COMPARISON OF THE 'BACK IN ACTION' TEST BATTERY TO STANDARD HOP TESTS AND ISOKINETIC KNEE DYNAMOMETRY IN PATIENTS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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ABSTRACT

Background: Limb symmetry after anterior cruciate ligament reconstruction may be evaluated using maximal strength and hop tests, which are typically reported using Limb Symmetry Indices (LSIs) which may overestimate function.

Purpose: The purpose of this study was to compare the Back in Action (BIA) test battery to standard hop and muscle strength tests used to determine readiness to return to sport (RTS).

Study Design: Prospective cohort.

Methods: Over two test sessions, 40 ACLR patients were assessed at a mean 11.3 months post-surgery. Initially, participants completed the 6 m timed hop and the single, triple and triple crossover hops for distance, and isokinetic knee extensor and flexor strength assessment. The second session involved completion of the BIA battery, including stability tests, single and double leg countermovement jumps (CMJ), and plyometric, speedy jump, and quick feet tests. Pass rates for test batteries were statistically compared, including the BIA, a four-hop battery ($\geq 90\%$ LSI in every one of the four hop tests) and a combined 4-hop and strength battery ($\geq 90\%$ LSI in every one of the four hop tests, as well as $\geq 90\%$ for both peak knee extensor and flexor strength). LSI differences between the four standard hop tests and the BIA single limb functional tests (the single limb CMJ and the speedy jump test) were evaluated.

Results: Significantly less participants passed the BIA battery ($n=1$, 2.5%), compared with the four-hop test battery ($n=27$, 67.5%) ($p<0.001$) and the four-hop test and isokinetic strength battery ($n=17$, 42.5%) ($p<0.001$). Collectively, LSI's for the standard hop tests were significantly higher than the BIA functional single limb tests (difference = 12.9%, 95% CI: 11.1% to 14.6%, $p<0.001$).

Conclusion: The BIA test battery appears to include some single limb functional tests that are more physically challenging than standard hop and isokinetic strength tests, highlighted by the significantly lower mean LSI's during the single limb BIA tests and the lower pass rate when employing the BIA protocol.

Level of Evidence: Level 4, case series.

Key words: Anterior cruciate ligament, return to sport, limb symmetry index, single limb hop test, isokinetic dynamometry.

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INTRODUCTION

Anterior cruciate ligament (ACL) tears are common,¹ with the estimated rate of re-injury at 15%.² In the 24 months following ACL reconstruction (ACLR) patients are almost six times more likely to re-tear compared to a healthy cohort,³ which remains important given individuals are often informed they can return to sport (RTS) well before 12 months.⁴ A patient's readiness to RTS and/or re-injury risk should they do so, may be influenced by a range of pre-operative (age, pre-operative rehabilitation, knee extension and neuromuscular control), intra-operative (ACLR graft choice) and post-operative (rehabilitation and psychological factors) factors.⁵ One major reported reason is the patient's inability to regain sufficient muscle function and strength.^{6,7} Recent authors have highlighted the increased rate of re-injury in patients who RTS without adequate strength and functional symmetry, derived from tests such as peak isokinetic knee strength evaluation and single-legged hop performance.^{8,9}

Single limb hop tests may be used to evaluate functional symmetry prior to a RTS, often combined in the form of a hop test battery.¹⁰ It has been recommended that these functional hop assessments be complemented along with measures of peak knee extensor and flexor strength.^{6,11} The outcomes of hop tests are generally reported via Limb Symmetry Indices (LSIs),⁷ which present the physical status of the operated limb as a percentage of the non-operated limb. Research has revealed an increased re-injury risk if patients do not meet strength and hop test LSIs of at least 90%,^{8,9} especially those returning to sports involving hard pivoting, cutting, running, twisting and/or turning maneuvers. However, recent research suggests that LSIs frequently overestimate knee function,¹² raising concerns about whether reported LSI cut-offs (i.e. 90%) are high enough to pass these physical tests and/or the tests employed are stringent enough to adequately evaluate lower limb function before RTS. Single limb hop tests have been criticized for not sufficiently evaluating functional capacity in ACLR patients,¹³ while maximal knee extensor and flexor strength measures are not functional movements reflective of a sporting situation. Therefore, various test batteries have been developed in an attempt to create a more comprehensive measure of strength, function and readiness to RTS.^{8,9,14-16}

Recently, a standardized test battery combining various subtests (power, speed, agility, coordination, unilateral cutting and side-to-side movements) was developed, with the intention of determining physical readiness to RTS.^{17,18} This seven-test battery ('Back in Action' - BIA, CoRehab, Trento, Italy) allows for LSIs to be calculated for the individual single limb test components, but further permits comparisons of every test with that of an age and gender matched cohort. Therefore, this battery may include single limb functional tests that may be more physically demanding than standard single limb hop tests. Furthermore, it may overcome some of the existing limitations when employing LSIs to report performance outcomes, such as the inability to evaluate the potential de-conditioning of the non-operated side after surgery (this issue may be bypassed if the comparison is instead made to that of an age and gender matched normative cohort, rather than the non-operated limb).⁷ The BIA test battery has not been compared to routinely employed functional assessments undertaken for the same purpose (determining readiness to RTS), including tests of functional hop capacity and muscle strength.

