily living

Alessandro Navacchia *, Chadd W. Clary, Hayden L. Wilson, Yashar A. Behnam, Paul J. Rullkoetter

Center for Orthopaedic Biomechanics, The University of Denver, CO, USA

ARTICLE INFO

Article history:
Accepted 24 June 2018
Available online xxxx

Keywords:
TKR
Micromotion
Finite element
Cementless

ABSTRACT

As fixation of cementless total knee replacement components during the first 4–6 weeks after surgery is crucial to establish bony ingrowth into the porous surface, several studies have quantified implant-bone micromotion. Relative motion between the tray and bone can be measured *in vitro*, but the full micromotion contour map cannot typically be accessed experimentally. Finite element models have been employed to estimate the full micromotion map, but have not been directly validated over a range of loading conditions. The goal of this study was to develop and validate computational models for the prediction of tray-bone micromotion under simulated activities of daily living. Gait, stair descent and deep knee bend were experimentally evaluated on four samples of a cementless tibial tray implanted into proximal tibial Sawbones™ constructs. Measurements of the relative motion between the tray and the anterior cortical shell were collected with digital image correlation and used to validate a finite element model that replicated the experiment. Additionally, a probabilistic analysis was performed to account for experimental uncertainty and determine model sensitivity to alignment and frictional parameters. The finite element models were able to distinguish between activities and capture the experimental trends. Best-matching simulations from the probabilistic analysis matched measured displacement with an average root mean square (RMS) difference of 14.3 μm and Pearson-product correlation of 0.93, while the mean model presented an average RMS difference of 27.1 μm and a correlation of 0.8. Maximum deviations from average experimental measurements were 40.5 and 87.1 μm for the best-matching and average simulations, respectively. The computational pipeline developed in this study can facilitate and enhance pre-clinical assessment of novel implant components.

1. Introduction

Cemented tibial trays are the gold-standard for tibial fixation in total knee replacement (TKR) (Ranawat et al., 2012). However, there is renewed interest in cementless tibial trays due to advancements in additive manufacturing. Initial fixation is crucial for bony ingrowth of cementless components (Bragdon et al., 1996). Previous *in vivo* studies on canine femora showed that micromotion larger than 150 μm can inhibit bony ingrowth onto porous surfaces and consequently lead to implant failure (Jasty et al., 1997).

Micromotion between implant and bone has been measured *in vitro* using either human cadaveric specimens (Kraemer et al., 1995) or bone substitute (Bhimji and Meneghini, 2012, 2014; Crook et al., 2017; Yildirim et al., 2016). While cadaveric studies provide more realistic bony support, synthetic bone is used for comparative studies because of its reduced cost and consistent material properties. Although some *in vitro* studies apply cyclic loads to the implant along a single degree-of-freedom (DoF) (Crook et al., 2017; Yoshii et al., 1992), loading profiles that combine compressive, shear and torsional loads are necessary to represent more physiological conditions (Bhimji and Meneghini, 2012). Subsequent studies measured micromotion while simulating stair descent (Bhimji and Meneghini, 2014; Yildirim et al., 2016) and peak loads during gait (Chong et al., 2010), but a comprehensive micromotion dataset that simulates multiple dynamic activities of daily living is not available.

Although *in vitro* experiments can measure relative motion between the exposed surfaces of the implant and bone, they cannot directly measure micromotion across the whole implant-bone interface. Previously, finite element (FE) models have been used to estimate micromotion for TKR cementless components (Chong et al., 2010; Fitzpatrick et al., 2014; Taylor et al., 2012), providing the relative motion across the entire implant-bone interface. Computational models can also be used to evaluate the impact of

* Corresponding author at: Center for Orthopaedic Biomechanics, The University of Denver, 2390 S. York St., Denver, CO 80208, USA.

E-mail address: alessandro.navacchia@du.edu (A. Navacchia).

https://doi.org/10.1016/j.jbiomech.2018.06.024
0021-9290/© 2018 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Navacchia, A., et al. Validation of model-predicted tibial tray-synthetic bone relative motion in cementless total knee replacement during activities of daily living. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.06.024

parameters such as fixation feature shape, stem length, and implant alignment. Once a model is validated, computational simulations can address limitations associated with experimental tests, such as increased cost, time, and prototype fabrication. Previous computational models that estimate the micromotion at the tray-bone interface were not directly validated over a range of simulated activities of daily living loading conditions.

Accordingly, the goal of the current study was to develop and validate computational models for prediction of tibial tray micromotion under simulated activities of daily living. Gait (GT), stair descent (SD) and deep knee bend (DKB) were simulated in a 6-DoF knee testing machine with a cementless TKR design implanted in synthetic bones. Relative motion between the exposed surfaces of tray and bone were measured and used to validate FE models simulating the same activities. We hypothesized that the FE model predictions would differentiate between activities and locations along the anterior aspect of the tray.

