Clinical Biomechanics xxx (xxxx) xxx-xxx

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: http://ees.elsevier.com

The single-leg vertical hop provides unique asymmetry information in individuals after anterior cruciate ligament reconstruction

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ARTICLE INFO

Keywords
ACL
Asymmetry
Hop testing
Biomechanics

ABSTRACT

Background: Traditional testing to identify asymmetries after anterior cruciate ligament reconstruction include four similar horizontal hopping tests. The purpose of this study was to determine whether a single-leg vertical hopping test can identify performance and biomechanical asymmetries, and whether performance asymmetries provide unique information compared to traditional tests.

Methods: Twelve women with history of anterior cruciate ligament reconstruction [age: 21.1 years (SD 3.2), height: 165.8 cm (SD 6.0), mass: 68.3 kg (SD 8.8)] completed traditional horizontal hop testing. Participants also performed a single-leg vertical hop for maximal height while instrumented for three-dimensional motion analysis. Paired *t*-tests were performed to identify side-to-side differences in performance variables and Spearman's rank correlations were performed of limb symmetry indices to identify whether the single-leg vertical hop test provides unique information. Repeated measures MANOVAs were performed to identify single-leg vertical hop biomechanical asymmetries.

Findings: Participants exhibited significant side-to-side performance differences during the single-leg vertical hop [mean difference = 0.02 m (SD 0.03), $P = .04$]. Only weak to moderate relationships were identified between limb symmetry indices of the single-leg vertical hop and other horizontal hopping tests. The vertical hop elicited significant asymmetries of joint kinematics ($P = .04$) and angular impulse ($P = .04$). Specifically, the involved limb showed lower peak ankle dorsiflexion ($P = .004$) and knee abduction ($P = .02$) angles, lower sagittal plane impulse at the knee ($P = .02$) and greater sagittal plane impulse at the hip ($P = .03$).

Interpretation: The single-leg vertical hop can identify performance and biomechanical asymmetries in individuals after anterior cruciate ligament reconstruction, potentially providing complementary information to standard horizontal hopping tests.

1. Introduction

Incident rates of anterior cruciate ligament (ACL) injury continue to increase annually.(Mall et al., 2014) These injuries result in immediate pain, as well as functional and emotional trauma; however the long-term ramifications of reduced physical activity (Bell et al., 2017) and accelerated joint degeneration (Luc et al., 2014) might be more consequential. After injury, only ~60% of athletes return to their pre-injury level of sport participation and only ~40% return to competitive sport.(Ardern et al., 2015) If an athlete is fortunate to return to sport, up to 30% suffer a second ACL injury, many of which occur in the first 1–3 months after return.(Paterno et al., 2014) These data indicate there is significant room for improvement in current clinical rehabilitation and return-to-play testing methods.

There is some existing evidence to support a battery of performance tests, that when used during the return-to-play process, are successful at reducing the risk of second ACL injury and leading to other successful outcomes.(Grindem et al., 2016) These tests shift the paradigm of clinical decision making from time-based to criterion-based metrics that compare performance of the surgically repaired limb to the uninvolved limb. At least 90–95% performance of the involved limb in relation to the non-involved limb is thought to signify good outcomes, though validation is needed for the specific percentages and tasks. Quadriceps and hamstrings function are quantified using either a handheld dynamome-

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https://doi.org/10.1016/j.clinbiomech.2020.105107
Received 2 March 2020; Accepted 11 July 2020
Available online xxx
0268-0033/© 2019.

ter (isometric) or isokinetic dynamometer (concentric/eccentric). Gross limb function is assessed with a series of four single-leg hopping tests (single hop for distance, triple hop for distance, crossover triple hop for distance, 6 m timed hop). Though each of these four tests have unique constructs, including speed, plyometric, and multidirectional movements, all the tests demand and assess horizontal jumping and landing performance and may not comprehensively represent an athlete's status. Additional tests that measure movement patterns specific to vertical motion may be beneficial to complement these standard horizontal tests.

