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Sex-specific gait adaptations prior to and up to six months after ACL reconstruction

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Abstract

STUDY DESIGN—Controlled longitudinal laboratory study.

OBJECTIVES—Compare sagittal plane gait mechanics of men and women before and up to 6 months after anterior cruciate ligament reconstruction (ACLR).

BACKGROUND—Aberrant gait patterns are ubiquitous after anterior cruciate ligament (ACL) rupture and persist after ACLR despite skilled physical therapy. Sex influences post-operative function and second ACL injury risk, but its influence on gait adaptations after injury have not been investigated.

METHODS—Sagittal plane knee and hip joint excursions during midstance and internal knee and hip extension moments at peak knee flexion were collected on 12 women and 27 men using 3-dimensional gait analysis before (Screen) and after pre-operative physical therapy (Pre-sx), and 6 months after ACLR (6mo). Repeated measures analysis of variance models were used to determine whether limb asymmetries changed differently over time in men and women.

RESULTS—Significant time x limb x sex interactions were identified for hip and knee excursions and internal knee extension moments ($P = .007$). Both sexes demonstrated smaller knee excursions on the involved compared to the uninvolved knee at each time point ($P = .007$), but only women demonstrated a decrease in the involved knee excursion from pre-sx to 6mo ($P = .03$). Women also demonstrated smaller hip excursions ($P < .001$) and internal knee extension moments

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Implications: Resolving asymmetrical joint mechanics following ACLR may positively influence the recovery of dynamic knee function and could help to reduce the sex-specific discrepancies in second ACL injury risk.

Caution: This exploratory study was performed on a small cohort of the poorest performing group of athletes following ACL injury. Our data indicate a potential effect of sex on gait mechanics in this population, but will need to be validated by a prospective examination of sex-specific gait patterns following ACL injury and reconstruction.

($P=.005$) on the involved limb compared to the uninvolved limb at 6mo. Men demonstrated smaller hip excursions and knee moments on the involved limb compared to the uninvolved limb (main effects, $P<.001$).

CONCLUSION—The persistence of limb asymmetries in men and women 6 months after ACLR indicates that current rehabilitation efforts are inadequate for some individuals following ACLR.

Keywords

ACL; sex differences; gait; physical therapy

Knee injuries predominate in sports¹¹ and rupture of the anterior cruciate ligament (ACL) is one of the most common knee injuries.³² The number of ACL injuries sustained by males is greater than that of their female counterparts;²¹ however, when comparing rate of injury in the same sports, females' risk for ACL injury is several times greater than males.^{3, 5, 40} Women not only demonstrate poorer function after ACL injury,^{17, 29} but they are also less likely to return to sports after ACL reconstruction (ACLR) compared to men,^{4, 8, 17} and are at significantly greater risk of sustaining a second ACL injury if they do return to sports.^{8, 37, 46} Once representative of less than 10% of the high school athletic population, female athletes now account for 42% of high school sports participants, whose total current population is nearly 7.7 million.⁶ As the number of women participating in vigorous sporting activities continues to rise steadily, and the incidence of ACL ruptures increases correspondingly, effective rehabilitation management of ACL injuries is of critical importance.

Sex influences knee function⁴ and second ACL injury risk following ACL reconstruction.³⁷ Biomechanical asymmetries during a drop-jump task accurately predict future second ACL injury,³⁷ but important changes in mechanics likely occur long before assessments of jumping tasks are safe. Walking gait mechanics are sensitive to changes following ACL injury⁴³ and reconstruction^{23,42} and may allow for early identification of risky biomechanics. Kinematic and kinetic asymmetries of the hip and knee are associated with reduced functional performance at the time of return to sport clearance.¹⁵ Importantly, alterations in the lower extremity biomechanics of athletes following ACLR exist in both limbs.^{9, 12, 15, 22-23, 35-36, 39, 41} Reduced joint motion and internal extension moments of the involved knee are common for many months following surgery,^{22-23, 41} but can also be accompanied by altered joint kinetics of the contralateral knee and hip.^{22, 39, 41} Post-operative guidelines emphasize bilateral limb training,^{1, 34} yet despite supervised rehabilitation and medical clearance to return to activity, abnormal neuromuscular strategies persist.^{9, 39, 41, 45} Evaluation of adaptations at the hip and knee in response to rehabilitation and ACLR, and whether these changes are sex-specific, will ultimately help refine evidence-based clinical care and return to sport decision-making.

