Active Feedback Gait Retraining to Modify Ambulatory Loads in Anterior Cruciate Ligament-Reconstructed Knees

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INTRODUCTION: The risk of developing osteoarthritis (OA) is increased after anterior cruciate ligament (ACL) injury, and it remains elevated despite reconstruction (ACLR).[1,2] Patients who suffer from ACL injury and undergo ACLR provide researchers with an opportunity to study potential therapeutic interventions.[3] Mechanical risk factors such as the knee adduction moment (KAM) interact with biological and structural factors, reflecting the ACLR knees' recovery trajectory.[4–7] At approximately 2 years post-ACLR, higher KAM has been cross-sectionally associated with subsurface cartilage matrix abnormalities,[6] and greater KAM relative to the contralateral knee predicted worse patient-reported outcomes (PROs) 6 years later.[7] Active feedback gait retraining using in-shoe sensors to shift load from the lateral to the medial foot has been shown to reduce KAM in healthy individuals and in those with medial knee OA[8] but has not been tested in ACLR recipients. The objective of this study was to determine the magnitude and duration of KAM reductions following 8 weeks of active feedback gait retraining. The hypothesis tested was that KAM would be reduced from baseline to immediately post-training, as well as at 3-month and 6-month follow-ups.

METHODS: ***Participants.*** Twenty-four individuals (13F/11M; age: 29 ± 6 years; BMI: 24 ± 3 kg/m²) consented to participate in this IRB-approved study. All had undergone ACLR 2.1 ± 0.4 years earlier for a primary ACL injury. At enrollment, the ACLR knees had neutral to varus alignment, no radiographic evidence of OA (20 Kellgren–Lawrence grade 0; 4 grade 1), and no history of additional injury or surgery. These ACLR knees were designated as the index knees for active feedback gait retraining. ***Protocol.*** Following baseline gait assessment, 5 participants completed eight weekly 30-minute laboratory-based gait retraining sessions, receiving active feedback delivered via an in-shoe force sensor and an ankle-mounted vibration motor, as originally designed. Due to COVID-related restrictions, the remaining participants completed daily 10-minute retraining and eight *remote* sessions via Zoom using a commercial pressure-detecting insole with a customized smartphone app (OpenGo, Moticon). In both setups, a personalized threshold was set so the lateral pressure signal turned on during normal walking and turned off when participants shifted weight from the lateral to the medial foot. Participants were re-assessed at completion of the 8-week program, as well as 3 and 6 months later. ***Assessments.*** Three self-paced walking trials per participant per assessment were recorded with 10 cameras (Qualisys) and a force plate (Bertec) synchronized at 120 Hz, using the point cluster technique (Stanford). External KAM relative to the tibial frame was computed using inverse dynamics in BioMove (Stanford) and normalized by percent body size (%BW×Ht). Early stance peak was the primary KAM metric. Frontal plane kinematics (minimum varus knee angle and maximum ankle eversion) previously reported to differ concurrently with KAM changes were additionally examined. Foot pressure distribution was assessed from the center of pressure (COP) measured by the force plate and mediolateral (ML) ratio measured by the insole. Per assessment, gait data were averaged across trials for each participant. PROs were surveyed using the Knee Injury and Osteoarthritis Score (KOOS) questionnaire. ***Statistical Analysis.*** Data normality was examined using the Shapiro-Wilk test. Differences in biomechanical metrics were analyzed with linear mixed models in SPSS, specifying repeated assessments within participants. Walking speed was included as a covariate in analyses of KAM, and in analyses of other gait metrics when speed explained significant variance in the dependent variable. When overall differences were significant, post-hoc pairwise comparisons were conducted between each follow-up and baseline, with Bonferroni correction applied for multiple comparisons. For KAM, additional analyses tested whether differences were explained by kinematic and foot pressure distribution metrics, in addition to the effect of speed. Each candidate metric was first examined individually, adjusting for speed when appropriate. To reduce the risk of overfitting, only variables that showed significant associations with KAM differences in these initial models were retained as candidates for a multivariable model, finalized via backward elimination. KOOS subscores differences over the study period were analyzed similarly, and changes in KOOS were tested for potential association with gait changes.