In healthy populations, the single-leg vertical countermovement hop (SLVH) has been reported as a hopping task that strongly discriminates limb asymmetries (Fort-Vanmeerhaeghe et al., 2016) but to date, has only been minimally studied in a population of individuals after ACL reconstruction (ACLr).(Petschnig et al., 1998) Because vertical and horizontal hopping tests may provide unique information, (Mulrey et al., 2020) the SLVH may make a valuable addition to current return-to-play testing batteries after ACLr. The purpose of this study was to determine whether the SLVH can identify performance and biomechanical asymmetries after ACLr, and whether performance asymmetries provide unique information compared to current clinical tests. It was hypothesized that the SLVH would be sensitive to identifying limb performance and biomechanical asymmetries and that there would be limited relationships between the vertical and horizontal tests.

2. Methods

2.1. Patients

Twelve female participants [age: 21.1 years (SD 3.2), height: 165.8 cm (SD 6.0), mass: 68.3 kg (SD 8.8)] with a history of ACL reconstruction were included in the study. To determine the study sample size ($n = 12$), an a priori power analysis was conducted for a comparison between like means using an effect size of 0.8 ($\alpha = 0.05$, $\beta = 0.80$) (G*Power 3.1.9.7).

Participants were included in the study if they had been cleared by their surgeon to return to competitive sport, had no other previous lower extremity surgery, and were free of balance or other vestibular disorders that would affect their jumping and landing biomechanics. On average, the participants were 4.7 years (SD 2.6) since their ACLr, 25% of which were patellar tendon grafts, 50% hamstring grafts, 8% quadriceps tendon grafts, and 17% cadaver allografts. All participants were informed of study benefits and risks and provided written informed consent/assent as approved by the Institutional Review Board at High Point University.

2.2. Procedures

After informed consent and the completion of standard self-report outcome measures [Knee Injury and Osteoarthritis Outcome Score (KOOS), Anterior Cruciate Ligament Return to Sport After Injury scale (ACL-RSI)], all participants donned standardized laboratory footwear (adidas adipure 360.2, adidas, Portland, OR, USA) and completed a five-minute warm-up on a stationary cycle ergometer.

2.2.1. SLVH

Participants were instrumented for three-dimensional biomechanical analysis with 45 retroreflective markers placed on the sternum, sacrum, left posterior superior iliac spines, C7, 3 points on the upper back via a thin, fitted backpack, and bilaterally on the shoulder, upper arm, elbow, wrist, anterior superior iliac spine, lateral iliac crest, greater trochanter, midthigh, medial and lateral knee joint line, tibial tubercle, mid-shank, distal shank, medial and lateral malleolus, and to the foot at the heel, dorsal surface of the lateral midfoot, lateral rearfoot, and toe via adhesive tape to the shoes (Fig. 1). A static calibration trial was then collected to determine the participants' neutral alignment, define each body segment, and establish joint coordinate systems by which subsequent biomechanical measures were referenced. Three-dimensional motion data were collected with Cortex software (version 7.1.0, Motion Analysis Corp) using a 16-camera system (200 Hz, 12 Raptor-12 and 4 Kestrel Cameras, Motion Analysis Corp, Rohnert Park, CA, USA). Ground reaction force data were collected by two in-ground, oversized multi-axis force platforms (1200 Hz, AMTI, Inc. Watertown, MA, USA).

After the static trial, a standard countermovement jump was performed to place an overhead target at a location where participants could barely touch the target with their fingertips during a maximal double-leg countermovement jump. Once the target was set, participants completed three trials of the SLVH on each foot, in a randomized order. Participants were instructed to stand on one leg underneath the target. Once the participant was confident in their balance on a single-leg, they performed a maximal vertical jump while reaching to the overhead target with the hand opposite of the jumping leg (Fig. 2). There were no limitations placed on the way participants landed from the SLVH.

