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Computational biomechanics of articular cartilage of human knee joint: Effect of osteochondral defects

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ABSTRACT

Articular cartilage and its supporting bone functional conditions are tightly coupled as injuries of either adversely affects joint mechanical environment. The objective of this study was set to quantitatively investigate the extent of alterations in the mechanical environment of cartilage and knee joint in presence of commonly observed osteochondral defects. An existing validated finite element model of a knee joint was used to construct a refined model of the tibial lateral compartment including proximal tibial bony structures. The response was computed under compression forces up to 2000 N while simulating localized bone damage, cartilage–bone horizontal split, bone overgrowth and absence of deep vertical collagen fibrils.

Localized tibial bone damage increased overall joint compliance and substantially altered pattern and magnitude of contact pressures and cartilage strains in both tibia and femur. These alterations were further exacerbated when bone damage was combined with base cartilage split and absence of deep vertical collagen fibrils. Local bone boss markedly changed contact pressures and strain patterns in neighbouring cartilage. Bone bruise/fracture and overgrowth adversely perturbed the homeostatic balance in the mechanical environment of articulate cartilage surrounding and opposing the lesion as well as the joint compliance. As such, they potentially contribute to the initiation and development of post-traumatic osteoarthritis.

1. Introduction

Articular cartilage functions as a nearly frictionless bearing while uniformly transferring loads on underlying bone preventing high stress concentrations. Poor capacity of repair and healing of this avascular soft tissue to its native state remains a challenging problem (Buckwalter and Mankin, 1998). Onset and progression of cartilage degeneration have been hypothesized to be associated with perturbations in underlying bone (Radin and Rose, 1986) through acute injuries and/or chronic changes. Local alterations in the subchondral bone stiffness are expected to influence stresses and deformations in the adjacent articular cartilage if not the entire knee joint. Overgrowth of the subchondral plate, known as bone boss (Henderson and La Valette, 2005), as well as softening following either bone bruises (Meyer et al., 2008) or degeneration (Boyd et al., 2002) are commonly detected in knee joints especially following ACL injury. In trauma or repetitive impact loads, local detachments of the articular cartilage from its underlying calcified cartilage and/or deep collagen fibrillation have been observed preceding early bone changes (Meachim and Bentley, 1978; Radin et al., 1984).

Despite extensive experimental studies on the interactions between cartilage and its underlying support (Karsdal et al., 2008), the relative importance of subchondral injuries and their likely effects on mechanical environment of both articular cartilage and bone remains yet not well quantified. Due to difficulties in controlled experimental studies of such injuries in the subchondral region as well as their detection by joint images, computational models are recognized as invaluable tools to simulate perturbed conditions and to determine their effects on the local and global mechanical environments of the joint. The success of such attempts, however, hinges on the accuracy of the computational model used as well as the incorporation of relevant physiological conditions, for example, on loading magnitude and rate.

In earlier computational investigations of articular cartilage, biphasic fibril-reinforced composite models were introduced and validated that represented the non-fibrillar solid matrix and collagen fibrils as distinct elements each playing a mechanical role for which it is optimally structured (Li et al., 1999; Shirazi and Shirazi-Adl, 2005). Such composite models have extensively been employed in recent model studies as well (Julkunen et al., 2007; Wilson et al., 2004). Alternatively, collagen fibrils have been taken

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implicitly into consideration in constitutive models of the solid matrix (Cohen et al., 1998; Soltz and Ateshian, 2000). The important role of vertical fibrils, and to a lesser extent of the horizontal fibrils, in cartilage mechanics at transient periods were recently demonstrated both in a fibril-reinforced axisymmetric model under creep and relaxation indentation loadings (Shirazi and Shirazi-Adl, 2008) and in a detailed 3-D model of the entire knee joint (Shirazi et al., 2008). This latter model of the joint incorporated, for the first time, a detailed consideration of microstructure of femoral and tibial cartilage layers as well as menisci. Subchondral bones were assumed rigid and hence absent in these studies. While bony elements do not noticeably affect contact predictions in the intact knee joint (Donahue et al., 2002), their incorporation is essential if subchondral injuries are to be investigated.

The objective of this study was to quantify the influence of alterations in osteochondral bone due to defects on mechanics of articular cartilage and the entire joint. To do so, initially the existing knee joint model was extended to incorporate proximal tibial bone. The transient response of the lateral compartment was subsequently investigated under axial compression forces up to ~6 times body weight. We hypothesized that acute injuries in the subchondral bone, horizontal splitting and bone overgrowth and hardening would markedly influence chondral mechanics.