RESULTS: All participants contributed gait data at baseline and immediately post-training, and 21 participants provided data at 3-month (missing: n=2 COVID, n=1 travel) and 6-month follow-ups (missing: n=2 COVID, n=1 relocation). ***Gait.*** At the end of the 8-week active feedback gait retraining program, the cohort showed reduced KAM (-0.31 95%CI[-0.48, -0.13]%BW×Ht, $p<0.001$) (**Figure 1**). The KAM reduction compared to baseline was attenuated by 3-month (-0.18 95%CI[-0.36, -0.00]%BW×Ht, $p=0.048$) and absent by 6-month ($p=0.537$). COP medialization compared to baseline was observed at all re-assessments (8-week: +3.3 95%CI[0.4-6.3] mm, $p=0.022$; 3-month: +3.8 [0.7-6.9] mm, $p=0.012$; 6-month: +4.3 95%CI[1.2-7.5] mm, $p=0.003$). An increase in the insole ML ratio was observed from baseline to 8 weeks (+0.15 95%CI[0.05-0.24], $p<0.001$). The various multivariable models tested suggest that KAM reduction was associated with decreased speed, decreased minimum varus knee angle, and increased insole ML ratio (**Table 1**). **PROs.** KOOS subscores improved from baseline to follow-ups for Symptoms (8-week: +4 95%CI[0-8], $p=0.035$; 3-month: +5 95%CI[1-9], $p=0.010$), function in sports and recreational activities (6-month: +6 95%CI[1-15], $p=0.020$), and knee-related quality of life (QOL; 3-month: +8 95%CI[0-15], $p=0.043$; 6-month: +11 95%CI[3-18], $p=0.002$). Changes in KOOS subscores did not associate with changes in gait metrics.

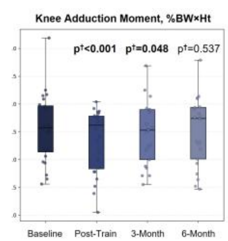

Figure 1. Knee adduction moment before (Baseline), immediately after the 8-week program (Post-Train), and follow-ups at 3 and 6 months. †speed-adjusted.

DISCUSSION: Completing the 8-week active feedback gait retraining program reduced KAM by medializing foot pressure distribution in ACLR recipients. The reduction in KAM persisted, albeit with some attenuation, for 3 months, and COP medialization persisted for 6 months. These findings suggest that participants may retain aspects of the retraining, indicating a need for booster training. A recently published study reported that providing booster sessions every 3 months following an initial bout of weekly lab-based training led to a sustained gait modification and reduced KAM through one year.[9] Our retraining program may therefore be optimized by offering participants a booster session within 3 months of the initial retraining. Such a booster session can be delivered remotely; notably, most participants in this study completed the retraining using a remote protocol. In addition to laboratory assessments, it is important to evaluate participants in their natural settings. Our findings suggest that sensor insole data could, in the future, be used to estimate KAM in real-world environments. Such wearables offer the potential for delivering, monitoring, and evaluating active feedback gait retraining in the real world. Lastly, KOOS scores significantly improved on three subscales. However, only the change in KOOS-QOL at 6 months exceeded the minimal detectable change,[10] and no significant associations were found between changes in KOOS and gait. These findings suggest that PROs may not be readily influenced by gait retraining, particularly in a pre-OA cohort with minimal symptoms.

SIGNIFICANCE: This study demonstrates that an 8-week active feedback gait retraining program, delivered using in-shoe sensors and primarily through a remote protocol, can redistribute foot pressure and reduce KAM in ACLR recipients at elevated risk of OA. The findings also highlight the potential need for booster training and the use of wearable insoles as a tool for continued monitoring and enhancement of gait retraining in real-world settings.

Table 1. Parameter estimate and 95% confidence interval (CI) associated with knee adduction moment (KAM) reductions from the multivariable models.

Independent Variables	**Model 1** Parameter Est. (95%CI)	p-value	**Model 2** Parameter Est. (95%CI)	p-value	**Model 3** Parameter Est. (95%CI)	p-value
ΔSpeed	0.85 (0.31-1.40)	**0.002**	1.32 (0.74-1.91)	**<0.001**	-	
ΔMin varus knee angle	-0.08 (-0.11, -0.04)	**<0.001**	-		-	
ΔInsole pressure M/L ratio	-0.35 (-0.73, 0.03)	0.074	-0.51 (-0.96, -0.06)	**0.028**	-0.35 (-0.85, 0.13)	0.150

REFERENCES: [1]Snoeker+ 2020 BJSM, [2]Liukkonen+ BJBS 2023, [3]Chu+ 2021 AJSM, [4]Büttner+ JOR 2025, [5]Zabala+ JBiomech 2013, [6]Titchenal+ AJSM 2018, [7]Erhart-Hledik+ JOR 2017, [8]Erhart-Hledik+ JOR 2017, [9]Uhlrich+ Lancet Rheum 2025, [10]Collins+ Arthritis Care Res 2011

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