Participants' biomechanics during the jumping phase of the SLVH were analyzed from the instant the velocity of the vertical center of mass transitioned from positive to negative (indicating participants had begun their descent before initiating the countermovement phase) until

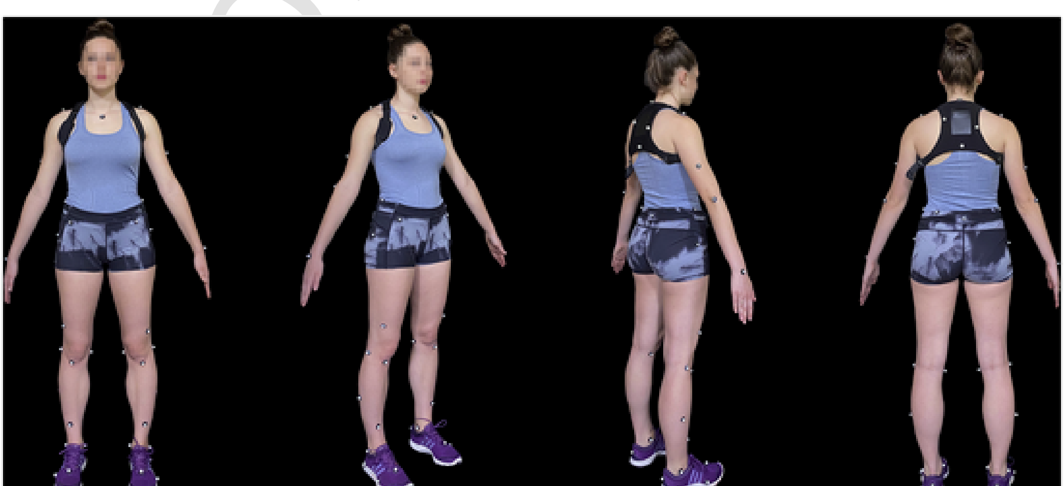

Fig. 1. Depiction of marker set used for biomechanical collection.

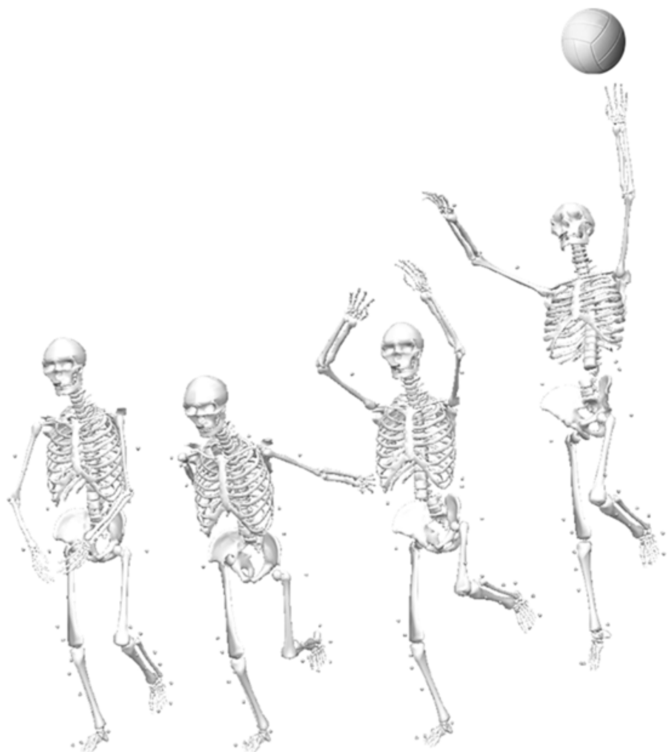

Fig. 2. Example participant performing the single-leg vertical hop test.

toe-off (when vertical ground reaction force ⟨10N) in Visual3D (version 6, C-Motion Inc., Germantown, MD, USA). Hip joint centers were calculated using the Bell method (Bell et al., 1990) and the knee and ankle joint centers were calculated as the centroid position of the medial and lateral epicondyles and medial and lateral malleoli markers, respectively. Joint moments, calculated using inverse dynamics, and kinematic data were lowpass filtered at 12 Hz.(Bisseling and Hof, 2006; Ford et al., 2010) The biomechanical variables of interest included peak kinematics, peak external joint moments normalized to body mass, and normalized angular impulse (computed as the area under the joint torque by time curve) during the concentric phase for sagittal hip (Fig. 3), knee and ankle and frontal plane knee variables (i.e. hip flexion, knee flexion, knee abduction, ankle dorsiflexion).

