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Differences in Gait Biomechanics Between Adolescents and Young Adults With Anterior Cruciate Ligament Reconstruction

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Context: Adolescents and adults are treated similarly in rehabilitation and research despite differences in clinical recovery after anterior cruciate ligament reconstruction (ACLR). Aberrant gait is a clinical outcome associated with poor long-term health post-ACLR but has not been compared between adolescents and adults.

Objective: To compare gait biomechanical waveforms throughout stance between adolescents (<18 years old) and young adults (≥18 years old) post-ACLR.

Design: Case-control study.

Setting: Laboratory.

Patients or Other Participants: Adolescents (n = 13, girls = 77%, age = 16.7 ± 0.6 years, height = 1.7 ± 0.1 m, weight = 22.2 ± 3.7 kg/m^2) were identified from a cross-sectional cohort assessing clinical outcomes 6 to 12 months post-ACLR. Young adults (n = 13, women = 77%, age = 22.3 ± 4.0 years, height = 1.7 ± 0.1 m, weight = 22.9 ± 3.3 kg/m^2) were matched based on sex, time since surgery (±2 months), and body mass index (±3 kg/m^2).

Intervention(s): Participants performed 5 gait trials at their habitual speed.

Main Outcome Measure(s): Three-dimensional gait biomechanics and forces were collected. Vertical ground reaction force normalized to body weight (xBW), knee-flexion angle (°), knee-abduction moment (xBW × height), and knee-extension moment (BW × height) waveforms were calculated during the stance phase of gait (0%–100%). Habitual walking speed was compared using independent *t* tests. We used functional waveforms to compare gait biomechanics throughout stance with and without controlling for habitual walking speed by calculating mean differences between groups with 95% CIs.

Results: Adolescents walked with slower habitual speeds compared with adults (adolescents = 1.1 ± 0.1 m/s, adults = 1.3 ± 0.1 m/s, $P < .001$). When gait speed was not controlled, adolescents walked with less vertical ground reaction force (9%–15% of stance) and knee-abduction moment (12%–25% of stance) during early stance and less knee-extension moment during late stance (80%–99% of stance). Regardless of their habitual walking speed, adolescents walked with greater knee-flexion angle throughout most stances (0%–21% and 29%–100% of stance).

Conclusions: Adolescents and adults demonstrated different gait patterns post-ACLR, suggesting that age may play a role in altered gait biomechanics.

Key Words: knee, age, pediatric, youth

Key Points

- After anterior cruciate ligament reconstruction (ACLR), adolescents walked at slower speeds, a spatiotemporal biomechanical outcome that has been associated with poor knee-joint health in adults post-ACLR.
- Adolescents walked with greater peak knee-flexion angles throughout stance compared with adults post-ACLR and may have shifted knee-joint contact forces posteriorly.
- Clinicians should consider gait-pattern differences between adolescents and young adults post-ACLR when developing age-specific rehabilitation approaches.

The incidence of anterior cruciate ligament (ACL) injury and ACL reconstruction (ACLR) in individuals under the age of 18 has consistently increased over the last several decades. From 2007 to 2011, adolescents (10–18 years old) demonstrated a 16% increase in ACL injuries compared with young adults (18–35 years old), who demonstrated only a 6% increase.[1] A history of ACL injury and ACLR was associated with persistent knee symptoms in approximately 39% of patients 6 years post-ACLR[2] and with the development of radiographic knee osteoarthritis in a third of patients within 10 years of ACL injury.[3] Sustaining an ACL injury earlier in life may lead to more years lived with knee-related symptoms and chronic joint disease. Therefore, identifying modifiable factors associated with persistent disability is critical for maintaining quality of life in adolescent patients with an ACL injury. Recovery during postoperative rehabilitation after ACLR could differ between adolescents and adults,[4,5] suggesting a need to develop age-appropriate rehabilitation interventions to improve long-term health. Lower extremity strength, functional performance, and self-reported knee function were associated with poor long-term outcomes.[6] Unfortunately, limited studies[4,5] have examined differences in strength, performance, and knee function between adolescents and young adults after ACLR. Persistent aberrant gait biomechanics were common post-ACLR[7,8] and were associated with the development of osteoarthritis among adolescent and adult participants.[9,10] However, to our knowledge, previous authors have not specifically evaluated whether gait biomechanics differ between adolescents and adults after ACLR.