The purpose of this study was to compare the BIA test battery to standard hop and muscle strength tests used to determine readiness to return to sport (RTS). Firstly, it was hypothesized that significantly less patients would pass the more comprehensive BIA test battery, compared with a standard four-hop test battery ($\geq 90\%$ LSI on all hops), or a combined four-hop and strength test battery ($\geq 90\%$ LSI on all hops, as well as peak isokinetic quadriceps and hamstrings strength). Secondly, it was hypothesized that group mean LSIs would be significantly higher across the four standard hop tests, compared with the more physically demanding single limb functional tests included in the BIA test battery (the single limb CMJ and the speedy jump test).

METHODS

Subjects

A total of 40 participants (25 men, 15 women) were evaluated at a mean of 11.3 months (range: 11-12) after ACLR utilizing a hamstring autograft. Individuals taking any analgesic or anti-inflammatory medications were excluded from this study. Furthermore, any

patient experiencing any persistent pain and/or perceived disability with their operated knee, contralateral knee and/or lower limbs in general, that they felt could affect their ability to participate well in the testing batteries, were excluded from study participation. Patients were also excluded if they had undergone any other ipsilateral or contralateral lower limb surgery, prior to their ACLR. For this study, only patients actively engaging in Level 1 (participation 4-7 days/week) or Level 2 (participation 1-3 days per week) activities that included jumping, hard pivoting, cutting, running, twisting and/or turning sports prior to their injury were included, as reported via the Noyes Activity Score (NAS).¹⁹ Patients who were not planning to return to the aforementioned NAS levels were further excluded.

The mean age of participants included in this study was 23.8 years (range: 15-43) and body mass index was 24.3 (range: 19.6-31.9). A total of 11 participants underwent concomitant meniscectomy. While a detailed review of each patient's rehabilitation was undertaken at the time of initial review, patients recruited for this study had undertaken rehabilitation through different rehabilitation clinics and under guidance from varied therapists and, therefore, they had not embarked on a standardized rehabilitation protocol. While this topic is irrelevant to the aims of the current study, all patients had been discharged from their orthopaedic surgeon's care and cleared to RTS from their individual practitioner. Despite this, upon initial consultation it was clear that only 10 patients (25%) had undergone any formal physical testing including the standard hop tests and/or knee strength measures employed in this study prior to RTS clearance. At the time of testing, 32 patients (80%) had already returned to the aforementioned Level 1 or 2 NAS levels. The other eight patients (20%) had not yet returned for reasons that included: 1) they had only recently been 'cleared' by their individual practitioner, 2) it was the 'offseason' period of their chosen sport and/or 3) other engagements/commitments had more recently interrupted their planned RTS. Ethics approval was obtained from the relevant hospital ethics committee. The written informed consent was obtained by all participants prior to testing, and the rights of all participants were protected.

This study consisted of two testing sessions undertaken within a private rehabilitation clinic, a mean 6.5 days (range 5-9 days) apart by a single therapist. Participants were asked to refrain from any strenuous exercise in the 48 hours prior to each evaluation, and every effort was made to undertake the two testing sessions for each patient at a similar time of day.

Testing Session 1

Firstly, a subjective patient review was undertaken, including the collection of patient demographics, occupational and current activity history employing the NAS,¹⁹ as well as completion of the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form.²⁰ The IKDC is a knee-specific outcome measure evaluating patient-perceived symptoms, physical function and sporting activity, and is scored from 0-100 with higher scores indicating a better score. Secondly, participants underwent the six-minute walk test (6MWT),²¹ employed as a standardized warm up that equally prepared both the operated and non-operated lower limbs. Participants were then offered an optional period of 5-10 minutes to perform any stretches they wanted, which were not standardized and varied between participants based on their own individual preferences and warm up routines.

Thirdly, participants underwent a four-hop test battery performed in the following order: 1) the single hop for distance, 2) the 6 m timed hop, 3) the triple hop for distance, and 4) the triple crossover hop for distance.¹⁰ A custom made mat (6m in length, 15cm in width) was created for the hop tests as described previously,¹⁰ which contained an embedded tape measure to accurately record distance measures. For the 6 m timed hop, a countdown (i.e. "3, 2, 1, go") was provided by the tester positioned at the end of the 6 m distance, with the timer started upon initial patient movement and stopped when the patient passed the 6 m mark. Patients were given a verbal description of the individual test prior to each hop test, and were permitted two to three warm-up hops on each limb (of the single hop for distance) prior to initiating the hop test battery. They were then provided with a single practice attempt on each limb for each of the following three hop tests, immediately prior to the individual test. All hop tests were initially performed

on the unaffected limb, and then alternated between the unaffected and operated limbs. A total of four, two, three and three test trials were collected for the single, 6 m timed, triple and triple crossover hop test, respectively. Previous research has reported three test efforts (one practice and two test efforts) for each of the four hop tests,¹⁰ though anecdotally it has been seen that often the fourth effort for the single hop for distance is required to ensure a peak is attained, while two test efforts for the 6 m timed hop is sufficient. The best effort for each standard hop test was used in the analysis. All distance hop tests were measured to the nearest 0.01 m and the 6 m timed hop to the nearest 0.01 sec using a stopwatch.