2.2.2. Single-leg hop test battery

After three-dimensional analysis, participants completed the standard single-leg hop battery of four tests (Noyes et al., 1991) in a randomized order on a basketball court surface with a tape measure affixed to the ground. The single-leg hop for distance was performed with the participant balancing on one leg with their toes behind the starting line. Participants maximally hopped forward off one leg and landed on the same leg, holding their balance while a member of the research team audibly counted to two. Similarly, the single-leg triple hop for distance test was performed as the participant maximally jumped forward three times (without pausing) on the same limb, balancing on the third landing for a count of two. The crossover triple hop began with an anterolateral hop over a 15-cm wide line, then subsequent anteromedial and anterolateral hop with a balanced, two second landing. The distance travelled for each test was measured as the distance from the starting line to the front edge of the toe on the final hop. The 6-m timed single-leg hop test was measured using a set of timing gates at the starting line and 6 m away from the timing gates (TracTronix Wireless Timing System, Belton, MO, USA). Participants were instructed to hop repetitively on one leg to travel 6 m as quickly as possible.

2.3. Statistical analysis

All statistical analyses were performed using SPSS version 26 (IBM corp.) ($\alpha = 0.05$). Paired *t*-tests were performed to identify side-to-side differences in performance testing variables for each test (i.e. heights, distances). To identify whether the single leg-hopping tests provide unique information on participant performance, Spearman's rank correlations were performed of the limb symmetry index values (involved/non-involved*100) for each test.

Additionally, for more detailed analysis of the SLVH, three repeated measures MANOVAs (1: joint kinematics, 2: peak joint moments, 3: impulse) were performed to identify side-to-side biomechanical asymmetries. Multivariate statistical significance was assessed for each model using Wilk's Lambda. Follow-up Cohen's *d* effect sizes and *post-hoc* pairwise comparisons were performed using paired *t*-tests to identify individual biomechanical differences if significance of the multivariate model was obtained.

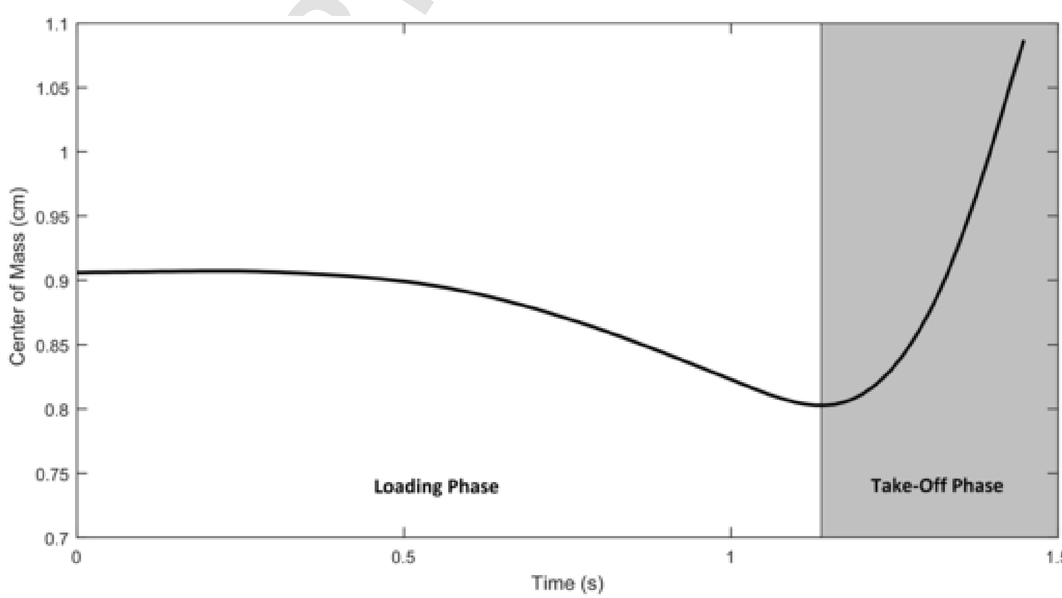

Fig. 3. Visual representation of phase of jump (from lowest position of center of mass to toe-off) analyzed for impulse.

