

COMPARISON OF CLINICAL FATIGUE PROTOCOLS TO DECREASE SINGLE-LEG FORWARD HOP PERFORMANCE IN HEALTHY INDIVIDUALS

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ABSTRACT

Background: Return to activity decisions after anterior cruciate ligament reconstruction (ACL-R) are limited by functional performance tests often performed in a non-fatigued state. Fatigue can improve test sensitivity, but current methods to induce fatigue are typically bilateral tasks or focus on the quadriceps muscle in isolation.

Hypothesis/Purpose: To determine the effects of a two-minute lateral step-down fatigue test compared to a 30-second side-hop test on single-leg forward hop distance in healthy individuals. It was hypothesized that participants would demonstrate decreased hop distance with both tests, but the two-minute lateral step-down fatigue test would result in greater deficits in single-leg forward hop distance.

Study Design: Randomized crossover

Methods: Twenty healthy participants (16 females, 4 males; age = 23.7 ± 3.0 years, height = 153.8 ± 36.2 cm; mass = 64.4 ± 12.8 kg; Tegner = 6.8 ± 1.2) were asked to perform single-leg forward hop for distance pre- and post-fatigue. Participants were randomly assigned to one of the two fatigue tests, 30-second side-hop or 2-minute lateral step-down test, during the first visit. They returned within a week and performed the same sequence of tests but underwent whichever fatigue test was not assigned at the prior visit.

Results: There was a significant decrease ($p < 0.001$) in single-leg forward hop distance following the 30-second side-hop test (pre = 134.1 ± 23.7 cm, post = 126.2 ± 24.4 cm) and the two-minute lateral step-down test (pre = 135.0 ± 26.1 cm, post = 122.7 ± 27.4 cm). The decrease in hop distance was significantly greater ($p < 0.001$) for the two-minute lateral step-down test compared to the 30-second side-hop test.

Conclusion: The two-minute lateral step-down test resulted in a greater decrease in hop performance compared to the 30-second side-hop test. The results establish a threshold for expected changes that occur in a healthy population and that can then be compared with an injured athlete population. The two-minute lateral step-down exercise may be an effective method of inducing fatigue to better mimic performance in a sports environment to inform return-to-sport decisions.

Level of Evidence: Level 1b- Therapy

Key Words: Anterior cruciate ligament reconstruction, fatigue, knee, rehabilitation, return to sport

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Study approval was granted by the Institutional Review Board at Creighton University (IRB 959318). This trial was registered on ClinicalTrials.gov (NCT03133078). No individual in this study has a financial or other interest in the products described.

Acknowledgements

This research was supported by the Creighton University School of Pharmacy and Health Professions Student Research Fellowship Grant. Authors would like to thank Barbara Bittner, MA, for assistance with technical editing and writing.

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INTRODUCTION

The knee is the most commonly injured joint by adolescents, with about 2.5 million injuries per year in the United States.¹ Estimates for anterior cruciate ligament (ACL) tears can range anywhere from 100,000 to up to 250,000 injuries per year; approximately 75% of those injuries result in ACL reconstruction (ACL-R).² Decisions regarding return to activity following ACL-R are partially informed by a battery of functional performance tests, consisting of a range of jumping tasks and strength measurements.^{3,4} These functional performance tests typically include, but are not limited to, vertical jump, triple hop, and single-leg forward hop.^{5,6} The single-leg forward hop test is one of the most commonly used functional performance tests to measure the abilities of an individual in the later phases of rehabilitation post-injury.^{4,7} Despite wide use, the single-leg forward hop test has relatively poor psychometric properties (sensitivity = 52%, specificity = 97%, +LR = 17.33, -LR = 0.49), reducing the ability to identify abnormal symmetry (LSI < 85%) between limbs after ACL injury.⁵