Finally, isokinetic strength of the quadriceps and hamstrings muscle groups was assessed using an isokinetic dynamometer (Isosport International, Gepps Cross, South Australia). Peak concentric knee extension and flexion strength were measured through a range of 0-90° of knee flexion, at a single isokinetic angular velocity of 90°/s. In total, three isokinetic strength trials were undertaken on each limb. Each of the three test trials consisted of four repetitions: three low intensity repetitions of knee extension and flexion, immediately followed by one maximal test effort. The first test trial was initiated on the unaffected limb, and then alternated between the unaffected and operated limbs until the six test trials (i.e. three on each limb) were completed. Participants were given adequate rest in between all hop and strength testing trials to minimize fatigue, though this was not standardized, and based upon the patient's readiness to proceed.

Testing Session 2

The second testing session consisted of an identical warm up as session 1, consisting of the 6MWT and optional stretching session, followed by a recently developed and published ACLR test battery (the BIA test battery).^{17,18} The BIA test package comes complete with a laptop and software, accelerometer (Myotester, Myotest S.A., Sion, Switzerland) and waistband, MFT Challenge Disc (TST, Trend Sport Trading, Grosshöflein, Austria) and the Speedy Basic Jump Set (TST Trendsport, Grosshöflein, Austria). Procedures for the BIA test battery have been published,^{17,18} and consist of the double leg stability test, the single leg stability test, a double leg

counter-movement jump (CMJ), a single leg CMJ, a plyometric jump test (consisting of four consecutive plyometric jumps), the speedy jump test and the quick feet test, performed in the above order.^{17,18} These tests are outlined briefly below.

The double and single leg stability tests required participants to stand on the MFT Challenge Disc and balance to the best of their ability over a 20 s period. Initially, participants were permitted time to familiarize with the board to nullify any learning effect. The test required participants to maintain balance for 20 s, standing on two feet with the knees slightly flexed (Figure 1). During the trial, participants received instantaneous visual feedback via a computer screen, in which they were required to keep a marker centered within a target for as much of the 20 s time period as possible (i.e. this was instantaneous feedback on center of pressure). After familiarization with the balance board, participants were provided one practice trial, which was followed by two recorded test trials. This was then followed by a single leg balance test over a 20 s period (Figure 1), following the same protocols. The test was initiated on the unaffected limb (one practice, followed by two test trials), then followed by the operated limb as per the published test battery and dictated by the BIA software package.

The double leg CMJ employed the accelerometer provided with the BIA pack which was fixed firmly

Figure 1. The double (A) and single (B) leg balance tests undertaken as part of the Back in Action (BIA) test battery.

Figure 2. The starting position required for the double (A) and single (B) counter-movement jumps, undertaken as part of the Back in Action (BIA) test battery. Participants were required to quickly flex the knee(s) and jump as high as possible, landing in a controlled manner.

using a Velcro strap around the patient's waist, just above the greater trochanter (Figure 2). Participants were instructed to jump as high and as fast as possible during a single jump, involving a quick bend at the knees and a forceful CMJ, jumping off both feet and landing in a controlled manner. For this test, the jump height (cm) and power output (W/kg) were measured via the accelerometer. An initial single practice jump was performed, followed by five individual recorded test trials, with a break in between each of the five individual test efforts. The best individual effort was employed in the analysis. This was followed by a single leg CMJ (Figure 2), initiated on the unaffected limb (one practice, followed by three individual test trials with a break in between) and followed by the operated limb. The accelerometer was fixed on the same side as the test (jump) leg, just above the greater trochanter. The plyometric jump test also employed the accelerometer, with participants instructed to perform four consecutive jumps off both limbs as high and as fast they could, involving a quick bend at the knees and forceful jumps, landing on both feet after each consecutive jump. Participants were instructed to maximize jump

Figure 3. The speedy jump test undertaken as part of the Back in Action (BIA) test battery. Participants hopped on one leg as fast as they could through the 16-hop course.

height and speed, while minimizing ground contact time between jumps. The jump height (cm) for each of the four jumps were measured. An initial practice test was performed, followed by two test trials.

