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Test–retest reliability and discriminative ability of forward, medial and rotational single-leg hop tests

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ABSTRACT

Background: Single-leg hop tests are commonly performed in the forward direction to evaluate functional performance. However, athletes move in multiple directions during pivoting sports. The first aim of this study was to examine test–retest reliability of single-leg hop tests in the forward, medial and rotational direction in non-injured athletes. Second, the discriminative ability to detect leg asymmetries with these hop tests in anterior cruciate ligament (ACL) reconstructed athletes was determined.

Methods: Sixteen recreational non-injured participants (eight females, eight males; 22.4 ± 1.9 years) were tested twice (one-week interval) and performed the single hop for distance (SH), triple hop for distance (TH), medial side triple hop for distance (MSTH) and 90° medial rotation hop for distance (MRH). Intraclass correlation coefficients (ICCs), standard errors of measurement (SEM) and smallest detectable differences (SDD) were calculated. Discriminative ability was determined in 32 ACL-reconstructed participants (four females, 28 males; 24.4 ± 4.6 years; six months postoperative) who performed the same hop tests once.

Results: The ICCs ranged between 0.93 and 0.98. The SEM and SDD were respectively 2.6–4.1% and 7.2–11.3% of the mean hop distance of the group. The proportion (%) of ACL-reconstructed participants passing the ≥90% limb symmetry cut-off was 62.5 (SH), 59.4 (TH), 40.6 (MSTH) and 46.9 (MRH).

Conclusion: Excellent test–retest reliability of forward, medial and rotational hop tests was found. This allows clinicians to make informed interpretations of changes in hop test distances when retesting athletes. Medial and rotational hop tests are more likely to show limb asymmetries in ACL-reconstructed participants compared to forward hop tests.

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1. Introduction

Physical performance measures such as single-leg hop tests are frequently used to assess the functional status of an athlete, detect limb asymmetries and monitor progression throughout an intervention [1–4]. These tests are easy to administer and only require minimal equipment, time and expertise [1].

A series of four single-leg hop tests including single hop for distance (SH), triple hop for distance (TH), crossover hop for distance and 6 m timed hop was originally described by Noyes et al. [5]. A limitation of the original hop test battery is that these tests predominantly consist of straight movements in the forward direction [6]. However, athletes move in multiple directions during pivoting sports [7]. Exclusively focusing on forward hop tests might limit the potential to elicit relevant deficits, typically expressed in terms of limb asymmetry, in function of performance enhancement, prevention or rehabilitation [8–10]. However, studies evaluating both relative and absolute reliability measures of multidirectional hop tests in comparison with forward-directed hop tests are lacking. Several test–retest reliability studies focusing on forward hop tests have been published in non-injured [2,11–16] and injured athletes [3,15,17], but the methodological quality is generally low [1,18,19]. Before multidirectional hop tests can be used confidently as an outcome measure across an intervention, it is critical that the measurement properties are known [1,18,19]. This will allow clinicians to make informed clinical decisions whether an observed change in the performance of hop tests is a meaningful change.

A decreased performance on the traditional set of hop tests has been related to self-reported function [20,21] and re-injury risk after anterior cruciate ligament (ACL) reconstruction [22–24]. Nevertheless, increased limb asymmetry has been reported during the side hop compared to the SH in the forward direction, leading to a lower percentage of ACL-reconstructed patients reaching satisfactory limb symmetry [17,25,26]. Therefore, the inclusion of multidirectional hop tests within the return to sport decision-making process after ACL reconstruction has been recommended to detect limb asymmetries [6], but more rigorous data are needed to support this suggestion.

The first aim of this study was to examine the test–retest reliability of single-leg hop tests in the forward, medial and rotational direction. Secondly, we aimed to investigate the discriminative ability to detect limb asymmetries of medial and rotational hop tests, in comparison with forward hop tests in a population of participants after ACL reconstruction.

