

[Athletic Training]

Neuromuscular Fatigue Alters Postural Control and Sagittal Plane Hip Biomechanics in Active Females With Anterior Cruciate Ligament Reconstruction

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Background: Females with history of anterior cruciate ligament (ACL) injury and subsequent ligament reconstruction are at high risk for future ACL injury. Fatigue may influence the increased risk of future injury in females by altering lower extremity biomechanics and postural control.

Hypothesis: Fatigue will promote lower extremity biomechanics and postural control deficits associated with ACL injury.

Study Design: Descriptive laboratory study.

Methods: Fourteen physically active females with ACL reconstruction (mean age, 19.64 ± 1.5 years; mean height, 163.52 ± 6.18 cm; mean mass, 62.6 ± 13.97 kg) volunteered for this study. Postural control and lower extremity biomechanics were assessed in the surgical limb during single-leg balance and jump-landing tasks before and after a fatigue protocol. Main outcome measures were 3-dimensional hip and knee joint angles at initial contact, peak angles, joint angular displacements and peak net joint moments, anterior tibial shear force, and vertical ground reaction force during the first 50% of the loading phase of the jump-landing task. During the single-leg stance task, the main outcome measure was center of pressure sway speed.

Results: Initial contact hip flexion angle decreased ($t = -2.82$, $P = 0.01$; prefatigue, $40.98^\circ \pm 9.79^\circ$; postfatigue, $36.75^\circ \pm 8.61^\circ$) from pre- to postfatigue. Hip flexion displacement ($t = 2.23$, $P = 0.04$; prefatigue, $45.19^\circ \pm 14.1^\circ$; postfatigue, $47.48^\circ \pm 14.21^\circ$) and center of pressure sway speed ($t = 3.95$, $P < 0.05$; prefatigue, 5.18 ± 0.96 cm/s; postfatigue, 6.20 ± 1.72 cm/s) increased from pre- to postfatigue. There was a trending increase in hip flexion moment ($t = 2.14$, $P = 0.05$; prefatigue, 1.66 ± 0.68 Nm/kg/m; postfatigue, 1.91 ± 0.62 Nm/kg/m) from pre- to postfatigue.

Conclusion: Fatigue may induce lower extremity biomechanics and postural control deficits that may be associated with ACL injury in physically active females with ACL reconstruction.

Clinical Relevance: Rehabilitation and maintenance programs should incorporate activities that aim to improve muscular endurance and improve the neuromuscular system's tolerance to fatiguing exercise in efforts to maintain stability and safe landing technique during subsequent physical activity.

Keywords: anterior cruciate ligament; fatigue; injury; postural control; rehabilitation

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The following author declared potential conflicts of interest: Darin Padua, PhD, ATC, received a grant from the National Academy of Sports Medicine.

DOI: 10.1177/1941738114530950

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Anterior cruciate ligament (ACL) injury is increasingly prevalent in the active population^{29,41} and is a significant annual burden on the health care system. ACL injury represents medical costs approaching \$1 billion to \$3 billion in injury-related treatment and management, adding to the current burden of musculoskeletal disease on the population, representing almost 9% of the gross domestic product of the United States.^{17,23(p1)} Furthermore, ACL injury has residual health-related consequences, such as an increased risk of hip and knee osteoarthritis after injury, limiting an individual's capacity to decrease their risk of chronic disease through physical activity participation.^{15,27,28,48} It is clear there is substantial need to reduce ACL injury incidence in the population, both for individual health benefits and economic impact.

One of the most perplexing issues surrounding ACL injury is that of a high incidence of reinjury. The likelihood of sustaining a second ACL injury to the reconstructed knee or contralateral knee has been reported to range from 6% to 20% in those with previous ACL reconstruction (ACLR).^{29,40,41,44,54} In particular, female athletes with ACLR have a reinjury rate 16 times that of healthy female controls and 4 times that of their male ACLR counterparts.^{17,23(p1),37} Recent evidence suggests that ACLR individuals may demonstrate neuromuscular control (NMC) strategies that are different than individuals who do not injure their ACLs.^{12,13,15,27,28,36,48}

Greater loading and rates of loading are seen on the uninvolved limb in females 2 years after ACLR.³⁶ Individuals who had undergone ACLR exhibited smaller knee and hip flexion angles and greater hip adduction and internal rotation angles during jump landing compared with healthy controls.¹² Persistent presence of asymmetrical limb loading and abnormal hip and knee biomechanics suggests that even after full return to sport, risk factors for ACL injury may linger in individuals with ACLR.¹⁴

