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A model of articular cruciate ligament reconstructive surgery: A validation construct and computational insights

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ABSTRACT

This study sought to develop a computational framework that emulates the articular cruciate ligament reconstruction surgery using transtibial portal technique. The proposed model included the tibia–femoral and patella–femoral joints, articular cartilage and menisci. Key surgical parameters were incorporated including bone-patellar-tendon-bone graft excision and pre-tensioning, tunnel morphology, bone plugs, and bone plug fixation. Several simulation steps were parameterized to reflect the clinically reported surgical procedure. Our focus was to explore the intra-operative effects of variations in tunnel directions on the selected metrics of joint mechanics during Lachman and Anterior Drawer tests. A mathematical construct capable of transforming the limited and heterogeneous experimental and surgical data to evidence-based validation was adopted to ensure the viability of the finite element models. We found that the proposed models, subject to a variation in tunnel directions, resulted in simulation outputs that favor the reported experimental data of Lachman and Anterior Drawer tests under uncertainty. Simulation results for a population of three-dimensional tunnel orientations provided insights into the graft–tunnel contact mechanics and the spatial stress distribution in the graft, insights that have been anecdotally observed in prior experimental studies. The intraarticular graft tension was found to be higher than the estimated *in tunnel* graft force, and larger differences were found for the least inclined tunnels exhibiting higher contact pressures, transverse bending and twisting of the graft and Von-Mises stress at the graft–femoral tunnel interface. Conversely, tunnels with high inclination angles exhibited higher intraarticular graft tension and Von-Mises stress at the graft–tibial bone plug interface.

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1. Introduction

The intraoperative outcome of the anterior cruciate ligament reconstruction (ACL-R) depends on several surgical factors including the graft stiffness, tunnel architecture, pre-tensioning of the graft and donor site morbidity issue. Tunnel properties (placement and orientation) are of significant clinical interest given their anticipated influence on the mechanics and functional outcomes of the reconstructed knee (Amis and Jakob, 1998; Abebe et al., 2011; Markolf et al., 2002; Musahl et al., 2005; Simmons et al., 2003; Zavras et al., 2005).

Surgical simulations that incorporate the detailed biomechanical changes associated with the ACL-R have the potential to improve the clinical outcomes of the surgery. However, the literature presents a few computational models of ACL-R. A 3D finite element (FE) model of the tibio-femoral (TF) joint was introduced to explore the effect of graft pre-tensioning (Pena et al., 2005) and tunnel angles (Pena et al., 2006). In this study, we facilitated realistic predictions of the stress distribution and deformed shape of the graft under excessive tibial loading. The exact geometry of the bone-patellar-tendon-bone (BPTB) graft was also incorporated. Moreover, we added a FE model of the patella–femoral (PF) joint to consider its impact on the performance of the ACL-R joint as reported by experimental investigation of Hsieh et al. (1998).

Variations in tunnel properties and biomechanical experiments across different subjects may strongly affect the predictive power of the ACL-R computational models. Often, the computationally derived in situ ligament forces and knee kinematics have been compared to experimental data for the validation purposes (Dhaher et al., 2010; Pena et al., 2006). However, examination of the available cadaveric literature shows a wide range of knee mechanics (Anterior Tibial Translation; ATT) and graft force following the same ACL-R surgery (Li et al., 2006; Loh et al., 2003). Similarly, sufficient data on tunnel parameters (location and direction) is lacking for precise representation of uncertainty associated with the surgical design.

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In this paper, we sought to develop a robust validation construct capable of accommodating the underlying imprecision in both validation and surgical design data. To this end, uncertainty measures of evidence theory are used to test the hypothesis that the developed FE models of the ACL-R subjected to surgical uncertainty will lead to simulation outputs that favor the reported experimental data under uncertainty. This construct allowed us to quantify the embedded imprecision in validation results. Moreover, we explored the intra-operative effects of variation in tunnel directions on the selected metrics of joint mechanics.

2. Validation of FE simulations under uncertainty

Given the anticipated imprecision and scarcity of available data on both the surgical parameters (tunnel orientations) and the outcomes of cadaveric data, tools of Evidence Theory are employed. Unlike probabilistic methods, intervals are assigned to variables based on the limited available data to characterize the associated uncertainty. Appendix A provides a brief overview of evidence theory. Complete development of evidence theory can be found in Dempster (1968) and Shafer (1976). In this theory, focal elements representing the body of evidence of an uncertain parameter x (Appendix A) may be nested (consonant), overlapped or disjointed. The nested belief structure is highly preferred when the available information is scarce or very imprecise (Soundappana et al., 2004). Individual focal elements in interval form may be narrow or wide depending on the range of supporting data, and the number of data determines the assigned value of basic belief assignment (Appendix A). Histograms of available data provide efficient means to identify key characteristics of the evidence-based uncertainty representation (Bloch, 1996; Salehghaffari, 2013; Salehghaffari and Rais-Rohani, 2013; Salehghaffari et al., 2012a, 2012b).

