Journal of Biomechanics 48 (2015) 1844–1851

Contents lists available at ScienceDirect

Journal of Biomechanics

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

A phenomenological contact model: Understanding the graft–tunnel interaction in anterior cruciate ligament reconstructive surgery

Shahab Salehghaffari [a,b,*], Yasin Y. Dhaher [a,b,c]

[a] Northwestern University, Physical Medicine and Rehabilitation Department, 345 East Superior Street, Chicago, IL 60611, United States
[b] Rehabilitation Institute of Chicago, Sensory Motor Performance Program, 345 East Superior Street, Chicago, IL 60611, United States
[c] Northwestern University, Biomedical Engineering Department, 2145 Sheridan Road, Evanston, IL 60208, United States

ARTICLE INFO

Article history:
Accepted 23 April 2015

Keywords:
Bayesian calibration
Multivariate Gaussian distribution
Epistemic uncertainty
Finite element model
Surgical variability
Experimental errors

ABSTRACT

In this paper, we sought to expand the fidelity of a validated model of the anterior cruciate ligament reconstruction (ACL-R) procedure by incorporating a stick–slip contact model with linear pressure–overclosure relationship at the interface. The suggested model is characterized by three unknown parameters, friction coefficient, shear stress softening and contact stiffness. In the absence of any isolated experiments exploring the graft–tunnel interactions during an aggregate joint load, the calibration data used in this study are derived from a reported biomechanical study. A Bayesian calibration procedure was employed to find the unknown probability distribution function (PDF) of these contact parameters. Initially, the response surface approximations of the predicted graft forces from laxity test simulations was adopted to estimate the likelihood of noisy experimental data reported in the literature. Then, the wide domain of contact parameters was sampled sequentially based on the Marcov Chain Monte Carlo (MCMC) method with acceptance–rejection criteria to search for population of samples in significantly narrower domain of unknown parameters that are associated with the highest occurrence likelihood of noisy experimental data. Our simulations with calibrated contact parameters indicate that pre-tensioning applied at 30° of flexion leads to larger graft force after the joint is fully extended compared to the graft force when the same pre-tensioning force is applied at full extension. Moreover, regardless of the pre-tensioning force, the graft–tunnel contact pressure is larger when the fixation of the graft is performed at full extension, increasing with the pre-tensioning force.

1. Introduction

It has been suggested that one of the underlying mechanisms of graft failure post-anterior cruciate ligament reconstructive (ACL-R) surgery can be attributed to the motion at the graft tunnel interface (Andersen et al., 1992; Graf et al., 1994; Gely et al., 1984; Sidles et al., 1990). While widely proposed as a mechanism, computational effort to understand the biomechanical correlates associated with the procedure have, for the most part, ignored the underlying mechanical properties of the graft–tunnel interactions at the tunnel aperture (Pena et al., 2006, 2005; Suggs et al., 2003). Our earlier computational model of ACL-R surgery incorporated the exact geometry of the harvested bone–patellar–tendon–bone (BPTB) graft and the reamed tunnel edges to improve the geometrical aspect of the graft–tunnel contact behavior (Salghaffari and Dhaher, 2014). In this study, our aim is to improve the constitutive description of the graft–tunnel contact by adopting a phenomenological contact model. The proposed stick–slip contact model is motivated in part by evidence of rupture at the graft–tunnel interface in patients undergoing revision surgery, highlighting the potential for graft-on-bone slip mediated abrasions (Pinczewski et al., 1997). Moreover, the development of a slip–stick contact model will facilitate the understanding of the effect of graft motion and subsequent mechanical loading on the healing process during the early stages post-surgery.

Accordingly, we propose a softened normal contact model described by a linear pressure–overclosure relationship and a stick–slip tangential behavior. The inclusion of the realistic normal and tangential (friction) behaviors introduced additional contact properties. Unfortunately, with the exception of limited experimental investigations on tendon-on-pulley friction coefficients (Shacham et al., 2010; Sun et al., 2004), experimental paradigms

* Corresponding author at: Rehabilitation Institute of Chicago, Sensory Motor Performance Program, Room 1406, 345 East Superior Street, Chicago, IL 60611, United States. Tel.: +1 312 238 1408; fax: +1 312 238 2208.
E-mail addresses: salehghaffari@gmail.com, shahabedin.salehghaffari@northwestern.edu (S. Salehghaffari).

http://dx.doi.org/10.1016/j.jbiomech.2015.04.034
0021-9290/

that explicitly target the graft–tunnel contact properties in an undisturbed state are non-existing. To circumvent this barrier, a Bayesian inverse statistical approach (Kennedy and O'Hagan, 2001; McFarland and Mahadevan, 2008; McFarland et al., 2008) will be employed to infer the marginal probability distributions of these contact parameters from aggregate joint mechanics derived from anterior tibial loading experiments (Hoher et al., 2001). The Bayesian calibration approach has gained popularity in various engineering applications (Cheung et al., 2011; Hawkins-Daarud et al., 2013) and provides a probabilistic estimate of the targeted parameters. One of the key attributes of this calibration approach is that it aims at correcting the discrepancy between the observed data and the model predictions with consideration of the underlying variations and noisiness in both experimental and simulation data. Finally, computational models of ACL-R with the calibrated frictional and contact parameters were used to explore the interplay between two important ACL-R surgical parameters, graft fixation angle and graft pre-tension force. The simplest form of normal relationship (linear) with single parameter was considered to reduce the computational cost of the presented statistical calibration process.

