Snappy Dissertation Title

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Chapter 1

Introduction

1.1 Background

Ligaments and articular contact define the limits of passive joint motion. Understanding the the forces acting across the knee and the resulting joint motion is important when assessing the causes and treatment of knee pathology (Thelen et al., 2014) (find better citation).

Studies have shown that variations in ligament properties can affect the knee's kinematics and contact mechanics under simulated passive (Baldwin et al., 2009; Dhaher et al., 2010) and dynamic (Smith et al., 2016) joint loading.

Computational knee models can use different representations of ligaments (Figure 1.1), however there are few studies that evaluate the effects of ligament representation on the model's performance, and improvements can be made to the studies that have addressed this topic. Beidokhti et al. (2017) used inverse modeling to generate comparable spring and continuum ligament models. The two types of models were considered equivalent if they yielded joint forces that were similar to experimentally measured values, however it was not shown that the spring and continuum ligament models yielded similar ligament forces under the same loading. Additionally, the prestrain definition may not be equivalent between the spring and continuum ligament representations. Conversely, Orozco et al. (2018) applied similar prestrain to their spring and continuum ligament models, however prestrain was uniformly applied throughout each ligament. Joint mechanics have been shown to be sensitive to ligament prestrain (Baldwin et al., 2009), and experimental studies have shown that prestrain is not uniform throughout a ligament (Hull et al., 1996; Gardiner et al., 2001).

Nonhomogeneous prestrain can be assigned to spring and continuum ligament representations. Inverse

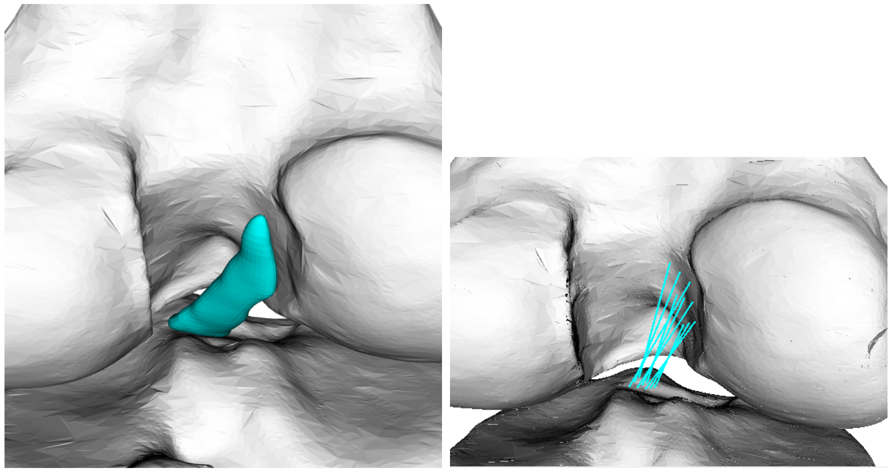

Figure 1.1: A comparison of the anterior cruciate ligament (ACL) modeled as a (left) continuum and (right) a bundle of nine individual springs arranged across the ligament's insertion site.

modeling has been used to estimate specimen-specific ligament properties (including nonhomogeneous prestrain) for knee models that represent ligaments as springs (Blankevoort and Huiskes, 1996; Baldwin et al., 2009; Ewing et al., 2015; Harris et al., 2016). With the exception of Gardiner and Weiss (2003), specimen-specific nonhomogeneous prestrain is not utilized in continuum ligament models. Literature is used to define prestrain values (Pea et al., 2006; Dhaher et al., 2010), which are derived from a combination of experimental studies and results of inverse modeling studies that utilize spring ligament models.

A calibrated knee model that represents ligaments as springs could be used to estimate specimen-specific nonhomogeneous prestrain in continuum representations of ligaments. Lu et al. (2007) estimated the prestrain in blood vessels using an inverse elastostatics approach, where the deformed state of the geometry and forces were known, and the stress-free shape of the geometry was estimated.