Adolescents undergo skeletal, sexual, and somatic maturation as they increase in age, all of which may elicit normal biomechanical adaptations due to changes in hormones and musculoskeletal growth. Known differences in gait biomechanics across the lifespan in uninjured individuals include greater knee-flexion angles during midstance and peak knee-joint kinetics (ie, internal knee-extension and knee-abduction moment [KAM]) during early stance with increasing age.[11–13] Uninjured children and adolescents also demonstrated slower habitual walking speeds than young and middle-aged adults.[14] Post-ACLR, aberrant gait biomechanics in mixed cohorts of adolescents and adults or primarily adults included slower habitual walking speed, knee-joint underloading (ie, smaller peak vertical ground reaction force [vGRF] in the first half of stance), small KAM, and a stiffened knee strategy (ie, less knee-flexion range of motion from early stance to midstance and smaller knee-extension moment [KEM] during the first half of stance),[7] which were associated with worse self-reported knee symptoms, deleterious cartilage changes, and knee osteoarthritis development.[9,10,15,16] Links between aberrant gait biomechanics and poor knee-joint health were prevalent 6 to 12 months post-ACLR, indicating a critical time for intervention. At 6 to 12 months post-ACLR, individuals are likely still undergoing rehabilitation and could benefit from gait retraining. Both age[12] and knee injury[7] affected gait biomechanical patterns, suggesting that adolescent gait biomechanics after ACL injury and ACLR may have been affected by both factors. Whether the interaction between age and injury in adolescents facilitated disruption or maintenance of normal age-specific gait patterns is unclear. Furthermore, earlier researchers[9,10,15] who assessed gait patterns post-ACLR studied heterogeneous samples of adolescent and adult participants, which contributed to our lack of understanding of how age was related to aberrant gait patterns post-ACLR. To clarify this gap in the literature, differences in gait biomechanics between adolescents and young adults post-ACLR should be established.

The purpose of our study was to compare gait biomechanics throughout stance between adolescents and adults who were 6 to 12 months post-ACLR and matched by sex, time since ACLR, and body mass index (BMI). We hypothesized that adolescents would demonstrate slower habitual walking speeds, smaller knee-flexion angle during midstance, and smaller vGRF and knee-joint moments (ie, KAM and KEM) during the first half of stance compared with adults.[11] Identifying differences in gait biomechanics associated with poor long-term health between adolescents and adults during a clinically relevant period of recovery post-ACLR is critical for determining the need for age-specific rehabilitation interventions after ACLR.

METHODS

We conducted a secondary case-control analysis on data collected from an ongoing cross-sectional cohort. Participants with a history of ACLR completed 3-dimensional (3D) gait biomechanical assessment and filled out the Knee injury and Osteoarthritis Outcome Score (KOOS) survey to assess self-reported knee function at a single study visit.[17] First, any adolescent <18 years of age who matched the inclusion criteria was assigned to the adolescent group. Young adults (≥ 18 years of age) were then matched to the adolescent participants as control participants based on sex, time post-ACLR (± 2 months), and BMI (± 3 kg/m^2). All aspects of this study were approved by the University of North Carolina at Chapel Hill's biomedical institutional review board, and all participants provided written informed consent before data collection.

Participants

Participants were recruited from local sports medicine orthopaedic clinics as well as through emails, flyers, and word of mouth in the local community and on the university's campus. Individuals who sustained a primary ACL injury and had undergone unilateral ACLR 6 to 12 months before the study visit with a bone-patellar tendon-bone graft were eligible. Recruits with a concomitant meniscal injury at the time of ACLR were also eligible. Individuals were excluded if they had a lower extremity fracture at the time of ACL injury, more than 1 ligament reconstructed at the time of surgery, previous ACLR, or a history of knee osteoarthritis.

Earlier investigators[18] using functional waveform analyses reported a moderate effect (Cohen $d = 0.60$) for statistically significant differences in vGRF between symptomatic and asymptomatic individuals less than 12 months post-ACLR. We determined that 10 participants per group and a group total of 45 gait trials would be needed to detect a moderate effect for differences between adolescents and adults who were 6 to 12 months post-ACLR (2 tailed α, $1 - \beta = 0.8$, $\alpha = .05$). G*Power statistical power analysis software (version 3.1; Heinrich-Heine-Universität) was used to estimate sample size.

Gait Biomechanical Assessment

Retroreflective markers (model High Precision Pearl Markers; B&L Engineering) were affixed to the first and fifth metatarsals, calcanei, medial and lateral malleoli, anterior tibias, medial and lateral femoral epicondyles, anterior thighs, greater trochanters, anterior-superior iliac spines, L4-L5 spinous process, right and left acromions, and manubrium of each participant.[7,10,18] A sacral plate consisting of 3 retroreflective markers was placed in line with the posterior-superior iliac spines. Marker trajectories and forces were collected using a 10-camera 3D motion-capture system (Nexus version 2.12.0121369h; Vicon) at

120 and 1200 Hz, respectively, with 2 staggered force plates embedded into the floor (model FP406010; Bertec Corp).[7,10,18]

