

Partial Meniscectomy Changes Contact Stress Distribution in Knee Joint under Combined Loading

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INTRODUCTION

Injuries to anterior cruciate ligament (ACL) and menisci as well as alterations thereof following replacement interventions influence overall knee joint response as well as mechanical role of remaining components with the likelihood to exacerbate the joint condition causing further injuries. Meniscal lesions are often detected to accompany ACL ruptures with the odds of having tears increasing further as time progresses after ACL initial injury. Due to the dramatic adverse effect of total meniscectomy on load redistribution and development of joint osteoarthritis (OA), partial meniscectomy is preferred involving the resection of torn tissues. As for the ACL, existing reconstruction techniques use different ligament pretension levels and replacement materials such as bone-patellar-tendon-bone and hamstrings grafts that possess much stiffer material properties. The graft material and pretension are recognized as primary variables influencing the outcome of reconstruction attempts. Despite ACL reconstructions and partial meniscectomies, mid- and long-term incidence of OA has persisted. The objective of this study is set to initially incorporate the detailed composite structure of articular cartilage and menisci into an existing model developing thus a complex novel model required to study knee joint biomechanics simulating partial meniscectomies and ACL reconstructions. Earlier knee model studies have failed to incorporate the realistic fibril-reinforced nature of joint soft tissues. The response is investigated under drawer and axial compression alone and combined. Attention is focused on the effect of loads and joint perturbations on cartilage stresses, contact loads and ACL forces.

METHODS

A validated knee model is used that simulates femur, tibia, menisci and articular cartilage layers as well as primary ligaments. The finite element mesh is modified by extensive refinement of articular cartilage and menisci. These refinements allowed for proper incorporation of fibrils networks along with depth-dependent variation in cartilage solid matrix properties. The cartilage non-fibrillar matrix is modeled by incompressible hyperelastic elements while the fibrils networks are simulated either by membrane or continuum elements. In accordance with literature, volume fractions of 15%, 18% and 21% are taken in superficial, transitional and deep cartilage zones. Similarly, in menisci, the equivalent collagen fibrils content is estimated based on tissue tensile properties. The joint passive response is studied at full extension under a femoral posterior drawer force up to 200 N acting alone or in presence of a 1500 N compression preload. Unconstrained boundary conditions are considered. Prior to the application of loads, the joint equilibrium at full extension is sought under pre-strains in ligaments. The ABAQUS finite element package program is used.

To examine the likely effects on response of partial meniscectomy, an internal layer (~40% of thickness) at posterior-central regions of either lateral or medial meniscus is resected. Moreover, to simulate ACL reconstruction attempts, cases are analyzed with ACL material either replaced by that of patellar tendon or modified to represent additional prestrains of +4% (tenser case) or -4% (slacker case). Finally, to examine the mechanical role of deep vertical fibrils, analyses are carried out with no vertical fibrils in both femoral and tibial cartilage layers.

RESULTS

In the reference intact joint, the femoral posterior translation demonstrated a nonlinear stiffening behavior in drawer alone that turned linear and stiffer with compression preload. In the intact case (REF in Fig. 1), large ACL force (in posterolateral bundle only) was computed in drawer (200 N) alone that further increased by 30% with compression preload (1500 N). Mean contact pressures under drawer alone were much smaller compared to those under compression especially on the lateral plateau; addition of drawer resulted in an increase of ~10% in mean pressure on all contact surfaces whereas contact areas remained nearly unchanged. Increasing ACL prestrain (+4% case) or replacing it with a stiffer material (PT case) both increased ACL force by ~10% (Fig. 1). In contrast, decreasing ACL prestrain by 4% strain (-4% case) or removing deep vertical fibrils (0%VF case) diminished ACL force drastically by 31% and 38% under combined load, respectively. Lateral

(PLM case) or medial (PMM case) meniscectomy influenced ACL forces only negligibly (<3%, Fig. 1). Partial meniscectomy altered the load distribution on the tibia and femur by shifting the applied compression away from the meniscus (covered region) onto the cartilage (uncovered region), in particular on the side of resection (Figs. 2 and 3). After meniscectomy (Fig. 2b,c) and contrary to the intact case (Fig. 2a), no contact was detected at areas under meniscal resection with the peak contact stress increasing by ~5%. Stiffer ACL cases increased the contact load especially at the uncovered areas (Fig. 3) whereas slacker ACL decreased contact loads on both covered and uncovered areas.

DISCUSSION

Predictions on femoral posterior translation, ACL force and contact pressure/area are in agreement with data in the literature. Partial meniscectomies alter the load distribution by shifting the applied compression away from the affected meniscus onto the nearby cartilage while completely unloading previously covered femoral/tibial cartilage areas that otherwise articulate with the meniscus (Fig. 2). The peak pressure on cartilage areas in contact also increases. These alterations (i.e., partial unloading of femoral/tibial cartilage that would otherwise be highly loaded and increasing the load on the nearby uncovered cartilage) would have, in mid- and long-term, an adverse effect on the cartilage function and health likely leading to OA. Alterations expected in ACL reconstructed knee joints would also influence, though to a lesser extent, the redistribution of contact forces. It is to be noted that the foregoing effects further increase in the event of greater external forces, larger meniscal resections and more ACL reconstruction perturbations. Combination of partial meniscectomy and ACL reconstruction could also further exacerbate the joint mechanical environment.

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