Dynamic Knee Joint Stiffness 1 and 2 Years Post Anterior Cruciate Ligament Reconstruction

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INTRODUCTION: Not all individuals after anterior cruciate ligament reconstruction (ACLR) attain satisfactory symptom states and report clinical outcomes comparable to age- and sex-matched healthy adults[1–3]. Worse patient-reported outcomes (PROs) in the longer term were shown to be predicted by abnormal knee mechanics associative with degenerative changes in the knee 2 years post-ACLR[4–6], evincing the role of mechanics in post-traumatic osteoarthritis development. Knee mechanics are often evaluated at discrete time points in the gait cycle, but such features may not fully capture the interrelationships between joint kinematics and kinetics. We sought to concurrently evaluate knee flexion angle (KFA) and moment (KFM) across midstance of gait. We employed the concept of dynamic joint stiffness (DJS), which integrates KFA and KFM and is reflective of "the resistance that muscles and other soft tissue structures that cross a joint offer during gait in response to an applied moment[7]." _Study Goal:_ This study compared the DJS between ACLR and contralateral (CL) intact knees 1 and 2 years post-ACLR and assessed relationships between DJS and PROs. We hypothesized that ACLR knees compared to CL knees show greater DJS, that DJS of ACLR knees decreases from 1 to 2 years post-ACLR, and that greater DJS associates with worse PROs.

METHODS: In this IRB-approved study, 25 individuals (18 men, 7 women; 34 ± 11 years; 24.8 ± 3.7 kg/m^2) completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) and underwent gait tests 1.1 ± 0.2 and 2.1 ± 0.2 years after unilateral ACLR. _Gait Analysis:_ Participants performed three walking trials at a self-selected comfortable speed. Marker trajectories and ground reaction force were acquired using a standard 3D motion capture system (Qualisys & Bertec) with the point-cluster technique. External joint moments were expressed relative to the tibial frame and normalized to percent body weight multiplied by height (%BW×Ht). _DJS Calculation:_ Midstance was defined as the interval between the KFM peak or KFA peak (~20 %stance), whichever occurred first to the second external knee extension peak (KEM2, ~70% stance)[8]. KFM and KFA were extracted from midstance. DJS was the slope of the fitted linear regression line of KFM and KFA across midstance. Potential contributors to DJS, KFM and KFA range, maximum, and minimum, were included as secondary outcome measures. _Statistical Analysis:_ Shapiro-Wilk tests and QQ plots suggested that all included variables, except some KOOS subscales, were normally distributed. Walking speeds, known covariates of knee moments and angles, did not differ between sides (ACLR vs.CL, $p = 0.720$) and time (1 vs. 2 years, $p = 0.339$). Thus, differences in DJS were evaluated using two-way repeated ANOVA tests, followed by pairwise comparisons with Bonferroni's corrections. The same approach was applied to analyzing the secondary outcome measures. Relationships between DJS and knee moment range and angle range (i.e., range-of-motion (ROM)) were evaluated using linear regression. The KOOS between time points were compared using paired t-tests, and their relationships with DJS were examined based on Pearson's (or Spearman's rank if non-normally distributed) correlation coefficients. Results are reported as mean (95% confidence interval (CI)).

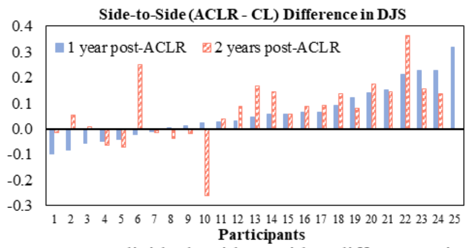

Fig 1. Individual side-to-side difference in midstance dynamic joint stiffness (DJS) 1 and 2 years post-ACLR. Positive values indicate greater stiffness in ACLR knees compared to contralateral (CL) intact knees.