In addition to a history of ACLR, fatigue can also induce changes in lower extremity biomechanics.^{2,8,9,42,43,48,55} Fatigue induces limited knee flexion angle at initial contact and increased peak knee valgus (or knee abduction) angle during stance,^{2,8,22,34,42,43} hip adduction angle increases at initial contact,^{33,34} as well as greater anterior tibial shear force (ATSF)^{8,31,42} during landing. Fatigue can provoke deficits in balance, or postural control.^{10,18,46,52} Similarly, postural control while balancing on a single leg is limited in ACLR individuals compared with healthy individuals.⁵⁶ ACLR individuals with postural control deficits in single-leg stance on their involved limb are twice as likely to sustain a second ACL injury compared with individuals without postural control deficits.³⁸

The NMC deficits induced by fatigue may interact with those resulting from ACLR and further degrade NMC, increasing the risk of repeat noncontact ACL injury.^{2,7,8,34,51} Epidemiological data implicate neuromuscular fatigue as a contributing factor to a higher incidence of injury during the latter portions of athletic competitions.^{20,21,49,50} Thus, biomechanical and epidemiological evidence suggests that there is potential for fatigue to increase

risk of ACL injury. The purpose of this study was to investigate the effects of fatigue on lower extremity biomechanics and postural control in active females with ACLR. We hypothesized that in a fatigued state, participants would exhibit hip and knee biomechanics and postural control deficits associated with ACL injury. Specifically, participants would present with increases in knee valgus motion and internal knee varus moment, decreases in sagittal plane motion at the knee and greater flexion motion and internal moment at the hip, as well as experience greater vertical ground reaction force (VGRF) and ATSF during the jump-landing task and would exhibit decreases in postural stability in the fatigued condition during single-leg balance.

MATERIALS AND METHODS

Study Design

A quasi-experimental single-group pretest-posttest design was employed to evaluate the effects of fatigue on lower extremity biomechanics and postural control in females who had undergone ACLR.

Participants

Participants were recruited from local rehabilitation clinics and physician practices and were all returned to full activity within 3 to 11 months following surgery (mean, 6 ± 2 months). Variability in time to return to full activity is attributable to heterogeneity in surgical technique and rehabilitation protocols, which is an accurate representation of the current state of the female ACLR population. A total of 14 females (mean age, 19.6 ± 1.5 years; mean height, 163.52 ± 6.18 cm; mean weight, 62.6 ± 13.97 kg) who had undergone ACLR completed this study. A priori power analysis of fatigue studies using lower extremity biomechanics during landing tasks indicated a minimum of 10 participants to achieve a power of 0.8.⁵¹ Inclusion criteria required that participants were female; exercised for at least 3 sessions per week, 30 minutes per session; and were between 18 and 30 years old.¹⁶ Individuals were excluded from participation if they were not medically cleared by their physician to participate in exercise; had a history of bilateral ACL injury or injury to the medial collateral ligament, posterior cruciate ligament, lateral collateral ligament, or meniscus in the contralateral knee; were more than 6 years post-ACLR; had any lower extremity injury episodes in the past 6 months that left them unable to participate in physical activity for more than 3 consecutive days; and had a history of more than 1 ACL injury.

Data Collection Procedures

Subject Preparation

All participants reported to the laboratory for a single data collection session, lasting approximately 1.5 hours. Prior to participation, all individuals read and signed informed consent documentation approved by The University of North Carolina at Chapel Hill Institutional Review Board. Participants completed a physical activity readiness⁴⁵ and injury history questionnaire (eg, ACL injury mechanism, surgical history, and graft type). To

determine postsurgical knee functional outcomes, participants were evaluated using the Knee Injury and Osteoarthritis Outcome Scale (KOOS)³⁹ and Tegner¹⁹ and Marx³² Activity Scales (see Appendix 1, available at <http://sph.sagepub.com/content/suppl>). Participants' heights and masses were measured with a stadiometer and digital scale, respectively. Each participant performed 5 minutes of a light, self-directed stationary bike warm-up followed by 5 minutes of self-directed stretching prior to testing.