Participants completed the gait assessment barefoot at their habitual walking speed across a 6-m runway. They were instructed to walk as if they were walking "comfortably on the sidewalk" at their normal pace. Infrared timing gates (model TF 100; TracTronix) were placed 0.97-m apart around the force plates to collect a participant's habitual walking speed.[7,10,18] Habitual walking speed was averaged from 5 walking trials. Next, individuals were instructed to walk across the 6-m track for 5 successful trials for motion capture. A trial was considered *successful* if the participant walked ±5% of his or her average habitual speed, walked without obvious deviations (ie, stutter step), and made full-foot contact with the force plates.[7]

Gait kinematics and kinetics of the ACLR limb and uninjured limb were processed using Visual3D software (version 2021.06.1; C-Motion Inc). We filtered kinematic and kinetic data using a low-pass fourth-order Butterworth filter and a 10-Hz cutoff. Ankle- and knee-joint centers were calculated as the midpoint distance between the medial and lateral malleoli and epicondyles, respectively, while hip-joint centers were calculated using the Bell method.[19] Knee-flexion angle was calculated via Euler angles using the shank position in relation to the thigh. An inverse-dynamic approach was used to calculate net internal KAM and KEM. The *stance phase* was defined from heel strike (vGRF > 20 N) to toe-off (vGRF < 20 N). The vGRF, knee-flexion angle, KAM, and KEM were extracted during stance and time normalized to 101 data points (0%–100%); vGRF and knee moments were normalized to body weight and height (xBW × height). The KAM and KEM were reported as positive values to aid in interpretation.

Statistical Analysis

Descriptive statistics (means, standard deviations, or percentages) were calculated for participant demographics, patient-reported outcomes, and gait biomechanical outcomes. We compared individual characteristics (ie, age, BMI, habitual walking speed, and time since surgery) and KOOS subscale scores between the adolescent and adult groups using independent *t* tests. The percentages of female participants and those who underwent a meniscal procedure at the time of ACLR (ie, meniscal injury) were compared using Fisher exact tests. Described comparisons were performed using SPSS (version 27; IBM Corp).

Earlier authors reported gait biomechanical differences throughout stance between individuals with and those without ACLR[7] as well as individuals who were symptomatic and those who were asymptomatic post-ACLR.[18] We performed functional waveform analyses to compare adolescent and adult gait biomechanics throughout the entire stance phase of walking. These analyses were conducted using R (version 3.6.3; R Foundation) with the package bayesFDA (version 0.6.0), which was modified from the warptk package.[20] Bayesian P-splines were fit to waveforms for each individual trial of the gait biomechanical outcome of interest in the adolescent and adult groups. Mean waveform differences between adolescent and adult groups and associated 95% CIs for each biomechanical variable of interest were calculated across each percentage of stance. Between-groups differences were considered statistically significant if the 95% CI did not cross zero. We performed 2 sensitivity analyses to determine the effects of gait speed for the primary comparison of ACLR-limb gait biomechanics in adolescents and adults and between-limbs differences in adolescents post-ACLR. Between-limbs differences in adults post-ACLR were not conducted because previous researchers[7] had reported these comparisons in adults 6 and 12 months post-ACLR. Due to known differences in habitual walking speed between adolescents and adults,[14] our comparisons between groups using functional waveforms incorporated a control for gait speed as a sensitivity analysis. The Bayesian P-spline model described earlier was modified to control for habitual walking speed using a functional regression based on previous frameworks.[21,22] To control for habitual walking speed during the sensitivity analysis, we created a covariate variable that represented the habitual walking speed during each testing trial relative to the average habitual walking speed of all study participants (ie, 1.24 m/s).

Cohen *d* effect sizes and associated 95% CIs were calculated as the percentage of stance with the largest biomechanical difference during portions of stance that were statistically significant to determine the magnitude of group or limb differences. Effects were interpreted as *small* ($d \leq 0.2$), *medium* ($d \leq 0.5$), or *large* ($d \leq 0.8$)[23] and reported in Supplemental Table 1 (available online at http://dx.doi.org/10.4085/1062-6050-0052.22.S1).

RESULTS

No differences were noted in height, BMI, months since surgery, concomitant meniscal injuries, or KOOS subscale scores between adolescents and adults (P range = .26–1.00; Table). Adolescents demonstrated slower habitual walking speeds than adults ($P = .01$).

Differences in Gait Biomechanics Between Adolescents and Adults

Adolescents demonstrated less vGRF between 9% and 15% of stance compared with adults. Adolescents also displayed a greater knee-flexion angle throughout the majority of stance (0%–20% and 29%–100%) versus adults. Adolescents exhibited less KAM and KEM than adults at 12% to 25% and 81% to 98% of stance, respectively. Mean biomechanical waveforms of the ACLR limb in adolescents and adults as well as mean differences between groups with associated 95% CIs are depicted in Figure 1.

