Journal of Athletic Training 2025;60(2):92–102
doi: 10.4085/1062-6050-0464.23

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Early Gait Biomechanics Linked to Daily Steps After Anterior Cruciate Ligament Reconstruction

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Context: Gait biomechanics and daily steps are important aspects of knee-joint loading that change after anterior cruciate ligament reconstruction (ACLR). Understanding their relationship during the first 6 months post-ACLR could help clinicians develop comprehensive rehabilitation interventions that promote optimal joint loading after injury, thereby improving long-term knee-joint health.

Objectives: To compare biomechanical gait waveforms throughout stance at early time points post-ACLR in individuals with different daily step behaviors at 6 months post-ACLR and to examine how these gait waveforms compare with those of uninjured controls.

Design: Case-control study.

Setting: Laboratory.

Patients or Other Participants: A total of 32 individuals with primary ACLR assigned to the low-step group (LSG; n = 13) or the high-step group (HSG; n = 19) based on their average daily steps at 6 months post-ACLR and 32 uninjured matched controls.

Main Outcome Measure(s): Gait biomechanics were collected at 2, 4, and 6 months post-ACLR for the ACLR groups and at a single session for the control group. Knee-adduction moment, knee-extension moment (KEM), and knee-flexion angle (KFA) waveforms were calculated during gait stance and then compared via functional waveform analyses. Mean differences and corresponding 95% CIs between groups were reported.

Results: Primary results demonstrated less KFA (1%–45% versus 79%–92% of stance) and greater KEM (65%–93% of stance) at 2 months and greater knee-adduction moment (14%–20% versus 68%–92% of stance) at 4 months post-ACLR for the HSG compared with the LSG. Knee-adduction moment, KEM, and KFA waveforms differed across various proportions of stance at all time points between the step and control groups.

Conclusions: Differences in gait biomechanics were present at 2 and 4 months post-ACLR between step groups, with the LSG demonstrating an overall more flexed knee and more profound stepwise underloading throughout stance than the HSG. The results indicate a relation between early gait biomechanics and later daily step behaviors post-ACLR.

Key Words: joint loading, loading frequency, physical activity, posttraumatic osteoarthritis, waveform analysis

Key Points

- Individuals engaging in fewer steps 6 months post–anterior cruciate ligament reconstruction (ACLR) demonstrated more deleterious gait biomechanics at 2 and 4 months post-ACLR, indicative of a stepwise underloading pattern compared with those taking more daily steps at 6 months.
- Independently of daily step counts at 6 months, individuals with ACLR demonstrated aberrant gait biomechanics at 2, 4, and 6 months post-ACLR compared with uninjured controls.
- Early gait biomechanics and later daily step behaviors were linked post-ACLR.

Approximately 35% of individuals who undergo anterior cruciate ligament reconstruction (ACLR) develop radiographic osteoarthritis (OA) in the injured limb within the first postsurgical decade.[1] Knee OA progresses to include irreversible structural changes to the knee joint and functional impairments that cause pain and reduced quality of life.[2,3] To maintain joint health, obtaining adequate knee-joint loading in terms of magnitude and frequency is necessary due to the mechanosensitive properties of the tibiofemoral articular cartilage, an important tissue for transmitting mechanical loads.[4,5] However, aberrant gait biomechanics that develop post-ACLR lead to altered knee-joint loading, which is linked to the development of tibiofemoral posttraumatic OA (PTOA).[6–10] There is also evidence that loading frequency, which can be measured in vivo by recording daily steps, contributes to articular cartilage health post-ACLR.[4,5] Although gait biomechanics and daily steps have been linked at 6 to 12 months post-ACLR, it remains unknown whether a relationship exists between aberrant gait biomechanics and loading frequency during the first 6 months post-ACLR, when patients are typically undergoing supervised rehabilitation.[11] Identifying links between gait biomechanics and daily steps may inform the development of more comprehensive rehabilitation interventions to promote optimal loading after injury.

Gait biomechanics (knee-adduction moment [KAM], knee-extension moment [KEM], and knee-flexion angle [KFA]), as well as daily steps, differ in individuals with ACLR compared with those in uninjured controls and may persist for years post-ACLR, despite completion of formalized rehabilitation.[12–14] A stiffened knee pattern, characterized by smaller knee-flexion excursion from early stance to midstance, less peak KEM, and less peak KAM during gait, has been observed in the ACLR limb compared with the uninjured limb and uninjured controls.[11,15–17] A stiffened knee pattern and less KAM during gait are associated with worse cartilage tissue outcomes as well as an increased concentration of biomarkers linked to joint-tissue breakdown and early OA development.[8,9,18,19] Individuals also take fewer daily steps as early as 6 months post-ACLR compared with age- and sex-matched uninjured controls.[12,20,21] Furthermore, researchers have reported that individuals engaging in fewer steps post-ACLR exhibit greater increases in serum cartilage oligomeric matrix protein after a standardized walking task, which is associated with greater cartilage degradation linked to PTOA progression.[20]

Lisee et al found that individuals with ACLR who engaged in fewer daily steps also exhibited a stiffened knee pattern compared with individuals with ACLR engaging in more daily steps 6 to 12 months post-ACLR.[11] These results suggest a link between aberrant gait biomechanics and fewer daily steps. However, the study was cross-sectional and did not consider gait biomechanical outcomes at multiple time points post-ACLR, specifically in the first 6 months post-ACLR, an important period for early interventions to be implemented. Thus, it remains unknown whether aberrant gait biomechanics develop early post-ACLR (eg, at 2 or 4 months post-ACLR) in individuals who demonstrate fewer daily steps at 6 months post-ACLR. Understanding the link between early gait biomechanics and daily step behavior may be important for determining timing and frequency of training interventions that combine gait retraining and physical activity promotion[22–25] to optimize joint loading as part of ACLR rehabilitation.