Biomechanical Data Collection

Following the warm-up, electromagnetic sensors were attached to the ACLR limb shank, thigh, and sacrum. Kinematic data were sampled at 140 Hz using an electromagnetic motion tracking system (trakSTAR; Ascension Technologies Inc, Burlington, Vermont) interfaced to a nonconductive force plate (Type 4060-08; Bertec Corporation, Columbus, Ohio) sampling at 1400 Hz. Biomechanical variables were quantified using the Motion Monitor for Research v8.0 (Innovative Sports Training, Chicago, Illinois) motion analysis software package.

A right-handed global coordinate system was defined with the positive *x*-axis corresponding with the anterior direction, positive *y*-axis corresponding with the leftward direction, and positive *z*-axis corresponding with the superior direction relative to the participant. The ankle joint center was defined as the midpoint between the medial and lateral malleoli, knee joint center as the midpoint between the medial and lateral femoral epicondyles, with the hip joint center estimated from the right and left anterior superior iliac spines using the Bell method.¹

Knee joint motion was defined as the motion of the shank segment relative to the thigh segment using a Cardan angle rotation sequence of Y ((+) flexion/(-) extension), X' ((+) varus (or tibial adduction)/(-) valgus (or tibial abduction)), Z'' ((+) internal rotation/(-) external rotation). Hip joint motion was defined as motion of the thigh segment relative to the pelvis segment using a Cardan angle sequence of Y ((+) extension/(-) flexion), X' ((+) adduction/(-)), Z'' ((+) internal rotation/(-) external rotation).

Double-Leg Jump Landing

The jump-landing task was performed with a 30-cm box placed at a distance equal to one half the participant's height from the leading edge of the force plate. Participants were instructed to jump from the box to the force plate. On landing, participants were instructed to jump up as high as possible.³ Participants were allowed 3 practice jumps to familiarize themselves with the task. A total of 5 successful trials were collected.

Single-Leg Balance

Each participant completed a single-leg balance assessment with eyes closed while standing unshod atop the center of a force plate. Participants were instructed to place their hands on their hips for the duration of the balance task. Each participant attempted to balance on their ACLR limb for 20 seconds while center-of-pressure (COP) data were recorded. A trial was

repeated if the participant touched down with the nonstance foot, took their hands off their hips, or opened their eyes. A total of 3 successful trials were collected.

Intervention

Fatigue Protocol

The fatigue protocol was adopted from a similar study by Padua et al.³⁵ Participants performed repeated squats at a rate of 25 squats per minute to the beat of a metronome with a weighted barbell (30% of the participant's weight) through a knee flexion range of approximately 0° to 60° controlled with a mechanical block. The fatiguing exercise was stopped when participants fell 4 squat cycles behind the 25 squats per minute set pace or failed to complete 2 sequential squat cycles. Investigators verbally encouraged participants to "keep up" with the metronome pace when they observed individuals to fall behind the squat cycle pace. After stop criteria were met, the participant reported a Borg rating of perceived exertion score.⁶

Data Processing

All data were exported from the Motion Monitor for Research v8.0 software and were reduced using a custom software program in Matlab v8.0 (MathWorks Inc, Natick, Massachusetts). All kinematic data were low-pass filtered at 14 Hz using a fourth-order Butterworth filter, while all ground reaction force data were unsmoothed.²⁵ Hip and knee joint angles were identified at initial contact (VGRF exceeded 10 N). Peak hip and knee joint angles and displacements, net internal knee and hip joint moments, proximal ATSF, and VGRF were identified during the loading phase (time from initial contact until VGRF dropped below 10 N). Joint moments were normalized to the product of body mass (kg) and height (m). ATSF and VGRF data were normalized to body mass (kg). All moments were reported as a positive value. The arithmetic mean was calculated across the middle 3 trials for each variable.

Postural control was quantified using COP data from the single-leg balance task during the first 14 seconds of each trial. To maximize the temporal effects of fatigue and minimize confounding effects of time, the first 14 seconds of the COP time series were used for analysis because participants could not successfully complete 3 full (20 seconds) consecutive single-leg balance trials in the postfatigue condition. All COP data were low-pass filtered with a 100-Hz cutoff frequency using a fourth-order Butterworth filter. COP sway speed (COPss) was calculated as COP excursion path divided by time (cm/s). The COPss for each participant was calculated as the arithmetic mean across the 3 trials for the single-leg stance task.

Statistical Analysis

Paired samples *t* tests were performed to compare pre- and postfatigue data for each dependent variable. An a priori alpha level for this study was set at $\alpha = 0.05$. All statistical analyses were performed using SPSS 19.0 for Macintosh (IBM, Armonk, New York).

