Clinical Biomechanics 34 (2016) 38–44

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

American Society of Biomechanics Clinical Biomechanics Award 2015: MRI assessments of cartilage mechanics, morphology and composition following reconstruction of the anterior cruciate ligament

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A R T I C L E I N F O

Article history:
Received 15 December 2015
Accepted 22 March 2016

Keywords:
Biomechanics
Cartilage
Anterior cruciate ligament reconstruction
Dynamic MRI
Thickness
Biomarkers

A B S T R A C T

Background: The pathogenesis of osteoarthritis following anterior cruciate ligament (ACL) reconstruction is currently unknown. The study purpose was to leverage recent advances in quantitative and dynamic MRI to test the hypothesis that abnormal joint mechanics within four years of reconstruction is accompanied by evidence of early compositional changes in cartilage.
Methods: Static MR imaging was performed bilaterally on eleven subjects with an ACL reconstruction (1–4 years post-surgery) and on twelve healthy subjects to obtain tibial cartilage thickness maps. Quantitative imaging (mcDESPOT) was performed unilaterally on all subjects to assess the fraction of bound water in the tibial plateau cartilage. Finally, volumetric dynamic imaging was performed to assess cartilage contact patterns during an active knee flexion–extension task. A repeated-measures ANOVA was used to test for the effects of surgical reconstruction and location on cartilage thickness, bound water fractions, and contact across the medial and lateral tibia plateaus.
Findings: No significant differences in cartilage thickness were found between groups. However, there was a significant reduction in the fraction of water bound by proteoglycan in the ACL reconstructed knees, most notably along the anterior portion of the medial plateau and the weight-bearing lateral plateau. During movement, reconstructed knees exhibited greater contact along the medial spine in the medial plateau and along the posterior aspect of the lateral plateau, when compared with their healthy contralateral knees and healthy controls.
Interpretation: This study provides evidence that abnormal mechanics in anterior cruciate ligament reconstructed knees are present coincidently with early biomarkers of cartilage degeneration.

1. Introduction

Early onset osteoarthritis (OA) is common in ACL-reconstructed (ACLR) knees, with greater than 50% of patients displaying some signs of radiographic OA within 20 years post-surgery (Liden et al., 2008). The underlying etiology of early OA in this patient population remains unknown, but identifying potential causes is important for establishing clinical management approaches that can best mitigate OA risk. However, investigating the pathogenesis of post-traumatic OA is challenging given the long time periods typically needed to detect clinical and radiographic manifestations of the disease (Haughom et al., 2012).

Recent developments in quantitative magnetic resonance imaging (MRI) have enabled noninvasive evaluation of cartilage composition and ultra-structure. For example, T1rho relaxation rates have been correlated with proteoglycan content (Duvvuri et al., 2002), while T2 relaxation rates have been shown to be sensitive to changes in the collagen fiber network and water content (Mosher et al., 2000). A more recent bi-component T2 mapping technique, mcDESPOT (Deoni et al., 2008; Liu et al., 2014, 2015), can provide relative measures of the fractions of the fast and slow relaxing water components of cartilage which are thought to respectively represent water bound to proteoglycan (F_{PG}) and bulk water loosely associated with the cartilage macromolecular matrix (Reiter et al., 2009). Thus, quantitative MRI can potentially detect compositional changes in cartilage that occur early on in the development in OA (Haughom et al., 2012; Li et al., 2011). Indeed, abnormal T1rho and T2 relaxation rates have been detected in specific regions of the tibiofemoral cartilage within 1–2 years of ACL reconstructive surgery (Li et al., 2011). However, it remains unclear whether biomechanical factors contribute to the changes in MRI biomarkers of early cartilage degeneration.

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http://dx.doi.org/10.1016/j.clinbiomech.2016.03.007
0268-0033/

There is ample evidence that ACLR knees often exhibit subtle abnormalities in knee motion when compared to the contralateral uninjured knee. For example, a small, but significant, shift toward external tibia rotation and medial tibia translation has been observed during locomotion in ACLR knees (Carpenter et al., 2009; Scanlan et al., 2010; Tashman, 2004), along with a potential progressive increase in anterior tibia translation (Hofbauer et al., 2014). It has been theorized that these abnormal kinematic patterns may alter cartilage loading patterns and thereby initiate a cyclic catabolic response that eventually leads to OA (Andriacchi and Mündermann, 2006; Chaudhari et al., 2008). New dynamic MRI sequences can be coupled with high resolution cartilage imaging to investigate whether abnormal kinematics influence cartilage contact patterns during motion (Borotikar and Sheehan, 2013; Kaiser et al., 2013). Further, quantitative MRI can then be used to investigate the association between changes in cartilage contact patterns and the onset of early cartilage degeneration in ACLR knees.

The goal of this study was to use static, dynamic and quantitative MRI to investigate whether abnormal knee mechanics is linked to the pathogenesis of early post-traumatic cartilage degeneration. To do this, we compared images of tibial cartilage morphology, composition, and contact patterns between healthy and ACLR knees within four years of reconstructive surgery. We hypothesized that ACLR knees would display different cartilage contact patterns than their contralateral knees and healthy control knees. Further, we hypothesized ACLR knees would exhibit no change in cartilage morphology but would exhibit region specific reductions in bound water.