1.2 Overview

The overall purpose of this work is to (1) develop an approach to estimating specimen-specific nonhomogeneous prestrain in ligaments that are represented as a continuum and (2) compare the performance of the continuum ligament representation to an equivalent spring ligament representation. To achieve this goal, experimental testing was conducted to collect specimen-specific MR images and force-displacement data. The MR images were used to generate specimen-specific geometry, including femur and tibia surfaces, and the insertion sites of ligaments (Figure 1.3). The forward kinematics model was used to simulate experimental tests in an inverse modeling scheme. This scheme used optimization to estimate ligament slack length by minimizing the residual between the calculated and experimentally measured tibial forces. This process is

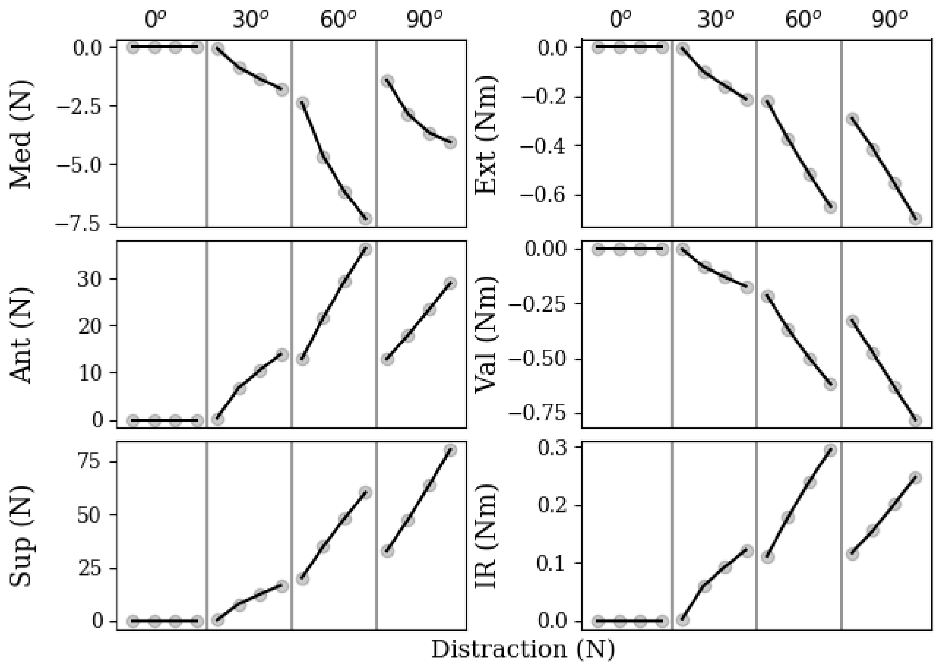

Figure 1.2: An example of the forces and moments that the alPCL exerts on the tibia at four points throughout a distraction test at 0°, 30°, 60°, 90° flexion.

similar to other studies that have used inverse modeling to estimate ligament properties (Blankevoort and Huiskes, 1996; Baldwin et al., 2012; Ewing et al., 2015; Harris et al., 2016).

This approach assumes that the calibrated spring ligament model recreates the ligament's forces at a given joint position. These loading data could be used to define the boundary conditions for a inverse elastostatics analysis of a ligament. Lu et al. (2007) used this approach to estimate the prestrain in blood vessels, where

Ligaments are commonly represented as bundles of nonlinear uniaxial springs (Blankevoort and Huiskes, 1996; Baldwin et al., 2009; Ewing et al., 2015), or as a solid continuum (Gardiner and Weiss, 2003; Pea et al., 2006; Dhaher et al., 2010) (Figure 1.1). Joint mechanics have been shown to be sensitive to ligament prestrain (Baldwin et al., 2009), and experimental studies have shown that prestrain is not uniform throughout a ligament (Hull et al., 1996; Gardiner et al., 2001). Studies that utilize spring ligament representations can simulate nonhomogeneous prestrain in a ligament by varying the prestrain in each spring that composes a specific ligament. Studies that utilize continuum ligament representations either apply uniform prestrain (Limbert et al., 2004; Song et al., 2004; Beidokhti et al., 2017), or apply nonhomogeneous prestrain based on values reported in the literature (Pea et al., 2006; Dhaher et al., 2010), where prestrains are derived from a combination of experimental studies and results of inverse modeling studies that utilize spring ligament models.