3. Results

Participants exhibited varying levels of self-perceived function on the KOOS pain (6.9% ± 14.3), KOOS-ADL (1.5% ± 3.7), KOOS-Sport (15.0% ± 21.7) and ACL-RSI (69.2% ± 22.2) scales.

3.1. Hopping test performance

Participants exhibited significant side-to-side performance differences during the SLVH [mean difference = 1.8 cm (SD 2.6), $P = .04$, $d = 0.48$)], triple hop for distance [mean difference = 19.9 cm (SD 27.1), $P = .03$, $d = 0.33$)], and 6 m timed hop [mean difference = 0.16 s (SD 0.20), $P = .02$, $d = 0.50$]. No differences were observed between sides during the hop for distance or crossover triple hop for distance ($P > .05$) (Table 1). When comparing limb symmetry index values elicited by each of the five hopping tests (Table 2), there were strong correlations identified between the single hop for distance and the triple hop for distance (Spearman's Rho = 0.65, $P = .22$) and crossover triple hop for distance (Spearman's Rho = 0.73, $P = .01$). A strong relationship was also identified between the triple hop for distance and crossover triple hop for distance (Spearman's Rho = 0.73, $P = .01$). There was only weak to moderate relationships identified between limb symmetry indices of the SLVH and single leg 6-m timed hop with each of the other tests (Table 1).

Table 1
Descriptive statistics (mean ± SD) of hop performance for each single-leg hopping test.

Test		Involved limb	Non-involved limb	P	d
1.	Single-leg vertical hop	31.7 ± 3.6 cm	33.5 ± 3.9 cm	0.04 *	0.48
2.	Single-leg hop for distance	151.4 ± 22.3 cm	155.4 ± 20.5 cm	0.21 *	0.19
3.	Single-leg triple hop for distance	399.9 ± 60.6 cm	419.8 ± 60 cm	0.03 *	0.33
4.	Single-leg crossover triple hop for distance	339.7 ± 79.8 cm	343.5 ± 82.0 cm	0.70 *	0.05
5.	Single-leg 6-m timed hop	2.60 ± 0.38 s	2.44 ± 0.28 s	0.02 *	0.50

* statistically significant difference between limbs, P < .05.

Table 2
Descriptive statistics and Spearman's correlations of performance limb symmetry indices of each single-leg hopping test.

Test	SLVH	SLH	3HOP	CROSS	TIMED
Single-leg vertical hop (SLVH)	–				
Single-leg hop for distance (SLH)	0.48	–			
Single-leg triple hop for distance (3HOP)	0.27	0.65 *	–		
Single-leg crossover triple hop for distance (CROSS)	0.11	0.73 *	0.73 *	–	
Single-leg 6-m timed hop (TIMED)	0.11	0.31 *	−0.03 *	0.11	–
Mean	94.9	97.4	95.3	99.2	94.3
SD	7.6	6.6	6.0	10.4	6.8
Range	85–110	87–105	84–102	86–116	79–104

* statistically significant correlation, P < .05.

3.2. Biomechanical analysis of SLVH

Descriptive statistics of the SLVH are displayed in Table 3. Significant side-to-side asymmetries of joint kinematics were identified during the SLVH ($\lambda = 0.24$, $P = .01$). Specifically, the involved limb showed lower peak ankle dorsiflexion ($P = .001$) and knee abduction ($p = .02$) angles than the non-involved limb. No side-to-side differences were found in peak hip or knee flexion angles ($P > .05$). Multivariate analysis revealed no side-to-side differences in peak joint moments ($\lambda = 0.36$, $P = .06$), but differences were identified for angular impulse ($\lambda = 0.29$, $P = .03$). Specifically, the involved limb exhibited greater sagittal plane angular impulse at the hip ($P = .03$) (Fig. 4a), but lower at the knee ($P = .02$) (Fig. 4b).

