

Original Research

Modified Biering-Sorenson Protocol Changes Joint Contributions to Total Support in Individuals with a History of Anterior Cruciate Ligament Reconstruction During Drop Vertical Jump Landings

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Background

There are persistent deficits of the proximal musculature in individuals with anterior cruciate ligament reconstruction. Previous research has shown that proximal musculature fatigue alters drop vertical jump performance in healthy individuals. It is unknown how proximal musculature fatigue will alter drop vertical jump performance in individuals who have undergone anterior cruciate ligament reconstruction.

Hypothesis/Purpose

The purpose of this study was to examine the effects of a proximal extensor musculature fatigue protocol on drop vertical jump landing biomechanics of individuals with a history of anterior cruciate ligament reconstruction using both single-joint parameters and total support moment analysis.

Study Design

Quasi-experimental pre-post laboratory experiment

Methods

Nineteen participants with a history of unilateral anterior cruciate ligament reconstruction were recruited. Three-dimensional motion analysis was performed bilaterally during a drop vertical jump. Participants then completed a proximal extensor musculature fatigue protocol and immediately repeated the drop vertical jump task. Sagittal plane kinetics and kinematics were collected. Joint contributions to peak total support moment were calculated. A condition-by-limb repeated measures analysis of variance was performed to explore the effects of the fatigue protocol, using an alpha level of 0.05.

Results

There were no interactions observed for any parameters. However, the injured limb demonstrated less vertical ground reaction force (13%, $p=0.013$) and reduced peak dorsiflexion angle (2°, $p=0.028$) both before and after the protocol. After the fatigue protocol both limbs demonstrated reduced hip extensor contribution to peak total support moment (4%, $p=0.035$).

Conclusions

Individuals with a history of anterior cruciate ligament reconstruction performed the drop vertical jump with an altered anti-gravity support strategy after the proximal extensor

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musculature fatigue protocol. The significant reduction in bilateral hip extensor contribution to peak total support moment suggests evidence of targeted fatigue.

Level of Evidence

III

INTRODUCTION

It is estimated that up to 250,000 anterior cruciate ligament (ACL) injuries are sustained each year.¹ Standard of care in the United States after complete ACL rupture is surgical ACL reconstruction (ACLR), with over 125,000 performed annually.² Individuals after ACLR typically demonstrate persistent neuromuscular deficits at the knee joint including, but not limited to muscular weakness,^{3,4} reduced proprioception,^{5,6} and altered walking⁷ and landing patterns⁸ characterized by altered knee biomechanics. Post-operatively it is recommended to restore thigh muscle performance.^{9,10} However, individuals after ACLR also appear to demonstrate persistent proximal neuromuscular impairments.¹¹ These include altered hip abductor activation,¹² hip extensor strength,¹³ reduced core motor control,^{14,15} and trunk extension endurance deficits.¹⁶

Neuromuscular fatigue can be described as the failure of a muscle to maintain a required or expected force output.¹⁷ Additionally, it has been suggested that experimental fatigue of a muscle may affect that muscle's contribution to a task.¹⁸ The effects of experimentally-induced proximal neuromuscular fatigue on lower extremity biomechanics have been explored in a growing body of literature, predominantly in healthy and able-bodied individuals.¹⁸⁻²³ Overall, it appears that when targeting specific muscle groups with a fatigue protocol, alterations in kinematics or kinetics are mainly observed in the primary plane of movement of those muscle groups.¹⁸⁻²³ These altered movement patterns have also been observed in joints distal to the fatigued muscle group.^{19,21-23} In a previous related study, an isometric fatigue protocol targeting the hip extensors led to an increase in gluteus maximus muscle activation with preservation of joint kinematics during bilateral jump-landings in healthy individuals.¹⁸ Fatigue of muscle groups proximal to the knee region overall appears to impact instrumented assessments during clinical tasks in healthy populations, but has not been tested after ACLR.