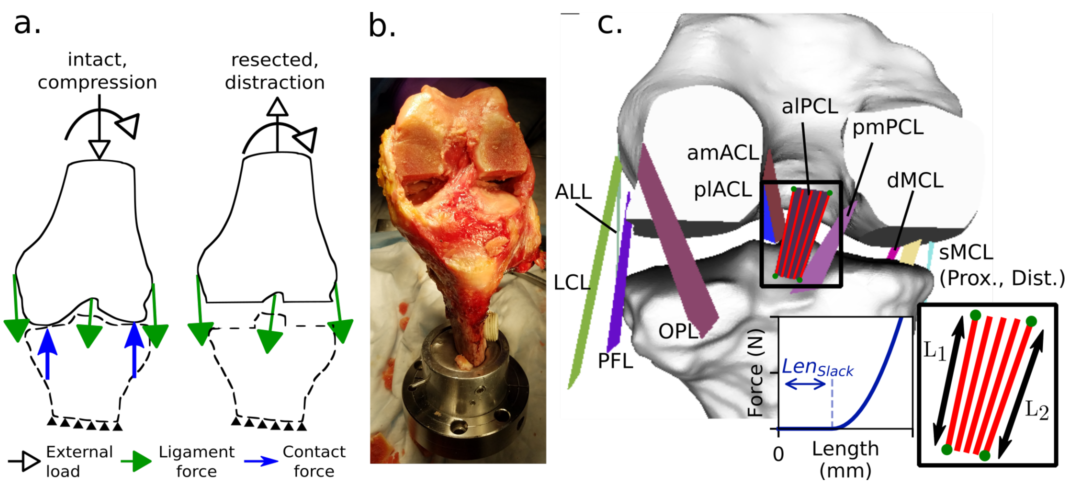

Figure 1.3: (a) A similified representation of the joint forces during an intact laxity-style test compared to a distraction laxity-style test. (b) The specimen with resected femoral articulating surfaces. (c) The knee model with 11 ligament bundles represented. (inset) The non-linear spring model, and the definition of slack lenghth for a ligament with five fibers.

