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Changes to the articular cartilage thickness profile of the tibia following anterior cruciate ligament injury

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SUMMARY

Objectives: We sought to determine if anterior cruciate ligament (ACL)-injured subjects demonstrated side-to-side differences in tibial cartilage thickness soon after injury, and if uninjured-control subjects displayed side-to-side symmetry in cartilage thickness. Second, we aimed to investigate associations between body mass index (BMI), cross-sectional area (CSA) of the proximal tibia, and articular cartilage thickness differences.

Methods: Bilateral Magnetic Resonance Images (MRIs) were obtained on 88 ACL-injured subjects (27 male; 61 female) a mean 27 days post-injury, and 88 matched uninjured control subjects. Within ACL-injured and uninjured control subjects, side-to-side differences in medial and lateral tibial articular cartilage thickness were analyzed with adjustment for tibial position relative to the femur during MRI acquisition. Associations between tibial CSA and cartilage thickness differences were tested within high and low BMI groups.

Results: Within the medial tibial compartment, ACL-injured females displayed significant increases: mean (confidence interval (CI)) = +0.18 mm (0.17, 0.19) and decreases: mean (CI) = −0.14 mm (−0.13, −0.15) in tibial cartilage thickness within the central and posterior cartilage regions respectively. Adjustment for tibial position revealed a decreased area of significant cartilage thickness differences, though 46% of points maintained significance.

In the lateral compartment anterior region, there was a significantly different relationship between cartilage thickness differences and CSA, within high and low BMI groups (BMI group*CSA interaction, $P = 0.007$). Within the low BMI group, a significant negative correlation between cartilage thickness and CSA was identified ($P = 0.03$).

Conclusions: ACL-injured females displayed cartilage thickness differences in the central, and posterior medial tibial cartilage regions. Tibial position effected thickness differences, but did not account for all significant differences.

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Introduction

Severe joint traumas, including injury to the anterior cruciate ligament (ACL), have lasting effects on joint heath, and often result in the early onset of post traumatic osteoarthritis (PTOA)[1–10]. Though surgical reconstruction of the ACL has become the conventional way to improve patient function, it does not prevent the ultimate development of PTOA[1,2,5,11]. Reports estimate the highest incidence of ACL-injury occurs in individuals between 15 and 26 years of age[5,12]. As a consequence, many young and otherwise healthy individuals inevitably present with PTOA within 10–15 years of the index injury[2,3,13,14]. Presently, little is known about the onset of cartilage degeneration after injury, though several studies

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suggest that the initial joint trauma[2,5–10,15], and corresponding alterations in joint contact mechanics[2,3,16–18] are paramount factors in the development of PTOA.

Magnetic Resonance Imaging (MRI) studies of ACL-injured patients often reveal concomitant injuries within the tibiofemoral joint[19,20], that are indicative of the large shear and compressive loads developed across the joint at the time of injury[2,3,5,19]. Though there might be an absence of gross defects within the articular cartilage surface, bone marrow lesions below the articular cartilage are common[19], and serve as evidence of the substantial forces transmitted through the cartilage at the time of ACL-injury[2,19]. Transmitted forces of this magnitude are capable of disrupting the organization of the collagen matrix, and there is evidence to suggest that this initial impact could initiate a cascade of biological events culminating in chondrocyte necrosis, alterations in cell metabolism, loss of proteoglycan, and the ultimate development of PTOA[2,4–10]. Previous research focused on cartilage status after ACL-injury has revealed important links between the presence of concomitant injuries and patient outcomes[2,5,9,19,21,22]. ACL-injured patients who sustain concomitant injuries develop PTOA at higher rates than patients who sustain isolated-ACL injuries[5,22,23].

In addition to the consequences of the initial joint trauma, ACL-injury results in alterations to the biomechanics of the tibiofemoral joint including: altered location and orientation of the tibia relative to the femur[17,24], as well as changes in the location and distribution of contact stresses[17,25–27]. These alterations are important to consider, and add to an understanding of the relationship between ACL-injury and subsequent PTOA development[7,16]. Though quantitative MRI measurements of cartilage thickness have been shown to accurately depict changes within cartilage morphology[5,28–34], current research has yet to include consideration for the effect of altered joint position on the measurement of cartilage thickness. To our knowledge no previous studies have measured significant side-to-side differences in tibial cartilage thickness soon after ACL-injury, though previous research has described both increased and decreased cartilage thickness on the medial femoral condyle and trochlear sulcus, respectively, at one- and two-year follow-ups after ACL-injury[1,35] Additionally, prior work has used radiographic based techniques to measured acute changes in joint space width, and has indicated both thinning and thickening of tibiofemoral articular cartilage within months after ACL-injury[36].