The speedy jump test required the Speedy Basic Jump Set which was used to create a pre-determined hop coordination course (Figure 3). This consisted of a series of 16 forward, backward and sideways single limb hops, whereby participants were informed that the aim was to perform the hopping course in the shortest time possible. For the hop course, all bars were 50 cm in length, while the height of each hop bar was set at 7 cm from the ground. The timer was initiated when the foot touched the ground in the first hop and was stopped when the foot touched the ground upon completion of the final hop. The test was initiated on the unaffected limb (one practice, followed by two test trials), then followed by the operated limb. The quick feet test also employed the Speedy Basic Jump Set. Participants were instructed

Figure 4. The quick feet test undertaken as part of the Back in Action (BIA) test battery. Participants had to complete 15 full cycles in the shortest possible time, with each cycle starting with both limbs outside the rectangles (A) and then initiated by bringing the operated limb in (B), the unaffected limb in (C), the operated limb out (D) and the unaffected limb out (E).

to repeatedly step into and out of two rectangles side by side, moving one foot after the other, until 15 repetitions were completed (Figure 4). Participants were instructed to complete the test in the shortest possible time, without touching the barriers, initiating the test with their operated limb, followed by their unaffected limb. Participants were provided one practice trial, followed by two recorded test trials.

Development of the BIA test battery involved the evaluation of 434 healthy participants, who each underwent the seven tests.¹⁸ Therefore, while LSIs can be obtained for the individual single limb tests, the normative database also permits comparison of the patient to an age and gender matched unaffected cohort, without any history of lower limb injury or dysfunction. As defined by Hildebrandt et al.¹⁸ this cohort was stratified by gender and age category: Children (10-14 years), Youth (15-19 years), Young Adults (20-29 years) and Adults (30-50 years). Within each of these categories, the mean was considered the average (Norm) and half of the standard deviation was then repeatedly added or subtracted from this average to create five scoring categories: Very Weak (Norm - 1 SD), Weak (Norm - 0.5 SD), Norm, Good (Norm + 0.5 SD), Very Good (Norm + 1 SD). As per the BIA test battery, safety to RTS was indicated by a score of at least 'Norm' in all seven BIA tests; correspondingly, failure to reach this level in all seven tests was deemed failure of the BIA test battery.

Data and Statistical Analysis

Firstly, LSIs were calculated for peak knee extensor and flexor torque, as well as all four standard hop tests undertaken in the first test session, and the single leg stability test, height in the single leg CMJ and time in the speedy jump test undertaken in the second test session as part of the BIA test battery. Where a higher score was indicative of better performance (e.g. peak knee flexor and extensor strength, single limb hops for distance, vertical height and power during CMJs), the LSI was calculated by dividing the best value derived from the operated limb by that of the non-operated limb and converting to a percentage. Where a lower score was indicative of better performance (e.g. 6 m timed hop, time on the speedy hop test and total excursion on the single leg stability test), the LSI was calculated by dividing the best value derived from the non-operated limb by that of the operated limb and converting to a percentage.

McNemar's exact test for dependent proportions was used to statistically compare the pass rates between the testing batteries, including: (1) $\geq 90\%$ LSI on all four hop tests, (2) $\geq 90\%$ LSI on all four hop tests, as well as peak isokinetic quadriceps and hamstrings strength, and (3) the full BIA test battery. An *a priori* power calculation estimated that a sample of 40 provided 85% power to test the hypothesis that of 30 (75%) participants passing the four hop test, 10 or less would not pass a more stringent test (the BIA

test battery). A multilevel linear model was used to test the difference between LSIs measured by the four standard hop tests (the 6 m timed hop and the single, triple and triple crossover hops for distance), versus the two single limb functional tests employed within the BIA test battery (the single limb CMJ and the speedy jump test). An *a priori* power calculation estimated that a sample of 40 provided over 97% power to test the hypothesis that the BIA single limb tests would be at least 5% lower than the four standard hop tests, assuming LSI test standard deviations of 10% and a correlation between tests of 0.6. Data were analysed using Stata/IC for Windows (StataCorp LP, TX USA) and statistical significance was determined at $p < 0.05$.

RESULTS

When employing the standard four-hop test battery and a RTS cut-off pass rate of $\geq 90\%$ for all four hops, 27 participants (67.5%) passed. When combining the standard four-hop test battery with isokinetic knee flexor and extensor strength, and employing a RTS cut-off pass rate of $\geq 90\%$ for all four hop and strength tests, a total of 17 participants (42.5%) passed. Significantly more participants passed the four-hop test in isolation than the four-hop test plus isokinetic strength testing ($p = 0.002$). When employing the complete BIA test battery, only one participant (2.5%) passed all criteria required to RTS. Significantly more participants passed the four-hop test battery in isolation ($p < 0.001$), and the four-hop test battery plus isokinetic strength testing ($p < 0.001$), compared with the BIA test battery.

The mean LSI was $> 90\%$ for all four standard hop tests and peak isokinetic knee extensor and flexor strength, with the majority of patients $\geq 90\%$ LSI for each test (Table 1). The mean LSI was $< 90\%$ for all three single limb tests included in the BIA test battery, with the majority of patients $< 90\%$ LSI for each test (Table 1). Collectively, the participants LSI's for the four standard hop tests were significantly higher than those for the two BIA functional single limb tests (single leg CMJ and speedy jump test) (difference = 12.9%, 95% CI: 11.1% to 14.6%, $p < 0.001$). The number of patients within each category (Very Weak, Weak, Norm, Good, Very Good) for each test, compared with the age and gender matched normative cohort, are provided in Table 2.