Imposing neuromuscular fatigue on proximal muscle groups may interact with persisting post-surgical deficits after ACLR to exacerbate or reveal aberrations in movement reflecting further compromise in neuromuscular control.²⁴ As lower limb neuromuscular control reflects a multi-joint coordinated strategy, analysis of total support moment (TSM) may provide novel insights into whole-limb movement strategies beyond that of single-joint parameters. The TSM is a summed moment from the extensor synergy of the hip, knee and ankle that represents the anti-gravity support of the center of mass of the body.²⁵ At the instance of peak TSM, the sagittal plane moments of the hip, knee, and ankle are assessed to calculate the contribution of each individual joint to the TSM. The TSM has previously been used to characterize differences in neuromuscular strategy during single-limb landing after ACLR compared to controls.²⁶

Most previous studies involving fatigue after ACLR have

utilized peripheral fatiguing tasks such as squatting and jumping to functional failure points.^{24,27-31} However, these fatiguing tasks have not directly targeted proximal neuromuscular control. With relevance to the current study, previous electromyography work has validated the ability of the isometric Biering-Sorensen test procedure to induce fatigue to the gluteus maximus, the body's primary hip extensor muscle.³² While the Biering-Sorensen test has been used to assess the effects of a hip extensor fatigue protocol on landing mechanics in healthy individuals,¹⁸ the effects after ACLR are unknown.

Therefore, the purpose of this study was to examine the effects of a proximal extensor musculature fatigue protocol on drop vertical jump landing biomechanics of individuals with a history of anterior cruciate ligament reconstruction using both single-joint parameters and total support moment analysis. The DVJ was utilized as the landing task of interest as it has been prospectively linked to secondary ACL injury risk,³³ and has been evaluated before and after Biering-Sorensen testing in healthy individuals.¹⁸ It was hypothesized that the injured limb would differentially demonstrate greater peak lower limb flexion single-joint parameters after the fatigue protocol. Instances of increased hip contributions to movements have been seen in individuals with a history of ACLR during landing³⁴ and squatting.³⁵ Based on this data, it was hypothesized that the within-limb TSM joint contribution profile would shift distally to reflect a decreased hip contribution, with the injured limb redistributing less to the knee than the uninjured limb.

MATERIALS AND METHODS

DESIGN

This study was a single group, pretest-posttest quasi-experimental study. Participants were recruited with electronic and paper flyers. Individuals presented to the laboratory and provided written informed consent approved by the university's Institutional Review Board prior to testing. The same examiners conducted all testing.

PARTICIPANTS

A convenience sample of nineteen participants between the ages of 18-40 years old with a history of unilateral ACLR at least one year prior was recruited for this study. To be included, participants needed to have completed formal rehabilitation and been fully cleared by a physician for return to sport or previous level of activity. Participants were excluded if they had any spinal or lower extremity pain or injury within the prior six months. Participants completed the Tegner Activity Scale and the International Knee Documentation Committee Scale (IKDC)³⁶ prior to motion capture.

MOTION CAPTURE

Video data were collected using an 8-camera motion capture system (VICON, Centennial, CO, USA, 150 Hz), and force data using two force plates (BERTEC Corp., Worthington, OH, USA, 1500 Hz). Individuals had 47 reflective markers placed over their bilateral lower extremities and pelvis. Marker locations included: L5-S1 interspinous space, iliac crests, anterior superior iliac crests, greater trochanters, medial and lateral femoral condyles, medial and lateral tibial plateaus, medial and lateral malleoli, first and fifth metatarsal heads, distal feet, and proximal, distal, and lateral heels. Rigid marker clusters were placed over the thigh and shank segments. Static standing and dynamic calibration trials were captured.

DROP VERTICAL JUMP

The DVJ was performed as previously described.³⁷ Briefly, participants stood atop a 30 cm box. They were instructed to fall off the box, land with one foot on each force plate and immediately perform a maximal effort counter-movement jump reaching with both hands for an overhead target. For a trial to be successful the following criteria were required: participants dropped off the box without jumping, landed with each foot on a force plate, and successfully reached overhead during the jump. After successfully completing four trials, participants completed the fatigue protocol, with special care taken to prevent reflective marker placement alteration. Once the fatigue protocol was completed, participants immediately performed four additional successful drop vertical jump trials. All trials were used for analysis.