The purpose of our study was to compare gait biomechanics (KAM, KEM, and KFA) throughout stance at 2, 4, and 6 months post-ACLR between individuals who differed in daily steps at 6 months post-ACLR in a hypothesis-generating manner. We evaluated daily steps at 6 months because 6 months marks a time in the rehabilitation process when patients have generally transitioned to more unsupervised rehabilitation settings and are allowed to engage in unrestricted walking and more vigorous activities such as jogging, jumping, or pivoting.[26,27] We hypothesized that individuals who engaged in $<$7000 daily steps at 6 months would display aberrant gait biomechanics (ie, less KAM, KEM, and KFA) at 2, 4, and 6 months post-ACLR compared with individuals who took more steps per day.[28] We also hypothesized that, although both ACLR groups would display aberrant gait biomechanics (ie, less KAM, KEM, and KFA) compared with uninjured controls, the low-step group (LSG) would display larger differences compared with the high-step group (HSG) at 2, 4, and 6 months post-ACLR.

METHODS

Study Design

We conducted a cohort comparison study of gait biomechanics in individuals with ACLR who engaged in different daily step counts at 6 months post-ACLR and matched uninjured controls. Gait biomechanical outcomes at habitual walking speed were compared at 2, 4, and 6 months post-ACLR between the two ACLR groups and between the ACLR groups and the uninjured control group. For each uninjured control participant, the gait biomechanics from the dominant limb (ie, the limb preferred to kick a ball) were assessed during a single session.[29] Based on objective step counts collected at 6 months post-ACLR, participants with ACLR were retrospectively assigned to the HSG ($\geq$7000 daily steps) or the LSG ($<$7000 daily steps). The cutoff of 7000 steps per day was selected because those who engage in $\geq$7000 steps per day are more likely to engage in 150 minutes of moderate to vigorous physical activity weekly, which is recommended for uninjured adults and more reflective of the expected recovery of daily walking post-ACLR.[28] All participants provided written informed consent or assent and, when appropriate, their parent or legal guardian provided informed consent. All study methods and recruitment strategies were approved by the Institutional Review Board at the University of North Carolina at Chapel Hill.

Participants

Anterior Cruciate Ligament Reconstruction. Participants with ACLR were between 16 and 35 years of age and were recruited at local health care facilities within 6 weeks of injury. They had undergone either primary unilateral arthroscopic bone–patellar tendon–bone (n = 31) or quadriceps tendon autograft ACLR (n = 1) and received supervised rehabilitation for 6 to 9 months. We excluded people who had an ACLR revision surgery, needed multiple-ligament surgery, had a meniscectomy that required removal of more than one-third of the medial or lateral meniscus during ACLR, demonstrated articular cartilage damage $>$3A according to the International Cartilage Repair Society criteria at the time of ACLR, sustained a lower extremity fracture during ACL injury, had a diagnosis of OA or any other disease that affects the knee joints before or at the time of ACLR, or were pregnant at the time of enrollment.[30] Individuals were included if they had complete biomechanics and daily step data at 6 months post-ACLR. Differing ACLR sample sizes at 2- and 4-month analyses were due to missing data at those time points (2 months: LSG = 13, HSG = 16; 4 months: LSG = 13, HSG = 18). We estimated the sample size for this study based on previous work in which researchers evaluated gait biomechanics (ie, KEM, KFA, and vertical ground reaction force [vGRF]) between individuals with ACLR with high and low daily step counts (version 3.1.9.7; G*Power, Heinrich-Heine-Universität Düsseldorf).[11] Based on the average maximum effect size (Cohen d = 1.04) for differences in KEM, KFA, and vGRF between daily step groups reported by Lisee et al, we determined that 13 participants per group would be needed to detect differences with a similar effect size (α = .05, 80% power) in our study.[11]

Uninjured Controls. A total of 32 uninjured control participants were matched to the 32 participants with ACLR based on sex (female or male), age (±2 years), and body mass index (BMI; ±3). Control participants were included in the study if they had no history of any lower extremity orthopaedic surgery, had no history of knee injury or any other lower extremity joint injury, had not been diagnosed with inflammatory arthritis, and were not pregnant.

Procedures

Biomechanical Gait Assessment. Gait biomechanics were collected using a 3-dimensional motion-capture system that included 10 infrared cameras (model Vicon Bonita; Vicon Motion Systems Ltd) and 2 embedded force plates (model FP406010; Bertec Corporation) nested within a 6-m walkway. A total of 29 retroreflective markers (bilateral markers: metatarsus 1, metatarsus 5, lateral and medial malleoli, calcaneus, tibia, lateral and medial epicondyles, thigh, trochanter major, anterior-superior iliac spine, posterior-superior iliac spine, and acromion; single markers: coccyx, L4-L5 joint space, and manubrium) were attached to the participants and defined a total of 8 segments (left and right foot, left and right shank, left and right thigh, pelvis, and trunk).[11,31] All participants performed 5 gait trials walking barefoot at their habitual walking speed with cameras capturing the marker trajectories at 120 Hz and kinetics at 1200 Hz. They were able to practice until they were comfortable performing the walking task in the laboratory. Next, we determined the average habitual walking speed for each participant from 5 trials to ensure each participant walked at a consistent gait speed throughout test trials. Gait speed was measured with 2 infrared timing gates (Dashr 2.0; Dashr Motion Performance Systems) that were placed 0.97 m apart from each other. A trial was considered successful if participants walked within ±5% of their average habitual speed and contacted the force plates with a single foot through the entirety of stance. The same gait assessment protocol has been followed in previous research.[11,15,18,32] Gait kinematic and kinetic data were imported and processed in Visual3D software (version 2020.06.1; C-Motion, Inc) using a custom script. Data were filtered using a recursive fourth-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Biomechanical outcomes were extracted and time normalized to 101 data points (0%–100%) throughout *stance phase*, which was defined as heel strike (vGRF > 20 N) to toe-off (vGRF < 20 N). Knee-flexion angle was determined as the angle of the shank relative to the thigh using Euler angles (sagittal-frontal-transverse sequence), and an inverse dynamics approach was used to calculate internal knee moments. The KAM and KEM were normalized to the product of body weight and height (in meters). For each biomechanical outcome, participants' average gait waveforms were calculated from their 5 recorded walking trials.