Fatigue may play a role in ACL injury risk, as rates tend to be higher toward the end of competition (e.g., second half, last quarter).^{8,9} A limitation of current functional performance test batteries is that they are often performed under non-fatigued conditions and may not be of sufficient demand to identify limb asymmetries.⁷ Although athletes following ACL-R are thought to be resistant to quadriceps fatigue in isometric conditions,^{10,11} they demonstrate deficits in explosive strength¹² and endurance with dynamic contractions.¹³ While the role of fatigue is not fully understood, it has been shown to have mixed effects on coordination and motor control¹⁴ and single-leg forward hop distance.⁶ These mixed effects seen with the incorporation of fatigue may be due to lack of uniformity in fatigue protocols,¹⁴ which may not facilitate enough fatigue to produce the biomechanical changes associated with increased risk for non-contact ACL injuries. Fatigue protocols often involve both limbs at the same time (e.g., agility drills, repeated squats or jumping, running),¹⁴ limiting between-side comparisons. An alternative is to induce unilateral fatigue. In two previous studies, participants completed a single-leg extension

task until failure at 50% or 80% of a one repetition maximum (1RM).^{6,15} This test has been shown to be reliable¹⁵ and results in decreased single-leg forward hop distance in both healthy¹⁵ and ACL-R populations.⁶ The addition of fatigue also improves the psychometric properties of the single-left forward hop test. Prior to fatigue, all individuals with a history of ACL-R demonstrated normal single-leg forward hop symmetry values (LSI \geq 90%), but following fatigue, 68% of the participants demonstrated relevant impairments in hop symmetry (LSI < 90%).⁶ This suggests that test sensitivity can be improved with the addition of a fatigue protocol. However, this approach has limitations: a leg extension machine may not be available in all clinical settings and the task only focuses on a single muscle, which is not reflective of sport demands. Although it is known that quadriceps muscle strength is an important outcome measure following ACL-R, it is not the only muscle group fatigued during physical activity; thus, a more global approach to fatigue may better simulate sports-related fatigue.

Several single-leg tasks have been used to provide insights into movement impairments following knee injury, including the side hop and lateral step-down.^{16,17} While these tests have not been used to specifically induce fatigue, both provide an anaerobic challenge and utilize minimal equipment. It is necessary to develop methods to effectively fatigue individuals in a manner that is more clinically pragmatic but still relevant (i.e., without the use of equipment), and can provide greater insight into rehabilitation progress and return-to-sport decision making. It is necessary to first determine whether either of these tests will impact single-leg hop performance, prior to introducing in a clinical population. Therefore, the purpose of this study was to determine the effects of a two-minute lateral step-down fatigue test compared to a 30-second side-hop test on single-leg forward hop distance in healthy individuals. It was hypothesized that participants would demonstrate decreased hop distance with both tests, but the two-minute lateral step-down fatigue test would result in greater deficits in single-leg forward hop distance due to the longer duration of the test and greater demands on lower extremity musculature.

METHODS

A randomized crossover design was used. Each participant performed one of two fatigue interventions, determined by a randomized table, during the first session and performed the other fatigue intervention during the second session, with three to seven days between testing sessions. The same investigator obtained measures during each session. The study was reviewed for ethical considerations and approved by the Institutional Review Board at Creighton University (IRB 959318). All participants completed an approved informed consent form, compliant with the Declaration of Helsinki, prior to study enrollment.

Twenty healthy participants (16 females, 4 males; age = 23.7 ± 3.0 years, height = 153.8 ± 36.2 cm; mass = 64.4 ± 12.8 kg; Tegner = 6.8 ± 1.2) volunteered for this study. Inclusion criteria included age 19-40 years, no history of knee surgery, and a Tegner Activity Scale score ≥ 5 (heavy labor, competitive endurance sports, recreational sports- jogging on uneven ground at least twice weekly). Exclusion criteria included traumatic spine or lower extremity injury within the prior six months and inability to give consent or understand the experimental procedures. All participants completed a standardized health history

form and the Tegner Activity Scale. Each session started with a five-minute warm up consisting of jogging on a treadmill at a self-selected speed and three single-leg vertical jumps with the dominant limb, defined as the preferred jumping limb (e.g., basketball layup), followed by the non-dominant limb. The single-leg vertical jump was performed as part of a separate reliability study.