FATIGUE PROTOCOL

Participants completed three repeated efforts of a modified Biering-Sorensen extension position,^{15,29} held until failure, modified in that three repeated efforts were performed rather than one. Individuals had their lower extremities fastened to a plinth with two belts. Using upper extremity support, they initially positioned their torso horizontally off the plinth. To begin each effort, they were instructed to hold their torso parallel to the ground, to cross their arms, and to maintain that position for as long as possible ([Figure 1](#)). Participants were provided verbal encouragement throughout the three efforts. For each effort, one verbal warning was given when positional failure was observed. The second positional failure resulted in termination of that effort. Between efforts, individuals received a 15 second rest break. After completion of the final effort, the participants were immediately unfastened from the plinth to perform the post-fatigue DVJs. The time to termination for each effort was recorded, as was the time between the end of the final effort and the start of the post-fatigue DVJ procedures.

BIOMECHANICAL DATA

Vicon Nexus was used for labelling and gap-filling of marker trajectories for the entire contact phase of the task, defined as the time in which a threshold of 20 Newtons of force was on the force plate. Trials were then exported and post-



Figure 1. Participant setup for modified Biering-Sorensen protocol

processed using Visual 3D (C-motion, Bethesda, MD, USA) and custom Labview code (National Instruments, Austin, TX, USA). Data were filtered using a low-pass Butterworth filter with a cutoff of 12 Hz. Joint angle and moment data were derived using X-Y-Z Cardan rotation sequences and traditional inverse dynamics procedures, respectively. Joint moments were normalized to body height (meters) and mass (kilograms) and reported as internal moments. Vertical ground reaction force (vGRF) was extracted and expressed normalized to body weight. For the single-joint parameters, the variables of interest were the sagittal plane peak joint angles and moments of the hip, knee and ankle, as well as peak vertical ground reaction force. For the TSM analysis, joint moment data were time normalized to ground contact, and were compared and summed at the instance of peak TSM.²⁵

STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS version 25 (IBM Corp, Armonk, NY, USA). Descriptive statistics were calculated on baseline parameters. Two-factor (condition-by-limb) analyses of variance with Bonferroni correction were performed to assess for potential interactions, main effects and simple effects for peak ground reaction force, peak joint moments and angles, and joint moments at the instance of peak total support. An alpha level of 0.05 was used. Post-hoc Pearson correlations were used to examine the relationship between change in percent contribution at the knee and hip to activity level (measured by Tegner), IKDC score, and time since surgery.

Table 1. Participant descriptive data

	Mean (SD)	Frequency
Sex Frequency (F:M)		16:3
Injured Limb (dominant:nondominant)		10:9
Age (years)	24.5 (4.8)	
BMI (kg/m ²)	23.53 (2.3)	
Tegner Activity Scale (0-10)	7.1 (2.2)	
IKDC Score (0-100)	83.4 (7.4)	
Time since surgery (months)	59.1 (37.2)	

Table 2. Modified Biering-Sorensen results (seconds)

	Mean (SD)
Effort 1	84.4 (44.0)
Effort 2	42.9 (19.0)
Effort 3	34.3 (18.0)
Cumulative Hold Time	161.7 (65.3)
Transition time from fatigue protocol to testing	24.1 (5.9)

RESULTS

Descriptive data for all participants are presented in [Table 1](#). The average participant was a young adult female with a normal body mass index, approximately five years removed from unilateral ACLR with an IKDC score slightly below age matched healthy individuals³⁶ and a Tegner score indicating recreational or competitive sport participation.

All participants completed all study procedures. In regards to the modified Biering-Sorensen fatigue protocol, an average reduction in time to positional failure of approximately 50 seconds (-59%) was observed between the first and third consecutive efforts. On average, participants transitioned to the post-protocol DVJ testing in less than 25 seconds after completing the third and final modified Biering-Sorensen effort ([Table 2](#)).

The single-joint results are presented in [Table 3](#). No interactions or main effects of condition were observed. Two main effects of limb were seen. The injured limb demonstrated less peak ankle dorsiflexion angle (2°, p=0.028), as well as less peak vGRF (13%, p=0.013).