Rehabilitation which includes neuromuscular training elicits positive effects on dynamic knee function^{18, 20, 28} and movement patterns^{10, 16} of athletes with ACL deficiency. Women, in particular, may have the most to gain from targeted pre-operative training. Women who sustain an ACL injury are more likely to report knee instability and significant functional disability²⁹ and have also demonstrated altered hip and knee mechanics which

were not identified in men.¹⁶ Progressive strength training and neuromuscular re-education successfully reduced the kinematic and kinetic asymmetries of the knee and hip in this small cohort of women after acute ACL injury,¹⁶ but whether these short-term improvements in gait mechanics gained prior to surgery persist following ACLR has not been evaluated.

The purpose of this study was to determine whether changes in sagittal plane hip and knee joint mechanics following ACL injury and reconstruction were limb and sex-specific. We hypothesized that females would demonstrate greater limb differences during gait than males and that the knees and hips of males and females would change differently over time. Evaluating longitudinal changes in gait patterns between men and women following ACL injury may help explain the biomechanical factors related to sex-specific outcomes following ACLR.

METHODS

Thirty-nine athletes with acute ACL injury (12 women, 27 men) from a larger randomized controlled trial (RCT) were included in this study. The protocol for this study was approved by the Institutional Review Board of the University of Delaware; written informed consent was obtained from each individual prior to participation and the rights of the participants were protected. All participants were screened and classified as non-copers by screening examination¹⁹ and underwent ACLR with a hamstring autograft or soft tissue allograft by a single orthopaedic surgeon. Prior to surgery, all participants received 10 sessions of progressive quadriceps strength training (STR) with weight-bearing and functional therapeutic exercises, neuromuscular electrical stimulation, and an isokinetic spectrum protocol.^{24, 33} As part of the RCT, 18 of the 39 total participants (7 women, 11 men) also received a type of pre-operative neuromuscular training called perturbation training (PERT) in addition to the strength training protocol. Perturbation training was administered prior to strength training to avoid the effects of muscular fatigue.¹⁹ Post-operative physical therapy was standardized by the use of criterion-based progression and emphasized the resolution of effusion, range of motion, strength deficits, and functional impairments; serial clinical testing was used to determine an athlete's progress towards goals and discharge from supervised physical therapy.^{1, 33}

Motion analysis data were collected before (Screen) and after pre-operative physical therapy (Pre-sx), and 6 months after ACLR (6 mo). Walking gait mechanics were collected with a passive, 8-camera 3-dimensional motion analysis system (VICON, Oxford Metrics Ltd., London, England), and a 6-component force plate (Model 6090, Bertec Corporation, Worthington, OH) embedded into the walkway. Prior to each gait analysis session, anthropometric data, including the participant's pelvic depth, mass, and height, were collected. Retro-reflective markers were then placed on the anatomical landmarks (metatarsal heads, malleoli, femoral condyles, and greater trochanters) of both lower extremities to determine segment lengths and joint centers. Tracking shells, each fitted with 4 retro-reflective markers, were strapped with elastic wraps (Superwrap, Fabrifoam, Inc., Exton, PA) to the pelvis and posterior-lateral shanks and thighs to calculate segment position during a standing calibration trial. This marker placement has excellent interrater and intersession reliability (ICC = 0.94);¹⁴ minimal detectable limb difference values during

gait in healthy athletic controls were calculated to be 3° for hip and knee kinematics, 0.04 Nm/kg*m for internal knee extension moments, and 0.06 for Nm/kg*m for internal hip extension moments.¹⁶ Marker data were sampled at 120Hz and synched with ground reaction force data sampled at 1080Hz. Following the standing calibration trial, participants were asked to walk over a 13-m walkway at their self-selected speed ($\pm 5\%$ within and between sessions), measured by 2 photocells 2.865 meters apart. Trials were excluded if isolated foot contact was not made with the force plate or the participants were noted to target the force plate. A total of 5 trials were used for post-processing and statistical analyses.