2. Method

2.1. Finite element mesh

An existing refined model of the knee joint was employed in this study (Shirazi et al., 2008). The fibrils networks at different regions of articular cartilages and menisci were considered. The cartilage non-fibrillar matrix was modelled as incompressible isotropic hyperelastic solid with depth-dependent properties (Schinagl et al., 1997). The fibrils networks were simulated either by membrane or continuum elements (Fig. 1). In superficial zones of femoral and tibial cartilage layers as well as bounding surfaces of menisci, the collagen fibrils were simulated by membrane elements with uniform fibrils distribution (Figs. 1 and 2). In the transitional zone of femoral and tibial cartilage layers with random fibrils (i.e., no dominant orientations), continuum brick elements that take the principal strain directions as the material principal axes represented collagen fibrils (Fig. 2). In the deep zone, however, vertical fibrils were modelled with vertical membrane elements similar to horizontal superficial ones while offering resistance only in their local fibril direction oriented initially normal to the subchondral junction (Fig. 2). In the bulk region of each meniscus in between peripheral surfaces, collagen fibrils that are dominant in the circumferential direction were represented by membrane elements with local material principal axes defined in orthogonal circumferential and radial directions.

For the current study, the tibial cartilage was further refined while the calcified cartilage as well as the bony structure of the proximal tibia (i.e., subchondral, trabecular and cortical bones) were added to a depth of ~16 mm (Fig. 1). Due to the stated objective, loading and large number of elements in the model, the joint lateral compartment alone was simulated in the current study neglecting thus the medial compartment and joint ligaments (Shirazi et al., 2008). Calcified cartilage thickness was taken constant as 0.2 mm while the subchondral and cortical bone

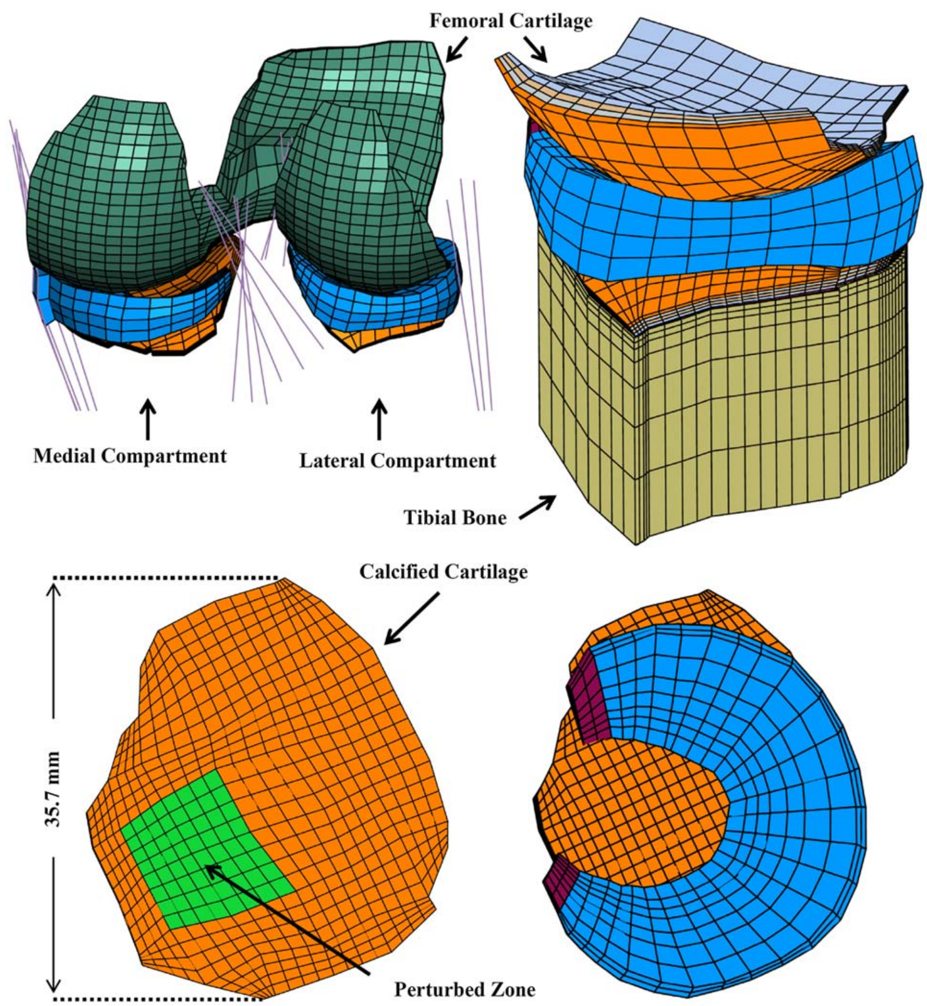

Fig. 1. Finite element model: top left: posterior view of the tibiofemoral joint used to extract the lateral compartment for the current study. Top right: lateral compartment of the joint with the calcified cartilage and tibial bony elements (subchondral, cancellous and cortical) incorporated. Bottom left: top view of the tibial lateral cartilage at the calcified region depicting the localized area for various osteochondral defect models used in this study. Bottom right: top view of menisci (horns in darker colour) and tibial articular cartilage.