DISCUSSION

ACLR is common,¹ though a high incidence of re-tear following surgery has been reported.² While several factors may contribute to re-injury risk, an important reason may be failure to regain muscle function and strength.^{6,7} The most important finding from this study was that the BIA test battery produced a significantly greater RTS fail rate in ACLR participants, when compared with standard testing batteries (including a combination of functional hop and peak muscle strength assessments).

Grindem et al.⁸ employed a RTS test battery that required patients to score $> 90\%$ LSI for quadriceps strength and functional hop capacity, and demonstrated that the re-injury rate was higher for patients who RTS without meeting objective cut-offs

Table 1. Mean International Knee Documentation Committee (IKDC) Subjective Knee Evaluation scores, and mean Limb Symmetry Indices (LSIs – score for the operated limb as a percentage of the non-operated limb) for each of the single limb tests undertaken by participants.

Variable	IKDC	Traditional Hop Test Battery				Isokinetic Knee Strength		Back in Action Single Limb Tests		
		Single Hop LSI	6 m Timed Hop LSI	Triple Hop LSI	Triple Crossover Hop LSI	Knee Extensor Torque LSI	Knee Flexor Torque LSI	Single Leg Stability Test LSI	Single Leg Countermovement Jump LSI	Speedy Jump test LSI
Mean (SD)	86.2 (12.3)	94.7 (7.6)	93.2 (8.9)	94.2 (7.8)	94.7 (9.1)	91.8 (10.7)	96.1 (14.0)	86.1 (9.5)	82.3 (10.6)	80.3 (15.2)
Range	54.0-100.0	69.6-105.0	51.2-102.2	66.7-108.9	60.4-115.4	61.8-110.2	63.9-156.1	71.5-105.2	51.1-108.6	25.2-105.0
$< 90\%$ LSI (n)	N/A	9	13	12	8	20	13	23	29	27
$\geq 90\%$ LSI (n)	N/A	31	27	28	32	20	27	17	11	13

Table 2. The number (n) of participants in each category (compared to normative data) for the seven Back in Action (BIA) tests employed as part of the BIA test battery, including the double and single leg stability tests, the double and single leg countermovement jumps (CMJ) (absolute jump height and power), the plyometric jump (absolute jump height and contact time), the speedy jump test and the quick feet test. Within each of these categories, the patient was compared to the normative data and mean of the normative data was considered the average (Norm), with half of the standard deviation then repeatedly added or subtracted from this average to create five scoring categories: Very Weak (Norm – 1 SD), Weak (Norm – 0.5 SD), Norm, Good (Norm + 0.5 SD), Very Good (Norm + 1 SD).

Category	Double leg stability test	Single leg stability test - Unaffected limb	Single leg stability test - Operated limb	Double leg CMJ (absolute jump height)	Double leg CMJ (power)	Single leg CMJ (absolute jump height) - Unaffected Limb	Single leg CMJ (absolute jump height) - Operated Limb
VERY GOOD (n)	0	1	0	1	8	0	0
GOOD (n)	8	9	9	8	14	2	0
NORM (n)	18	17	18	14	14	23	11
WEAK (n)	5	7	7	8	2	4	6
VERY WEAK (n)	9	6	6	9	2	11	23
Category	Single leg CMJ (power) - Unaffected Limb	Single leg CMJ (power) - Operated Limb	Plyometric jump (absolute jump height)	Plyometric jump (contact time)	Speedy jump test - Unaffected limb	Speedy jump test - Operated limb	Quick feet test
VERY GOOD (n)	19	6	2	1	2	0	2
GOOD (n)	6	7	2	2	3	3	3
NORM (n)	11	23	11	11	11	9	13
WEAK (n)	2	2	11	11	4	6	4
VERY WEAK (n)	2	2	14	15	20	22	18

(38.2%), versus those who did (5.6%). Similarly, Kyritsis et al.⁹ reported a four times greater re-injury risk in those who RTS after ACLR, if not meeting certain discharge criteria including >90% LSIs in three of the hop tests employed in the current study, as well as peak isokinetic quadriceps strength. While the present study did not evaluate re-injury rates associated with poor lower limb strength and/or functional symmetry, considering the requirement of >90% LSIs in hop and strength symmetry in existing test batteries, 17 participants (42.5%) in this study would have been considered physically ready to RTS.

In comparison to the current findings, Toole et al.²² recently demonstrated an inability of many young patients already cleared to RTS, to pass similar RTS cut-offs as that employed in the current study. Similar to the current study, the mean LSIs for hop and strength measures were all generally around or above 90%, though only 53% of patients were able to achieve ≥90% in all four standard hop tests, with only 13.9% able to score ≥90% in all four standard hop tests as well as peak isokinetic knee strength (they also included a score >90 on the IKDC). Another

recent study also demonstrated the high proportion of community-level patients already engaging (or seeking engagement) in sport who were <90% LSI on many of the standard hop and strength measures employed, when assessed at a mean 11.0 months (range 10-14) post-surgery.²³ Therefore, even with more conventional physical testing methods, these combined results are alarming particularly given the association between re-injury and a failure to meet existing reported cut-offs in these tests.