Daily Step Assessment. After the gait assessment at 6 months post-ACLR, daily steps for participants with ACLR were recorded using an ActiGraph GT9X Link activity monitor (ActiGraph LLC) with an integrated triaxial accelerometer, which they affixed to the right hip for 7 days consecutively.[33] Participants were instructed to wear the activity monitor during all waking hours, excluding any water activities such as showering or swimming. Activity data were recorded at 30 Hz, processed at 60-second epochs, and analyzed using ActiLife software (ActiGraph LLC).[11,20,21,34] First, we validated and estimated the wear time using the recommendations of Choi et al.[35] Step data were considered valid if participants wore the monitor for at least 10 hours per day on 4 days (3 weekdays and 1 weekend).[36] Next, daily steps were calculated using the ActiLife step-detecting algorithm. Average daily step counts for each participant were calculated over the number of valid wear days.

Demographics and Self-Reported Knee Function. We collected demographics (age, sex, and BMI) from all participants and surgical history and patient-reported outcomes from the Knee injury and Osteoarthritis Outcome Score (KOOS) for participants with ACLR. The KOOS is a reliable and valid questionnaire that consists of 5 subscales (Symptoms, Pain, Activities of Daily Living, Sports and Recreation, and Knee-Related Quality of Life).[37,38]

Statistical Analysis

Descriptive Statistics. Group differences between the LSG, the HSG, and the control group in age, BMI, and gait speed were assessed using separate 1-way analyses of variance. A post hoc analysis with Bonferroni correction was performed when main group effects were found. The differences in daily steps, monitor wear time, time since ACLR, and KOOS scores between the LSG and the HSG were assessed using either an independent *t* test or a Mann-Whitney *U* test. Percentage of female participants and meniscal injuries between step groups were compared using a Fisher exact test of independence. All analyses were performed in RStudio (version 4.1.2; Posit PBC), and the α level was set at .05.

Primary Analysis. To compare the biomechanical outcomes between step groups throughout the stance phase of gait, we conducted separate functional waveform analyses for KAM, KEM, and KFA of the ACLR limb at 2, 4, and 6 months post-ACLR. The functional waveform analysis allows for the evaluation of gait differences throughout stance.[39] This approach was chosen because differences in gait biomechanics at multiple points of stance have been observed post-ACLR in various cohort comparisons.[11,15,18,32] Individual average gait waveforms were then divided into the various groups and fit with Bayesian functional models using a P-spline model to gain a representative waveform of each group. The waveform analysis then computed the differences between the representative waveform of each step group as well as the corresponding 95% CIs. We included gait speed as a covariate in the waveform analysis because this variable has been shown to influence gait biomechanics outcomes.[40] Differences were considered statistically significant if the 95% CIs did not include 0 for >3% of a consecutive portion of the stance waveform. Cohen d effect sizes and maximum differences for areas with significant differences were also calculated. Effect sizes were interpreted as *small* (d = 0.2), *medium* (d = 0.5), or *large* (d = 0.8). The waveform analyses were performed in RStudio (version 4.1.2) using the bayesFDA package (version 3.0).

Secondary Analysis. We conducted a secondary analysis comparing the LSG and the HSG biomechanics with those of the uninjured control group. Similar to the primary analysis, we conducted separate waveform analyses between the HSG and the uninjured control group as well as between the LSG and the uninjured control group using the same approach as described above to detect differences during stance phase between groups.

Table 1. Anthropometric Data of the Low-Step Group, High-Step Group, and Uninjured Controls

Characteristic	Low-Step Group (n = 13)	High-Step Group (n = 19)	Uninjured Controls (n = 32)
Female sex, % (No.)	76.9 (10)	63.2 (12)	68.8 (22)
Meniscal injury, % (No.)	76.9 (10)	78.9 (15)	NA
Graft type, No.			
Bone–patellar tendon–bone autograft	12	19	NA
Quadriceps tendon autograft	1	0	NA
Age, mean ± SD, y	21.4 ± 4.3	20.9 ± 3.9	21.4 ± 3.7
Body mass index, mean ± SD, kg/m^2	24.1 ± 2.8	24.4 ± 4.7	23.6 ± 2.9
Gait speed, mean ± SD, m·s^{-1}			
2 mo post-ACLR	1.14 ± 0.12[a]	1.17 ± 0.11[a]	NA
4 mo post-ACLR	1.19 ± 0.10[a]	1.22 ± 0.11[a]	NA
6 mo post-ACLR	1.21 ± 0.13[a]	1.23 ± 0.10[a]	NA
Controls	NA	NA	1.32 ± 0.11
No. of daily steps at 6 mo post-ACLR, mean ± SD	5030.4 ± 1235.8[b]	9490.0 ± 1406.4	NA
Monitor wear time, mean ± SD, min	852.0 ± 82.9	847.7 ± 99.2	NA
Time since ACLR, mean ± SD, d			
2 mo post-ACLR	56.8 ± 4.3	55.8 ± 4.5	NA
4 mo post-ACLR	113.4 ± 6.4	113.6 ± 6.7	NA
6 mo post-ACLR	170 ± 6.2	172.9 ± 8.0	NA
Knee injury and Osteoarthritis Outcome Score Subscale, mean ± SD			
Knee-Related Quality of Life			
2 mo post-ACLR	38.0 ± 12.9	40.5 ± 11.5	NA
4 mo post-ACLR	43.8 ± 13.6	53.0 ± 16.2	NA
6 mo post-ACLR	51.0 ± 18.0	55.9 ± 17.0	NA
Pain			
2 mo post-ACLR	73.7 ± 11.8	77.2 ± 9.5	NA
4 mo post-ACLR	81.0 ± 8.4	83.3 ± 7.8	NA
6 mo post-ACLR	81.4 ± 10.6	85.1 ± 7.9	NA
Symptoms			
2 mo post-ACLR	66.8 ± 12.7	65.0 ± 12.8	NA
4 mo post-ACLR	72.6 ± 15.7	75.4 ± 11.1	NA
6 mo post-ACLR	75.5 ± 12.1	79.7 ± 9.3	NA
Activities of Daily Living			
2 mo post-ACLR	87.7 ± 6.6	88.4 ± 7.9	NA
4 mo post-ACLR	93.8 ± 5.2	95.0 ± 7.1	NA
6 mo post-ACLR	95.9 ± 3.5	95.2 ± 7.4	NA
Sports and Recreation			
2 mo post-ACLR	35.4 ± 26.7	32.4 ± 25.2	NA
4 mo post-ACLR	51.3 ± 22.3	56.6 ± 19.8	NA
6 mo post-ACLR	61.2 ± 21.6	65.3 ± 19.8	NA

