Knee Loading Patterns Differ by Symptom State 2 Years Post Anterior Cruciate Ligament Reconstruction

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INTRODUCTION: Anterior cruciate ligament (ACL) tears greatly increase osteoarthritis (OA) risks[1]. Following ACL reconstruction (ACLR) and up to 12 months of rehabilitation, most patients receive clearance for return to unrestricted activity[2]. However, not all individuals report attaining an acceptable symptom state between 1-5 years post-ACLR[3]. As abnormal mechanics associated with degenerative cartilage changes continue to be observed post-ACLR[4–7], secondary OA prevention strategies are needed. The Knee Injury and Osteoarthritis Outcome Score (KOOS) is commonly used to assess patient-reported outcomes (PROs)[8]. Patient acceptable symptom state (PASS) criteria were developed to aid in the interpretation of the KOOS regarding whether individuals "feel well" about their knee-related health[3]. Quantitative loading metrics have been shown to complement the interpretation of patient-reported outcomes in response to interventions for OA[9,10]. Combined assessment of PROs and quantitative loading metrics may increase the potential to identify individuals post-ACLR who may need additional intervention and provide insights into developing appropriate rehabilitative strategies to optimize joint health. *Purpose:* This study aimed to determine if quantitative loading metrics correspond to patient-perceived symptom states 2 years post-ACLR by testing the hypothesis that absolute and relative loading of the ACLR knees differ between individuals achieving an acceptable symptom state (PASS-Y) and those who did not (PASS-N).

METHODS: This IRB-approved study involved 59 individuals with primary unilateral ACLR (**Table 1**). At 2 years after ACLR, all participants completed the KOOS and underwent a gait assessment. *Gait Analysis:* Marker trajectories and ground reaction force of three walking trials at a self-selected comfortable pace were acquired using a standard 3D motion capture system (Qualisys & Bertec) synchronized at 120 Hz and with the point cluster technique. Knee moments were calculated using an inverse dynamic approach, expressed as external moments relative to the tibial frame, and normalized to percent body weight multiplied by height (%BW×Ht). The total joint moment (TJM) was calculated for each time point of the stance phase by taking the square root of the sum of the squares of the flexion (KFM), adduction (KAM), and rotation (KRM) moments. Absolute loading metrics, the peak KFM, KAM, KRM, and TJM, were extracted from early stance. Relative loading metrics included the %KFM, %KAM, and %KRM contribution to peak TJM. *Dichotomization:* Participants were dichotomized based on ACLR-specific KOOS PASS-Y criteria: 88.9 (pain), 57.1 (symptoms), 100 (function in activities of daily living, ADL), 75 (function in sports and recreation, sport/rec), 62.5 (knee-related quality of life, QoL). *Statistical Analysis:* Participant factors, surgical factors, and loading metrics of the ACLR knees between PASS-Y and PASS-N were compared using independent t-tests (or Mann-Whitney U tests if non-normally distributed; Fisher's exact test for categorical variables) in SPSS v28. Relationships between loading metrics and PASS were examined with mixed effects logistic regression. Odds ratios were computed (lme4 package in R v4.2). Results are reported as mean [95% confidence interval (CI)].

Table 1. Participant and Surgical Factors

Demographics	**N = 59**
Age, mean (95%CI) years	33 (31, 36)
BMI, mean (95%CI) kg/m^2	24.8 (23.9, 25.8)
Gender-Female, N (%)	33 (56%)
Injury and Surgery Factors	
ACL deficiency exposure time, mean (95%CI) weeks	28.9 (10.1, 47.6)
ACLR exposure time, mean (95%CI) years	2.16 (2.09, 2.22)
Graft Type, missing N = 4	
Hamstring Autograft, N (%)	8 (15%)
Bone-Patella Tendon-Bone Autograft, N (%)	21 (38%)
Allograft, N (%)	26 (47%)
Meniscus Tear, missing N = 3	
Medial, N (%)	11 (19%)
Lateral, N (%)	25 (45%)
Medial Meniscus Treatment, missing N = 3	
Intact, N (%)	45 (80%)
Repair, N (%)	5 (9%)
Resect, N (%)	3 (5%)
Tear, not treated, N (%)	3 (5%)
Lateral Meniscus Treatment, missing N = 3	
Intact, N (%)	31 (55%)
Repair, N (%)	13 (23%)
Resect, N (%)	9 (16%)
Tear, not treated, N (%)	3 (5%)
Radiographic Factors	
Kellgren-Lawrence grade of ACLR Knees	
0, N (%)	50 (85%)
1, N (%)	9 (15%)
Mechanical axis of ACLR Knees, mean (95%CI)°	-0.62 (-1.16, -0.09)
Kellgren-Lawrence grade of Contralateral Knees	
0, N (%)	55 (93%)
1, N (%)	4 (7%)
Mechanical axis of Contralateral Knees, mean (95%CI)°	-0.79 (-1.49, -0.10)