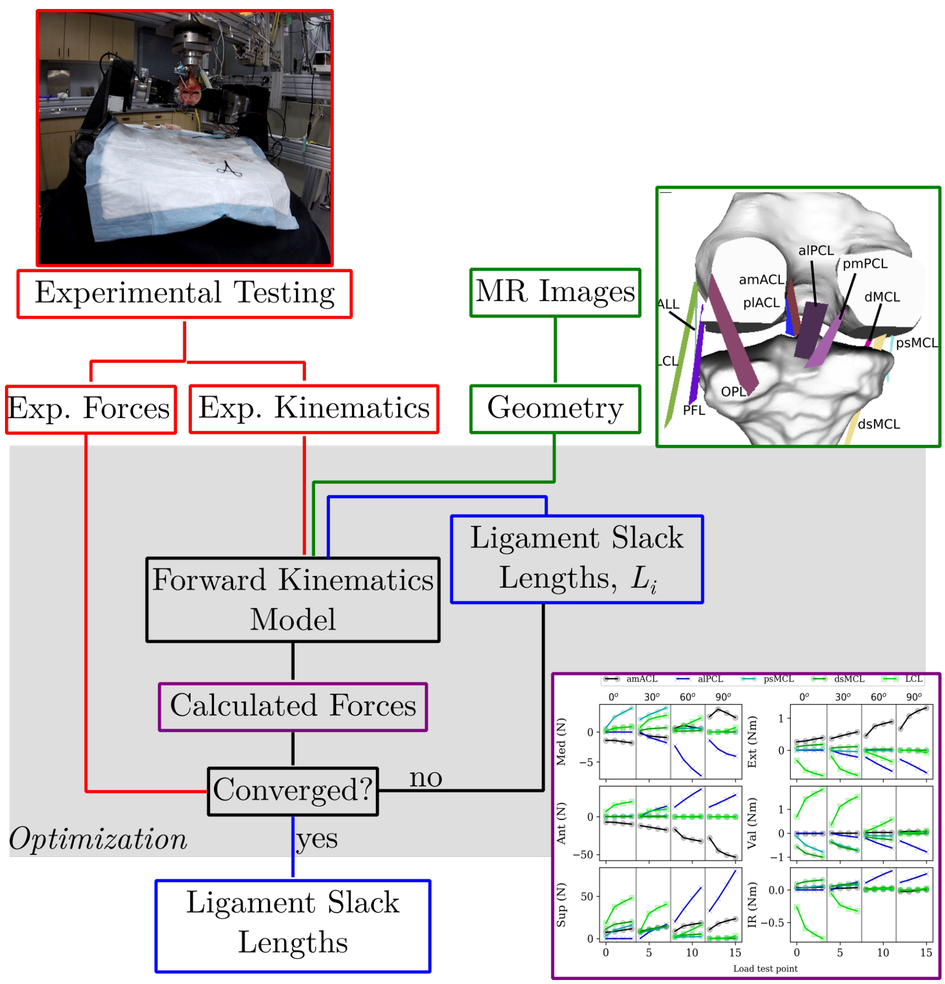

Figure 1.4: An overview of the inverse modeling scheme.

Representing ligaments as springs allows for the prediction of joint level mechanics such as kinematics (Weiss and Gardiner, 2001). Ligaments are normally modeled as bundles of springs, where each spring's insertion lies within the insertion area of the ligament. Nonhomogenous prestrain can be simulated by varying the prestrain assigned to each spring in a ligament. Due to their computational efficiency, spring ligament models are used in inverse modeling studies to estimate ligament properties, including as prestrain (Blankevoort and Huiskes, 1996; Baldwin et al., 2012; Ewing et al., 2015; Harris et al., 2016).

Specimen-specific knee models are defined with geometry derived from MR images, and ligament material properties are normally estimated with inverse modeling (Blankevoort and Huiskes, 1996; Baldwin et al., 2012; Ewing et al., 2015; Harris et al., 2016). These models normally utilize spring representations of ligaments because they have been shown to allow for the prediction of joint kinematics (Weiss and Gardiner, 2001), and they are computationally efficient. A recent study by Beidokhti et al. (2017) compared the effects of ligament representation on a knee model's predicted joint mechanics. That study used inverse modeling to estimate ligament properties for two different knee models, one with spring ligament representations, and the other with continuum ligament representations.

A recent study compared joint mechanics between knees modeled with spring and continuum ligament representations for passive loading (Beidokhti et al., 2017). This study evaluated the effects of ligament representation on joint mechanics, however the prestrain definition between two types of ligament representations may not be equivalent. Beidokhti et al. (2017) used inverse modeling to generate comparable spring and continuum joint level models. Multiple springs were used to model each of the cruciate and collateral ligaments, where each spring can have a unique prestrain. Conversely, each continuum ligament was modeled as one body that had prestrain uniformly applied throughout. Gardiner and Weiss (2003) showed that an nonhomogenous prestrain can have an impact on the strain distribution within a ligament under load.

1.2.1 Specific Aims

Distraction Experiment

Distraction testing will provide a novel data set that is suitable to estimate ligament properties with an inverse modeling scheme. Two knee specimens will be prepared and MR imaged to facilitate model development. The specimens will be tested with common laxity-style loads, and with novel laxity-style distraction loads. The applied joint forces and the corresponding joint kinematics will be measured throughout testing. The MR imaging will provide the data necessary to create specimen-specific geometry, and the measurements taken during preparation and testing will provide the data necessary for estimation of ligament properties with inverse modeling.

Status: Complete

Contribution: Data necessary to create specimen-specific models and simulate the experimental tests.