Differences in Gait Biomechanics Between the ACLR Limb and Contralateral Limb of Adolescents

The vGRF between limbs did not differ throughout stance in adolescents post-ACLR. Adolescents demonstrated a greater knee-flexion angle during early stance between 0% and 6% and midstance to late stance between 40% and 100% in the ACLR limb compared with the uninjured limb. Adolescents also showed less KEM in early stance from 8% to 19% but greater KEM in midstance to late stance from 51% to 81% in the ACLR limb than the uninjured limb. For KAM, adolescents displayed greater KAM during late stance

Table. Summary of Participant Characteristics Between Adolescents and Adults[a]

Participant Characteristics	Adolescents (n = 13)	Adults (n = 13)	*P* Value
Sex	10 girls, 3 boys	10 women, 3 men	NA
Age, y	16.7 ± 0.6	22.4 ± 4.0	<.001[b]
Height, m	1.7 ± 0.1	1.7 ± 0.1	.63
Body mass index, kg/m^2	22.2 ± 3.7	22.9 ± 3.3	.63
Days between injury and surgery	82.92 ± 99.2	49.2 ± 55.9	.30
Months since surgery	7.2 ± 1.9	7.1 ± 2.3	.93
Meniscal injury, %	54	54	1.00
Habitual walking speed, m/s	1.14 ± 0.11	1.28 ± 0.13	.01[a]
Knee Injury and Osteoarthritis Outcome Score			
Symptoms	74.1 ± 18.3	81.0 ± 11.2	.26
Pain	83.9 ± 17.7	85.7 ± 8.6	.76
Activities of Daily Living	90.5 ± 17.6	96.3 ± 3.2	.26
Sport	66.9 ± 29.2	73.1 ± 15.8	.51
Quality of Life	61.1 ± 22.9	56.3 ± 16.3	.55

Abbreviation: NA, not applicable.

[a] Mean ± SD unless otherwise indicated.

[b] Significant group difference ($P < .05$).

from 86% to 99% in the ACLR limb versus the uninjured limb. Mean biomechanical waveforms of the ACLR and uninjured limbs and mean between-limbs differences with associated 95% CIs are reported in Figure 2.

Differences in Gait Biomechanics Between Adolescents and Adults After Controlling for Habitual Walking Speed

Habitual walking speed affected vGRF (3%–29%, 37%–60%, and 87%–93% of stance), knee-flexion angle (0%–40% of stance), KAM (13%–48% and 79%–95% of stance), and KEM (7%–42% and 90%–100%). After we accounted for habitual walking speed, adolescents demonstrated greater vGRF from 3% to 9% and 16% to 19% of stance compared with adults. Additionally, adolescents continued to exhibit greater knee-flexion angle throughout stance (0%–100% of stance) than adults and greater KEM from 16% to 31% and 79% to 91% of stance but no difference in KAM versus adults. Mean adjusted biomechanical waveforms between the ACLR limbs of adolescents and adults, mean differences between groups with associated 95% CIs, and habitual walking speed effects are provided in Figure 3.

DISCUSSION

Consistent with our hypothesis, adolescents post-ACLR walked with smaller vGRF, KAM, and KEM in the ACLR limb during early stance at habitual walking speeds (1.14 ± 0.11 m/s). However, they walked at slower habitual walking speeds than adults post-ACLR (1.28 ± 0.13 m/s) and at slower habitual walking speeds than previously