Only one patient passed the full BIA test battery, and the almost universal failure rate was significantly higher than a battery consisting of standard functional hop tests, even when supplemented with peak isokinetic strength testing. Comparison of participants in all tests (operated and non-operated limbs) to a healthy age and gender matched cohort proved the contributing factor in overall failure rates of the BIA battery. An argument could be made to suggest that the BIA test battery is too rigorous and not realistically attainable, given the low pass rate. The authors of this study would disagree, given the anecdotal evidence of healthy subjects (of varied

ages and activity levels) consistently passing the battery, as well as the fact that the threshold required to pass each of the seven tests is relatively low, given each is based on attaining an 'average' score.

When considering the single limb CMJ employed in the BIA test battery, 29 participants were below average on the operated limb, while 15 participants were still below average on the non-operated limb. Studies have shown that reduced strength may occur in the non-operated limb after ACLR.^{24,25} Whether this was pre-existing or a result of the lengthy period of relative inactivity post-surgery, the true deterioration after surgery and the contribution it plays to the calculation of LSIs is unknown, though must be addressed prior to a RTS. This was also the case for the speedy jump test, whereby 28 (70%) and 24 (60%) participants were below average on the operated and non-operated limbs, respectively, compared to normative data. Even the four-jump plyometric test, which permits the use of both limbs, showed that the majority of participants (63%) were below average. Finally, the speedy jump and quick feet tests which assess speed showed the majority of participants were below average compared to norms. As outlined in the recommendations of Kyritsis et al.,⁹ in addition to addressing lower limb strength and functional deficits, readiness to RTS should also be based on the patient's ability to complete on-field sport-specific rehabilitation. In this context, the BIA test battery may be useful earlier in the rehabilitation program to identify deficits, as well as later in the program to help guide patients toward a sport-specific conditioning program and/or eventual RTS.

Recent studies have demonstrated an increased re-injury risk if patients do not meet objective test LSIs within testing batteries of $\geq 90\%$ before RTS,^{8,9} inclusive of functional hop and strength assessments. While this evidence does support the use of these physical objective tests in reducing the risk of knee re-injury, it may be argued that reported LSI cut-offs (i.e. 90%) are not high enough to be considered 'passing'. This may essentially set a lower required performance pass rate in a patient who may actually require lower limb strength and functional abilities beyond their pre-injury status. Furthermore, given recent research has suggested that LSIs overestimate knee function,¹² standard testing methods (e.g.

standard single-legged hop tests) may not be stringent enough to adequately evaluate lower limb function, and achieve a safe and successful RTS. As mentioned above, LSIs do not account for limb asymmetry that may have existed prior to the initial injury, nor the potential de-conditioning of the non-operated side after surgery.⁷ These are barriers encountered when evaluating outcomes in community level patients who do not have pre-injury comparative measures.

Maximal knee extensor and flexor strength measures, although objective and reliable, are not functional movements reflective of sport, and hop tests have been criticized for not sufficiently evaluating functional capacity in ACLR patients.¹³ While the group mean LSI for each of the four hop tests ranged from 93-95%, the group mean LSI for the single leg CMJ (i.e. single leg vertical hop) and the speedy jump test within the BIA battery were significantly lower, being 82% and 80%, respectively. Only 28% (single limb CMJ) and 33% (speedy jump test) of participants were $\geq 90\%$ LSI for these tests. The aim of the single limb CMJ is to generate maximum power to propel the body upwards against gravity, while the speedy jump test evaluates function in forwards, sideways and backwards directions over 16 consecutive hops. Three out of four of the standard hop tests evaluate functional hop capacity in a horizontal and forwards direction only and, while the triple crossover hop for distance does involve some cross directional movement, the magnitude of these angular movements are relatively low given the patient only needs to cross over a 15 cm mat. Therefore, the speedy jump test may be more physically demanding and therefore sensitive to side-to-side differences in functional capacity, compared with the standard hop tests.

In addition to the nature of the test, it is important to note that the single leg CMJ employed as part of the BIA battery requires participants to have their hands fixed on their waist, while arms were not fixed during the four-hop test battery. The decision to allow the use of the arms was made with the aim of closely following the four-hop test battery previously published by Reid et al.,¹⁰ which placed no restrictions on the use of the arms. A study by Gustavsson et al.²⁶ found a strong correlation between the single hop for distance and the vertical jump performed as a CMJ, though the arms were fixed for both tests. Hamilton et

al.²⁷ reported a strong correlation between triple hop for distance and vertical jump performed as a CMJ, with arm action being unrestricted during both tests. By controlling hand position and the use of the arms for propulsion, participants are only able to generate power through their lower limbs. As a result, future studies should consider the possible contribution of unrestricted arm action on patient's scores and control for this by outlining restrictions within the four-hop test battery. Nevertheless, while restricted (or unrestricted) arm use may affect performance, it would likely not affect side-to-side LSIs during the hop tests.