Inverse Modeling with Distraction Testing

Inverse modeling will be used to estimate specimen-specific ligament slack-length using data from distraction testing. Use of an experimentally novel joint state and joint loads allows for joint contact to be neglected in the computational model, and may focus the joint's force-displacement behavior on the ligaments. Neglecting contact enables the use of a computationally efficient forward kinematics model, which is used in an inverse modeling scheme to estimate ligament slack-length. This will provide a calibrated model that recreates the experimental conditions.

Status: Complete

Contribution: A novel approach to using inverse modeling to estimate ligament properties.

Ligament Recruitment Probability

Status:

Contribution:

Continuum Ligament Prestrain

Status:

Contribution:

Chapter 2

Distraction Experiment

2.1 Introduction

Laxity tests are used by physicians to assess the integrity of specific ligaments. These tests can involve the physician moving the joint to a specific position and manually applying loads to the joint. Different tests are used for specific ligaments, and the physician assess the amount of joint motion and restraint that is provided (or not provided) by the targeted ligament. In a research setting, similar laxity-style tests are conducted on cadaveric specimens with custom fixtures (**?**Walker et al., 2014; Rachmat et al., 2016)CITATIONS, or six degree-of-freedom robots CITATIONS. Previous work has used physical experiments to quantify the effect of injury CITATION, and different techniques for ligament reconstruction CITATION, joint replacement CITATION,

Experimental data were collected for use in the inverse modeling scheme described in chapter 3. The purpose of the distraction experiments is to collect specimen-specific kinematic and kinetic data under traditional laxity-style loads, and novel distraction laxity-style loads. The traditional laxity-style loads are meant to simulate clinical tests that a physician may use to assess the integrity of specific ligaments. For a given joint position, the

This section describes the experimental protocol that was used to test specimens under traditional and distraction laxity-style tests.

2.2 Methods

2.2.1 Initial Specimen Preparation and Testing

Experimental tests were conducted on two knee specimens (AGE, BMI). The specimens were initially prepared following the OpenKnee(s) protocol (Erdemir, 2016). In short, whole leg specimens from femoral head to foot were initially dissected by removing the soft tissue proximal and distal to the knee, leaving soft tissues intact from 8 cm proximal to the joint line to 8 cm distal. To facilitate model generation, three registration markers were fixed to the femur and tibia (six markers total) approximately 8 cm proximal and distal to the joint line, respectively. Optoelectronic sensors were fixed to the femur and tibia, and the position and orientation of the sensors was measured with an optoelectronic camera system (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada). Osseous landmarks (medial and lateral femoral epicondyles, femoral head, medial and lateral tibial plateau, and the medial and lateral malleolus) and ten points around each registration marker were digitized. After digitization, the tibia and femur were cut approximately 19 cm proximal and distal to the joint line, respectively. The specimen was them MR imaged. Following MR imaging, the femur and tibia were potted into fixtures that are used to mount to the robot.

A six degree-of-freedom simVITRO$^{\mathrm{TM}}$robot (Cleveland Clinic, Cleveland, OH) was used to apply laxity style loading to the specimen. Following this testing, and orthopedic surgeon dissected the skin, muscle, patella, and menisci, leaving the ligament structures intact. Note the osteoarthritis. The laxity-style tests were performed again on the now cleaned specimen. These tests were performed to increase the amount of data that was collected. The details of these tests are not described here because they do not relate to the distraction testing.

2.2.2 Distraction Testing

The specimens were dissected again following the intact and cleaned testing. An orthopedic surgeon

2.3 Results

Chapter 3

Inverse Modeling

3.1 Introduction

Chapter 4

Bibliography

Bibliography

Mark Baldwin, Peter Laz, Joshua Stowe, and Paul Rullkoetter. Efficient probabilistic representation of tibiofemoral soft tissue constraint. *Computer Methods in Biomechanics and Biomedical Engineering*, 12 (6):651–659, December 2009. doi: 10.1080/10255840902822550.