Presently, a paradigm exists where interventions for both primary osteoarthritis (OA) and PTOA have been targeted at individuals who already exhibit clinical signs and symptoms of an irreparable disease process. Quantification of early changes within the articular cartilage soon after ACL-injury may help to describe early structural damage, and give insight to onset of PTOA; at a point in time where structural deterioration may be reversible[4,37,38].

Building on prior research the objectives of this study were twofold. First, we sought to determine if ACL-injured subjects exhibited significant side-to-side differences in tibial plateau articular cartilage thicknesses within a short time interval after injury and, if uninjured control subjects displayed side-to-side symmetry in tibial cartilage thickness. Additionally, we aimed to determine if cartilage thickness differences were affected by the position of the tibia relative to the femur during MRI acquisition. Our second objective was designed to build on our first, by defining effects of overall subject size (body mass index (BMI)) and the size of a subject's proximal tibia (defined by cross-sectional area (CSA)), on the measurement of cartilage thickness.

Methods

Our Institutional Review Board gave approval for this study and all subjects provided written consent prior to their participation. MRI data in this study were originally collected as part of a larger longitudinal cohort study with a nested matched case-control design[39]. The aforementioned study was designed to identify the risk factors for noncontact ACL-injury, and resulted in a multivariate model of risk[39]. Additional details of the MRI cohort, including the recruitment protocol and subject demographics, have been previously described[40].

Varsity athletes from 28 high schools and 8 colleges were monitored prospectively over a 4-year time interval for the occurrence of non-contact ACL-injures. Non-contact ACL-injury was defined as: an ACL-injury that had occurred in the absence of a direct blow to the knee. 88 ACL-injured subjects (27 male, 61 female) who had sustained a first time, grade III, non-contact ACL-injury, during participation in organized high school or college sport were included in this study. Uninjured control subjects (27 males, 61 females), were recruited teammates of the ACL-injured subjects, who were matched on age, and sex. Case-control matching of subjects from the same sports team was performed to control for the type, amount, and level of activity of each case subject.

Using the Phillips Achivia 3.0T Research MRI (Fletcher Allen Healthcare, Burlington, VT) bilateral MRI scans were obtained on both ACL-injured, and uninjured-control subjects. Subjects were positioned supine, with their knees in extension inside an 8-channel SENSE coil. Sagittal plane, T1 weighted, Fast-Field Echo (FFE) scans with a slice thickness of 1.2 mm, and a within-plane resolution of 0.3 mm by 0.3 mm, were obtained on all subjects. MRIs were acquired on ACL-injured subjects after injury, but preceding any surgical reconstruction (days post-injury: median 15, average 27, range 1–110). Using OsiriX Software (Pixmeo, Geneva, Switzerland, version 3.6.1, open source) and a Cintiq 21 UK Digitizing tablet (Wacom Tech Corp, Vancouver, WA, USA), digital imaging and communications in medicine (DICOM) images were viewed and manually segmented. Medial and lateral compartments of the tibial plateau were segmented and considered separately. Articular cartilage surfaces were segmented in both the sagittal and coronal planes, from the edge of each compartment to the last slice on the tibial spine where the cartilage surface was discernable. Medial and lateral tibial plateau subchondral bone surfaces were segmented in the sagittal plane (See Fig. 1 of Supplemental text). Intraclass correlation coefficient (ICC) values were obtained from an analysis of reliability between two separate time points, indicated a high level of cartilage thickness measurement reliability (Table I). Because MRI data were acquired in the coordinate system of the scanner, and the position of the tibia relative to the femur varied both within and between subjects, MRI data were transformed into three-dimensional bone based femoral and tibial coordinate systems [Fig. 1(A)]. Tibial and femoral coordinate systems were used to obtain measurements that were referenced to the anatomical planes of each bone, allowing for comparison of data both between, and within subjects. Methods used to establish and locate the coordinate systems have been described[41]. Respective locations of the tibial and femoral coordinate system origins allowed for a quantitative description of the position of the tibia relative to the femur during MRI acquisition. With this approach medial-lateral (ML) and

Table I
ICC values for measurement reliability between two separate time points presented for medial and lateral compartments, anterior, central and posterior regions

Compartment	Regions	ICC
Lateral	Anterior	0.88
	Central	0.97
	Posterior	0.96
Medial	Anterior	0.91
	Central	0.95
	Posterior	0.85