Abbreviations: ACLR, anterior cruciate ligament reconstruction; NA, not applicable.
[a] Different from uninjured controls ($P \leq .05$).
[b] Different from the high-step group ($P \leq .05$).

RESULTS

Descriptive Outcomes

Descriptive variables for the groups are reported in Table 1. The LSG (daily step range, 2713–6295 steps) demonstrated fewer daily step counts at 6 months post-ACLR compared with the HSG (daily step range, 7290–11631 steps) ($P < .001$). The LSG and the HSG demonstrated slower walking speeds at 2, 4, and, 6 months post-ACLR compared with the control group ($P \leq .003$), but gait speed did not differ between step groups ($P \geq .35$). No between-groups differences were found for age, BMI, KOOS, monitor wear time, time since ACLR, percentage of female participants, or percentage of participants with meniscal injuries (Table 1).

Waveform Analysis: Gait Biomechanical Outcomes

Outputs of the waveform analysis are displayed in Figures 1, 2, and 3, and a detailed breakdown of the maximal differences and mean effect sizes is presented in Table 2.

Knee-Adduction Moment. At 2 months post-ACLR, the LSG and the HSG exhibited less KAM than the control group during late stance, at 97% to 100% and 91% to 100%, respectively. No differences in KAM were observed between step groups (Figure 1A, D, G, and J).

At 4 months post-ACLR, KAM was greater in the HSG than the LSG during early (14%–20%) and late stance (68% to 92%). The LSG demonstrated less KAM during early stance (13%–17%) and greater KAM during late stance (96%–100%) compared with the control group, whereas the HSG demonstrated greater KAM compared with the control group at late stance (72%–100%), (Figure 1B, E, H, and K).

At 6 months post-ACLR, the LSG and the HSG displayed greater KAM compared with the control group during late stance at 96% to 99% and 70% to 100%, respectively. No differences in KAM were observed between step groups at 6 months post-ACLR (Figure 1C, F, I, and L).