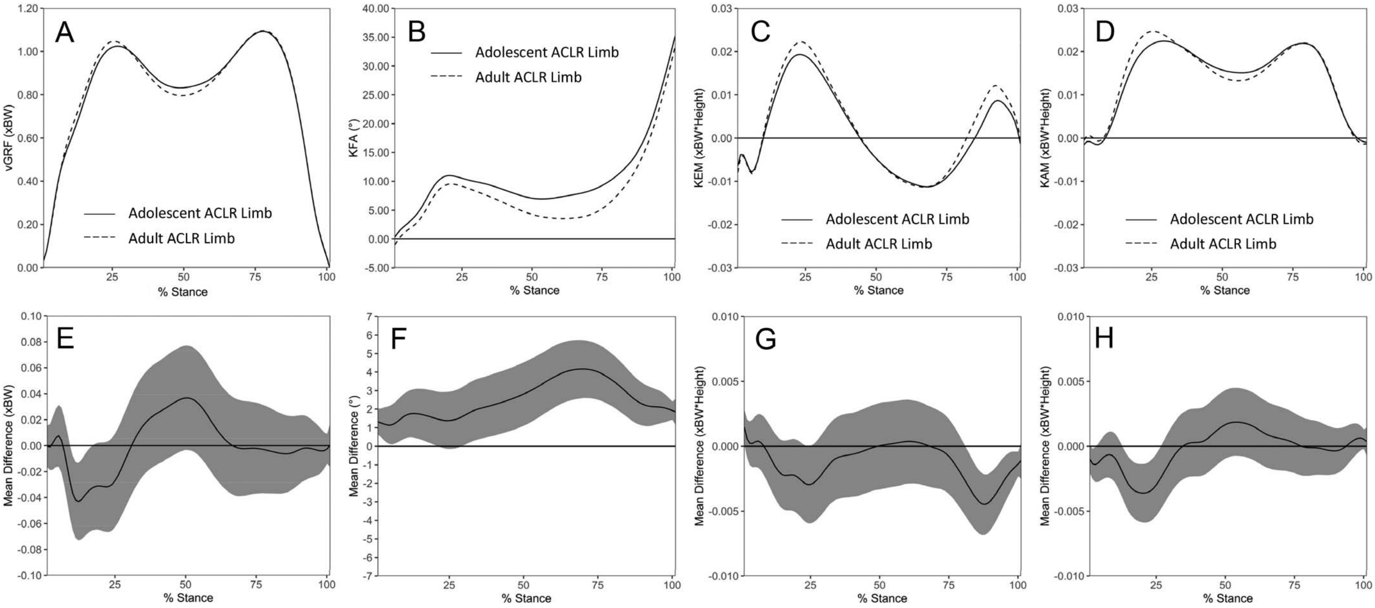

Figure 1. Mean biomechanical waveforms and waveform differences with 95% CIs throughout gait stance between the anterior cruciate ligament reconstruction (ACLR) limb of adolescents and adults post-ACLR. A, Mean vertical ground reaction force (vGRF); B, knee-flexion angle (KFA); C, knee-extension moment (KEM); and D, knee-abduction moment (KAM) waveforms in the ACLR limb of adolescents (solid line) and adults (dashed line) post-ACLR. E–H, Mean differences and associated 95% CIs in E, vGRF; F, KFA; G, KEM; and H, KAM throughout gait stance in the ACLR limb of adolescents compared with adults post-ACLR. Statistically significant between-groups differences existed when the 95% CIs did not cross zero. Abbreviation: xBW, normalized to body weight.