Lower extremity kinematic and kinetic data were calculated for the hip and knee and post-processed using the Professional Version of Visual3D (C-Motion, Inc., Germantown, MD) with scripts created in a custom LabView program (National Instruments, Austin, TX). Marker data were filtered at 6 Hz and rigid body analysis was performed with Euler angles (x-y-z) with the distal segment referenced to the proximal segment. Force plate data were low-pass filtered at 40 Hz. Inverse dynamics were used to calculate external joint moments in Visual 3D, which were then normalized to the participant's body mass in kilograms multiplied by height in meters. The stance phase of gait was determined using a force plate threshold of 50N. Five walking trials were time normalized to 100% of stance and then averaged for statistical analyses. Midstance was defined as the period of the gait cycle between peak knee flexion (PKF) angle and peak knee extension angle. Variables of interest were sagittal plane hip and knee joint excursions during midstance and the internal joint extension moments at PKF.

This study was a secondary analysis of a larger RCT within our laboratory where the effectiveness of 2 pre-operative training regimens was assessed; therefore, an a priori power analysis was not performed. Histogram plots, Kolmogorov-Smirnov, and Levene's Tests were used to confirm the assumptions of an analysis of variance for the variables of interest. Our analysis of variance (ANOVA) model showed no significant interactions or main effect of treatment group (PERT or STR) for any of our 4 variables (knee and hip excursions during midstance and internal knee and hip extension moments at peak knee flexion) ($P = .087$). Thus the PERT and STR groups were collapsed for our data analysis. A repeated measures ANOVA (within-group variables of time and limb, and between group variable of sex) was used to determine whether limbs changed differently over time (Screen, Pre-sx, 6 mo) in men and women with ACL injury followed by ACLR. When a significant time x limb x sex interaction was found, time x limb interactions were examined independently for men and women with a repeated measures ANOVA. When interactions were found for men or women, paired t-tests were used to determine at which time point limb differences existed and whether each limb changed over time. Main effects were reported only when interactions were not significant. Due to the exploratory nature of this study, no adjustment for multiple comparisons was applied; the a priori alpha level was set at 0.05. Statistical analyses were performed with PASW 22.0 (SPSS, IBM, Somers, NY).

RESULTS

Age, walking speed, time from injury to screening, and treatment group allocation (PERT or STR) did not differ between sexes (**TABLE 1**).

Joint Excursions during Midstance

There was a significant time x limb x sex interaction for knee joint excursion ($P=0.001$). Significant time x limb interactions were identified for both men ($P=.019$) and women ($P=.026$) (**FIGURE 1**), and both sexes demonstrated smaller knee excursions on the involved limb compared to the uninvolved limb at each of the three time points (Men: $P=.001$; Women: $P=.007$). Men demonstrated a significant increase in the involved knee excursion from screening (17.0° , 95% CI: 14.7° , 19.3°) to 6 months after ACLR (18.4° , 95% CI: 16.0° , 20.9° ; $P=.032$); whereas the uninvolved limb did not change over time ($P=.341$). Women demonstrated increased involved knee joint excursions following pre-operative physical therapy (Screen: 14.8° , 95% CI: 11.4° , 18.2° ; Pre-sx: 16.8° , 95% CI: 13.6° , 20.1° ; $P=.044$), which then decreased from the time of completion of pre-operative physical therapy to 6 months after ACLR (14.0° , 95% CI: 10.4° , 17.7° ; $P=.03$). There was no change in the uninvolved knee excursions of women over time ($P=.176$).