Mark A. Baldwin, Chadd W. Clary, Clare K. Fitzpatrick, James S. Deacy, Lorin P. Maletsky, and Paul J. Rullkoetter. Dynamic finite element knee simulation for evaluation of knee replacement mechanics. *Journal of Biomechanics*, 45(3):474–483, February 2012. ISSN 0021-9290. doi: 10.1016/j.jbiomech.2011.11.052. URL http://www.sciencedirect.com/science/article/pii/S0021929011007469.

Hamid Naghibi Beidokhti, Dennis Janssen, Sebastiaan van de Groes, Javad Hazrati, Ton Van den Boogaard, and Nico Verdonschot. The influence of ligament modelling strategies on the predictive capability of finite element models of the human knee joint. *Journal of Biomechanics*, 65:1–11, December 2017. ISSN 0021-9290, 1873-2380. doi: 10.1016/j.jbiomech.2017.08.030. URL http://www.jbiomech.com/article/S0021-9290(17)30452-9/abstract.

L. Blankevoort and R. Huiskes. Validation of a three-dimensional model of the knee. *Journal of Biomechanics*, 29(7):955–961, July 1996. ISSN 0021-9290. doi: 10.1016/0021-9290(95)00149-2. URL http://www.sciencedirect.com/science/article/pii/0021929095001492.

Yasin Y. Dhaher, Tae-Hyun Kwon, and Megan Barry. The effect of connective tissue material uncertainties on knee joint mechanics under isolated loading conditions. *Journal of Biomechanics*, 43 (16):3118–3125, December 2010. ISSN 0021-9290. doi: 10.1016/j.jbiomech.2010.08.005. URL http://www.sciencedirect.com/science/article/pii/S0021929010004380.

Ahmet Erdemir. Open Knee: Open Source Modeling & Simulation to Enable Scientific Discovery and Clinical Care in Knee Biomechanics. *The journal of knee surgery*, 29(2):107–116, February 2016. ISSN 1538-8506. doi: 10.1055/s-0035-1564600. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4876308/.

Joseph A. Ewing, Michelle K. Kaufman, Erin E. Hutter, Jeffrey F. Granger, Matthew D. Beal, Stephen J. Piazza, and Robert A. Siston. Estimating patient-specific soft-tissue properties in a TKA knee. *Journal of Orthopaedic Research*, pages 435–443, September 2015. ISSN 1554-527X. doi: 10.1002/jor.23032. URL http://onlinelibrary.wiley.com/doi/10.1002/jor.23032/abstract.

J. C. Gardiner, J. A. Weiss, and T. D. Rosenberg. Strain in the human medial collateral ligament during valgus loading of the knee. *Clinical Orthopaedics and Related Research*, (391):266–274, October 2001. ISSN 0009-921X. WOS:000171523600032.

John C. Gardiner and Jeffrey A. Weiss. Subject-specific finite element analysis of the human medial collateral ligament during valgus knee loading. *Journal of Orthopaedic Research*, 21(6):1098–1106, January 2003. ISSN 0736-0266. doi: 10.1016/S0736-0266(03)00113-X. URL http://www.sciencedirect.com/science/article/pii/S073602660300113X.

Michael D. Harris, Adam J. Cyr, Azhar A. Ali, Clare K. Fitzpatrick, Paul J. Rullkoetter, Lorin P. Maletsky, and Kevin B. Shelburne. A Combined Experimental and Computational Approach to Subject-Specific Analysis of Knee Joint Laxity. *Journal of Biomechanical Engineering*, 138(8):081004–081004, June 2016. ISSN 0148-0731. doi: 10.1115/1.4033882. URL http://dx.doi.org/10.1115/1.4033882.

M. L. Hull, Gregory S. Berns, H. Varma, and Hugh A. Patterson. Strain in the medial collateral ligament of the human knee under single and combined loads. *Journal of Biomechanics*, 29(2):199–206, February 1996. ISSN 0021-9290. doi: 10.1016/0021-9290(95)00046-1. URL http://www.sciencedirect.com/science/article/pii/0021929095000461.