4. Discussion

The current clinical rehabilitation paradigm after ACLr results in poor rates of return-to-play and relatively high incidence of second ACL injury.(Ardern et al., 2015; Paterno et al., 2014) While current testing procedures may help identify athletes that should or should not return to sport, (Grindem et al., 2016) optimization of these protocols are needed to improve overall outcomes. Findings from this study indicate that standard single-leg horizontal hopping tests may result in similar performance limb symmetry indices and that a single-leg vertical hopping test may complement these standard tests by providing unique information. Further, when analyzing quality of movement, the SLVH test elicits asymmetrical biomechanics (e.g. sagittal plane angular impulse reduced at the knee and increased at the hip) that may be indicative of neuromuscular quadriceps dysfunction, a known risk factor for poor post-surgical outcomes. The SLVH warrants consideration for future clinical use.

Our results indicate that not all standard single-leg horizontal hopping tests provide unique information for clinical decision making. Specifically, the single-leg hop for distance test was highly correlated with the single-leg triple hop for distance and single-leg crossover hop for distance tests. Other studies have also reported strong correlations between the single- and triple-hop for distance, (Nagai et al., 2020) and yet the conventional testing battery used in clinical settings continues to include all horizontal hopping tests that elicit similar results. Consistent with data from healthy athletes, (Fort-Vanmeerhaeghe et al., 2015) asymmetries elicited during the SLVH in individuals after ACLr showed only weak relationship to any of the other horizontal

Table 3
Descriptive statistics [means (SD)] of the biomechanics elicited during the single-leg vertical hop.

Measure	Involved	Non-involved	p	d
Kinematics ($\lambda = 0.24$, p = .01)				
Peak hip flexion (°)	62.3 (11.0)	60.8 (12.5)	0.30	0.13
Peak knee flexion (°)	60.2 (7.7)	63.3 (8.1)	0.06	0.40
Peak ankle dorsiflexion (°)	22.9 (3.8)	25.7 (3.2)	***0.001***	0.80
Peak knee abduction (°)	3.4 (2.5)	4.9 (2.5)	***0.02***	0.59
Kinetics – peak moment ($\lambda = 0.36$, p = .06)				
Hip flexion (Nm/kg)	2.45 (0.62)	2.34 (0.68)	–	
Knee flexion (Nm/kg)	1.73 (0.36)	1.95 (0.36)	–	
Ankle dorsiflexion (Nm/kg)	2.14 (0.41)	2.11 (0.43)	–	
Knee abduction (Nm/kg)	0.18 (0.10)	0.19 (0.16)	–	
Kinetics - impulse ($\lambda = 0.29$, p = .03)				
Hip flexion (Nm·s/kg)	0.42 (0.13)	0.36 (0.16)	***0.004***	0.46
Knee flexion (Nm·s/kg)	0.36 (0.10)	0.40 (0.09)	***0.02***	0.43
Ankle dorsiflexion (Nm·s/kg)	0.51 (0.09)	0.51 (0.10)	0.81	0.03
Knee abduction (Nm·s/kg)	0.04 (0.05)	0.02 (0.07)	0.13	0.35