Typically, only the mean (μ) and standard deviation (σ) of biomechanical outcomes (ATT and graft forces) and surgical design parameters (tunnel directions) for a few specimens are reported. In the absence of individual data points, imprecise representation of normal probability density function (PDF) was considered (Salehghaffari and Rais-Rohani, 2013; Salehghaffari et al., 2012a,

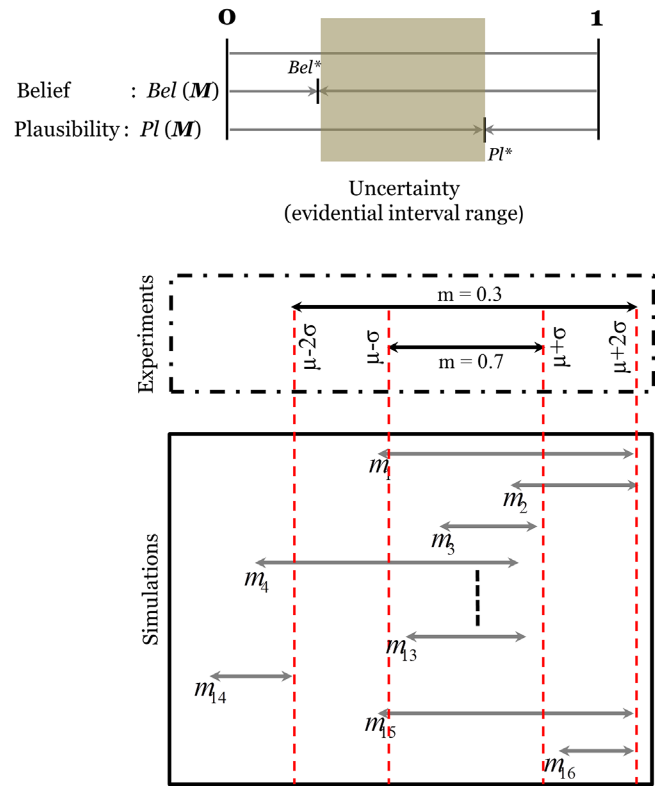

Fig. 2. Experimental-based and simulation-based representation of uncertainty for a selected biomechanical outcome (graft force or ATT) is shown. Also, validation assessment of computational outcomes with belief and plausibility measures is depicted. Appendix A provides detailed description.

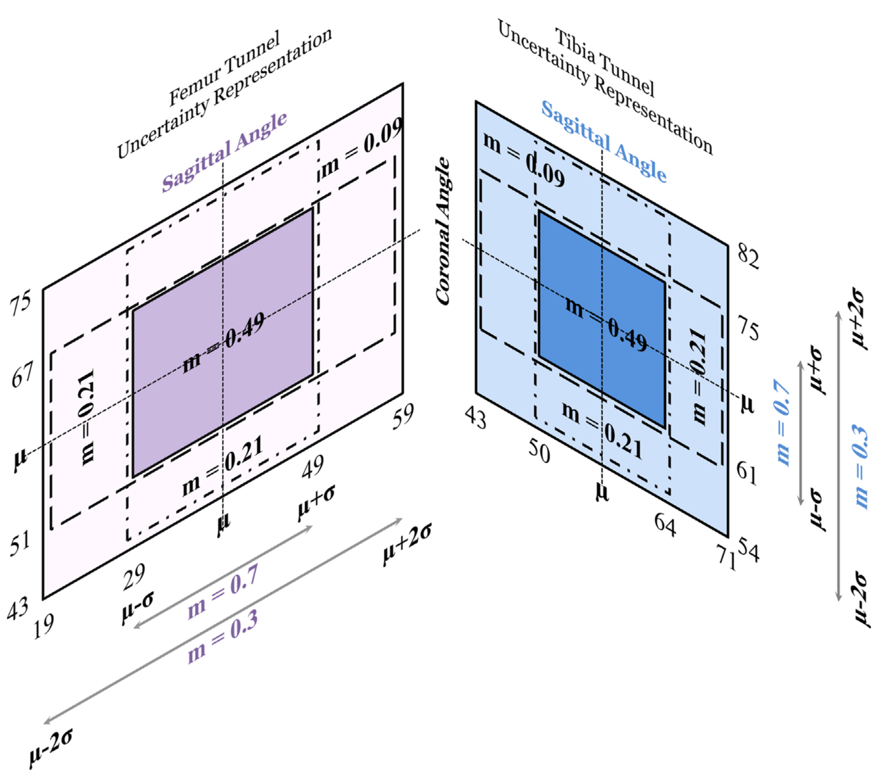

Fig. 1. Separate (1D intervals) and coupled (2D rectangles) representation of uncertainty for the tibial and femoral tunnel angles in the sagittal and coronal planes are depicted. Basic belief assignment (BBA) for each 1D and 2D focal elements is represented by m. Appendix A provides detailed description.