The study protocol consisted of three parts: pre-fatigue evaluation, fatigue intervention, and post-fatigue evaluation. First, participants performed the single-leg hop for distance (Figure 1).^{5,17} They were instructed to hop as far forward as possible with a controlled single-limb landing, defined as maintaining position on a single leg for two to three seconds. A loss of balance or placing the contralateral limb on the ground to maintain support was determined to be a failed trial and the trial was repeated. The first trial was used as a warm-up and the maximum single-leg hop distance (cm) of trials two and three was used for data analysis. The dominant limb was tested prior to the non-dominant limb. Single-leg hop for distance has good within-session reliability (ICC = 0.98),¹⁵ good between-session reliability (ICC = 0.92 to .95),^{18,19} and an established minimal



Figure 1. Single-leg forward hop test starting and finish position. The orange arrow indicates hop direction.

detectable change of 8.1% for the limb symmetry index¹⁹ and 13-14 cm for absolute single-leg hop distance.¹⁸

Next, participants were randomized to either a 30-second side-hop (Figure 2A) test or two-minute lateral step-down test (Figure 2B). The 30-second side-hop test required participants to jump as many times as possible over two parallel strips of tape placed 40 cm apart on the floor.¹⁷ An unsuccessful jump was defined as touching the tape or the area inside the tape. The two-minute lateral step-down test required participants to perform a unilateral step-down from a 30.5 cm box (12-inches), tapping their heel to the floor each time, and completing this as many times as possible for two minutes. The number of step downs and side hops performed was recorded for descriptive purposes. Immediately following the fatiguing intervention, participants performed the single-leg hop for distance three more times, using the same protocol as the pre-fatigue measures. Following a three to five minute rest, participants repeated the same protocol (pre-fatigue, fatigue exercise, and post-fatigue) on the opposite limb. Participants returned three to seven days later and performed the same sequence of tests, but performed the fatigue test, which was not performed at the prior visit.

Sample size was based on a previous study¹⁵ utilizing an isolated quadriceps fatigue exercise to decrease single-leg forward hop distance (mean change=10 cm, SD=15) in healthy individuals. It was determined that at least 16 participants were necessary in order to detect a significant ($\alpha = .05$, $1-\beta = .80$) change in single-leg forward hop distance following the fatigue protocol. The independent variables included the fatigue test (30-second side hop, two-minute lateral step-down), time (pre-test, post-test), and side (dominant, non-dominant). The dependent variable was single-leg forward hop distance (cm). Descriptive statistics, including frequency counts, were calculated for the outcome variables. A mixed model ANOVA was used to determine differences between sides and pre- and post-test measures for each fatigue test. A separate paired t-test was used to determine differences in hop test performance between tests using the average of the dominant and non-dominant limbs. Statistical significance was set *a priori* at $p \leq 0.05$. Effect sizes (Cohen's *d*) were calculated

