



Frontal plane knee mechanics and medial cartilage MR relaxation times in individuals with ACL reconstruction: A pilot study



Deepak Kumar^{a,*}, Abbas Kothari^a, Richard B. Souza^{b,c}, Samuel Wu^a, C. Benjamin Ma^c, Xiaojuan Li^a

^a Department of Radiology and Biomedical Imaging, UCSF, United States

^b Department of Physical Therapy and Rehabilitation Science, United States

^c Department of Orthopaedic Surgery, UCSF, United States

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ABSTRACT

Background: The objective of this pilot study was to evaluate cartilage $T_{1\rho}$ and T_2 relaxation times and knee mechanics during walking and drop-landing for individuals with anterior cruciate ligament reconstruction (ACL-R).

Methods: Nine patients (6 men and 3 women, age 35.8 ± 5.4 years, BMI 23.5 ± 2.5 kg/m²) participated 1.5 $\pm$ 0.8 years after single-bundle two-tunnel ACL reconstruction. Peak knee adduction moment (KAM), flexion moment (KFM), extension moment (KEM), and peak varus were calculated from kinematic and kinetic data obtained during walking and drop-landing tasks. $T_{1\rho}$ and T_2 times were calculated for medial femur (MF), and medial tibia (MT) cartilage and compared between subjects with low KAM and high KAM. Biomechanical variables were compared between limbs.

Results: The high KAM group had higher $T_{1\rho}$ for MT ($p = 0.01$), central MT ($p = 0.05$), posterior MF ($p = 0.04$), posterior MT ($p = 0.01$); and higher T_2 for MT ($p = 0.02$), MF ($p = 0.05$), posterior MF ($p = 0.002$) and posterior MT ($p = 0.01$). During walking, ACL-R knees had greater flexion at initial contact ($p = 0.04$), and lower KEM ($p = 0.02$). During drop-landing, the ACL-R knees had lower KAM ($p = 0.03$) and KFM ($p = 0.002$).

Conclusion: Patients with ACL-R who have higher KAM during walking had elevated MR relaxation times in the medial knee compartments. These data suggest that those individuals who have undergone ACL-R and have higher frontal plane loading, may be at a greater risk of knee osteoarthritis.

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1. Introduction

Over 50% of individuals with an anterior cruciate ligament (ACL) injury and reconstruction develop post-traumatic osteoarthritis (PTOA) [1–3]. Multiple studies have shown that individuals with ACL-reconstruction (ACL-R) continue to demonstrate abnormal walking mechanics of the reconstructed knee when compared to the contralateral knee and compared to control subjects [4–6]. It has been hypothesized that abnormal gait mechanics may contribute to altered cartilage loading and subsequent PTOA following an ACL-R [7]. Specifically, higher external knee adduction moment (KAM) and dynamic knee varus during walking have been implicated in the pathogenesis of knee OA [8–11]. These metrics, along with static varus deformity [12], are associated with an increase in frontal plane knee loading predisposing the medial knee cartilage to greater loading and subsequent degeneration [8,13,14]. Furthermore, abnormal movement patterns for the reconstructed knee have also been demonstrated for other activities including running [4], stair climbing [5,7], and drop landing [15–17]. However,

there are also studies that report no difference in KAM [7] or lower KAM in the ACL-R knees. [5] Hence, it is possible that considerable variability in movement patterns exists post ACL-R between individuals. Those who have movement patterns characterized with high KAM may have greater risk of cartilage degeneration compared to those who do not have such movement patterns. Although, some recent work has shown an association between abnormal knee sagittal kinematics during walking, and cartilage morphology in individuals with ACL-R, [18] no studies have been performed to evaluate the relationship between frontal plane knee mechanics and early cartilage degeneration in individuals with ACL-R. Therefore, it is important to evaluate if cartilage composition post ACL-R is different between individuals who have high KAM vs. those who have low KAM.

