

Longitudinal Changes in Medial Femoral Cartilage Stress After ACL Reconstruction and Their Association With Knee Flexion Angle

Kelsey Neal¹, Jack R Williams², Ashutosh Khandha³, Lynn Snyder-Mackler, Thomas S Buchanan²

¹School of Medicine, ²Mechanical Engineering, ³Biomedical Engineering

INTRODUCTION:

Altered biomechanics after anterior cruciate ligament reconstruction (ACLR) are hypothesized to alter cartilage stress, potentially initiating degenerative changes associated with post-traumatic osteoarthritis (PTOA) [1,2]. Despite this, it is unknown how altered knee mechanics affect tissue-level stress magnitudes and distributions post-surgery. Thus, this study examined changes in interlimb differences in femoral cartilage stress over a 24-month period post-ACLR and examined the relationship between stress location and knee flexion angle (KFA), a modifiable gait parameter [3–5]. **We hypothesized that (1) the involved limb would experience lower cartilage stress than the uninvolved limb early after surgery, with asymmetries decreasing over time, and (2) stress location in femoral cartilage would be associated with KFA, with smaller flexion angles shifting stress anteriorly.**

METHODS:

Fifteen individuals (7 female, age: 23 ± 6 years, BMI: 24.5 ± 3.4 kg/m²) who underwent ACLR were evaluated using motion capture, EMG-driven musculoskeletal modeling, and finite element (FE) modeling of the knee at 3, 6, and 24 months postoperatively. Subjects walked at a self-selected speed that was held consistent across time points. During walking, kinematic (120 Hz), kinetic (1080 Hz), and surface electromyography (1080 Hz) data were collected bilaterally. These data were used to calculate subject-specific joint contact forces for the medial and lateral compartments via a validated EMG-driven musculoskeletal model [6]. Using magnetic resonance imaging scans, a FE model was developed from the healthy knee of one subject (female, age:19) [7]. Model inputs included medial (MCF) and lateral (LCF) compartment forces and knee flexion angles (KFA) throughout gait. Instead of scaling the geometry of the model to each individual, joint forces were normalized to the body weight (BW) of the model's primary subject, creating a scale factor for each individual's joint load. This allowed for direct comparison of FE mesh results while reducing model development time. The average Von Mises stress of the anterior, central, and posterior regions of medial femoral cartilage of both limbs were calculated during peak medial compartment loading [8–10]. A two-tailed paired t-tests with Bonferroni corrections were used to compare stresses between limbs at each time point. To assess associations between knee flexion angle at peak medial compartment force (pMCF) and the average regional stress across time points, Pearson correlations and simple linear regressions were used. Correlation strength was interpreted using R² thresholds: small (>0.02), medium (>0.13), and large (>0.26).

RESULTS:

No significant differences were present in peak MCF at any time point between limbs. KFA at peak MCF was significantly lower in the involved limb (vs. uninvolved) at three and six months, these differences resolved by 24 months (**Fig 1**). Three months after ACLR, participants displayed lower stresses in the central ($p=0.005$) and posterior femoral ($p = 0.001$) cartilage of their involved limb (vs. uninvolved, **Fig 2**). At six months, stress was higher in the involved limb (vs. uninvolved) in the anterior femoral ($p = 0.001$) regions. There were no significant differences between limbs at 24-months. When assessing KFA vs stress (**Table 1**), the femoral cartilage experienced strong negative associations at all three time points for both the involved and uninvolved limbs in the anterior region of cartilage, while the posterior region showed strong positive correlations at all three time points for the involved limb and at 6 months in the uninvolved limb. No large correlations were seen in the central region.

DISCUSSION AND CONCLUSION:

These findings support the hypothesis that medial cartilage stress is initially reduced in the involved limb post-ACLR but progresses toward symmetry over time. Knee flexion angle (KFA) showed strong negative correlations with stress magnitude in the anterior femoral region and strong positive associations in the posterior femoral region, suggesting a shift in stress posteriorly with increased flexion and anteriorly with reduced flexion. This cohort displayed stiff gait patterns, indicative of less flexion during gait, in their involved limbs at both 3 and 6 months. Taken together, this suggests stress patterns may be shifting anteriorly after ACLR, potentially over stressing the anterior cartilage while under stressing the posterior cartilage. Since cartilage is a mechanosensitive tissue, this shift in stress distribution, along with swelling and trauma from the initial injury, could place these regions at a heightened risk for eventual PTOA development [1,2,10].

References: [1] Andriacchi et al. (2004), [2] Chu & Andriacchi (2015), [3] Di Stasi et al. (2013), [4] Gardinier et al. (2013), [5] Butler et al. (2009), [6] Manal, Buchanan (2013), [7] Neal et al. (2022), [8] Erdemir et al. (2019), [9] Wellsandt et al. (2016), [10] Buchanan et al. (2006), [11] Andriacchi et al. (2009), [12] Shimizu et al. (2019)

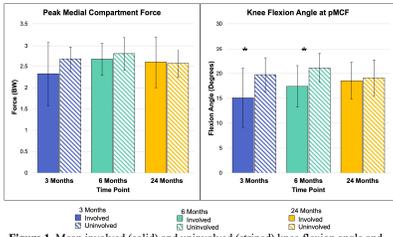


Figure 1: Mean involved (solid) and uninvolved (striped) knee flexion angle and medial compartment force at 3 (blue), 6 (green), and 24 (yellow) months post-ACL. (*p < 0.05).

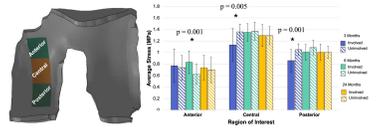


Figure 2: Mean Von Mises stress in medial femoral cartilage regions (anterior, central, posterior) at peak medial compartment force for involved (solid) and uninvolved (striped) limbs (*p < 0.016).

Table 1: Involved and uninvolved limbs association between KFA and average regional femoral cartilage stress for all three time points. Significant associations are bolded.

Region	Time Point	Involved Limb			Uninvolved Limb		
		r	Effect Size (R ²)	p Value	r	Effect Size (R ²)	p Value
Anterior	3 Months	-0.857	0.734	<0.001	-0.927	0.86	<0.001
	6 Months	-0.826	0.683	<0.001	-0.735	0.54	0.002
	24 Months	-0.780	0.609	0.001	-0.889	0.79	<0.001
Central	3 Months	0.239	0.057	0.390	0.039	0.0015	0.890
	6 Months	0.359	0.129	0.188	0.461	0.2122	0.084
	24 Months	0.415	0.172	0.124	0.032	0.001	0.913
Posterior	3 Months	0.606	0.368	0.017	0.385	0.148	0.156
	6 Months	0.702	0.493	0.004	0.647	0.418	0.009
	24 Months	0.617	0.380	0.014	0.281	0.079	0.312