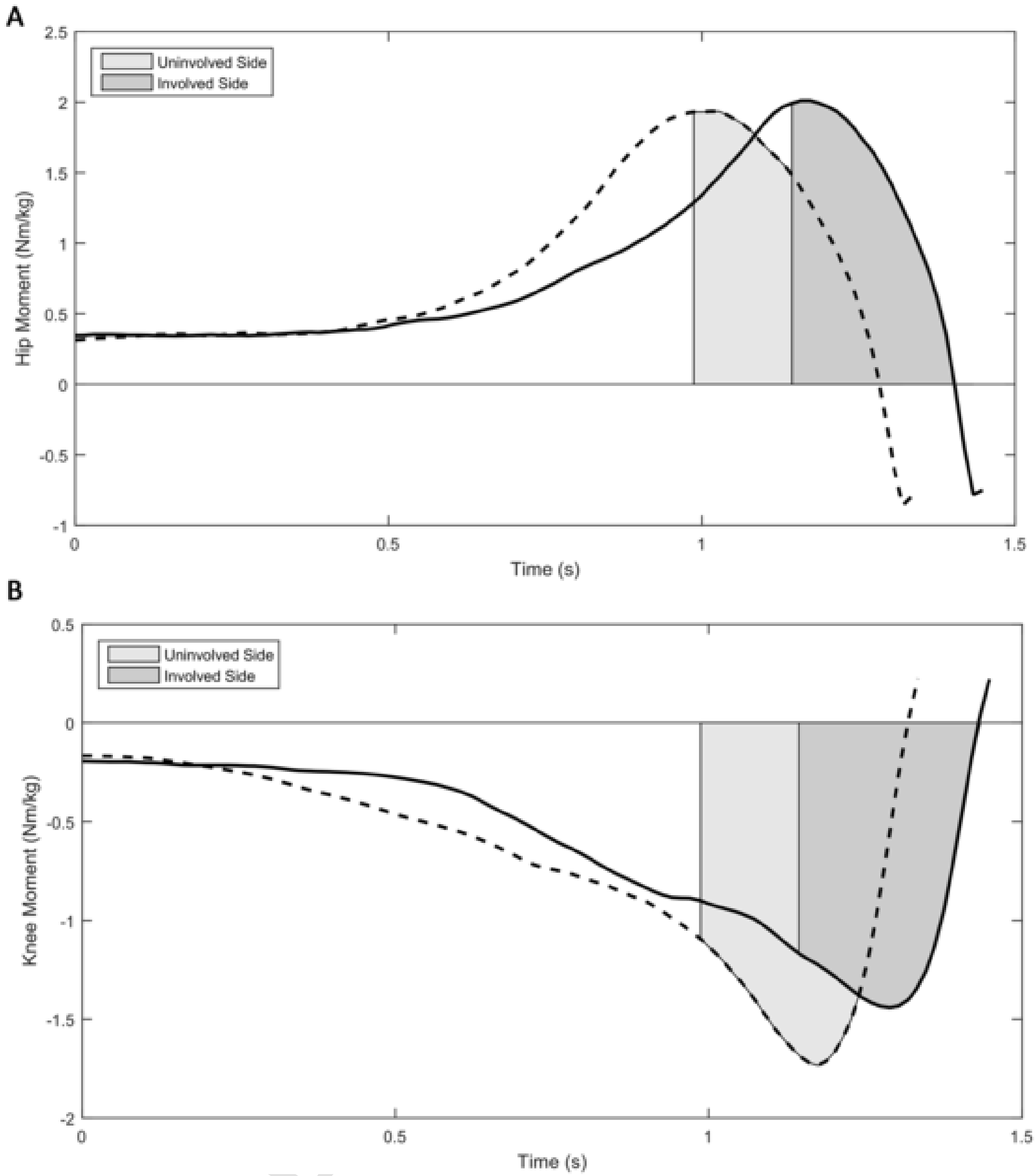

Fig. 4. Ensemble curves of sagittal plane (a) hip and (b) knee torque during the single-leg vertical hop. Shaded areas represent the angular impulse calculation.

hopping tests, indicating it may provide complementary and unique information to clinicians. The SLVH has been reported to elicit greater limb-to-limb performance asymmetries than various horizontal hopping tests in healthy athletes.(Fort-Vanmeerhaeghe et al., 2015; Fort-Vanmeerhaeghe et al., 2016) One limitation to the SLVH is that because of the lower magnitudes of movement, the net difference between limbs is smaller than horizontal hopping tests. Thus, a 10% side-to-side asymmetry may not be as clinically meaningful as those identified during horizontal testing.