G. Limbert, M. Taylor, and J. Middleton. Three-dimensional finite element modelling of the human ACL: simulation of passive knee flexion with a stressed and stress-free ACL. *Journal of Biomechanics*, 37 (11):1723–1731, November 2004. ISSN 0021-9290. doi: 10.1016/j.jbiomech.2004.01.030. URL http://www.sciencedirect.com/science/article/pii/S0021929004000740.

Jia Lu, Xianlian Zhou, and Madhavan L. Raghavan. Computational method of inverse elastostatics for anisotropic hyperelastic solids. *International Journal for Numerical Methods in Engineering*, 69(6):1239–1261, February 2007. ISSN 1097-0207. doi: 10.1002/nme.1807. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/nme.1807.

G. A. Orozco, P. Tanska, M. E. Mononen, K. S. Halonen, and R. K. Korhonen. The effect of constitutive representations and structural constituents of ligaments on knee joint mechanics., The effect of constitutive representations and structural constituents of ligaments on knee joint mechanics. *Scientific reports,* *Scientific Reports*, 8, 8(1):2323–2323, 2018. ISSN 2045-2322. doi: 10.1038/s41598-018-20739-w,10.1038/s41598-018-20739-w. URL http://europepmc.org/abstract/MED/29396466,http://europepmc.org/articles/PMC5797142/?report=abstract.

E. Pea, B. Calvo, M. A. Martnez, and M. Doblar. A three-dimensional finite element analysis of the combined behavior of ligaments and menisci in the healthy human knee joint. *Journal of Biomechanics*, 39(9):1686–1701, January 2006. ISSN 0021-9290, 1873-2380. doi: 10.1016/j.jbiomech.2005.04.030. URL http://www.jbiomech.com/article/S0021-9290(05)00211-3/abstract.

H. H. Rachmat, D. Janssen, G. J. Verkerke, R. L. Diercks, and N. Verdonschot. In-situ mechanical behavior and slackness of the anterior cruciate ligament at multiple knee flexion angles. *Medical Engineering & Physics*, 38(3):209–215, March 2016. ISSN 1350-4533. doi: 10.1016/j.medengphy.2015.11.011. URL http://www.sciencedirect.com/science/article/pii/S1350453315002696.

Colin R. Smith, Rachel L. Lenhart, Jarred Kaiser, Michael F. Vignos, and Darryl G. Thelen. Influence of Ligament Properties on Tibiofemoral Mechanics in Walking. *Journal of Knee Surgery*, 29(2):99–106, February 2016. ISSN 1538-8506. doi: 10.1055/s-0035-1558858. WOS:000373292000003.

Yuhua Song, Richard E. Debski, Volker Musahl, Maribeth Thomas, and Savio L. Y. Woo. A three-dimensional finite element model of the human anterior cruciate ligament: a computational analysis with experimental validation. *Journal of Biomechanics*, 37(3):383–390, March 2004. ISSN 0021-9290. doi: 10.1016/S0021-9290(03)00261-6. URL http://www.sciencedirect.com/science/article/pii/S0021929003002616.

Darryl G. Thelen, Kwang Won Choi, and Anne M. Schmitz. Co-Simulation of Neuromuscular Dynamics and Knee Mechanics During Human Walking. *Journal of Biomechanical Engineering*, 136(2):021033–021033–8, February 2014. ISSN 0148-0731. doi: 10.1115/1.4026358. URL http://dx.doi.org/10.1115/1.4026358.

Peter S. Walker, Michael T. Lowry, and Anoop Kumar. The Effect of Geometric Variations in Posterior-stabilized Knee Designs on Motion Characteristics Measured in a Knee Loading Machine. *Clinical Orthopaedics and Related Research*, 472(1):238–247, January 2014. ISSN 0009-921X, 1528-1132. doi: 10.1007/s11999-013-3088-2. URL http://link.springer.com/10.1007/s11999-013-3088-2.

J. A. Weiss and J. C. Gardiner. Computational modeling of ligament mechanics. *Critical Reviews in Biomedical Engineering*, 29(3):303–371, 2001. ISSN 0278-940X.