Table 1. Participants' self-reported Marx Scale scores (mean \pm standard deviation), classifying frequency of participation in activities involving running, cutting, deceleration, and pivoting motions^a

Running	Cutting	Deceleration	Pivoting
3.1 \pm 0.9	2.9 \pm 1.4	2.9 \pm 1.1	2.9 \pm 1.2

^a0 = less than 1 time in a month, 1 = 1 time in a month, 2 = 1 time in a week, 3 = 2 or 3 times in a week, 4 = 4 or more times in a week.

Table 2. Joint angles (degrees) at initial contact during the jump landing

Joint Angle at Initial Contact	Prefatigue		Postfatigue		P Value	Effect Size
	Mean	SD	Mean	SD		
Hip kinematics						
Hip flexion ^a	40.98	9.79	36.75	8.61	0.014	0.43
Hip adduction	7.44	9.69	6.89	9.57	0.552	0.06
Hip internal rotation	3.17	8.43	3.08	9.84	0.954	0.01
Knee kinematics						
Knee flexion	30.24	7.24	28.03	6.49	0.253	0.31
Knee valgus	3.12	5.78	2.78	6.66	0.589	0.06
Knee internal rotation	5.08	7.19	6.08	11.56	0.640	0.14

SD, standard deviation.

^aSignificant difference ($P < 0.05$) between pre- and postfatigue conditions.

RESULTS

Sample Characteristics

Ten (71%) participants reported a noncontact mechanism of injury, while 4 (29%) reported contact with another player as the mechanism of injury. Nine (64%) participants received hamstring grafts, while 4 (29%) reported receiving a patellar tendon graft. One (7%) participant did not know what graft type was used for their ACLR procedure. Participants were 2.92 ± 1.41 years (range, 9 months to 6.25 years) post-ACLR and had been cleared to return to activity for 2.36 ± 1.52 years (range, 2 months to 5.7 years) at the time of the study. The average time to fatigue for all participants was 7.85 ± 4.23 minutes, with a mean Borg rating of 16.42 ± 1.88 . The average post-ACLR Tegner Activity level was 7.71 ± 1.59 . Marx scale data are presented in Table 1. The average KOOS score was 94.39 ± 2.86 .

Kinematics

Hip flexion at initial contact significantly decreased from pre- to postfatigue ($t = -2.82$, $P = 0.01$) (Table 2). Hip flexion displacement significantly increased from pre- to postfatigue ($t = 2.23$, $P = 0.04$) (Table 3). There were no statistical

differences for peak joint angles during the first 50% of the loading phase (Table 4).

Kinetics

No significant differences between pre- and postfatigue in peak kinetics were observed during the first 50% of the loading phase. However, internal hip flexion moment trended ($t = 2.14$, $P = 0.05$) toward an increase in the postfatigue condition compared with the prefatigue condition (Table 5).

Postural Stability

COPs significantly increased ($t = 3.95$, $P = 0.02$) from prefatigue (5.18 ± 0.96 cm/s) to postfatigue (6.20 ± 1.72 cm/s). A large effect size (1.06) was observed.

DISCUSSION

Deficits in postural control may predict a second ACL injury in females with ACLR with excellent specificity and sensitivity.³⁸ Fatigue promoted greater hip flexion displacement during the initial 50% of the loading phase during the jump-landing assessment. A flexed hip posturing has been consistently reported during the initial phase of landing or ground contact

Table 3. Joint angular displacement (degrees) during the loading phase of the jump landing

Joint Displacement During Loading	Prefatigue		Postfatigue		P Value	Effect Size
	Mean	SD	Mean	SD		
Hip kinematics						
Hip flexion ^a	45.19	14.10	47.48	14.21	0.04	0.16
Hip adduction	3.00	2.85	3.88	2.98	0.28	0.31
Hip abduction	2.38	1.97	2.08	2.07	0.53	0.15
Hip internal rotation	2.16	3.24	2.64	4.06	0.58	0.15
Hip external rotation	12.82	10.09	12.39	9.78	0.15	0.04
Knee kinematics						
Knee flexion	72.89	14.16	72.84	13.03	0.97	0.00
Knee valgus	6.97	5.60	6.71	5.79	0.85	0.05
Knee varus	3.22	3.98	3.74	5.11	0.66	0.13
Knee internal rotation	1.71	2.78	1.66	2.80	0.25	0.02
Knee external rotation	13.73	12.72	15.30	14.33	0.95	0.12

SD, standard deviation.