There was a significant time x limb x sex interaction for hip joint excursion ($P=.007$). A significant time x limb interaction was identified in women ($P=.018$), but not men ($P=.637$) (**FIGURE 2**). Women demonstrated significantly smaller hip joint excursions of the involved limb (31.1° , 95% CI: 26.4° , 35.8°) compared to the uninvolved limb (38.2° , 95% CI: 34.4° , 42.1°) 6 months after ACLR ($P<.001$); limb differences were not found at screening or pre-surgery testing ($P=.209$). Hip joint excursions of the involved ($P=.142$) and uninvolved ($P=.069$) limbs of women did not change significantly over time. A significant main effect of limb was identified in men ($P<.001$), indicating the hip excursion of the involved limb was smaller than the uninvolved limb; there was no main effect of time ($P=.918$).

Internal Joint Moments at Peak Knee Flexion

There was a significant time x limb x sex interaction for the internal knee extension moment ($P=.007$). A significant time x limb interaction was found in women ($P=.011$), but not men ($P=.537$) (**FIGURE 3**). Women demonstrated smaller internal knee extension moments on the involved limb compared to the uninvolved limb at screening (Involved: $0.27 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.18 , 0.36 ; Uninvolved: $0.38 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.29 , 0.47 ; $P=.025$) and 6 months after ACLR (Involved: $0.33 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.24 , 0.41 ; Uninvolved: $0.51 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.44 , 0.59 ; $P=.005$). The involved limb internal knee extension moment increased in women following pre-operative physical therapy (Screen: $0.27 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.18 , 0.36 ; Pre-sx: $0.35 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.26 , 0.42 ; $P=.029$). The uninvolved limb internal knee extension moment was significantly larger 6 months after ACLR ($0.51 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.44 , 0.59 ; $P=.001$) when compared to screening (Screen: $0.38 \text{ Nm/kg}\cdot\text{m}$, 95% CI: 0.29 , 0.47 ; $P=.001$) and pre-surgical values ($0.40 \text{ Nm/kg}\cdot\text{m}$; 95% CI: 0.28 , 0.52 ; $P=.010$). A significant main effect of limb was identified in men ($P<.001$), indicating the internal knee extension moment of the involved limb was smaller than the uninvolved limb regardless of

time. A trend toward a main effect of time ($P=0.052$) showing increasing internal knee extension moments over time was also found.

There was no significant time x limb x sex or time x limb interactions for the internal hip extension moment at PKF ($P=.502$; **FIGURE 4**). No main effects of limb ($P=.079$) or time ($P=.113$) were found.

DISCUSSION

The purpose of this study was to evaluate whether interlimb lower extremity joint mechanics during gait differed between men and women following ACL injury and ACLR. While kinematic and kinetic asymmetries were characteristic of both men and women following injury and surgery, the responses to pre-operative physical therapy and surgery were sex-specific. Men demonstrated significantly smaller hip and knee joint excursion and smaller knee joint moments on the involved limb, regardless of time. In contrast, the women demonstrated improved gait symmetry following pre-operative physical therapy, but a subsequent increase in hip and knee excursion asymmetry and knee joint moment asymmetry returned 6 months after ACLR. These sex-specific gait adaptations following ACL injury, physical therapy, and ACLR may be particularly important when attempting to understand the mechanisms underlying sex-specific differences in return to sport and second injury rates.

Pre-operative rehabilitation has yielded mixed results in terms of improving function and gait mechanics in athletes with recurrent knee instability after injury (non-copers)^{14, 16, 23-24} and the effect of sex may explain some of the variance in outcomes. In this study, pre-operative physical therapy successfully increased the involved limb knee joint excursions and internal knee extension moments in women but not men. Importantly, this resulted in internal knee extensor moment symmetry, and supports previously published data which showed that progressive strength and neuromuscular training successfully reduces gait asymmetries in women early after ACL injury.¹⁶ Improved mechanics as a result of pre-operative treatment positively influences post-operative function, as larger pre-operative external knee flexion moments can predict an athlete's ability to pass criteria to return to sport.²⁵ The gait mechanics of the men in this study did not change following pre-operative physical therapy, indicating that other forms of treatment may be needed to remediate aberrant hip and knee mechanics in men who have sustained an ACL injury.