2. Materials and methods

2.1. Participants

2.1.1. Test–retest reliability in non-injured participants

Sixteen recreational participants (eight females, eight males; age: mean ± SD = 22.4 ± 1.9 years; weight: mean ± SD = 68.1 ± 10.3 kg; height: mean ± SD = 176.3 ± 9.3 cm; body mass index: mean ± SD = 21.8 ± 2.1 kg/m^2) participated in the study. All participants participated in multidirectional sports (11 football (soccer), four volleyball, one multisport including kickboxing) [7]. Inclusion criteria for the study were (1) age 18–45 years, (2) no musculoskeletal injuries of the lumbar spine or lower limb in the last six months and (3) willing to sign the informed consent form. Exclusion criteria were (1) history of a major trauma and/or major orthopedic surgery in lumbar spine, pelvis or lower limb, and (2) presence of one of the following conditions/constitutions: neurologic or vestibular disorders, pregnancy.

2.1.2. Discriminative ability in ACL-reconstructed participants

Thirty-two ACL-reconstructed participants (four females, 28 males; age: mean ± SD = 24.6 ± 4.6 years; weight: mean ± SD = 77.0 ± 11.3 kg; height: mean ± SD = 177.3 ± 7.2 cm; body mass index: mean ± SD = 24.4 ± 2.6 kg/m^2, 6.2 ± 0.3 months postoperatively) participated in the study. Inclusion criteria were (1) unilateral ACL reconstruction with an ipsilateral hamstring autograft, six months postoperatively, (2) age 18–45 years, (3) willing to sign the informed consent form. Exclusion criteria were (1) a revision ACL reconstruction, (2) meniscectomy involving more than one third of the meniscus, (3) posttraumatic cartilage lesions (Outerbridge > grade 2) [27], assessed pre-operatively by magnetic resonance imaging and arthroscopically, (4) history of a grade 3 injury to the posterior cruciate ligament or collateral ligaments, or injury of the posterolateral corner of the ACL-reconstructed knee, (5) history of a grade 3 ligamentous injury in the contralateral knee, (6) history of a major trauma and/or major orthopedic surgery in the lumbar spine, pelvis or lower limb (except the ACL reconstruction), (7) presence of one of the following conditions/constitutions: neurologic or vestibular disorders, pregnancy. The ACL reconstruction was performed on the knee of the dominant leg, defined by the preferred leg to kick a ball, in 19 of the 32 participants (59%). All participants were operated in the same hospital with the same orthopedic procedure. Rehabilitation was not controlled for the current study, as this was performed in different private clinical practices. The scores on patient-reported outcome measures (mean ± SD) were 58.3 ± 20.0 for ACL-Return to Sports after Injury (ACL-RSI) scale [28,29], 77.3 ± 12.9 for International Knee Documentation Committee (IKDC) subjective knee form [30,31], 76.1 ± 17.2 for Knee injury and Osteoarthritis Outcome Score (KOOS) pain subscale [32,33], 85.5 ± 12.3 for KOOS symptoms subscale, 92.9 ± 11.0 for KOOS activities of daily living subscale, 71.2 ± 21.1 for KOOS sport/recreation subscale and 63.4 ± 16.9 for KOOS quality of life subscale. All participants participated in multidirectional sport activities before the ACL injury.

Appropriate ethical approval was granted by the local ethical committee prior to the commencement of the study. Before participating in the study, all participants read and signed the informed consent form.

2.2. Procedure and measurements

All participants wore a short, t-shirt and their own sports shoes. Before the start of the tests, all participants executed a standardized warm-up program, consisting of a series of double-leg squats (2 × 8) and jumps (2 × 5) [34].