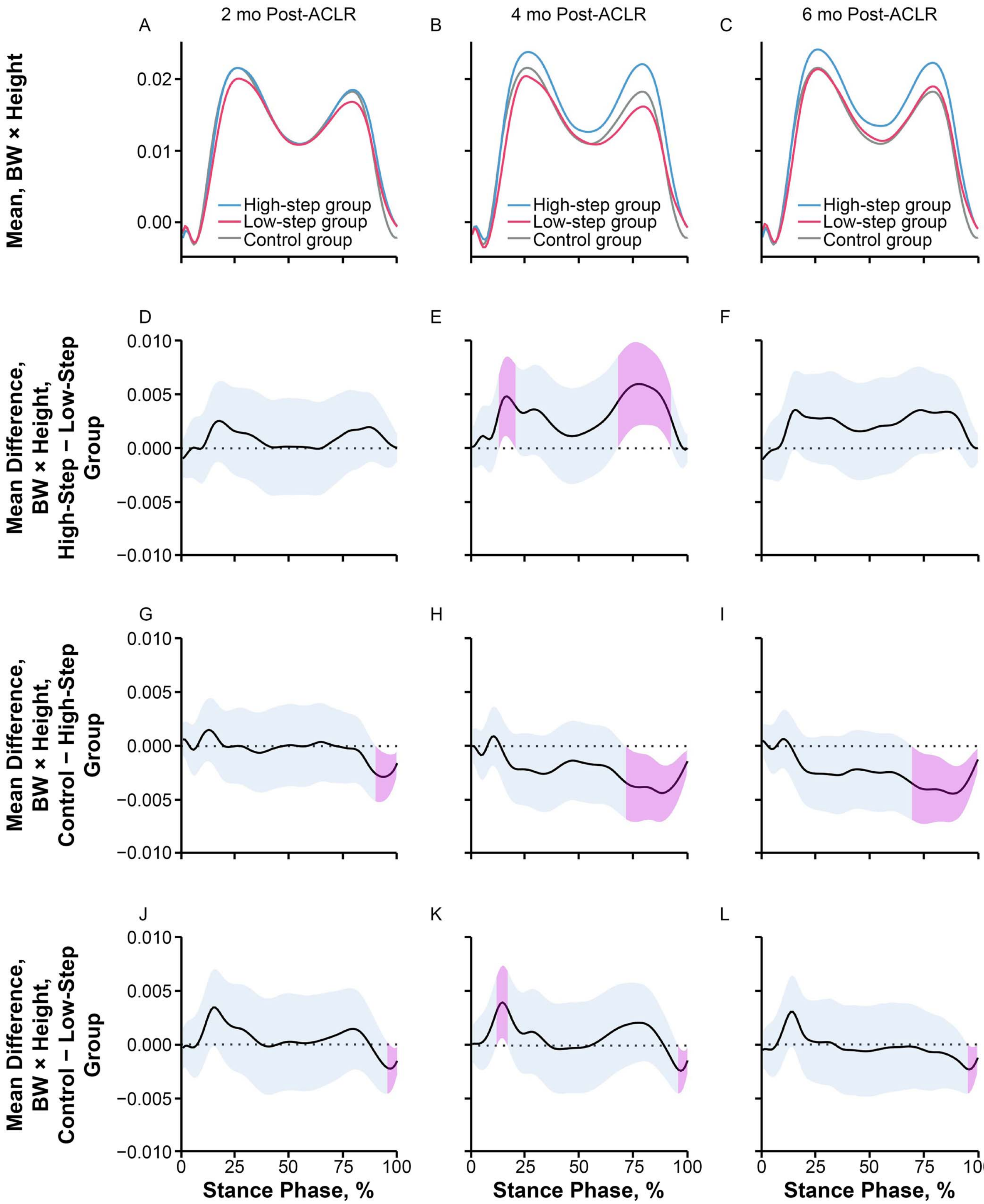

Figure 1. Mean knee-adduction moment (KAM) waveforms and mean KAM differences with 95% CIs (light blue areas) throughout gait stance in the anterior cruciate ligament reconstruction (ACLR) limb between the low-step, high-step, and uninjured control groups at 2, 4, and 6 months post-ACLR. A–C, Mean KAM waveforms. D–F, Mean differences between the high- and low-step groups. G–I, Mean differences between the control and high-step groups. J–L, Mean differences between the control and low-step groups. A, D, G, and J represent the 2-month time point. B, E, H, and K represent the 4-month time point. C, F, I, and L represent the 6-month time point. Differences in KAM between groups are highlighted in purple and exist when 95% CIs of mean differences do not include zero for >3% of a consecutive portion of the stance waveform. Abbreviation: BW, body weight.

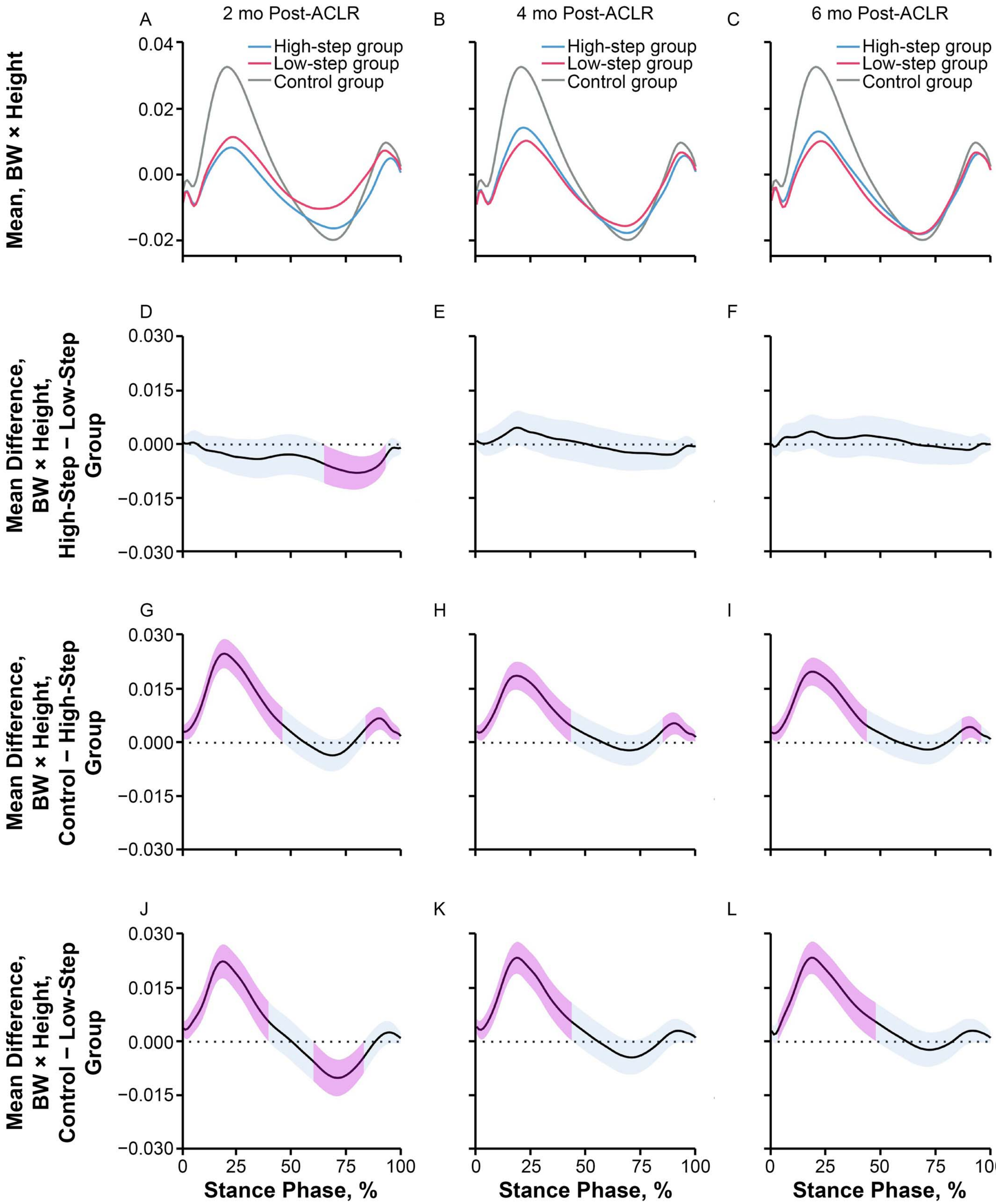

Figure 2. Mean knee-extension moment (KEM) waveforms and mean KEM differences with 95% CIs (light blue areas) throughout gait stance in the anterior cruciate ligament reconstruction (ACLR) limb between the low-step, high-step, and uninjured control groups at 2, 4, and 6 months post-ACLR. A–C, Mean KEM waveforms. D–F, Mean differences between the high- and low-step groups. G–I, Mean differences between the control and high-step groups. J–L, Mean differences between the control and low-step groups. A, D, G, and J represent the 2-month time point. B, E, H, and K represent the 4-month time point. C, F, I, and L represent the 6-month time point. Differences of KEM between groups are highlighted in purple and exist when 95% CIs of mean differences do not include zero for >3% of a consecutive portion of the stance waveform. Abbreviation: BW, body weight.