The joint contributions and peak TSM data are presented in [Figure 2](#). No interactions or main effects of limb were observed. However, a single main effect of condition at peak TSM was seen for the hip contribution. After the protocol, at peak TSM, the hips showed a 4% decreased contribution to TSM (p=0.035).

Post-hoc analysis revealed a significant correlation (r = 0.527, p =0.02) between percent change in knee contribution post-protocol and time since surgery. The relationship was such that as time since surgery increased, individuals

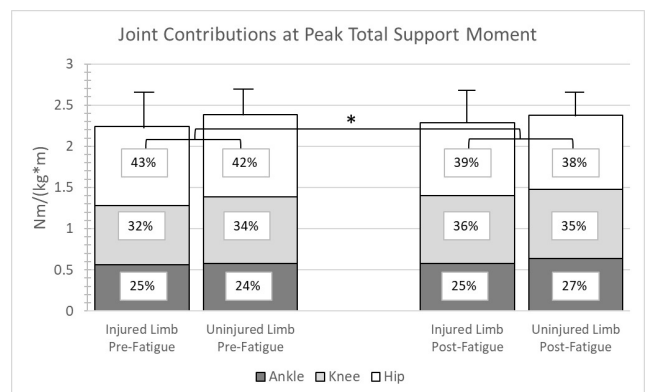


Figure 2. Redistribution of joint moments relative to peak total support moment

Note the significant reduced contribution from the hip after completion of the protocol.

had a higher percentage contribution at the knee post-protocol. Otherwise, no other significant correlations were noted (p >0.05).

DISCUSSION

The overall purpose of this study was to examine if a proximal extensor fatigue protocol elicited differential alterations in sagittal plane lower extremity kinematics and kinetics during a DVJ in individuals with a history of ACLR. Neither the single-joint nor whole-limb results directly supported the differential effect hypothesis, as no interac-

Table 3. Condition by limb results, presented as Mean (SD)

	Injured Limb		Uninjured Limb		Interaction p-value	Condition Main Effect p-value	Limb Main Effect p- value
	Pre- fatigue	Post- fatigue	Pre- fatigue	Post- fatigue			
Peak Hip Flexion Angle (degrees)	76.4 (12.8)	74.9 (13.6)	75.2 (13.3)	72.9 (14.0)	0.130	0.090	0.097
Peak Knee Flexion Angle (degrees)	86.9 (10.6)	86.3 (10.1)	86.7 (11.4)	85.4 (10.5)	0.095	0.326	0.527
Peak Ankle Dorsiflexion Angle (degrees)	26.9 (5.1)	26.8 (5.6)	29.2 (4.6)	29.3 (4.4)	0.709	0.904	0.028
Peak Internal Hip Extension Moment (Nm/(kg*m))	1.17 (0.21)	1.18 (0.23)	1.26 (0.28)	1.26 (0.27)	0.757	0.774	0.179
Peak Internal Knee Extension Moment (Nm/(kg*m))	1.04 (0.24)	1.07 (0.26)	1.11 (0.26)	1.14 (0.26)	0.927	0.096	0.519
Peak Internal Ankle Plantarflexion Moment (Nm/(kg*m))	0.71 (0.20)	0.74 (0.20)	0.78 (0.16)	0.79 (0.16)	0.366	0.148	0.164
Peak Vertical Ground Reaction Force (N)	1.45 (0.23)	1.47 (0.20)	1.65 (0.24)	1.65 (0.23)	0.807	0.446	0.013
Peak Total Support Moment	2.24 (0.44)	2.28 (0.45)	2.38 (0.36)	2.37 (0.29)	0.248	0.588	0.256

Bolded – statistically significant

tions were observed. When considering single-joint parameters, the participants loaded the injured limb less, and dorsiflexed less at maximum as well, which is consistent with findings in previous literature. When considering the whole-limb TSM analysis, the proximal extensor fatigue protocol generally elicited a decrease in the hip joint contribution to anti-gravity support, which provides supporting evidence that the fatigue protocol affected the targeted muscles.