The following single-leg hop tests were performed: SH, TH, medial side triple hop for distance (MSTH) and 90° medial rotation hop for distance (MRH). For the SH, participants were instructed to stand on the leg to be tested, hopped as far as possible in the forward direction and landed on the same leg [3,5]. For the TH, participants were instructed to stand on the leg to be tested, performed three consecutive maximal forward hops and landed on the same leg [3,5]. The total hop distance was measured from toe to toe for SH and TH (Fig. 1). For the MSTH, participants were instructed to stand on the leg to be tested, with the medial side of the foot perpendicular to the hop direction [35–37]. Three consecutive hops were performed on the same leg, landing on the same leg as far as possible in the direction of the rolling meter (medial direction of the stance leg). The direction of the foot had to remain perpendicular to the hop direction. The total hop distance of the three consecutive hops was measured from the medial side of the foot at take-off to the medial side of the foot at landing (Fig. 1). For the MRH, participants were instructed to stand on the leg to be tested, with the medial side of the foot perpendicular to the hop direction. One single-leg jump was performed in the transversal plane, hereby rotating 90° in the medial direction during the swing phase. The foot was not allowed to rotate in the direction of the jump prior to take-off. At landing, the foot should be directed in the direction of the rolling meter. This direction was checked visually by the examiner. Trials where participants failed to land in the direction of the rolling meter (>10° deviation from the rolling meter) were excluded. The hop distance was measured from the medial side of the foot at take-off to the toes at landing (Fig. 1).

The procedures of each hop test were first explained and each hop test was demonstrated by the examiner. For each hop test, one practice trial was allowed for each leg to familiarize with the test procedures. Each test was performed three times, alternating between the dominant and non-dominant leg, beginning with the non-dominant leg. The dominant leg was defined as the preferred leg to kick a ball. For the ACL-reconstructed participants, the non-operated leg was always tested first, and both legs were tested in an alternating order. The best performance (maximum distance to the nearest cm) of three trials of each test was the outcome measure. If the maximum distance was achieved during the third repetition, one additional trial was allowed. If the maximum distance was achieved during this fourth trial, this was used for data analysis. Before each test, participants were instructed to jump as far as possible in the direction of the rolling meter that was attached on the floor. Participants were allowed to freely use their arms during the hop tests, and no standardization was given for the positioning of the uninvolved leg to ensure a more natural movement pattern [35]. All tests were graded by the same examiner.

A hop test was considered successful if the participant was able to maintain the landing for at least two seconds [3]. A hop test was considered unsuccessful when the participant touched the floor with the contralateral lower or upper extremities, lost balance, or needed an additional short hop after the initial landing [3]. After a failed trial, participants were reminded of the requirement to maintain balance for two seconds at landing, and allowed to do a new attempt [3]. After each trial of the same hop, a rest interval of 30 s was used [3]. To minimize fatigue, a rest period up to two minutes was provided between each of the different hop tests [3]. The order of tests was randomized by asking each participant to give a random order of the numbers 1–4. The order of hop tests was the same on both test sessions for each participant of the reliability study. The non-injured participants were tested twice with a one-week interval. The ACL-reconstructed participants were tested only once.

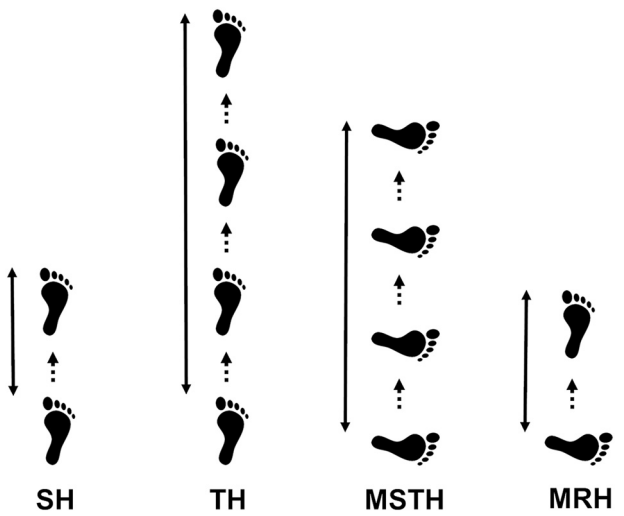

Figure 1. Graphical illustration of the single-leg hop tests including single hop for distance (SH), triple hop for distance (TH), medial side triple hop for distance (MSTH), 90° medial rotation hop for distance (MRH). The solid vertical arrow indicates how the hop distance was measured.