^aSignificant difference ($P < 0.05$) between pre- and postfatigue conditions.

Table 4. Peak joint angles (degrees) during loading phase

Peak Joint Angle During Loading	Prefatigue		Postfatigue		P Value	Effect Size
	Mean	SD	Mean	SD		
Hip kinematics						
Hip flexion	86.17	20.86	84.23	19.56	0.168	0.09
Hip adduction	10.44	10.84	10.77	10.69	0.619	0.03
Hip abduction	5.06	10.18	4.81	9.62	0.711	0.02
Hip internal rotation	1.01	8.97	0.44	10.94	0.786	0.06
Hip external rotation	16.00	12.07	15.47	14.78	0.723	0.04
Knee kinematics						
Knee flexion	103.15	17.45	100.87	14.21	0.278	0.13
Knee valgus	10.09	9.51	9.49	10.04	0.688	0.06
Knee varus	0.10	7.56	0.96	8.83	0.558	0.11
Knee internal rotation	6.79	6.93	7.74	10.12	0.552	0.14
Knee external rotation	8.66	12.08	9.22	13.25	0.648	0.05

SD, standard deviation.

Table 5. Peak net joint kinetics (Nm/kg/m) and linear kinetics (N/kg) during the loading phase of the jump landing

Peak Kinetics During Loading	Prefatigue		Postfatigue		P Value	Effect Size
	Mean	SD	Mean	SD		
Hip moments						
Hip extension	1.93	1.44	2.21	1.69	0.340	0.19
Hip flexion	1.66	0.68	1.91	0.62	0.052	0.37
Hip adduction	0.56	0.66	0.62	0.79	0.399	0.09
Hip abduction	1.03	0.80	1.15	1.00	0.359	0.15
Hip internal rotation	0.31	0.29	0.28	0.32	0.393	0.10
Hip external rotation	0.51	0.45	0.53	0.49	0.820	0.04
Knee moments						
Knee extension	1.78	0.51	1.80	0.45	0.666	0.04
Knee flexion	0.80	0.14	0.13	0.23	0.293	4.79
Knee valgus	0.48	0.37	0.50	0.44	0.829	0.05
Knee varus	0.34	0.23	0.39	0.34	0.228	0.22
Knee internal rotation	0.54	0.46	0.57	0.50	0.549	0.07
Knee external rotation	0.23	0.29	0.24	0.32	0.598	0.03
Linear kinetics						
Proximal ATSF	8.18	2.16	7.91	1.67	0.357	0.13
VGRF	23.18	6.38	24.19	5.95	0.418	0.16

ATSF, anterior tibial shear force; SD, standard deviation; VGRF, vertical ground reaction force.

during ACL injury events in athletes.^{5,26} There was a decrease in hip flexion angle at initial contact with a trending increase in hip flexion moment, suggesting that although individuals landed with lesser hip flexion at initial contact in the postfatigue condition, there was an inclination to increase hip flexion motion during the first 50% of the loading period. Our findings suggest that fatigue may be a significant factor influencing the increased risk of secondary ACL injury in physically active females post-ACLR.^{9,37}

The effects of fatigue on postural control are inconsistent.^{4,10,14,18,46,55} However, the majority of previous research was performed in healthy subjects, with the effects of fatigue in females with ACLR not being well described. Numerous accounts of increases in COPs and excursion velocity after fatigue exposure are reported in the healthy population, which has been linked to an increased risk of lower leg injury.^{4,10,11,14,18,46,55} Our results suggest that females with ACLR experience similar deficits in postural control in a fatigued state compared with a nonfatigued condition.

Lower extremity fatigue protocols that have focused on the ankle,^{4,10,18} knee,¹⁸ and hip^{4,18} or multijoint repetitive motions^{14,55} have observed significant increases in COPs and velocity following fatigue. To date, no study involving a functional squat protocol to induce fatigue and assess its effects on postural stability has been described. A single-leg step up exercise has been utilized to induce fatigue and showed increases in eyes-closed COPs (prefatigue, 6.82 ± 2.18 cm/s; postfatigue, 7.68 ± 1.60 cm/s), representing an increase in sway speed with an observed medium effect size of 0.39.⁵⁵ ACLR may influence response to fatiguing exercise and potentially induce greater decrements in postural control compared with healthy individuals. Future research is needed in this area.