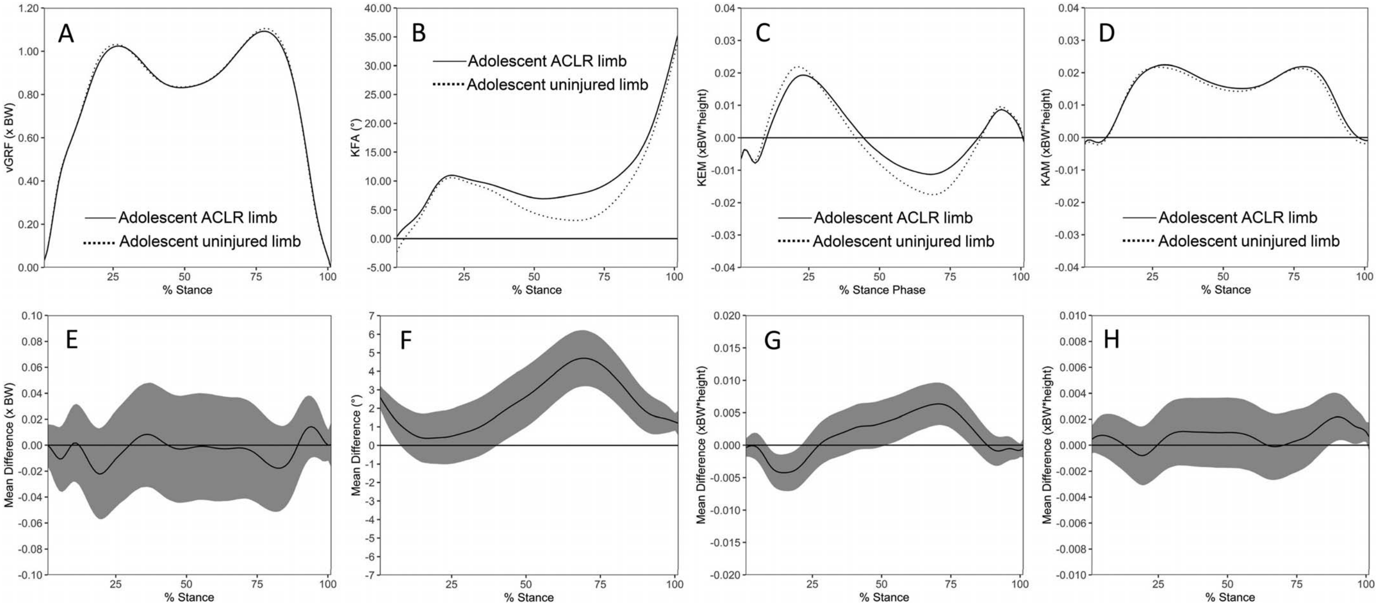

Figure 2. Mean biomechanical waveforms and waveform differences with 95% CIs throughout gait stance between the anterior cruciate ligament reconstruction (ACLR) limb and uninjured limb of adolescents post-ACLR. A, Mean vertical ground reaction force (vGRF); B, knee-flexion angle (KFA); C, knee-extension moment (KEM); and D, knee-abduction moment (KAM) waveforms in the ACLR limb (solid line) and contralateral limb (dotted line) of adolescents post-ACLR. E–H, Mean differences and associated 95% CIs in E, vGRF; F, KFA; G, KEM; and H, KAM throughout gait stance of the ACLR limb compared with the uninjured limb in adolescents post-ACLR. Statistically significant between-groups differences existed when the 95% CIs did not cross zero. Abbreviation: xBW, normalized to body weight.

reported in uninjured adolescents (1.28 ± 0.15 m/s) and uninjured young adults (1.36 ± 0.17 m/s).[14] Slower walking speeds were linked to deleterious changes in composition[10] and cartilage metabolism post-ACLR[23]; this may be a concern for knee-joint health changes in adolescents post-ACLR if future studies in larger cohorts support walking at slower habitual speeds by adolescents post-ACLR compared with uninjured adolescents. After removing the effects of habitual walking speed, we found that differences between knee-joint kinetics in the ACLR limb were reversed, indicating greater vGRF, KAM, and KEM in adolescents. It is important to note that including a sensitivity analysis to control for the effects of habitual walking speed differences on biomechanical outcomes was challenged in the literature[25] when performed in populations whose habitual walking speed differences may have resulted from age or injury (ie, ACL injury, ACLR). Our results from the sensitivity analyses that controlled for habitual walking speed should be interpreted with caution because this may not be the speed at which participants walk in real-world settings. Regardless, earlier researchers[25] suggested that walking speed affected gait kinematics and kinetics. At slower walking speeds, individuals walked with smaller vGRF, knee-joint moments, and knee-flexion angles.[26] Therefore, we expected that adolescents, who walked at slower habitual walking speeds, would also walk with less KAM and KEM in the ACLR limb. We would anticipate that a slower habitual walking speed would also result in smaller knee-flexion angles, but this was not the case in adolescents compared with adults post-ACLR (Figure 2). Contrary to our hypothesis, adolescents continued to demonstrate greater knee-flexion angles throughout stance, even when the effects of habitual walking speed were controlled. Greater knee-flexion angles in the ACLR limb during early stance and midstance may have changed the contact forces on the knee joint during walking. Overall, our results indicated that gait patterns post-ACLR may have differed by age and that future investigators should account for age when evaluating cohorts of both adolescents and young adults with ACLR.

Trends toward small increases in knee-flexion angle during midstance (ie, knee-flexion angle difference = 0.5°) in every decade from childhood to late adulthood (10–79 years old)[11] and greater knee-joint moments during early stance to midstance of gait with increasing age and skeletal maturation have been seen in uninjured individuals.[12,13] We expected knee-joint moments to be smaller in adolescents, but the consistently greater knee-flexion angles in adolescents post-ACLR throughout stance were unexpected. Knee-flexion angles were also greater in the ACLR limb than the uninjured limb of adolescents throughout midstance to late stance, which may have reflected aberrant gait biomechanics in the surgical limb. Our adolescents walked with greater knee-flexion angles in the ACLR limb during midstance (ie, adolescents = 8.3° and adults = 3.5°), regardless of whether gait speed was controlled; these values exceeded the previously reported knee-flexion angle differences between uninjured adolescents and adults. Limited studies assessing gait biomechanics by age in healthy, uninjured adolescents and adults were available. Most relied on small sample sizes or compared young adults with middle-aged or older adults.[11–14] Although we demonstrated age-related differences between adolescents and adults with ACLR, future authors should expand on these findings by including age-matched cohorts of uninjured control individuals to understand the effect of ACLR on gait in adolescents.