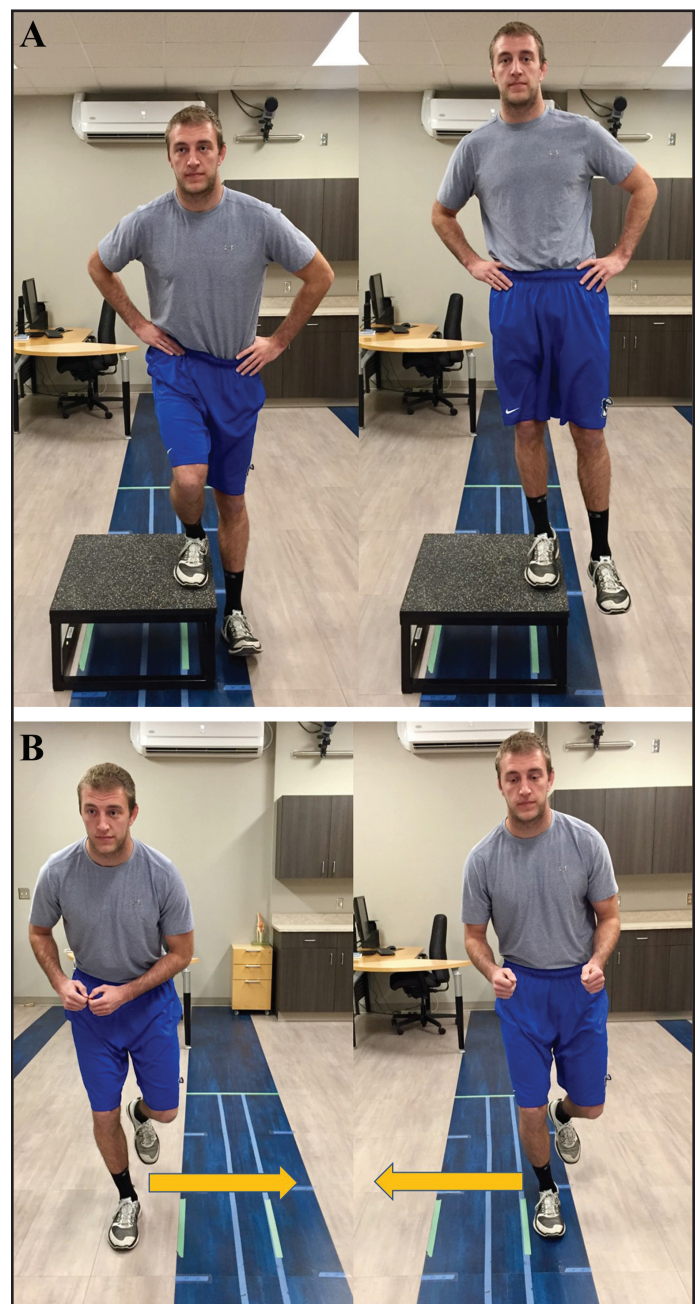


Figure 2. A) 30-second side-hop, B) 2-minute lateral step-down test starting and finish position. The orange arrow indicates hop direction.

for outcome variables using the mean difference between pre- and post-test trials and the pooled standard deviation. Effect sizes were interpreted as follows: small (.20), moderate (.50), and large (.80).²⁰

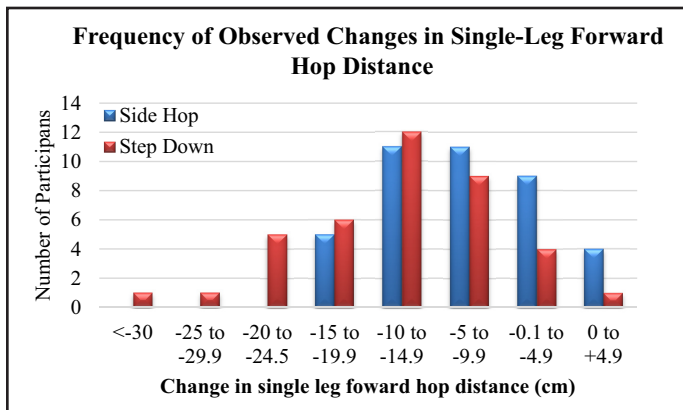
RESULTS

There was not a significant interaction (side x time) for the 30-second side-hop test ($p = 0.86$) or the two-minute lateral step-down test ($p = 0.33$). The

Table 1. Single-limb forward hop distance (cm) mean values (SD) before and after fatigue intervention.