Early changes in knee OA consist of loss of proteoglycans (PG) and increase in water content of the articular cartilage, along with loosening, disorganization and loss of collagen matrix [19]. Loss of PG and collagen disruption hampers the load bearing ability of cartilage leading to further cartilage degeneration [19]. These biochemical changes can be detected using non-invasive quantitative MR imaging techniques of $T_{1\rho}$ and T_2 relaxation times which are sensitive to loss of PG and collagen disruption respectively, and are promising biomarkers of early disease [20–24]. An increase in $T_{1\rho}$ and T_2 relaxation times indicates loss of PG

* Corresponding author at: 1700 4th St, Suite 203, UCSF Mission Bay, Byers Hall, San Francisco, CA 94158, United States. Tel.: +1 415 514 9663; fax: +1 415 514 9656.

E-mail addresses: krdeepak2pro@gmail.com, Deepak.kumar@ucsf.edu (D. Kumar).

and disruption of collagen matrix, which is invisible to conventional radiography and morphologic MR imaging [20,23–26]. It has been shown that in people with ACL injuries, or knee OA, there is an increase in these MR relaxation times showing cartilage degeneration [20,23–26].

Abnormal knee mechanics following an ACL-R, especially greater KAM, may be related to accelerated medial knee cartilage degeneration. However, the association of these MR relaxation time parameters with frontal plane knee mechanics in individuals with ACL-R has not been performed. If abnormal frontal plane mechanics are associated with early cartilage degeneration in individuals with ACL-R, it may allow for development of early intervention programs targeted at training healthier movement patterns. Hence, the objective of this pilot study was to evaluate the articular cartilage $T_{1\rho}$ and T_2 relaxation times, and knee mechanics during walking and drop-landing for individuals with ACL-R. Specifically, we evaluated the differences in medial articular cartilage global and sub-regional $T_{1\rho}$ and T_2 relaxation times between individuals with high vs. low KAM during walking post ACL-R.

2. Methods

2.1. Subjects

Nine patients (6 men and 3 women, age 35.8 ± 5.4 years, BMI 23.5 ± 2.5 kg/m²) were referred by their orthopaedic surgeon 1.5 ± 0.8 years after single-bundle two-tunnel ACL reconstruction. Six patients had isolated ACL repair with either posterior tibialis allograft (from a cadaver) or hamstring autograft (from self), one patient had a concurrent partial lateral meniscectomy with a hamstring autograft, one patient had a concurrent partial medial meniscectomy with a posterior tibialis allograft and one patient had a concurrent medial meniscus repair with a posterior tibialis allograft. The study was performed in accordance with the rules of our institution's Committee on Human Research. Informed consent was obtained from each patient after the nature of the study had been explained.

2.2. Motion analysis

Three-dimensional kinematic data were collected at 250 Hz using a passive 10-camera system (VICON, Oxford Metrics, UK), and kinetic data were collected at 1000 Hz from two embedded force platforms (AMTI, Watertown, MA). Fourteen millimeter spherical retro-reflective markers were placed on bony landmarks of bilateral lower extremities for the identification of joint centers and rigid clusters placed on the lateral surface of the subject's thighs, legs and heel shoe counters were used to track segment motions [27]. Each subject performed a walking task and a drop jump task. For the walking task, patients were instructed to walk at a pace of 1.3 ± 0.07 m/s. A trial was considered acceptable when there was a clean foot-strike on any of the force platforms and the speed was within $\pm 5\%$ of the defined speed. Three good trials were collected from both lower extremities. The drop jump task, as described by Pollard et al. [28], involved the patient standing on a 30.5 cm platform and stepping off with 1 ft landing on each of the force plates. The subjects were instructed to land with both feet contacting the ground simultaneously, and then immediately jump "as high as possible". A successful trial was defined as one where the patient stepped off the platform (as opposed to jumping off or lowering themselves down), landed with both feet simultaneously with 1 ft on each force plate and immediately performed a maximal vertical jump. Three drop jump trials were collected.

Kinematic and kinetics were calculated using Visual3D (C-motion, Georgetown, MD). All net joint moments are expressed as external moments and normalized to body mass (Nm/kg). Variables were calculated for the stance phase when the foot was in contact with ground and included – peak KAM (early stance), peak external knee flexion moment (KFM) (early stance during walking, not present during drop-landing), peak external knee extension moment (KEM) (late stance during

walking), and peak adduction angle (peak varus). 1st peak KAM (early stance) was selected to stratify the subjects into high-KAM and low-KAM groups because it has been shown to be related to the progression of knee OA and medial cartilage and meniscus damage in earlier studies [9,29,30].