Finally, the single limb stability test employed as a measure of balance and postural control, demonstrated a mean LSI of 86%. Barber-Westin et al.²⁸ reported that deficits in balance, proprioception and neuromuscular control persist for months post-surgery, and suggested that dynamic neuromuscular control should be assessed before embarking on a RTS. While limited evidence exists as to the link between proprioceptive deficits and function in ACL-deficient and post-operative ACLR patients,²⁹ it has been suggested that a longer post-operative recovery phase may be needed until proprioceptive deficits are resolved.³⁰ The standard four-hop test battery used in this study fails to examine this construct directly, with the only indication that a deficit exists observed through the patient's ability to control the landing of the final hop. Thorough therapist assessment of jumping and landing control, as well as lower limb and trunk mechanics is imperative during these hop tests. However, while inability to control the land during a single limb hop test of any kind would rule the test ineligible, losses of control or biomechanical imperfections are often not quantified. Patients may score well on performance-based tests and present with sound LSIs, in the absence of quality hopping and landing biomechanics (such as lower limb and trunk alignment, adequate knee flexion on weight acceptance and excessive ground reaction forces). Therefore, 'biomechanical symmetry' in addition to 'performance symmetry' should still be evaluated throughout these testing batteries, given its potential link to ACL injuries.³¹⁻³³

Some limitations in this study are acknowledged. Firstly, two testing batteries were undertaken over

two different sessions in order to minimize any fatigue effect and, while every effort was made to standardize the test conditions, the order of the two test sessions was not randomized. Secondly, for the standard four-hop battery and isokinetic knee strength evaluations, testing alternated between the unaffected and affected limb minimizing any learning effect. However, each test of the BIA battery was always initiated on the unaffected limb, completing all required practice and test efforts before repeating the process on the operated limb. Therefore, there is the possibility that the results obtained from the operated limb could be exaggerated in comparison to the unaffected limb, given the proficiency gained through prior learning. The BIA tests, however, reported lower mean LSIs when compared with the standard hop and strength tests, which would suggest that this possible learning effect may have only presented the LSIs better than they actually were. Thirdly, this study only evaluated patients who had undergone ACLR utilizing hamstring autografts in order to better standardize the cohort. However, while caution should be applied in generalized surgical outcomes across all graft types, research does suggest that post-operative strength and functional outcomes do not significantly differ between hamstrings autografts and other reconstruction methods.³⁴⁻³⁷ Fourthly, it is acknowledged that the patients recruited for this study received guidance from different rehabilitation clinics and under varied therapists and, therefore, they did not have a standardized rehabilitation protocol. While it was recently demonstrated that rehabilitation is associated with performance during standard hop and strength measures,²³ this study sought to investigate differences amongst tests and testing batteries within patients, rather than between patients (making varied rehabilitation pathways irrelevant for this study), at a time when many patients assume (and are informed) they can return to their chosen sport.

While the comparison of performance outcomes to an age and gender matched healthy cohort is considered an advantage of the BIA test battery, this comparison remains limited by the large range of ages included in each sub-grouping. For example, a 28 year old patient would be compared to the young adult bracket (20-29 years), meaning that while the comparison to individuals in the upper end of the age bracket would

be appropriate, there would also be comparison to a younger population. Furthermore, published studies highlighting the development of the BIA test battery failed to provide detailed information on the characteristics of the normative cohort (other than gender, age, height, weight and body mass index, as well as stating that subjects were engaging in competitive sports).^{17,18} Therefore, normative data relating to a specific activity or sport that may be developed over time, will permit matching these ACLR patients more closely for the demands required of the specific sport. At this stage, patients are being matched with healthy subjects engaging in competitive sport, without knowing the exact sports. This will further improve the utility of the BIA test battery above and beyond reporting LSIs during standard tests of hop function and strength. Finally, this study did not seek to investigate actual ACL re-tears in patients returning to sport, and their association with LSI and BIA test battery outcomes. This provides an important avenue for future research, in determining whether the BIA test battery has an improved ability over standard hop and strength tests in predicting re-injury.

CONCLUSION

The BIA test battery appears to include some single limb functional tests that are more physically challenging than standard hop and isokinetic strength tests, highlighted by the significantly lower mean LSI's during the single limb BIA tests and the lower pass rate when employing the BIA protocol. Future research should seek to investigate the association between outcomes measured using the BIA and the rate of secondary re-injury.