2. Methods

2.1. Subjects

The bilateral knees of eleven subjects with a primary unilateral, isolated ACL-reconstruction (6 F, 24.7 (SD: 4.7) yrs, 83.9 (SD: 17.8) kg, 2.1 (SD: 0.7) years since surgery, 6 patellar tendon grafts, 5 hamstrings grafts, 1 partial lateral meniscectomy, 1 subject with small, stable medial and lateral meniscal tears) and the dominant knees of twelve healthy controls (5F, 24.5 (SD: 4.7) years, 74.9 (SD: 10.0) kg) were tested after obtaining informed consent according to an IRB-approved protocol. Control subjects and the contralateral knees of ACLR subjects had no history of knee pain, injury or surgery and no history of septic, inflammatory or crystalline induced arthritis. ACLR subjects had no history of septic, inflammatory or crystalline induced arthritis, and no postoperative complications. Leg dominance of the control subjects was determined by a self-report of the leg with which they would kick a ball.

2.2. Static and quantitative MRI

Subjects underwent a static MR protocol consisting of an axial fat-suppressed three-dimensional spoiled gradient recall-echo (3D SPGR) sequence (TR/TE = 10.48/2.24 ms, in-plane resolution = 0.37 × 0.37 mm, slice thickness = 0.90 mm resolution, image matrix size = 512 × 512 × 304 pixels) and a sagittal three-dimensional fast spin-echo (3D FSE Cube) sequence (TR/TE = 2066.7/19.8 ms, in-plane resolution = 0.39 × 0.39 mm, slice thickness = 1.0 mm resolution, acquisition matrix size = 384 × 384 pixels) (Fig. 1). These sequences were performed bilaterally for patient subjects and unilaterally for control subjects. A mcDESPOT sequence, consisting of twenty five (8 spoiled gradient echo SPGR, 1 inversion recovery SPGR and 16 balanced steady-state free precession bSSFP) steady-state image sequences with varying flip angles, was performed on the reconstructed knee of the patient subjects and the dominant knee of the control subjects (in-plane resolution = 0.62 × 0.62 mm, slice thickness = 3.0 mm, image matrix size = 256 × 256 pixels, (Liu et al., 2014). The mcDESPOT sequence was only performed unilaterally due to limitations in scanning time. All static scans were performed in a 3.0 T clinical MR scanner (Discovery MR750, GE Healthcare, Waukesha, WI, USA) using an 8-channel phased array extremity coil (InVivo, Orlando, FL, USA). Foam padding was used to firmly secure the knee within the coil to minimize subject motion during the static MR examination.

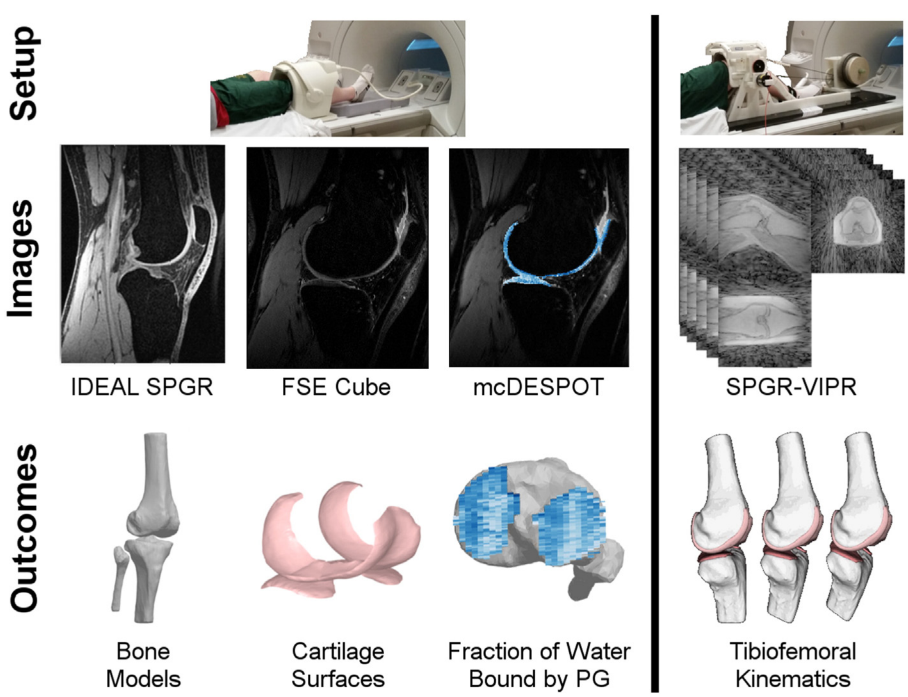

Fig. 1. Experimental Protocol. Subjects underwent a MR protocol consisting of two static sequences (IDEAL SPGR, FSE Cube), a quantitative sequence (mcDESPOT) and dynamic imaging (SPGR-VIPR) of a knee flexion–extension task. The static images were used to create subject-specific models of the bone and cartilage geometries. mcDESPOT was used to compute maps of the fraction of water bound by proteoglycan (F_{PG}). Finally, the bone and undeformed cartilage models were registered to the dynamic images, providing a quantitative characterization of the tibiofemoral contact patterns.