	Pre-Fatigue			Post-Fatigue			Change in Hop Distance
	Dominant	Non-Dominant*	Average	Dominant	Non-Dominant	Average	
30-Second Side Hop	137.0 (25.0)	131.3 (22.9)	134.1 (23.7)	128.9 (25.5)	123.5 (24.3)	126.2 (24.4) †	8.0 (3.4) ‡
2-Minute Lateral Step-Down	137.9 (26.4)	132.0 (27.3)	135.0 (26.1)	124.1 (23.7)	120.7 (28.7)	122.7 (27.4) †	12.3 (6.5) ‡

* significant difference ($p < .05$) in single-limb forward hop distance between dominant and non-dominant limbs
† significant decrease in single-limb forward hop distance post-fatigue compared to pre-fatigue ($p < 0.001$)
‡ significant difference between fatigue tests ($p < 0.004$)

**Figure 3.** Frequency of observed changes in single-leg forward hop distance following fatiguing exercise.

dominant limb demonstrated significantly greater ($p < 0.05$) single-leg forward hop distance compared to the non-dominant limb for both tests. Both fatigue tests significantly decreased ($p < 0.001$) single-leg forward hop distance (Table 1), but the magnitude of this decrease was significantly greater ($p < 0.001$) with the two-minute lateral step-down test compared to the 30-second side-hop test (Table 1). The frequency of observed changes in single-leg forward hop distance following fatiguing exercise is provided in Figure 3. Effect sizes were considered small to moderate for changes in single-leg forward hop distance following the 30-second side-hop test ($d = -0.33$) and the two-minute lateral step-down test ($d = -0.46$). The 30-second side-hop test resulted in decreased single-leg hop distance exceeding the 13 cm minimal detectable change in 15% of the trials, compared to 40% of the trials after the two-minute lateral step-down test.

DISCUSSION

The purpose of this study was to determine the effects of a two-minute lateral step-down fatigue test

compared to a 30-second side-hop test on single-leg forward hop distance in healthy individuals. The results confirmed our hypothesis that both fatigue tests would decrease single-leg forward hop performance, and that the two-minute lateral step-down test resulted in a significantly greater decrease in single-leg hop performance compared to the 30-second side-hop test. The two-minute lateral step-down test resulted in not only a greater average change from pre- to post-testing relative to the 30-second side-hop test (12.3 cm versus 8.0 cm), but also a larger effect size (-0.46 versus -0.33), allowing interpretation of the magnitude of this change. Thus, the current study provides evidence that single-leg forward hop distance is negatively impacted by the fatigue tests.

Currently, return-to-sport protocols include functional hop tests, as well as objective quadriceps strength measures, in the clinical decision-making tree of returning athletes to sport after ACL-R. An LSI of $\geq 85-90\%$ has been established as sufficient criteria to begin a return-to-sport progression.²¹ Limb dominance may impact LSI as the dominant limb demonstrated significantly greater single-leg forward hop performance compared to the non-dominant limb (Table 1). This finding is supported by previous work²² and suggests that LSI values after knee injury may be influenced by limb dominance. Although athletes may reach a single-limb forward hop LSI $\geq 85-90\%$, it is possible this threshold may not be sufficient, as deficits in quadriceps strength and altered landing biomechanics may still be present at return to sport.^{6,23,24} These deficits may persist for years, leading to increased risk of re-injury^{23,25,26} and an earlier onset of knee osteoarthritis.²⁷ The addition of testing single-leg forward hop performance in a fatigued state has been shown to improve the sensitivity of single-leg forward hop LSI,⁶ allowing a more

accurate representation of the presence of asymmetry. Previous research demonstrated that, prior to fatigue, all individuals with a history of ACL-R demonstrated normal single-leg forward hop symmetry values (LSI $\geq 90\%$), but following fatigue, 68% of the participants demonstrated relevant impairments in hop symmetry (LSI $< 90\%$).⁶ This indicates that a non-fatigued single-leg forward hop LSI greater than 90% may not be a sufficient cut-off to allow athletes to return to sport.^{6,28} Adding a unilateral fatigue test may improve our ability to detect clinically meaningful differences between limbs for single-leg forward hop performance that may not be expressed in non-fatigued hop testing conditions.⁶