2.3. MR imaging

Imaging for the ACL-R knee was performed using a 3T GE Signa HDx MR Scanner (General Electric, Milwaukee, WI, USA) and an 8-channel phased-array knee coil (Invivo, Orlando, FL, USA) with the patient in a supine position. The imaging protocol included clinical T_2 -weighted FSE images (TR/TE = 4300/51 ms, FOV = 14 cm, matrix = 512×256 , 2 mm slice thickness), sagittal 3D fat-saturated high-resolution spoiled gradient-echo (SPGR) images (TR/TE = 15/6.7 ms, FOV = 14 cm, matrix = 512×512 , 1 mm slice thickness) and 3D $T_{1\rho}/T_2$ quantification sequence developed previously in our lab [31] (TR/TE = 9.1/3.3 ms, TSL: 0/10/40/80 ms, spin-lock frequency: 500 Hz, FOV = 14 cm, matrix = 256×128 , 4 mm slice thickness; for T_2 : preparation TE = 0/13.7/27.3/54.7 ms; total acquisition time = 9 min 30 s).

Medial femoral condyle (MF), and medial tibial (MT) cartilage compartments were segmented on multiple slices semi-automatically in high resolution SPGR images using the in-house software developed with Matlab (Mathworks, Natick, MA, USA) based on edge detection and Bezier splines [32]. These compartments were further divided into sub-regions as shown in Fig. 1. $T_{1\rho}$ and T_2 maps were reconstructed by fitting the $T_{1\rho}$ - and T_2 -weighted images pixel-by-pixel to the equations below using in-house developed software:

$$S(TSL) \propto \exp\left(-TSL/T_{1\rho}\right) \text{ for } T_{1\rho}$$

$$S(TE) \propto \exp(-TE/T_2) \text{ for } T_2$$

$T_{1\rho}$ and T_2 maps were rigidly registered to SPGR images and cartilage contours generated from SPGR images after segmentation were overlaid to the registered $T_{1\rho}$ and T_2 maps. Mean $T_{1\rho}$ and T_2 values were calculated in defined regions. To reduce artifacts caused by partial volume effects with synovial fluid, pixels with relaxation time greater than 130 ms in $T_{1\rho}$ or 100 ms for T_2 maps were removed from the data used for quantification.

2.4. Statistical analysis

Patients were divided into two groups using median peak KAM during walking: Group A) low KAM, and Group B) high KAM. Mean and standard deviation for all variables were calculated. Group comparisons were made using independent samples t-tests for MF and MT $T_{1\rho}$ and T_2 relaxation time parameters. Paired t-tests were used to compare the sagittal plane metrics, peak KAM, peak varus angle during the walking and drop-landing tasks between the ACL-R and contralateral knees. All statistical analyses were done using SPSS (SPSS Inc. Chicago, IL) with one-tailed significance level set at $p \leq 0.05$.

3. Results

3.1. Motion analysis

Frontal plane analyses showed no significant differences between the ACL-R and contralateral knees for peak KAM (Mean $\pm$ SD – ACL-R: 0.53 ± 0.20 Nm/kg vs. contralateral: 0.58 ± 0.19 Nm/kg, $p = 0.12$) and peak varus angle (Mean $\pm$ SD – ACL-R: 2.64 ± 3.09 vs. contralateral: $2.86 \pm 2.86^\circ$, $p = 0.39$) during walking. Sagittal plane analyses showed that during walking, the ACL-R patients made initial contact with greater knee flexion (Mean $\pm$ SD – ACL-R: $4.3 \pm 4.3^\circ$ vs. contralateral: $3.0 \pm 3.9^\circ$, $p = 0.04$), had a lower peak external extension moment (Mean $\pm$ SD – ACL-R: -0.44 ± 0.12 Nm/kg vs. contralateral: -0.50 ± 0.11 Nm/kg, $p = 0.02$), and a close to significance lower peak external flexion moment (Mean $\pm$ SD – ACL-R: 0.44 ± 0.11 Nm/kg vs. contralateral: 0.53 ± 0.20 Nm/kg, $p = 0.06$).

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