Adolescents post-ACLR displayed slower habitual walking speeds compared with adults post-ACLR and previously reported habitual walking speeds in uninjured

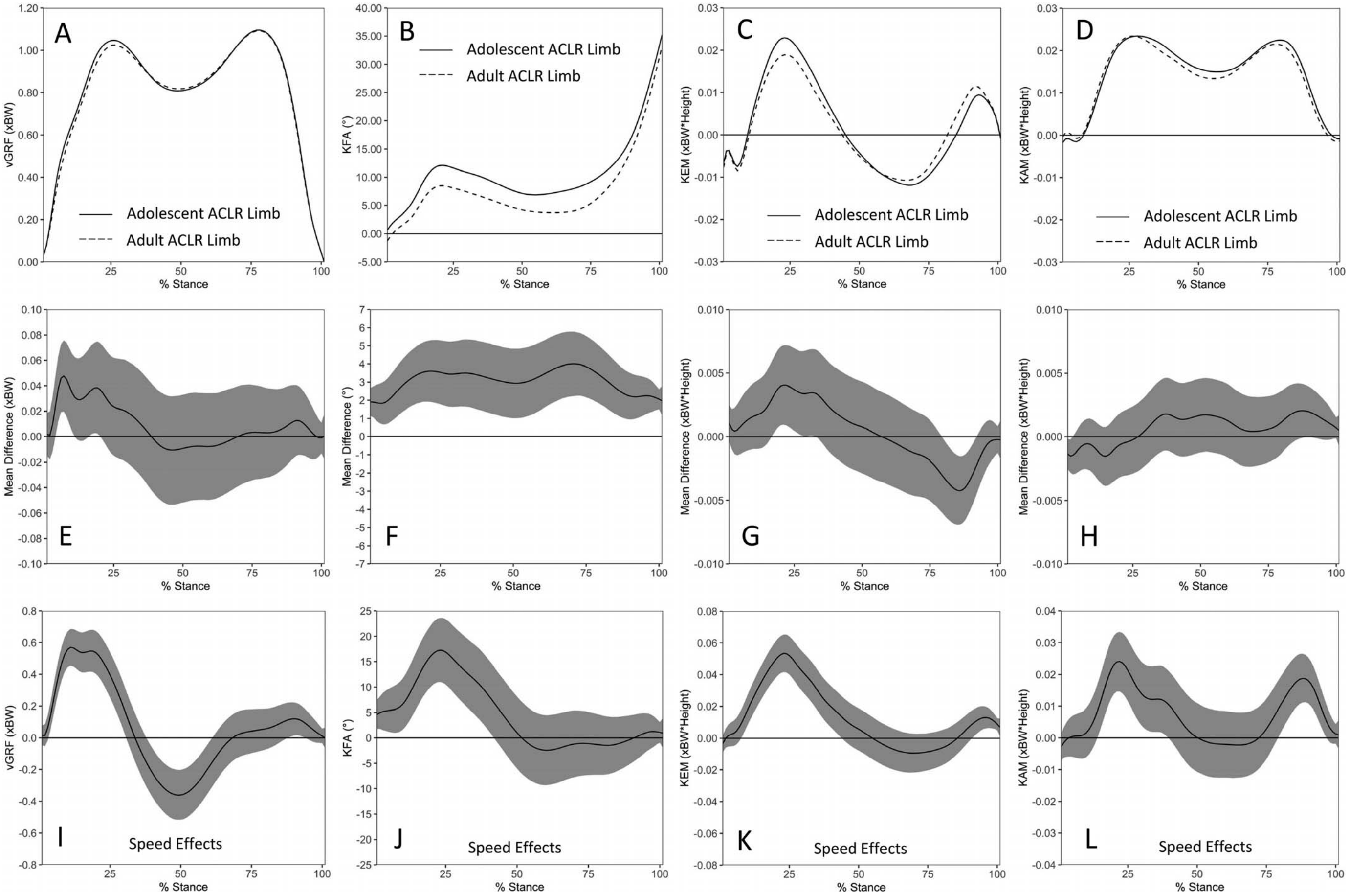

Figure 3. Mean biomechanical waveforms and waveform differences with 95% CIs throughout gait stance between the anterior cruciate ligament reconstruction (ACLR) limb of adolescents and adults post-ACLR with habitual walking speed controlled. A, Mean vertical ground reaction force (vGRF); B, knee-flexion angle (KFA); C, knee-extension moment (KEM); and D, knee-abduction moment (KAM) waveforms in the ACLR limb of adolescents (solid line) and adults (dashed line) post-ACLR with habitual walking speed controlled. E-H, Mean differences and associated 95% CIs in E, vGRF; F, KFA; G, KEM; and H, KAM throughout gait stance in the ACLR limb of adolescents compared with adults post-ACLR. I–L, Mean change in I, vGRF; J, KFA; K, KEM; and L, KAM for a 1.0 m/s increase in habitual walking speed throughout gait stance. Statistical differences and habitual walking-speed effects existed when the 95% CIs did not cross zero. Abbreviation: xBW, normalized to body weight.