Deficits in postural control may predict ACL reinjury with high sensitivity and specificity in the ACLR population.³⁸ Thus, interventions aimed at increasing fatigue resistance in females with ACLR are warranted in clinical practice.

Contrary to our hypothesis, we did not observe increases in ATSF in the postfatigue condition. Our findings contrast

previous reports of increased proximal ATSF after fatigue in healthy individuals.⁸ This discrepancy may be explained, as we did not observe a concomitant decrease in knee flexion angle or an increase in VGRF and internal knee extension moment during the jump-landing task. Limited knee flexion, greater VGRF, and knee extension moment are factors that can increase ATSF.^{8,30,33} Rather, we observed altered hip flexion kinematics after fatigue.

Our findings of greater hip flexion displacement are similar to reports of greater hip flexion motion during the first 33 to 55 ms of ground contact during ACL injury events.^{5,26} In contrast, our observation of lesser hip flexion at initial contact postfatigue disagrees with previous findings in healthy females.^{24,47} Thus, it appears there are inconsistencies regarding the effect of fatigue on sagittal plane hip angles at initial contact. It is possible that these differences may be explained by previous research using healthy females, as females post-ACLR may respond differently to fatigue.

There are significant limitations to this study design. The current study did not compare the effects of fatigue between the participants' uninvolved and ACLR limbs. This study cannot implicate a direct interaction between ACLR limb and fatigue.

CONCLUSION

The results of our study suggest that fatigue may induce deficits in postural control and sagittal plane hip mechanics associated with ACL injury in active females with ACLR. Rehabilitation and maintenance programs should incorporate activities that improve muscular endurance and the neuromuscular system's resistance to fatiguing exercise to maintain stability during physical activity.

REFERENCES

- Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech*. 1990;23:617-621.
- Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc*. 2008;16:400-407.
- Beutler A, la Motte de S, Marshall S, Padua DA, Boden B. Muscle strength and qualitative jump-landing differences in male and female military cadets: the jump-ACL study. *J Sports Sci Med*. 2009;8:663-671.
- Bisson EJ, McEwen D, Lajoie Y, Bilodeau M. Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance. *Gait Posture*. 2011;33:83-87.
- Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med*. 2009;37:252-259.
- Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med*. 1970;2:92-98.
- Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech*. 2008;23:81-92.
- Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *Am J Sports Med*. 2005;33:1022-1029.
- Collins JE, Katz JN, Donnell-Fink LA, Martin SD, Losina E. Cumulative incidence of ACL reconstruction after ACL injury in adults: role of age, sex, and race. *Am J Sports Med*. 2013;41:544-549.
- Corbeil P, Blouin J-S, Bégin F, Nougier V, Teasdale N. Perturbation of the postural control system induced by muscular fatigue. *Gait Posture*. 2003;18:92-100.
- Dallinga JM, Benjaminse A, Lemmink KA. Which screening tools can predict injury to the lower extremities in team sports? A systematic review. *Sports Med*. 2012;42:791-815.
- Delahunt E, Prendiville A, Sweeney L, et al. Hip and knee joint kinematics during a diagonal jump landing in anterior cruciate ligament reconstructed females. *J Electromyogr Kinesiol*. 2012;22:598-606.
- Delahunt E, Sweeney L, Chawke M, et al. Lower limb kinematic alterations during drop vertical jumps in female athletes who have undergone anterior cruciate ligament reconstruction. *J Orthop Res*. 2012;30:72-78.
- Fox ZG, Mihalik JP, Blackburn JT, Battaglini CL, Guskiewicz KM. Return of postural control to baseline after anaerobic and aerobic exercise protocols. *J Athl Train*. 2008;43:456-463.
- Friel NA, Chu CR. The role of ACL injury in the development of posttraumatic knee osteoarthritis. *Clin Sports Med*. 2013;32:1-12.
- Garber CE, Blissmer B, Deschenes MR, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Med Sci Sports Exerc*. 2011;43:1334-1359.
- Gianotti SM, Marshall SW, Hume PA, Bunt L. Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. *J Sci Med Sport*. 2009;12:622-627.
- Gribble PA, Hertel J. Effect of lower-extremity muscle fatigue on postural control. *Arch Phys Med Rehabil*. 2004;85:589-592.
- Hambly K. The use of the Tegner Activity Scale for articular cartilage repair of the knee: a systematic review. *Knee Surg Sports Traumatol Arthrosc*. 2011;19:604-614.
- Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. *Br J Sports Med*. 1999;33:196-203.
- Hägglund M, Waldén M, Ekstrand J. Injury incidence and distribution in elite football—a prospective study of the Danish and the Swedish top divisions. *Scand J Med Sci Sports*. 2005;15:21-28.
- Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33:492-501.
- Jacobs J. *Burden of Musculoskeletal Diseases in the United States: Prevalence, Societal and Economic Cost*. Rosemont, IL: American Academy of Orthopaedic Surgeons; 2008.
- Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med*. 2008;36:554-565.
- Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45:666-671.
- Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35:359-367.
- Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med*. 2007;35:1756-1769.
- Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004;50:3145-3152.
- Lyman S, Koulouvaris P, Sherman S, Do H, Mandl LA, Marx RG. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J Bone Joint Surg Am*. 2009;91:2321-2328.
- Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13:930-935.
- Markolf KL, Wascher DC, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part II: the effect of section of the posterolateral structures. *J Bone Joint Surg Am*. 1993;75:387-394.
- Marx RG, Stump TJ, Jones EC, Wickiewicz TL, Warren RF. Development and evaluation of an activity rating scale for disorders of the knee. *Am J Sports Med*. 2001;29:213-218.
- McLean SG, Fellin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39:502-514.
- McLean SG, Samorezov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. *Med Sci Sports Exerc*. 2009;41:1661-1672.
- Padua DA, Arnold BL, Perrin DH, Gansnedter BM, Carcia CR, Granata KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train*. 2006;41:294-304.

36. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med.* 2007;17:258-262.
37. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22:116-121.
38. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38:1968-1978.
39. Roos EM, Lohmander LS. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. *Health Qual Life Outcomes.* 2003;1:64.
40. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy.* 2005;21:948-957.
41. Sampson N. Knee injuries in children and adolescents: has there been an increase in ACL and meniscus tears in recent years? <https://aap.confex.com/aap/2011/webprogram/Paper14815.html>. Accessed March 25, 2014.
42. Santamaria LJ, Webster KE. The effect of fatigue on lower-limb biomechanics during single-limb landings: a systematic review. *J Orthop Sports Phys Ther.* 2010;40:464-473.
43. Schmitz RJ, Cone JC, Tritsch AJ, et al. Changes in drop-jump landing biomechanics during prolonged intermittent exercise. *Sports Health.* 2014;6:128-135.
44. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med.* 2009;37:246-251.
45. Shephard RJ. PAR-Q, Canadian Home Fitness Test and exercise screening alternatives. *Sports Med.* 1988;5:185-195.
46. Springer BK, Pincivero DM. The effects of localized muscle and whole-body fatigue on single-leg balance between healthy men and women. *Gait Posture.* 2009;30:50-54.
47. Thomas AC, McLean SG, Palmieri-Smith RM. Quadriceps and hamstrings fatigue alters hip and knee mechanics. *J Appl Biomech.* 2010;26:159-170.
48. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis.* 2004;63:269-273.
49. Walden M, Hägglund M, Ekstrand J. UEFA Champions League study: a prospective study of injuries in professional football during the 2001-2002 season. *Br J Sports Med.* 2005;39:542-546.
50. Waldén M, Hägglund M, Magnusson H, Ekstrand J. Anterior cruciate ligament injury in elite football: a prospective three-cohort study. *Knee Surg Sports Traumatol Arthrosc.* 2011;19:11-19.
51. Webster KE, Santamaria LJ, McClelland JA, Feller JA. Effect of fatigue on landing biomechanics after anterior cruciate ligament reconstruction surgery. *Med Sci Sports Exerc.* 2012;44:910-916.
52. Wilkins JC, Valovich McLeod TC, Perrin DH, Gansneder BM. Performance on the Balance Error Scoring System decreases after fatigue. *J Athl Train.* 2004;39:156-161.
53. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med.* 2006;34:269-274.
54. Wright RW, Dunn WR, Amendola A, et al. Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. *Am J Sports Med.* 2007;35:1131-1134.
55. Zech A, Steib S, Hentschke C, Eckhardt H, Pfeifer K. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *J Strength Cond Res.* 2012;26:1162-1168.
56. Zouita Ben Moussa A, Zouita S, Dziri C, Ben Salah FZ. Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. *Ann Phys Rehabil Med.* 2009;52:475-484.

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