RESULTS: _DJS between Sides and over Time:_ Mean midstance DJS of the ACLR knees was greater than that of the CL knees both 1 and 2 years post-ACLR (+0.06 (0.02, 0.10) %BW*Ht/°, $p = 0.003$). The majority of subjects, 19 out of 25 (76%), showed greater DJS in their ACLR knees compared to CL knees at both time points, 3 (12%) participants showed greater DJS at 1 year and lower DJS 2 years post-ACLR, and 3 (12%) showed the opposite pattern (**Fig 1**). _Contributors to Side-to-Side Differences in DJS:_ The ACLR knees showed a narrower range for midstance knee moment range (-0.76 (-1.11, -0.42) %BW*Ht, $p < 0.001$), attributable to a lower KFM (-0.34 (-0.62, -0.06) %BW*Ht, $p = 0.020$) and a higher (more positive) KEM2 (0.43 (0.14, 0.72) %BW*Ht, $p = 0.006$) (**Fig 2**). Also, midstance knee ROM was reduced in the ACLR knees compared to the CL knees (-2.75 (-4.20, -1.30) °, $p < 0.001$), attributable to greater flexion at the time of KEM2 (2.02 (0.47, 3.58)°, $p = 0.013$). The narrower range of knee moment and ROM in the ACLR knee explained significant variance of the side-to-side difference in midstance DJS at 1 and 2 years post-ACLR ($R = 0.823$, $p < 0.001$; $R = 0.681$, $p < 0.001$, respectively). _PROs over Time:_ From 1 to 2 years post-ACLR, mean KOOS pain and function in sports and recreation activities improved (3.0 (0.0, 6.1), $p = 0.048$; 9.5 (4.8, 14.2), $p < 0.001$, respectively). _DJS vs. PROs:_ The side-to-side difference in midstance DJS did not correlate with PROs at 1 and 2 years, and the side-to-side difference in midstance DJS at 1 year did not predict PRO changes. These might relate to the high variability in PROs among the participants (**Fig 3**).

DISCUSSION: The data revealed greater midstance DJS in ACLR knees compared to CL knees 1 and 2 years post-ACLR. Contributors to greater midstance DJS were lower KFM, higher KEM2, and extension loss. Lower KFM may reflect quadriceps weakness and/or altered quadricep/hamstring activities[9,10]. Higher KEM2 reflects extension loss towards the end of midstance when the knee is extending, allowing the body weight to be continually supported by one limb and the center-of-mass to advance over the foot[11]. KEM2 was reported to increase from 2 to 8 years post-ACLR and significantly deviated from KEM2 of age-, sex-, and BMI-matched healthy controls at the 8-year follow-up[12]. Moreover, despite improved mean PROs, greater midstance DJS remained in the ACLR limb of the majority of participants from 1-2 years post-ACLR. These findings suggest that some patients may benefit from physical therapy interventions *beyond a commonly used ACLR rehabilitation timeframe*—supervised rehabilitation ≤5 months and clearance for unrestricted activities in 9-12 months[13]—to specifically address residual quadriceps and hamstring strength imbalances that may compromise joint health post-ACLR.

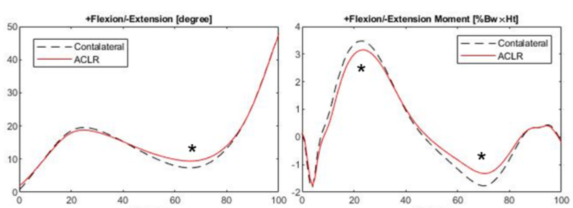

Fig 2. Knee flexion angle and moment. * denotes significant differences between ACLR and contralateral knees.

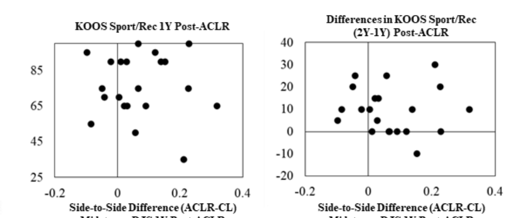

Fig 3. Greater midstance dynamic joint stiffness (DJS) in ACLR than contralateral (CL) knees and participant-reported outcomes.

SIGNIFICANCE: Dynamic joint stiffness is a multidimensional metric that can detect and quantitatively measure abnormal sagittal-plane mechanics post-ACLR to help identify patients who may benefit from additional rehabilitative interventions to improve knee function and longer term joint health.

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