adolescents[14] that exceeded the minimal detectable difference (ie, 0.1 m/s).[27] Slower habitual walking speed at 6 and 12 months post-ACLR was associated with worse cartilage composition in the posteromedial femoral condyle of the ACLR limb in a combined cohort of adolescents and adults.[9] It is still unclear if walking at slower habitual speeds, which was inherent to adolescents, negatively influenced knee-joint health or if adolescents were resilient to the potential effects of slower habitual walking speeds due to normal maturational development. Adolescents post-ACLR also walked with a smaller knee-flexion angle range of motion from initial peak knee flexion during early stance to the knee-flexion minimum in midstance to late stance (ie, adolescents = 2.7° and adults = 6.0°) in the ACLR limb. We speculated that walking at habitual walking speeds with greater peak knee-flexion angles during early stance may have shifted the tibiofemoral contact locations more posteriorly.[28] As the knee moved through less range of motion in the sagittal plane from early stance to midstance, tibiofemoral contact forces may have been concentrated in more posterior areas of the tibiofemoral cartilage. Targeting a smaller peak knee-flexion range of motion from early stance to midstance in the ACLR limb was a primary goal of gait-retraining interventions to improve knee-joint health[29] and may have been relevant to address in adolescents if they walked at uncharacteristically slow speeds. Future researchers should focus on determining if aberrant gait outcomes have the same effect on long-term health in adolescents as in adults post-ACLR and whether changing gait mechanics in adolescent patients may modify disease progression. Elucidating gait differences between adolescents and adults may help us develop age-specific rehabilitation approaches for clinicians.

The mechanisms driving differences in knee-flexion angles throughout stance in the ACLR limb between adults and adolescents post-ACLR are unknown. Knee-flexion angles were greater throughout stance in adolescents than in adults post-ACLR, which was opposite the expected knee-flexion angle differences between uninjured adults and adolescents based on earlier literature. Although speculative, several potential factors may have affected gait differences between adolescents and adults, including recovery of lower extremity muscle strength, psychological barriers, or lack of appropriate gait retraining post-ACLR. Adolescents and adults had different quadriceps strength profiles[4] and psychological experiences post-ACLR.[5]

Specifically, adolescents exhibited more symmetric quadriceps strength and reported greater psychological readiness and knee self-efficacy[30] in the first 12 months post-ACLR. Previous investigators showed that quadriceps weakness was associated with less knee-flexion range of motion throughout stance in those with ACLR.[31] How the relationship between quadriceps weakness and gait biomechanics after ACLR may be affected by age or maturity status remains unknown. Therefore, the mechanisms driving aberrant gait patterns post-ACLR in adolescents versus adults should be further explored.

Limitations

To our knowledge, we are the first to compare gait patterns between adolescents and adults post-ACLR. Functional waveform analyses allowed for comparison of gait biomechanics throughout stance and was a strength of the study, but some limitations should be considered. Our design was cross-sectional and included a modest sample size of participants at 6 and 12 months post-ACLR, reducing the power of our statistical analysis and restricting our ability to generalize the results to larger populations. Our sample-size estimation approach was based on previous studies[7,18,29,31] that powered functional waveform analyses using a single effect during gait stance, which may have underestimated the sample size. Portions of stance that were not different might be recognized as different in an analysis with more participants. The current analysis was novel and should be considered hypothesis generating for future studies with larger sample sizes.

We compared our results with the earlier literature assessing gait in uninjured adolescents, yet we did not compare gait biomechanics post-ACLR with those preinjury or uninjured individuals. The age range of adolescents in the study was limited based on age criteria (ie, <18 years of age) used to enroll participants in the cross-sectional cohort. Adolescents younger than 16 years old were not included, and the average age of participants was approximately 17 years, thus placing them at the upper end of the adolescent age range. Therefore, future research is needed to determine the effect of ACLR on gait in individuals <16 years old. Future authors should explore longitudinal changes between adolescents and adults post-ACLR versus uninjured control individuals to best characterize age-related gait adaptations post-ACLR.

CONCLUSIONS

After ACLR, adolescents walked at slower habitual speeds and with greater knee-flexion angles throughout stance in the ACLR limb compared with adults. Adolescents also walked with smaller vGRF, KAM, and KEM during early stance than adults post-ACLR, but these differences were reversed when habitual walking speed was controlled. The effects of age on gait biomechanics should be considered when implementing age-specific rehabilitation interventions in individuals post-ACLR.

FINANCIAL DISCLOSURE

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SUPPLEMENTAL MATERIAL

Supplemental Table. Largest biomechanical group or limb differences, statistically significant portions of gait stance, and Cohen *d* effect sizes with 95% CIs for the largest differences during the statistically significant portions of stance.

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