Table 1
Test–retest reliability of hop tests.

	Absolute difference between measures (cm) (mean (SD))	$ICC_{2,2}$ (95% CI)	SEM (cm)	SDD (cm)	SDD/hop distance (%)
Dominant leg					
Single leg hop for distance	10.0 (10.1)	0.94 (0.83–0.98)	7.1	19.6	10.4
Triple hop for distance	21.3 (19.2)	0.97 (0.92–0.99)	14.1	39.1	7.2
Medial side triple hop for distance	20.0 (13.6)	0.98 (0.94–0.99)	12.0	33.3	8.1
Medial rotation hop for distance	9.1 (7.6)	0.95 (0.84–0.98)	5.9	16.4	9.5
Non-dominant leg					
Single leg hop for distance	8.6 (7.6)	0.96 (0.90–0.99)	5.7	15.7	8.3
Triple hop for distance	27.4 (18.1)	0.96 (0.89–0.99)	16.3	45.1	8.3
Medial side triple hop for distance	24.5 (19.8)	0.97 (0.90–0.99)	15.4	42.7	10.4
Medial rotation hop for distance	10.4 (9.4)	0.93 (0.80–0.98)	7.0	19.5	11.3

SD: standard deviation; ICC: intraclass correlation coefficients; CI: confidence interval; SEM: standard error of measurement; SDD: smallest detectable difference.

2.3. Data analysis

2.3.1. Test–retest reliability in non-injured participants

The absolute differences of the hop distances between test and retest, and intraclass correlation coefficients ($ICC_{2,2}$) were calculated for both the dominant and non-dominant leg. The ICC values were interpreted as poor (<0.50), moderate (0.50–0.74), good (0.75–0.89) or excellent (0.90–1.00) [38]. The standard error of measurement (SEM) and smallest detectable difference (SDD) were calculated using the formulas $SD * \sqrt{(1\text{-ICC})}$ and $1.96 * SEM * \sqrt{2}$ respectively [39]. To facilitate the interpretation of the SEM and SDD, we also calculated the percentages of the SEM and SDD of the mean distance of each hop test. All data were normally distributed (Shapiro–Wilk). Differences between hop test distances at test and retest were compared with paired *t* tests. Statistical significance was set at $P < .05$.

2.3.2. Limb symmetry index and absolute limb symmetry index in non-injured participants

All hop distances were normally distributed (Shapiro–Wilk). The hop distance of the dominant and non-dominant leg was compared at both sessions with paired *t* tests. The limb symmetry index was calculated for each test, by dividing the hop distance of the dominant leg by the hop distance of the non-dominant leg, multiplied by 100 (%) [2]. Limb symmetry indices were compared between sessions with paired *t* tests. Within each session, differences between limb symmetry indices of the different hop tests were evaluated with repeated measure analysis of variance (ANOVA). Statistical significance was set at $P < .05$.

As the dominant or non-dominant leg was not consistently the leg with the best performance, absolute limb symmetry indices were calculated by the absolute difference between 100% and the limb symmetry index for each participant and each test. These absolute limb symmetry indices were mainly not normally distributed (Shapiro–Wilk). Absolute limb symmetry indices were compared between sessions with Wilcoxon signed-rank tests. Within each session, differences between absolute limb symmetry indices of the different hop tests were evaluated with Friedman tests. Statistical significance was set at $P < .05$.