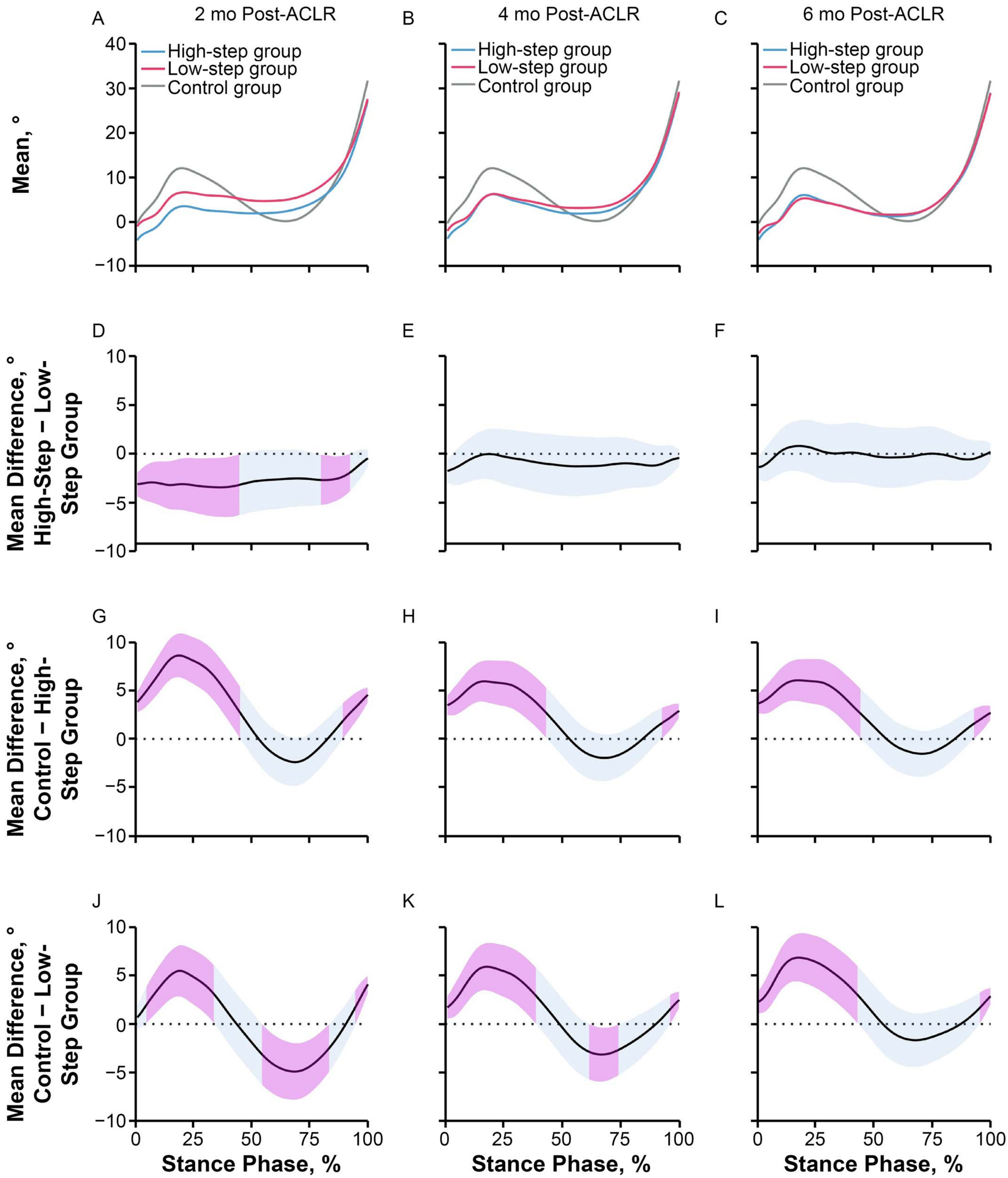

Figure 3. Mean knee-flexion angle (KFA) waveforms and mean KFA differences with 95% CIs (light blue areas) throughout gait stance in the anterior cruciate ligament reconstruction (ACLR) limb between the low-step, high-step, and uninjured control groups at 2, 4, and 6 months post-ACLR. A–C, Mean KFA waveforms. D–F, Mean differences between the high- and low-step groups. G–I, Mean differences between the control and high-step groups. J–L, Mean differences between the control and low-step groups. A, D, G, and J represent the 2-month time point. B, E, H, and K represent the 4-month time point. C, F, I, and L represent the 6-month time point. Differences in KFA between groups are highlighted in purple and exist when 95% CIs of mean differences do not include zero for >3% of a consecutive portion of the stance waveform.