There are two potential advantages of using the 30-second side-hop or the two-minute lateral step-down fatigue tests as opposed to previous fatigue protocols (i.e. leg extensor machine testing). The first is that there is strong potential of more effectively detecting strength and functional deficits post-ACL-R.⁶ A second benefit is that both fatigue tests may also provide insights into anaerobic performance differences between limbs or in comparison to healthy controls.^{17,29,30} The side-hop test has been utilized as an endurance task and used to differentiate between performance of the involved and uninvolved limb following ACL injury and reconstruction.¹⁷ As the quadriceps and other lower extremity muscles fatigue,

this test can provide critical insights into what the knee can potentially withstand during sport. The lateral step-down test has been used clinically to examine performance as well as movement quality.^{16,31} The authors' application of the lateral step-down test included two minutes per limb versus five repetitions¹⁶ or three minutes³¹ which have been used in previous studies. The decreases in single-leg forward hop distance after fatigue demonstrate potential for the fatigue test to decrease jumping performance. Although the number of repetitions performed for each of the tests was monitored, other measures were not captured to better quantify fatigue (e.g., rating of perceived exertion, electromyography). Previous studies^{6,15} have performed a unilateral leg-extension task at 50% or 80% of 1RM until failure to fatigue the quadriceps muscle.^{6,15} This resulted in a 17 cm decrease in hop performance for healthy individuals (Figure 4). Greater deficits following fatigue are seen in individuals with a history ACL-R on both the involved (30 cm) and uninvolved limb (25 cm).^{6,15} The minimal detectable change of the single-leg forward hop test is 13-14 cm,¹⁸ which indicates that changes less than 13-14 cm cannot be differentiated from measurement error and should be viewed with caution. While the 12 cm decrease in forward hop distance was close to the minimal detectable change, there is a compelling potential that when applied in a population with ACL-R, results would yield those that would

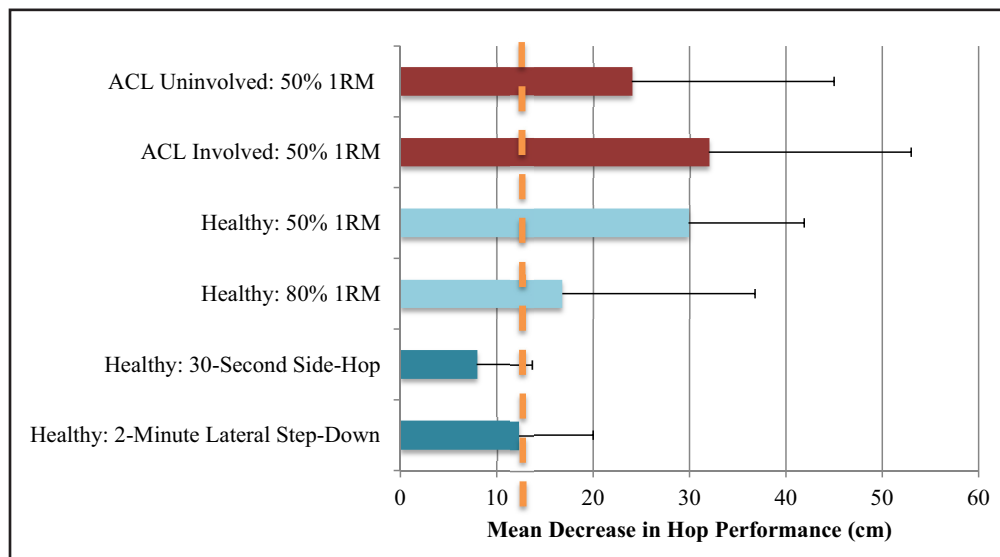


Figure 4. Results of mean decrease in hop performance of our study and adapted data from Augustsson et al. Shades of blue indicate healthy subject values, shades of red indicate non-healthy values. Values shown are in centimeters of change in hop distance between pre- and post-fatigue of fatigue protocols. The vertical line indicates the minimal detectable change 13-14 cm.¹⁸

