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Biomechanics of the human knee joint in compression: reconstruction, mesh generation and finite element analysis

M Z Bendjaballah¹, A Shirazi-Adl², D J Zukor²

¹Division of Applied Mechanics, Department of Mechanical Engineering, École Polytechnique, Montréal, Québec, Canada; ²Chief, Orthopaedic Surgery, Jewish General Hospital, Montréal, Québec, Canada

Summary

Computer assisted tomography with direct digitization and measurements were used to reconstruct the detailed geometry of an entire human knee joint specimen. These data were then merged with a mesh generation algorithm and material properties reported in the literature to develop a three dimensional non-linear finite element model of the knee joint. This model consists of three bony structures (tibia, femur and patella), their articular cartilage layers, medial and lateral menisci, and five principal ligaments (collaterals, cruciates and patellar tendon). The menisci are represented as a non-homogeneous assemblage of a solid matrix reinforced by radial and circumferential collagen fibres. The articulations of cartilage layers with each other as well as with intervening menisci and the wrapping of the medial collateral ligament with tibia are treated as general large displacement frictionless contact problems. The incremental response of the tibiofemoral joint in full extension is determined under axial forces of up to 1000 N applied on the femur. Analysis are carried out with the tibia fixed while the femur is set free to translate in medial-lateral, anterior-posterior, and proximal-distal directions; the internal-external rotation is either left free or fixed. Cases simulating total meniscectomy are also analyzed. The joint exhibits a non-linear stiffening response in the axial direction with large oriented displacements. At 1000 N, the load transferred through the joint is found to be greater for the lateral compartment than for the medial compartments and at the cartilage-cartilage contact than at the meniscus-cartilage contact. The menisci, fully attached by their horns to the tibia, are radially extruded under the axial compression and create greater contact areas and smaller, more uniform, contact pressures. Removal of menisci markedly increases the primary and coupled laxities of the joint, reduces total contact areas, and increases contact stresses. The predictions are in general agreement with measurements reported in the literature.

Key words: Reconstructive knee joint, meniscectomy, finite element modelling

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Introduction

The human knee joint is distinguished by its complex three dimensional geometry and multibody articulation, that generate complex mechanical responses under physiological loads. The knee joint compliance and stability required for optimal duty function are provided by various articulations, menisci, ligaments and muscle forces. A proper understanding of knee joint bio-

mechanics significantly improves the prevention and treatment of knee joint disorders and injuries. Total knee arthroplasty and prosthetic ligament replacement are two examples that directly benefit from such knowledge.

Knee joint mechanics have consequently been the subject of a large number of studies, the majority of which are experimental and aim at the measurement of the gross multidirectional load-displacement response of the joint under both static and perturbed states¹⁻⁴. Measurements have also been reported on the biomechanical role of the ligaments and menisci⁵⁻¹¹, as well as the mechanism of load transfer and contact areas and pressures at the tibiofemoral and

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Correspondence and requests for Dr A. Shirazi-Adl, Division of Applied Mechanics, Department of Mechanical Engineering, École Polytechnique, PO Box 6070, Stn. Ave. P, Montréal, Québec, Canada H3C 3A7

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