Alterations in the lower extremity biomechanics are common to both limbs following ACLR^{9, 12, 15, 22-23, 35-36, 39, 41} and are associated with poorer knee function 6 months after surgery,¹⁵ a time when many athletes are attempting to return to sport. Importantly, the unique gait adaptations of the men and women in this cohort were most apparent 6 months after ACLR. The positive effects of pre-operative physical therapy did not persist in women following surgery; in fact, some of the largest limb asymmetries hip and knee mechanics were identified at this time point. While both men and women demonstrated smaller knee joint excursions and smaller internal knee extension moments on the involved limb 6 months after ACLR, only women demonstrated smaller hip joint excursions on the involved limb. The changes in gait mechanics over time, however, were not limited to the involved limb

alone. Bilateral adaptations in knee moments after ACL injury were identified exclusively in this group of women, resulting in significantly lower internal knee extension moments on the involved limb, and occurring in spite of surgical reconstruction and criterion-based post-operative physical therapy. Interestingly, the gait mechanics of men did not change following ACLR and post-operative rehabilitation, further suggesting that our current rehabilitation model is inadequate for restoring symmetrical gait in both men and women.

Poor functional outcomes and second injury risk are linked to a number of modifiable and non-modifiable factors^{7, 27, 30-31, 44, 46-47} including sex.^{2, 4, 8, 37, 46} A prospective trial of several thousand individuals before and after ACLR showed that women reported worse function on subscales of the Knee injury and Osteoarthritis Outcome Score both before and 1 and 2 years after surgery.² Women are also less likely to return to their pre-injury level of sport⁴ and 6 times more likely to sustain a contralateral ACL injury than men.³⁷ The mechanisms underlying low rates of return to pre-injury sports and increased second ACL injury risk in both sexes may be due in part to the asymmetrical limb behaviors adopted following injury and ACLR. Smaller internal knee extension moments on the involved limb were characteristic in this group of non-copers, and most pronounced in the women. This asymmetry in loading strategy has also been identified during drop-jump landings, where athletes cleared to return to sport after ACLR demonstrate an attenuation of forces through the reconstructed limb.^{9, 36, 38} Limb differences in sagittal plane knee moments during jump-landings are part of a highly accurate prediction model for second ACL injury primarily in young female athletes.³⁹ The sex-specific gait adaptations identified in this study may be an important component of the risk for poorer function and increased risk for a second ACL injury in women. Developing specific treatments to address aberrant mechanics throughout supervised rehabilitation may be a key factor in restoring knee function and improving safety for those athletes returning to sport.

This study highlights the continuation of maladaptive gait strategies following ACL injury and reconstruction in spite of current, evidence-based rehabilitation. Neither rehabilitation nor ACLR remediated aberrant gait patterns in men, and while pre-operative physical therapy improved some gait asymmetries in women, limb differences returned following ACLR. The persistence of limb differences in men and the recurrence of gait asymmetries in women 6 months after ACLR indicate that current rehabilitation efforts are still inadequate for some individuals following ACLR.^{26, 48} These data also indicate that the ideal timing of rehabilitation augmented by neuromuscular training may be an important factor in maximizing the recovery of function following ACL injury. The effects of neuromuscular training administered post-ACLR on the outcomes of non-copers are currently under investigation.^{26, 48}

Limitations

Due to the exploratory nature of this study and the multiple comparisons performed on the variables of interest, we recognize the increased risk of alpha error as a limitation in our analyses. The small sample of non-copers examined in this study also limits the generalizability of our results to potential copers, or those athletes who do not experience recurrent joint instability or significant functional limitations following ACL injury. Neither

the total support moment nor the vertical ground reaction force data were examined, which may have further characterized any sex-specific gait adaptations in this cohort. Several participants underwent partial meniscectomies or meniscal repairs at the time of ACLR; these additional procedures were not accounted for in the statistical analyses and may have influenced the results. However, none of our study participants had a meniscal repair which warranted delayed weight-bearing or range of motion restrictions; treatment for all participants was progressed per criterion-based rehabilitation guidelines.¹ Future work should consider the effects of sex on recovery of dynamic knee function and normal movement after ACL injury as well as the potential of rehabilitation to reduce risk of second ACL injury.