be comparable to that of the leg-extensor fatigue test (Figure 4) at 80% of a 1RM which resulted in approximately 17 cm decrease in forward hop distance.^{6,15} As seen in Figure 4, healthy participants (blue bars) had decreases in forward hop performance that were lower in magnitude compared to participants with a history of ACL reconstruction (red bars). Future studies should determine changes in single-leg forward hop distance following the fatigue protocols, outlined in the current study, for individuals with a history of ACL-R. The two-minute lateral step-down test and 30-second side-hop test offer a more pragmatic solution, as compared to current fatigue methods, to implementing fatigue testing in the clinic. Both require minimal time and equipment (30.5 cm step, stopwatch) and are relatively inexpensive compared to a leg-extension machine. Not only are these tests clinically useful, but also are more functional evaluative tests. During sporting activity quadriceps fatigue does not occur in isolation, but involves both central and peripheral mechanisms.³² It is also possible that avoidance patterns or compensatory strategies may be utilized to allow task completion and preserve quadriceps function. Individuals with a history of ACL reconstruction have been shown to rely more heavily on contributions from the hip and ankle to offset decreased contributions from the knee when performing a vertical jump³³ or single-leg forward hop.³⁴ Although the side-hop or lateral step down may be considered more functional-type tasks, compensatory strategies to preserve quadriceps function would not be able available during a strictly knee extensor fatigue protocol. Future research should focus on the use of fatigue tests in athletes following ACL-R, as well as the use of 3-D motion capture and/or electromyographic (EMG) data to investigate the compensatory strategies individuals with a history of ACL-R use when fatigued.^{15,33,35} This information may better determine which type of fatigue protocol provides to most relevant information to inform return to sport decisions.

A limitation of this study was that only young, healthy individuals were included, consisting of a greater number of female participants. It is known that females may demonstrate a different fatigue profile than males.^{36,37} Future studies should employ a more balanced recruitment of female and male

participants and of sufficient sample size to allow between sex comparisons. A second limitation was that the order of limb testing was not randomized. Instead, the authors elected to test the dominant limb prior the non-dominant limb, a method used in previous studies.^{38,39} There is little consensus regarding an appropriate testing sequence for injured (involved then uninvolved; randomized) or healthy participants (right then left, dominant then non-dominant, randomized). A third limitation was that time-anchored tests (30 seconds, 2 minutes) were used that did not include a subjective or objective measure of fatigue such as rating of perceived exertion^{40,41} or changes in quadriceps EMG profile.³⁷ It could be possible for a participant to not provide full effort during the fatigue test, which would then underestimate likely changes in single-leg forward hop performance. The data provided by this study and future studies can give clinicians greater insight into the challenges associated with athletes post-ACL-R, as well as provide a more thorough return to pre-injury levels of performance in order to reduce the likelihood of re-injury and promote a safe and smooth return to sport.

CONCLUSION

Return-to-sport/activity decisions are informed by a battery of functional and strength tests that are typically performed in a non-fatigued state, which may inaccurately determine whether an athlete is fully ready to return to sport. Fatiguing exercise is thought to better identify asymmetries in single-limb forward hop performance, as demonstrated previously with a leg-extensor fatigue test. This results of the current study indicate that the two-minute lateral step-down test has the ability to significantly decrease hop performance in a healthy population, and that these decreases are comparable to changes observed in a healthy population with the leg-extensor fatigue test (Figure 4). Even more so, the two-minute lateral step-down test is a more pragmatic solution to testing athletes in a fatigued state as compared to a leg-extension machine because it is inexpensive and targets the muscles of the entire lower extremity. Future research should evaluate the use of the two-minute lateral step-down test as a fatiguing protocol for persons following ACL-R to make appropriate determinations for return-to-sport readiness.

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