2. Methods

2.1. Contact models and parameters

A previously developed computational model of BPTB ACL-R incorporating key surgical parameters together with the detailed surgical procedure (Salghaffari and Dhaher, 2014; Dhaher et al., 2010) is updated to include a phenomenological constitutive model of contact mechanics at the graft and tunnel edges (Fig. 1). A "softened" contact relationship in which the contact pressure is a linear function of the clearance between the surfaces was used. Such representation of the normal behavior introduces a normal constant k, the slope of the pressure–overclosure relationship (Fig. 1). In addition, a stick–slip friction model is proposed to describe the dynamic aspect of friction, the gliding of the graft over the bony tunnel edges (Oden and Martins, 1985). The stick–slip model includes an additional contact parameter, τ_{max}, the maximum value of shear stress at the graft–tunnel interface prior to the slip, and a friction coefficient (η). The model assumes a constant shear stress with increasing contact pressure over the stick behavior of the model (Fig. 1). In total, the contact model includes three contact parameters: η and τ_{max} (MPa) to predict tangential contact forces and k (MPa/mm) to predict normal forces (Fig. 1). A statistical calibration is followed to find the unknown probability distribution function (PDF) of these contact parameters. In the following section, $\theta = (\eta, \ \tau_{max}, \ k)$ refers to the vector of contact parameters. The geometry of BPTB graft was incorporated in the model by separating the appropriate elements from the patella tendon (PT) mesh. Surgically, the intra-articular entrance of the tunnel is smoothed to minimize graft abrasion (Hardin and Bach, 1992). In this model, the tunnel edges were filleted to simulate this surgical smoothing procedure (Fig. 1). Due to the lack of data, the radius of the fillet was arbitrarily chosen. Note that the tunnel opening into the intra-articular space exhibited the oval shape identified from Computed Tomography (CT) images of ACL-R knees (Hensler et al., 2013). A sensitivity study on the mesh size of the contacting surfaces (graft and tunnel edge) was conducted and the mesh sizes were refined until 7% difference in peek contact forces was achieved.

2.2. Calibration data and experiments: ACL-R surgery and biomechanical experiments

In the absence of any isolated experiments exploring the graft–tunnel interactions during an aggregate joint load, the calibration data used in this study are derived from the reported biomechanical study by Hoher et al. (2001) on ACL-R cadaveric knees subjected to an anterior tibial load of 134 N. In Hoher's study, two different sets of ACL-Reconstructed knees were considered. In the first set (10 specimens), the graft was pre-tensioned with a 44 N and was fixed at 30° of flexion. The second set of data (10 specimens) was derived from a graft fixation at full extension with a 44 N pre-tensioning force. For both sets, the tibial and femoral tunnels were drilled at 90°of the knee flexion using *transtibial* portal *technique* and a 10 mm width BPTB graft was used. The anterior tibial load of 134 N was applied at 30° of flexion (defined herein as calibration experiment 1) and full extension (defined as calibration experiment 2) for the first and second set of subjects, respectively. The reported mean of the graft forces of the 10 cadaveric specimens in each of the experimental sets were used as the targeted calibration data. Here, we define $D = (d_1, \ d_2)$ where, μ_1 and σ_1 refers to mean and standard deviation of graft forces for the first calibration set d_1, while μ_2 and σ_2 are related to the second calibration set d_2.

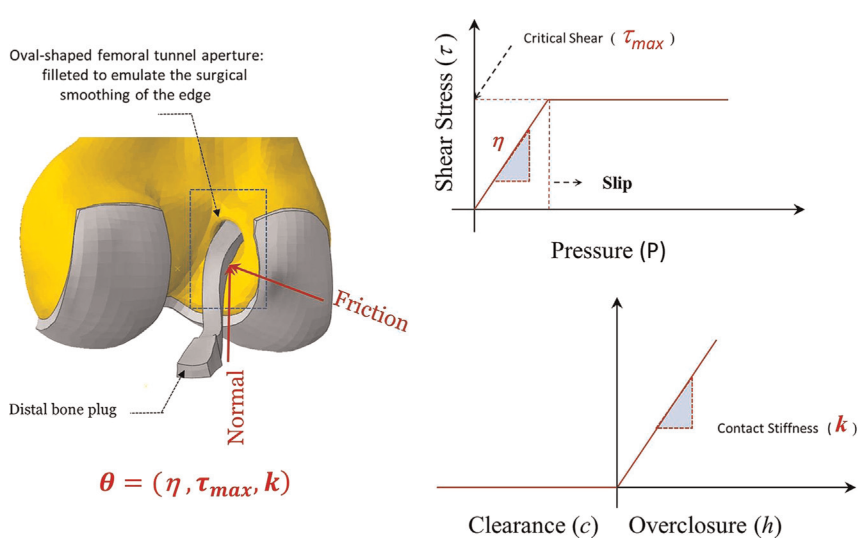

Fig. 1. The softened normal contact model and Coulomb frictional model with shear softening is depicted. Also, normal and frictional contact model parameters are shown.