2. Methods

2.1. Experimental testing

A generic tibial tray design with representative fixation features was tested. Specifically, it presented a 35-mm-long central conical stem and four 10-mm-long cylindrical pegs with a 7.6-mm diameter. The distal surface of the tray, the four pegs, and the proximal 7 mm of the stem were covered with a 1.2-mm-high porous titanium surface (Fig. 1). Four tray samples were implanted into proximal tibial Sawbones™ constructs with a 12.5 lb/cubic foot (pcf) density polyurethane cancellous foam core surrounded by a 50 pcf solid cortical shell (Pacific Research Laboratories Inc, Vashon Island, WA). The bone constructs were manufactured into a shape matching that of a 9-mm-depth resection plane of a medium-sized tibial sawbones specimen. The constructs were 57 mm high and the surface cut presented medio/lateral and anterior/posterior dimensions of 76 and 46 mm, respectively. This construct is the bone substitute commercially-available for fixation studies, and it was used previously for the same application (Bhimji and Meneghini, 2012, 2014; Yildirim et al., 2016). The tibial bone preparation instrumentation was designed to create consistent fit around the pegs. The femoral component and insert are commercially available (fixed bearing cruciate retaining ATTUNE®, DePuy Synthes, Warsaw, IN), unlike the cementless tray, which was manufactured for the present study. The specimens were loaded in simulated GT, SD, and DKB cycles using a 6-DoF AMTI VIVO™ knee simulator (AMTI, Watertown, MA) (Fig. 2) (Fitzpatrick et al., 2016). Experimentally-applied loads and kinematics were derived from a combination of published telemetric implant data (Kutzner et al., 2010) and ASTM standard F3141-15 (Van Valkenburg et al., 2016). Since ASTM F3141-15 does not include varus/valgus moments, loads about this DoF were derived by averaging moments from the same five Orthoload patients used by Van Valkenburg et al. (2016) performing GT, SD, and DKB. Fifty cycles of each activity were applied to each sample in the experiment. Relative displacement between tray and bone was measured with an ARAMIS digital image correlation system (GOM mbH, Braunschweig, DE), recording the change in distance between lateral, central, and medial marker couples during the fortieth cycle (Fig. 2).

2.2. Computational models

Two modeling strategies were used to estimate micromotion, the *Fully predictive* and *Partially predictive* pipelines (Fig. 3).

2.2.1. Fully predictive pipeline

The first strategy was designed to estimate interface micromotion using the same inputs necessary to run the experiment: a flexion/extension motion profile and tibiofemoral loading profiles in the remaining five DoFs. A sequence of two FE models (*full implant model* and *tray-only model*) was developed in Abaqus/Standard (SIMULIA, Providence, RI) (Fig. 2, black arrows) and validated against experimental measurements.

2.2.1.1. Full implant model. The first model included a deformable representation of the bone, tray, insert, and a rigid femoral component (Fig. 3, top left corner). TKR components were meshed with 1-mm linear tetrahedral elements, which are sufficiently fine for convergence (Godest et al., 2002; Halloran et al., 2005), and modeled as linearly elastic, except the insert, which was modeled with an elasto-plastic isotropic hardening material (Table 1). The porous and solid portions of the tray were tied to each other, but they were modeled with different material models to represent their different mechanical properties (Table 1, Fig. 1). The bone construct was meshed with linear tetrahedral elements and modeled as elastic with material properties from the manufacturer (Table 1).

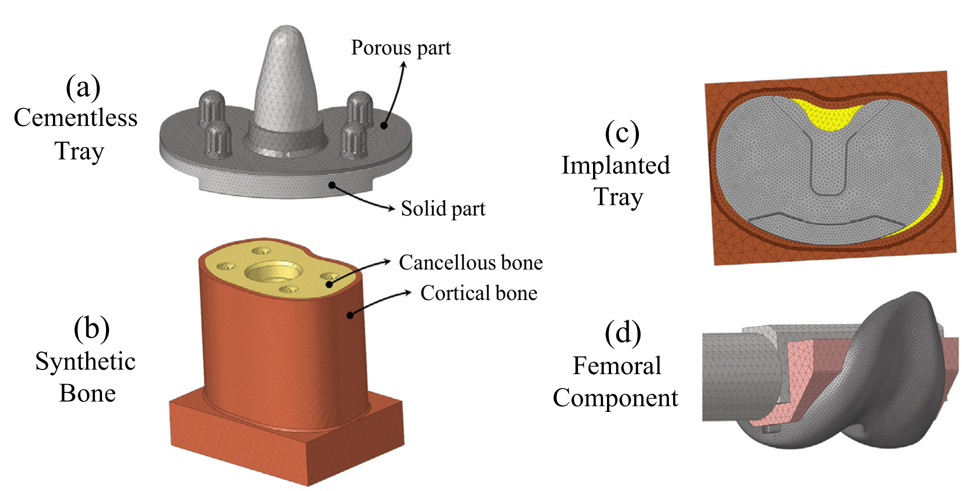

Fig. 1. TKR components and synthetic bone construct. (a) Bottom view of the cementless tray showing both porous and solid parts. (b) Synthetic bone construct showing cortical (brown) and cancellous bone (yellow). (c) Top view of the tray implanted in the synthetic bone, which shows the regions of the cortical bone on which the tray rests. (d) Femoral component mounted on the AMTI VIVO™ condylar adapter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Navacchia, A., et al. Validation of model-predicted tibial tray-synthetic bone relative motion in cementless total knee replacement during activities of daily living. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.06.024