Table 2. Output of the Waveform Analyses by Gait Variable Over Time Post-ACLR Between Groups

Gait Variable	Group Comparison	Time Post-ACLR, mo	Stance Phase, %[a]	Maximum Difference[b]	Maximum Cohen d Effect Size[c]
Knee-adduction moment	LSG and HSG	2	ND	ND	ND
		4	14–20	0.005	0.84
			68–92	0.006	0.83
		6	ND	ND	ND
	LSG and control	2	97–100	0.002	1.08
		4	13–17	0.004	0.94
			96–100	−0.002	1.15
		6	96–99	−0.002	1.22
	HSG and control	2	91–100	−0.003	−1.10
		4	72–100	−0.004	−0.55
		6	70–100	−0.004	−0.65
Knee-extension moment	LSG and HSG	2	65–93	−0.008	−0.91
		4	ND	ND	ND
		6	ND	ND	ND
	LSG and control	2	1–40	0.023	2.52
			61–83	−0.010	−1.14
		4	1–44	0.023	2.39
		6	4–48	0.023	2.26
	HSG and control	2	1–46	0.025	2.44
			84–100	0.007	1.83
		4	1–43	0.019	1.89
			86–100	0.005	1.39
		6	1–44	0.020	1.85
			87–95	0.004	1.11
Knee-flexion angle	LSG and HSG	2	1–45	−3.45	−0.54
			79–92	−2.70	−0.63
		4	ND	ND	ND
		6	ND	ND	ND
	LSG and control	2	5–34	5.50	1.27
			55–83	−4.92	−1.05
			95–100	4.45	0.78
		4	1–38	5.91	1.25
			62–74	−3.16	−0.75
			97–100	2.66	0.53
		6	1–43	6.86	1.45
			96–100	3.09	0.59
	HSG and control	2	1–45	8.62	1.69
			90–100	4.76	0.88
		4	1–43	5.96	1.26
			93–100	3.05	0.63
		6	1–44	6.05	1.22
			93–100	2.80	0.54

Abbreviations: ACLR, anterior cruciate ligament reconstruction; HSG, high-step group; LSG, low-step group; ND, no difference between waveforms at the corresponding time point.

[a] Areas of gait stance with differences.

[b] Maximum differences that occurred within areas of gait stance with differences.

[c] Effect sizes for areas that were different: *small* ($d = 0.2$), *medium* ($d = 0.5$), and *large* ($d = 0.8$).

Knee-Extension Moment. At 2 months post-ACLR, the HSG demonstrated greater negative KEM, also defined as knee-flexion moment (KFM), at midstance to late stance (65%–93%) compared with the LSG. The LSG demonstrated less KEM at early stance to midstance (1%–40%) and less KFM from midstance to late stance (61%–83%) compared with controls. The HSG displayed less KEM at early stance to midstance (1%–46%) and late stance (84%–100%) compared with the control group (Figure 2A, D, G, and J).

At 4 months post-ACLR, less KEM was observed during early stance to midstance (1%–44%) in the LSG than the control group. The HSG demonstrated less KEM at early stance to midstance (1%–43%) and late stance (86%–100%) compared with the control group. No differences in KEM were observed between step groups at 4 months post-ACLR (Figure 2B, E, H, and K).

At 6 months post-ACLR, the KEM was less at early stance to midstance (4%–48%) in the LSG than the control group. Similar to observations at 4 months, the HSG demonstrated less KEM at early stance to midstance (1%–44%) and late stance (87%–95%) compared with the control group. Again, no differences in KEM were observed between step groups at 6 months (Figure 2C, F, I, and L).

Knee-Flexion Angle. At 2 months post-ACLR, the HSG demonstrated smaller KFA throughout large portions of early (1%–45%) and late (79%–92%) stance compared with the LSG. For the LSG, KFA was smaller compared with the control group at early (5%–34%) and late (95%–100%) stance but greater during midstance to late stance (55%–83%). The KFA was smaller during early stance to midstance (1%–45%) and late stance (90%–100%) in the HSG than the control group (Figure 3A, D, G, and J).

At 4 months post-ACLR, similar to findings at 2 months, the LSG demonstrated smaller KFA at early (1%–38%) and late stance (97%–100%) and greater KFA at midstance to late stance (62%–74%) compared with the control group. Smaller KFA was observed for the HSG in early stance to midstance (1%–43%) and late stance (93%–100%) compared with the control group. Yet, no differences in KFA were observed between step groups 4 months post-ACLR (Figure 3B, E, H, and K).

At 6 months post-ACLR, the LSG had smaller KFA at early stance to midstance (1%–43%) and late stance (96%–100%) compared with the control group. The same pattern was observed for the HSG, which demonstrated smaller KFA from early stance to midstance (1%–44%) and late stance (93%–100%) compared with the control group. Again, no differences in KFA existed between step groups at 6 months (Figure 3C, F, I, and L).

DISCUSSION

The results partially supported our hypotheses, as differences in gait biomechanics between the HSG and the LSG were present at 2 and 4 months post-ACLR. In particular, the HSG walked with more extended knees (smaller KFA) during early and late stance at 2 months post-ACLR and demonstrated greater KAM during early and late stance at 4 months post-ACLR compared with the LSG. The HSG also exhibited a greater KFM during midstance to late stance at 2 months post-ACLR. In contrast to our hypotheses, no differences between step groups were found at 6 months post-ACLR. Our results indicate that different gait biomechanics may develop early between individuals with ACLR who go on to engage in different daily step behaviors at 6 months post-ACLR. The differences in gait biomechanics between step groups further support the hypothesis that gait biomechanics and daily steps are linked post-ACLR.[11] In addition, both the HSG and the LSG demonstrated aberrant gait biomechanics at 2, 4, and 6 months compared with the control group, including less KEM and KFA during early stance to midstance as well as greater KAM during late stance. This study is one of the first to identify a link between early aberrant gait biomechanics at 2, 4, and 6 months post-ACLR and fewer daily steps at 6 months post-ACLR.