The SLVH also elicited significant asymmetries in the movement strategy employed to perform the task. Specifically, the involved limb exhibited lower ankle dorsiflexion and knee abduction angles, lower sagittal plane knee impulse and greater sagittal plane hip impulse. These kinematic findings are consistent with previous reports of reduced ankle dorsiflexion during a single-leg squat jump task in individuals 7-months after ACL reconstruction.(Pairot de Fontenay et al., 2015) This altered movement pattern was likely not the result of restricted range of motion, rather poor control of the involved limb leading to an overall reduced ability to lower the center of mass during the countermovement phase. Other studies have also reported that individuals after ACLr reduced overall forces during a single-leg vertical jump (Pairot de Fontenay et al., 2015); however, our results show a redistribution of forces (impulse) rather than an overall reduction throughout the limb. This redistribution has been similarly identified during jump landings, (Garrison et al., 2018; Pozzi et al., 2017) stair ascent, (Hall et al., 2012) and squatting.(Roos et al., 2014; Salem et al., 2003) In healthy athletes performing the SLVH, jump height is predicted by a combination of greater knee power and lesser hip extension moment.(Johnston et al., 2015) Considering that the quadriceps consistently show reduced torque production during isolated and gross motor activities after ACLr, (Lepley and Kuenze, 2018) redistribution of forces to the hip may be an unwanted compensatory movement pattern that the SLVH can detect.

While more validation of the SLVH is needed before widespread incorporation into return-to-play testing, the test can be used by clinicians to better inform them about their patients' asymmetrical lower extremity function. In addition to reliability and validity, expense, convenience, and ease of administration should be considered when selecting functional tests to evaluate return-to-play readiness following ACL reconstruction. While our study used an elaborate and clinically inaccessible method of measuring vertical hopping height, the ability to measure vertical jump/hop in a clinical setting is becoming easier and more affordable with the progression of technology. Jump mats, portable force platforms, wearable accelerometers, and inertial measurement units have all been reported to provide reliable measures of jump height.(Brooks et al., 2018; Loturco et al., 2017; Pueo et al., 2018; Rantalainen et al., 2018) Such technology typically comes with a proprietary software that does not require clinicians to have the technical knowledge to calculate jump heights. An even less costly method of measuring jump height is with a Vertec jump and reach device that is commonly used in the clinic.

Regardless of the method, the SLVH can be performed at any time during rehabilitation. For early identification of potential asymmetrical lower extremity function, we recommend serial assessments of SLVH jump height during the rehabilitation process after the patient has been cleared for single-leg hopping and landing. The SLVH can function as an intervention. Verbal and/or visual cueing can be used during the task, especially when performed on the involved side, to correct faulty movement strategies (e.g. generate more symmetrical ankle dorsiflexion and knee abduction angles), and to preferentially activate the quadriceps during the concentric phase (i.e., power generation) of the jump. Additionally, clinicians can consider using the SLVH as a complementary single-leg test to assess their patients' status during the return-to-play process. The addition of the SLVH to the return-to-play test battery may provide a more comprehensive assessment of lower extremity function following ACL reconstruction.

5. Conclusion

The SLVH shows potential as a valuable addition to standard return-to-play testing procedures after ACLr. This test provides unique information when compared to horizontal hopping tests and elicits asymmetrical biomechanics that may place the athlete at risk of future injury. Future research is needed to validate the SLVH test as predictive assessment of unsuccessful performance outcomes or subsequent injury.

CRediT author statement

JBT was involved in conceptualization, methodology, formal analysis, investigation, writing, visualization, supervision, and project administration.

AW was involved in conceptualization, methodology, investigation, data curation, writing, and visualization.

PH was involved in conceptualization and writing.

KG was involved in writing, reviewing, and editing.

MP was involved in conceptualization and writing.

KF was involved in conceptualization, methodology, investigation, data curation, writing, project administration and visualization.

Declaration of Competing Interest

None.

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