RESULTS: The number (%) of participants meeting the PASS-Y criteria were 39 (66%) for pain, 59 (100%) for symptoms, 25 (42%) for ADL, 43 (73%) for sport/rec, and 39 (66%) for QoL (**Figure 1**). *Participant & Surgical Factors:* Compared to PASS-Y, PASS-N for pain and ADL showed a more varus mechanical axis (-1.0 [-2.1, 0.2]°, $p = 0.043$; -1.3 [-2.3, -0.3]°, $p = 0.014$, respectively). PASS-N for ADL also showed a lower Tegner score than PASS-Y (-1.1 [-2.0, -0.0], $p = 0.043$). No differences in graft type or meniscus status were observed. *Absolute Loading:* In comparison to PASS-Y, PASS-N for pain and QoL showed a lower KFM (-0.85 [-1.49, -0.22] % BW×Ht, $p = 0.016$; -0.75 [-0.14, -0.10] % BW×Ht, $p = 0.024$ respectively). For ADL, a higher KAM was evident (0.42 [0.11, 0.74] % BW×Ht, $p = 0.009$) in PASS-N compared to PASS-Y. No differences in KRM and TJM were found. *Relative Loading:* Across the KOOS pain, ADL, sport/rec, and QoL subscales, PASS-N consistently demonstrated a lower %KFM and a higher %KAM compared to PASS-Y (**Figure 2**). *Loading Metrics vs. PASS*: Participants with a lower KFM had odds of 1.94 [1.11, 3.40] ($p = 0.020$) and 1.75 [1.04, 2.96] ($p = 0.035$) for not attaining PASS in pain and QoL, respectively. Participants with a higher KAM had odds of 3.53 [1.29, 9.61] ($p = 0.014$) for not attaining PASS in ADL. These results still applied with the addition of independent explanatory variables (i.e., mechanical axis for KFM vs. pain; Tegner for KAM vs. ADL).

DISCUSSION: The data show that different loading patterns were exhibited by patients 2 years after ACLR who achieved PASS compared to those who did not. The observed group differences in loading are consistent with gait abnormalities previously reported for this patient population[4–6,11]. ACLR knees with a lower KFM than contralateral knees exhibited altered extensor/flexor co-activation patterns[12]. A higher KAM 2 years post-ACLR correlated with medial knee degenerative changes[5] and predicted worse outcomes 8 years after ACLR[11]. While the TJM did not differ from 2-8 years post-ACLR, the relative percentages of KFM and KAM did, and their changes over the 6-year period correlated with changes in the mediolateral cartilage thickness ratio[6]. Given that these loading metrics were responsive to changes in pain (KFM & TJM)[9,10] and indicative of knee muscle strength and activation (KFM)[12,13], interventions to increase KFM and to restore the relative loading contributions (%KFM & %KAM) to TJM may lead to improved quadriceps strength and pain relief. The absolute loading metrics, as suggested by the logistic regression analyses, may have predictive value for identifying participants who may benefit from additional interventions.

SIGNIFICANCE: Quantitative gait data reflecting altered loading known to reduce longer-term outcomes correlated with failure to achieve patient acceptable symptom states (PASS) 2-years after ACL reconstruction. These data suggest that factors influencing relative knee loading, in addition to absolute loading, are important targets for the design and evaluation of new therapeutic strategies to reduce OA risk and to optimize joint health.

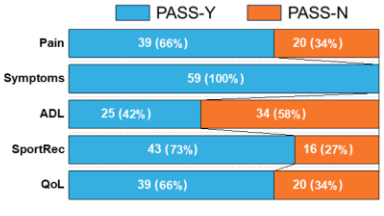

Figure 1. The number (%) of individuals post-ACLR meeting patient acceptable symptom state (PASS-Y) and those who did not (PASS-N).

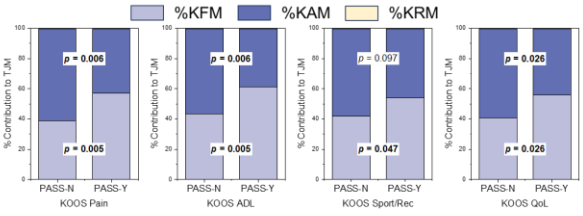

Figure 2. Percent knee flexion and adduction (%KFM & %KAM) moment contribution to the total joint moment (TJM) of individuals attaining an acceptable symptom state (PASS) and those who did not.

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