The differences in gait biomechanics in individuals post-ACLR, regardless of daily steps, compared with controls reflect a stiffened knee-gait profile, characterized by less knee-flexion excursion and less KEM from early stance to midstance. The stiffened-knee strategy is commonly observed post-ACLR and is likely affected by less muscle strength and impaired neuromuscular control.[11,15,41,42] Neither step group's biomechanical gait patterns were normalized 6 months post-ACLR compared with the controls. These findings are not surprising, because differences in gait biomechanics have been reported up to 12 months post-ACLR.[13–15,18] Even though the LSG and the HSG waveforms appeared to be relatively similar across time points, differences were found between step groups in KFA and KEM at 2 months and in KAM at 4 months post-ACLR. The differences between the LSG and the HSG were smaller compared with those between step groups and controls. The medium to large effect sizes (Table 2) may indicate, however, that the differences between step groups are meaningful. Yet, future research needs to be done to assess the effect of the small differences in the gait biomechanics of the LSG compared with the HSG at 2 and 4 months post-ACLR on early outcomes of OA development. The LSG exhibited a flexed-knee gait pattern (greater KFA) throughout weight acceptance and during parts of midstance and late stance relative to the HSG at 2 months post-ACLR. This behavior could stem from less knee range of motion early post-ACLR in those individuals. It is likely that the greater knee flexion at late stance also contributed to less KFM in the LSG compared with the HSG, leading to an overall less-dynamic KEM waveform in the LSG. Furthermore, the LSG demonstrated less KAM around the peak values at early and late stance 4 months post-ACLR, indicating less loading in the medial knee compartment in the LSG. Less KAM post-ACLR, as reported in the LSG, is associated with worse tibiofemoral cartilage outcomes linked to PTOA development.[9,18] Given the observed differences in gait biomechanics between step groups at 2 and 4 months post-ACLR, the gait biomechanical profiles of the LSG may be more deleterious than those of the HSG.

Lisee et al reported differences in gait biomechanics at 6 to 12 months post-ACLR in a cross-sectional study between individuals engaging in different daily step behaviors.[11] However, they reported smaller KFA throughout stance and greater KFM at late stance for the lowest step group compared with the highest step group. The discrepancy in KFA and KEM between our results and those of Lisee et al might be explained by the differing time points post-ACLR at which testing was completed.[11] At 2 months post-ACLR, participants in the LSG exhibited smaller knee range of motion, in which they did not extend their knees as far as participants in the HSG in midstance, resulting in a flexed-knee gait. Although KFA changed over time for both groups, the LSG may have developed a more pronounced stiffened knee strategy compared with the HSG, which may have recovered to a KFA pattern more similar to that of the controls. Further longitudinal studies are needed to characterize the relationship between daily steps and biomechanics over multiple time points.

Both gait biomechanics and daily steps are associated with poor knee-joint health linked to OA development post-ACLR, but the ideal loading conditions for maintaining long-term knee health remain unclear.[8–10,18–20,43,44] The combination of optimizing gait biomechanics and daily steps may be a key determinant in influencing joint health. In our study, the number of daily steps of the HSG was comparable to that of uninjured controls, as reported previously.[12,21,34] However, initial research has shown that more steps in combination with more deleterious gait biomechanics are associated with worse cartilage outcomes at 1 month post-injury.[45] In contrast, less cumulative joint loading, a combined loading variable of daily steps, and KAM impulse, at 2 and 4 months post-ACLR has been associated with greater cartilage degradation at 6 months after surgery.[46] Although it remains unclear which factor (ie, aberrant gait biomechanics or daily steps) contributes most to PTOA development, improving gait biomechanics combined with addressing insufficient daily step counts may be optimal in ensuring that proper joint loading is conducted within the most appropriate frequency ranges.

We demonstrated an association between early gait biomechanics and daily steps at 6 months post-ACLR. Unfortunately, our study design did not enable us to establish the mechanistic link between variables, which is important to determine the effect of knee-joint loading on PTOA post-ACLR. One can postulate that fewer daily steps could contribute to aberrant gait biomechanics because individuals may be less capable of biomechanical improvements with less overall practice of the movement. Conversely, the existence of aberrant gait biomechanics could hinder individuals from engaging in daily walking. Given that gait biomechanics and daily steps are modifiable (eg, targeted gait retraining or physical activity promotion), paradigms that modify one variable to discern the mechanistic effect on the other should be investigated in future studies.[23–25,47]

We acknowledge some limitations of our study that can inform future research. We performed between-groups comparisons at limited time points of 2, 4, and 6 months post-ACLR, and changes that may have occurred between time points in individuals with ACLR could not be assessed. In addition, as mentioned, the study design did not allow us to assess the mechanistic links between gait biomechanics and daily steps. We did not match controls based on daily steps. We do not know if the number of daily steps and gait biomechanics are related in the uninjured population. We evaluated daily steps only at 6 months post-ACLR and cannot draw any conclusions about how changes in physical activity post-ACLR may have influenced gait biomechanical outcomes. Daily step outcomes may also have been affected by demographic factors, which could be of importance for developing more comprehensive prediction models of daily step outcomes post-ACLR. Furthermore, we did not evaluate additional factors such as muscle strength or passive knee range of motion that could affect gait biomechanical outcomes or daily step counts.[48,49] This study was an initial hypothesis-generating study with a relatively small sample size. Nevertheless, differences with medium to large effect sizes were detected in gait biomechanics between step groups as well as between step groups and controls. Only participants with a primary ACL injury who received either a bone–patellar tendon–bone or quadriceps tendon autograft were included in the study. Given that the number of ACL injuries and graft type may influence gait biomechanics, daily step behavior, or both, the results may not be transferrable to individuals who received different grafts, are ACL deficient, or had multiple ACL injuries.

CONCLUSIONS

Our data supported the hypothesis that early gait biomechanics and later daily step behaviors are linked post-ACLR. Individuals engaging in fewer daily steps 6 months post-ACLR demonstrated more aberrant gait biomechanics at 2 and 4 months post-ACLR, indicative of a stepwise underloading pattern, than those taking more daily steps at 6 months. Further research needs to be done to assess the relevance of such early differences in gait biomechanics on long-term knee-joint health.

ACKNOWLEDGMENTS

This study was funded by the Arthritis Foundation, Atlanta, Georgia (Ms Büttner, Dr Lisee, Ms Buck, Ms Bjornsen, Dr Thoma, Dr Spang, and Dr Pietrosimone).

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