Of particular relevance to the current study are the findings of Hollman et al.¹⁸ In a comparable study, healthy women performed a bilateral jump-landing task and isometric hip dynamometry before and after a modified Biering-Sorensen fatigue protocol. Hollman and colleagues measured hip and knee kinematics and gluteus maximus muscle activations, and found no change in peak hip and knee angles after the modified Biering-Sorensen fatigue protocol. However, peak isometric hip extension force was reduced and gluteus maximus electromyographic activation was increased after the fatigue protocol. The authors suggested that the kinematics may have stayed consistent due to increased neural drive to the gluteus maximus. In the current study, electromyographic data were not collected, and there was no change in single-joint kinematics or kinetics supporting the results of Hollman and colleagues¹⁸ despite the history of unilateral ACLR. In regards to whole-limb neuromuscular strategy, the proximal extensor fatigue protocol resulted in a reduction in hip extensor contribution to peak TSM. Both the increased gluteal activations seen in the Hollman study and the altered TSM seen in this study may be considered evidence of compensatory motor solutions used to preserve requisite task-level kinematics.

Two discrete parameters were suggestive of altered func-

tion in the ACLR limb, peak vGRF and ankle dorsiflexion angle. In regards to decreased vGRF during landings, a recent systematic review with meta-analysis identified that 9/10 included studies showed reduced peak vGRF in adolescents with a history of ACLR.³⁸ This study's pre-protocol data add to the robust literature identifying loading asymmetry in individuals after ACLR. The lack of change in peak vGRF post-protocol suggests that proximal extensor fatigue does not strongly influence the magnitude of whole-limb vertical loading after ACLR.

There was less ankle dorsiflexion observed in the injured limb compared to the uninjured limb during the DVJ. Reduced peak ankle dorsiflexion and reduced ankle dorsiflexion at initial contact has been observed in the injured limb compared to both the uninjured limb and to controls during the DVJ.^{39,40} However, clinical measurement of maximum ankle dorsiflexion after ACL injury has been found to not differ between limbs.⁴¹ The combination of these studies may suggest that performance of the DVJ may not consistently engage physiological end-range dorsiflexion. Therefore, the difference between limbs in peak dorsiflexion after ACLR may be largely attributable to an avoidance strategy of the injured limb.⁴⁰ In the current study, the observed combination of reduced peak ankle dorsiflexion angle and vGRF in the injured limb provides supportive evidence for this avoidance phenomenon.

The fatigue protocol elicited reduced hip moment contributions to peak TSM. The reduction in hip contribution may reflect decreased muscle force output from the hip extensors after the protocol at the instance of peak anti-gravity demand. Hollman and colleagues¹⁸ previously reported a 25% reduction in isometric hip extension strength after a similar protocol. The reduced hip contribution to peak

TSM seen in the current study participants may reflect a transient reduction in hip strength from the protocol. This reduction in hip contribution may impact performance of other tasks after a proximal extensor fatigue protocol and thus be of interest to clinicians observing movement in a post-fatigued state. Interestingly, the knee contribution in the injured limb appeared to improve after the protocol. Previous studies have shown that the ACLR population demonstrates a decreased knee contribution to TSM during single limb landing.²⁶ While the joint moment redistribution elicited by hip extensor fatigue would be transient, there may be potential rehabilitative and training applications to further explore.

The correlation between increasing knee contribution and time since surgery aligns with previous literature demonstrating increases in knee extensor strength over time after ACLR. Barford and colleagues found that over the course of rehabilitation a higher percentage of individuals developed adequate knee extension strength as measured by isokinetic limb symmetry index.⁴² Additionally, in a review of literature, it was recommended that it could take up to two years for knee extensor strength to recover.⁴⁵ The average length of time since surgery of the current cohort was nearly five years, meaning they had greater opportunity to recover quadriceps strength. It is unknown if time since surgery and percent change in knee contribution would have a different relationship in those closer to surgery.