CONCLUSION

Rehabilitation following ACL injury and ACLR should aim to address the unique gait strategies of men and women. Women in this cohort responded favorably to pre-operative rehabilitation with improved involved limb mechanics, and then demonstrated increased gait asymmetries in spite of ACLR and progressive post-operative rehabilitation. Consistent with previous findings,²² reduced internal knee extension moments persisted after ACLR regardless of sex, and may have important implications in second injury risk for those who return to sport. Prospective analysis of biomechanical adaptations in athletic men and women may not only clarify the sex-specific outcomes following ACL injury, but also aid in the development of effective, evidence-based peri-operative rehabilitation guidelines for cohorts at high risk for poor outcomes.

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Findings: Interlimb gait asymmetries are common to both men and women even after progressive, criterion-based rehabilitation and ACLR. While pre-operative physical therapy and ACLR had a greater effect on the interlimb gait asymmetries of women compared to men, both sexes may benefit from targeted post-operative neuromuscular training to address aberrant gait patterns. Grant support: R01AR048212 and S10RR022396 Public trials registry and registration number: The Institutional Review Board of the University of Delaware approved this study.

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FIGURE 1.

Midstance knee excursions of women (black) and men (gray) before pre-operative physical therapy (Screen), after pre-operative physical therapy (Pre-sx), and 6 months after anterior cruciate ligament reconstruction (6 mo). Means and 95% confidence intervals are reported; * = significant limb differences in women; § = significant limb differences in men; ¥ = involved limb of women changed significantly over time; ‡ involved limb of men changed significantly over time; † = statistical significance ($p < 0.05$). Abbreviations: inv, involved; unin, uninvolved

FIGURE 2.

Midstance hip excursions of women (black) and men (gray) before pre-operative rehabilitation (Screen), after pre-operative rehabilitation (Pre-sx), and 6 months after anterior cruciate ligament reconstruction (6 mo). Means and 95% confidence intervals are reported; * denotes significant limb differences in women ($P < .05$). Abbreviations: inv, involved; unininv, uninvolved

FIGURE 3.

Internal knee extensor moments at peak knee flexion (PKF) of women (black) and men (gray) before pre-operative rehabilitation (Screen), after pre-operative rehabilitation (Pre sx), and 6 months after anterior cruciate ligament reconstruction (6 mo). Means and 95% confidence intervals are reported; * significant limb differences in women; ‡ involved limb of women changed significantly over time; † uninvolved limb of women changed significantly over time; statistical significance ($p < 0.05$). Abbreviations: inv, involved; unin, uninvolved

FIGURE 4.

Internal hip extensor moments at peak knee flexion (PKF) of women (black) and men (gray) before pre-operative rehabilitation (Screen), after pre-operative rehabilitation (Pre sx), and 6 months after anterior cruciate ligament reconstruction (6 mo). Means and 95% confidence intervals are reported. Abbreviations: inv, involved; uninv, uninvolved

Table 1

Demographic data of study subjects.

	# of subjects	Age (years)	Treatment group allocation	Walking speed (m/s)	Time from injury (wks)
Men	27	28 ± 10	11 PERT, 16 STR	1.51 ± 0.12	12.0 ± 10.0
Women	12	32 ± 12	7 PERT, 5 STR	1.54 ± 0.12	9.0 ± 10.3
<i>p-values</i>	--	0.35	0.49	0.61	0.27