REFERENCES

1. Salmon L, Russell V, Musgrove T, et al. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21(8):948-957.
2. Wiggins AJ, Grandhi RK, Schneider DK, et al. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Am J Sports Med*. 2016;44(7):1861-1876.
3. Paterno MV, Rauh MJ, Schmitt LC, et al. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42(7):1567-1573.
4. Ardern CL, Webster KE, Taylor NF, et al. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med*. 2011;39(3):538-543.
5. Irarrázaval S, Kurosaka M, Cohen M, et al. Anterior cruciate ligament reconstruction. *J ISAKOS*. 2016;1:38-52.
6. Thomee R, Kaplan Y, Kvist J, et al. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(11):1798-1805.
7. Thomee R, Neeter C, Gustavsson A, et al. Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(6):1143-1151.
8. Grindem H, Snyder-Mackler L, Moksnes H, et al. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50(13):804-808.
9. Kyritsis P, Bahr R, Landreau P, et al. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *Br J Sports Med*. 2016;50(15):946-951.
10. Reid A, Birmingham TB, Stratford PW, et al. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther*. 2007;87(3):337-349.
11. Lynch AD, Logerstedt DS, Grindem H, et al. Consensus criteria for defining 'successful outcome' after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. *Br J Sports Med*. 2015;49(5):335-342.
12. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb Symmetry Indexes Can Overestimate Knee Function After Anterior Cruciate Ligament Injury. *J Orthop Sports Phys Ther*. 2017;47(5):334-338.
13. Narducci E, Waltz A, Gorski K, et al. The clinical utility of functional performance tests within one-year post-acl reconstruction: a systematic review. *Int J Sports Phys Ther*. 2011;6(4):333-342.
14. Bjorklund K, Andersson L, Dalen N. Validity and responsiveness of the test of athletes with knee injuries: the new criterion based functional performance test instrument. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(5):435-445.
15. Bjorklund K, Skold C, Andersson L, et al. Reliability of a criterion-based test of athletes with knee injuries; where the physiotherapist and the patient

- independently and simultaneously assess the patient's performance. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(2):165-175.
16. Gokeler A, Welling W, Zaffagnini S, et al. Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2016;25(1):192-199.
17. Herbst E, Hoser C, Hildebrandt C, et al. Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part II: clinical application of a new test battery. *Knee Surg Sports Traumatol Arthrosc.* 2015;23(5):1283-1291.
18. Hildebrandt C, Muller L, Zisch B, et al. Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part I: development of a new test battery. *Knee Surg Sports Traumatol Arthrosc.* 2015;23(5):1273-1281.
19. Noyes FR, Barber SD, Mooar LA. A rationale for assessing sports activity levels and limitations in knee disorders. *Clin Orthop Relat Res.* 1989(246):238-249.
20. Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the international knee documentation committee subjective knee form. *Am J Sports Med.* 2001;29(5):600-613.
21. Enright PL. The six-minute walk test. *Respiratory care.* 2003;48(8):783-785.
22. Toole AR, Ithurburn MP, Rauh MJ, et al. Young athletes cleared for sports participation after anterior cruciate ligament reconstruction: How many actually meet recommended return-to-sport criterion cutoffs? *J Orthop Sports Phys Ther.* 2017;47(11):825-833.
23. Ebert JR, Edwards P, Yi L, et al. Strength and functional symmetry is associated with post-operative rehabilitation in patients following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2017; doi: 10.1007/s00167-017-4712-6.
24. Hiemstra LA, Webber S, MacDonald PB, et al. Contralateral limb strength deficits after anterior cruciate ligament reconstruction using a hamstring tendon graft. *Clin Biomech (Bristol, Avon).* 2007;22(5):543-550.
25. Larsen JB, Farup J, Lind M, et al. Muscle strength and functional performance is markedly impaired at the recommended time point for sport return after anterior cruciate ligament reconstruction in recreational athletes. *Hum Mov Sci.* 2015;39:73-87.
26. Gustavsson A, Neeter C, Thomee P, et al. A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(8):778-788.
27. Hamilton RT, Shultz SJ, Schmitz RJ, et al. Triple-hop distance as a valid predictor of lower limb strength and power. *J Athl Train.* 2008;43(2):144-151.
28. Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed.* 2011;39(3):100-110.
29. 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.
30. Iwasa J, Ochi M, Adachi N, et al. Proprioceptive improvement in knees with anterior cruciate ligament reconstruction. *Clin Orthop Relat Res.* 2000(381):168-176.
31. Myer GD, Ford KR, Khoury J, et al. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *Br J Sports Med.* 2011;45(4):245-252.
32. Pappas E, Shiyko MP, Ford KR, et al. Biomechanical deficit profiles associated with ACL injury risk in female athletes. *Med Sci Sports Exerc.* 2016;48(1):107-113.
33. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
34. Bjornsson H, Samuelsson K, Sundemo D, et al. A randomized controlled trial with mean 16-year follow-up comparing hamstring and patellar tendon autografts in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2016;44(9):2304-2313.
35. Chee MY, Chen Y, Pearce CJ, et al. Outcome of patellar tendon versus 4-strand hamstring tendon autografts for anterior cruciate ligament reconstruction: A systematic review and meta-analysis of prospective randomized trials. *Arthroscopy.* 2017;33(2):450-463.
36. Herrington L, Wrapson C, Matthews M, et al. Anterior cruciate ligament reconstruction, hamstring versus bone-patella tendon-bone grafts: a systematic literature review of outcome from surgery. *Knee.* 2005;12(1):41-50.
37. Holm I, Oiestad BE, Risberg MA, et al. No difference in knee function or prevalence of osteoarthritis after reconstruction of the anterior cruciate ligament with 4-strand hamstring autograft versus patellar tendon-bone autograft: a randomized study with 10-year follow-up. *Am J Sports Med.* 2010;38(3):448-454.