There are limitations to this study. As this is a cross-sectional study, it cannot be determined if the observed re-

sponse to the hip extensor fatigue protocol would have been seen prior to injury. The sample size is relatively small and therefore prone to sampling error, a larger sample would improve the generalizability of the results to confidently characterize the ACLR population. While biomarkers of fatigue were not collected, participants performed three efforts of a validated single effort hip extensor fatiguing task. Trunk data were not collected, but could help explain the total body impact of the modified Biering-Sorensen fatigue protocol. Also, as with any study utilizing traditional motion capture techniques, skin movement artifact can affect the joint motion estimates.

CONCLUSION

The results of this study demonstrate that a hip extensor fatigue protocol elicits reduced bilateral hip extensor contribution to total support moment when anti-gravity demands are greatest in persons with ACLR. The clinical implications of this redistribution warrant further investigation.

CONFLICTS OF INTEREST

The authors have no relationships/activities/interests to disclose that are related to the content of this manuscript.

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REFERENCES

1. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* 2006;34(9):1512-1532.
2. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med.* 2014;42(10):2363-2370. doi:10.1177/0363546514542796
3. Lautamies R, Harilainen A, Kettunen J, Sandelin J, Kujala UM. Isokinetic quadriceps and hamstring muscle strength and knee function 5 years after anterior cruciate ligament reconstruction: comparison between bone-patellar tendon-bone and hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(11):1009-1016. doi:10.1007/s00167-008-0598-7
4. Lisee C, Lepley AS, Birchmeier T, O'Hagan K, Kuenze C. Quadriceps strength and volitional activation after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Sports Health.* 2019;11(2):163-179. doi:10.1177/1941738118822739
5. Gokeler A, Benjaminse A, Hewett TE, et al. Proprioceptive deficits after ACL injury: are they clinically relevant? *Br J Sports Med.* 2012;46(3):180-192. doi:10.1136/bjism.2010.082578
6. Kim HJ, Lee JH, Lee DH. Proprioception in patients with anterior cruciate ligament tears: a meta-analysis comparing injured and uninjured limbs. *Am J Sports Med.* 2017;45(12):2916-2922. doi:10.1177/0363546516682231
7. Hart HF, Culvenor AG, Collins NJ, et al. Knee kinematics and joint moments during gait following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Br J Sports Med.* 2016;50(10):597-612. doi:10.1136/bjsports-2015-094797
8. Lepley AS, Kuenze CM. Hip and knee kinematics and kinetics during landing tasks after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *J Athl Train.* 2018;53(2):144-159. doi:10.4085/1062-6050-334-16
9. Logerstedt DS, Scalzitti D, Risberg MA, et al. Knee stability and movement coordination impairments: knee ligament sprain revision 2017. *J Orthop Sports Phys Ther.* 2017;47(11):A1-a47. doi:10.2519/jospt.2017.0303
10. van Melick N, van Cingel RE, Brooijmans F, et al. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med.* 2016;50(24):1506-1515. doi:10.1136/bjsports-2015-095898
11. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. *Arch Orthop Trauma Surg.* 2014;134(10):1417-1428. doi:10.1007/s00402-014-1992-x
12. Dalton EC, Pfile KR, Weniger GR, Ingersoll CD, Herman D, Hart JM. Neuromuscular changes after aerobic exercise in people with anterior cruciate ligament-reconstructed knees. *J Athl Train.* 2011;46(5):476-483. doi:10.4085/1062-6050-46.5.476
13. Bell DR, Trigsted SM, Post EG, Walden CE. Hip strength in patients with quadriceps strength deficits after ACL reconstruction. *Med Sci Sports Exerc.* 2016;48(10):1886-1892. doi:10.1249/mss.00000000000000999
14. Noehren B, Abraham A, Curry M, Johnson D, Ireland ML. Evaluation of proximal joint kinematics and muscle strength following ACL reconstruction surgery in female athletes. *J Orthop.* 2014;32(10):1305-1310. doi:10.1002/jor.22678
15. Werner DM, Barrios JA. In-line half-kneeling as a motor control test of core stability: known-groups validity and reliability. *J Sport Rehabil.* 2019;28(4):395-398. doi:10.1123/jsr.2018-0031
16. Werner DM, Barrios JA. Trunk muscle endurance in individuals with and without a history of anterior cruciate ligament reconstruction. *J Strength Cond Res.* 2021;35(1):118-123. doi:10.1519/jsc.00000000000002395
17. Bigland-Ritchie B, Woods JJ. Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve.* 1984;7(9):691-699. doi:10.1002/mus.880070902
18. Hollman JH, Hohl JM, Kraft JL, Strauss JD, Traver KJ. Effects of hip extensor fatigue on lower extremity kinematics during a jump-landing task in women: a controlled laboratory study. *Clin Biomech (Bristol, Avon).* 2012;27(9):903-909. doi:10.1016/j.clinbiomech.2012.07.004

19. Geiser CF, O'Connor KM, Earl JE. Effects of isolated hip abductor fatigue on frontal plane knee mechanics. *Med Sci Sports Exerc.* 2010;42(3):535-545. [doi:10.1249/MSS.0b013e3181b7b227](https://doi.org/10.1249/MSS.0b013e3181b7b227)
20. Thomas AC, Palmieri-Smith RM, McLean SG. Isolated hip and ankle fatigue are unlikely risk factors for anterior cruciate ligament injury. *Scand J Med Sci Sports.* 2011;21(3):359-368. [doi:10.1111/j.1600-0838.2009.01076.x](https://doi.org/10.1111/j.1600-0838.2009.01076.x)
21. Carcia C, Eggen J, Shultz S. Hip-abductor fatigue, frontal-plane landing angle, and excursion during a drop jump. *J Sport Rehabil.* 2005;14(4):321-331.
22. Patrek MF, Kernozek TW, Willson JD, Wright GA, Doberstein ST. Hip-abductor fatigue and single-leg landing mechanics in women athletes. *J Athl Train.* 2011;46(1):31-42. [doi:10.4085/1062-6050-46.1.31](https://doi.org/10.4085/1062-6050-46.1.31)
23. Hollman JH, Beise NJ, Fischer ML, Stecklein TL. Hip extensor fatigue alters hip and knee coupling dynamics during single-limb step-downs: a randomized controlled trial. *J Biomech.* Published online 2019:109583. [doi:10.1016/j.jbiomech.2019.109583](https://doi.org/10.1016/j.jbiomech.2019.109583)
24. Frank BS, Gilsdorf CM, Goerger BM, Prentice WE, Padua DA. Neuromuscular fatigue alters postural control and sagittal plane hip biomechanics in active females with anterior cruciate ligament reconstruction. *Sports Health.* 2014;6(4):301-308. [doi:10.1177/1941738114530950](https://doi.org/10.1177/1941738114530950)
25. Winter DA. Overall principle of lower limb support during stance phase of gait. *J Biomech.* 1980;13(11):923-927. [doi:10.1016/0021-9290\(80\)90162-1](https://doi.org/10.1016/0021-9290(80)90162-1)
26. Pozzi F, Di Stasi S, Zeni JA Jr, Barrios JA. Single-limb drop landing biomechanics in active individuals with and without a history of anterior cruciate ligament reconstruction: a total support analysis. *Clin Biomech (Bristol, Avon).* 2017;43:28-33. [doi:10.1016/j.clinbiomech.2017.01.020](https://doi.org/10.1016/j.clinbiomech.2017.01.020)
27. Thomas AC, Lepley LK, Wojtys EM, McLean SG, Palmieri-Smith RM. Effects of neuromuscular fatigue on quadriceps strength and activation and knee biomechanics in individuals post-anterior cruciate ligament reconstruction and healthy adults. *J Orthop Sports Phys Ther.* 2015;45(12):1042-1050. [doi:10.2519/jospt.2015.5785](https://doi.org/10.2519/jospt.2015.5785)
28. 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(5):910-916. [doi:10.1249/MSS.0b013e31823fe28d](https://doi.org/10.1249/MSS.0b013e31823fe28d)
29. Lessi GC, Serrao FV. Effects of fatigue on lower limb, pelvis and trunk kinematics and lower limb muscle activity during single-leg landing after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2017;25(8):2550-2558. [doi:10.1007/s00167-015-3762-x](https://doi.org/10.1007/s00167-015-3762-x)
30. Lessi GC, Silva RS, Serrao FV. Comparison of the effects of fatigue on kinematics and muscle activation between men and women after anterior cruciate ligament reconstruction. *Phys Ther Sport.* 2018;31:29-34. [doi:10.1016/j.ptsp.2018.01.009](https://doi.org/10.1016/j.ptsp.2018.01.009)
31. Gokeler A, Eppinga P, Dijkstra PU, et al. Effect of fatigue on landing performance assessed with the landing error scoring system (less) in patients after ACL reconstruction. A pilot study. *Int J Sports Phys Ther.* 2014;9(3):302-311.
32. Coorevits P, Danneels L, Cambier D, et al. Test-retest reliability of wavelet - and Fourier based EMG (instantaneous) median frequencies in the evaluation of back and hip muscle fatigue during isometric back extensions. *J Electromyogr Kinesiol.* 2008;18(5):798-806. [doi:10.1016/j.jelekin.2007.01.007](https://doi.org/10.1016/j.jelekin.2007.01.007)
33. 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 of Sports Med.* 2010;38(10):1968-1978. [doi:10.1177/0363546510376053](https://doi.org/10.1177/0363546510376053)
34. Malafrente J, Hannon J, Goto S, et al. Limb dominance influences energy absorption contribution (EAC) during landing after anterior cruciate ligament reconstruction. *Phys Ther Sport.* 2021;50:42-49. [doi:10.1016/j.ptsp.2021.03.015](https://doi.org/10.1016/j.ptsp.2021.03.015)
35. Sigward SM, Chan MM, Lin PE, Almansouri SY, Pratt KA. Compensatory strategies that reduce knee extensor demand during a bilateral squat change from 3 to 5 months following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2018;48(9):713-718. [doi:10.2519/jospt.2018.7977](https://doi.org/10.2519/jospt.2018.7977)
36. Anderson AF, Irrgang JJ, Kocher MS, Mann BJ, Harrast JJ. The international knee documentation committee subjective knee evaluation form: normative data. *Am J Sports Med.* 2006;34(1):128-135. [doi:10.1177/0363546505280214](https://doi.org/10.1177/0363546505280214)
37. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc.* 2007;39(11):2021-2028. [doi:10.1249/mss.0b013e318149332d](https://doi.org/10.1249/mss.0b013e318149332d)

38. Hughes G, Musco P, Caine S, Howe L. Lower limb asymmetry after anterior cruciate ligament reconstruction in adolescent athletes: a systematic review and meta-Analysis. *J Athl Train*. 2020;55(8):811-825. [doi:10.4085/1062-6050-0244-19](https://doi.org/10.4085/1062-6050-0244-19)
39. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med Sci Sports Exerc*. 2002;34(9):1408-1413. [doi:10.1097/00005768-200209000-00002](https://doi.org/10.1097/00005768-200209000-00002)
40. Mueske NM, VandenBerg CD, Pace JL, et al. Comparison of drop jump landing biomechanics and asymmetry among adolescents with hamstring, patellar and quadriceps tendon autografts for anterior cruciate ligament reconstruction. *Knee*. 2018;25(6):1065-1073. [doi:10.1016/j.knee.2018.09.005](https://doi.org/10.1016/j.knee.2018.09.005)
41. Wahlstedt C, Rasmussen-Barr E. Anterior cruciate ligament injury and ankle dorsiflexion. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(11):3202-3207. [doi:10.1007/s00167-014-3123-1](https://doi.org/10.1007/s00167-014-3123-1)
42. Barfod KW, Feller JA, Hartwig T, Devitt BM, Webster KE. Knee extensor strength and hop test performance following anterior cruciate ligament reconstruction. *Knee*. 2019;26(1):149-154. [doi:10.1016/j.knee.2018.11.004](https://doi.org/10.1016/j.knee.2018.11.004)
43. Nagelli CV, Hewett TE. Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. *Sports Med*. 2017;47(2):221-232. [doi:10.1007/s40279-016-0584-z](https://doi.org/10.1007/s40279-016-0584-z)