In addition, we calculated the proportion of participants (%) passing different cut-off levels for the limb symmetry index (≥85%, ≥90%, ≥95% ≥100%) and the absolute limb symmetry index (≤15%, ≤10%, ≤5%), for each hop test of the first session.

2.3.3. Discriminative ability in ACL-reconstructed participants

The absolute distances of the operated and non-operated leg were compared for each hop test with Wilcoxon signed-rank tests, as the operated leg of all hop tests was not normally distributed (Shapiro–Wilk). The limb symmetry index was calculated for each hop test of each participant in the ACL-reconstructed group. Absolute limb symmetry indices were not calculated, as the

Table 2
Differences between test and retest.

	Test (cm) (mean (SD))	Retest (cm) (mean (SD))	*P* value
Dominant leg			
Single leg hop for distance	186.9 (30.0)	190.9 (27.5)	0.265
Triple hop for distance	549.3 (87.6)	539.5 (83.5)	0.174
Medial side triple hop for distance	407.3 (80.4)	416 (84.2)	0.120
Medial rotation hop for distance	172.0 (27.2)	173.7 (24.0)	0.580
Non-dominant leg			
Single leg hop for distance	188.9 (30.7)	192.2 (29.9)	0.265
Triple hop for distance	545.6 (79.9)	538.4 (87.2)	0.394
Medial side triple hop for distance	403.3 (94.4)	417.9 (82.6)	0.057
Medial rotation hop for distance	171.3 (28.7)	174.9 (24.7)	0.307

SD: standard deviation.

Table 3
Differences between the limb symmetry index at test and retest.

	Test (%) (mean (SD))	Retest (%) (mean (SD))	*P* value
Single leg hop for distance	99.1 (5.4)	99.7 (5.5)	0.642
Triple hop for distance	100.6 (5.7)	100.4 (4.4)	0.827
Medial side triple hop for distance	102.1 (9.7)	99.9 (7.3)	0.303
Medial rotation hop for distance	100.8 (7.8)	99.4 (5.7)	0.392

SD: standard deviation.

injured leg is consistently compared with the non-injured leg within an injured group. All limb symmetry indices were not normally distributed (Shapiro–Wilk). To evaluate whether differences between limb symmetry indices would exist between hop tests, Friedman tests were conducted. Statistical significance was set at $P < .05$.

The proportion of participants (%) passing different cut-off levels for the limb symmetry index (≥85%, ≥90%, ≥95%, ≥100%) were calculated for each hop test.

All statistical analyses were performed using SPSS (SPSS Science, version 24 for Windows, USA).

3. Results

3.1. Test–retest reliability in non-injured participants

Excellent test–retest reliability was found for all hop tests, with ICC values ranging from 0.93 to 0.98. The SEM for SH, TH, MSTH and MRH were respectively 5.7–7.1 cm, 14.1–16.3 cm, 12.0–15.4 cm and 5.9–7.0 cm (2.6–4.1% of the mean distance of each hop test). The SDD for SH, TH, MSTH and MRH were respectively 15.7–19.6 cm, 39.1–45.1 cm, 33.3–42.7 cm and 16.4–19.5 cm (7.2–11.3% of the mean distance of each hop test). The absolute differences, ICC, SEM, SDD and SDD/hop distance values of all hop tests are presented in Table 1. All hop distances were not significantly different between test and retest ($P > .05$) (Table 2).

3.2. Limb symmetry index and absolute limb symmetry index in non-injured participants

No statistically significant differences were found between the dominant and non-dominant leg at test and retest ($P > .05$). The limb symmetry indices ranged between 99.1% and 102.1%, and were not different between test and retest ($P > .05$) (Table 3). The repeated measures ANOVA determined no significant differences between limb symmetry indices of different hop tests within each session ($P > .05$).

The absolute limb symmetry index was significantly lower at retest for MRH compared to the first test session ($P = .027$)(Fig. 2.). Friedman tests determined no significant differences between absolute limb symmetry indices of different hop tests within each session ($P > .05$).

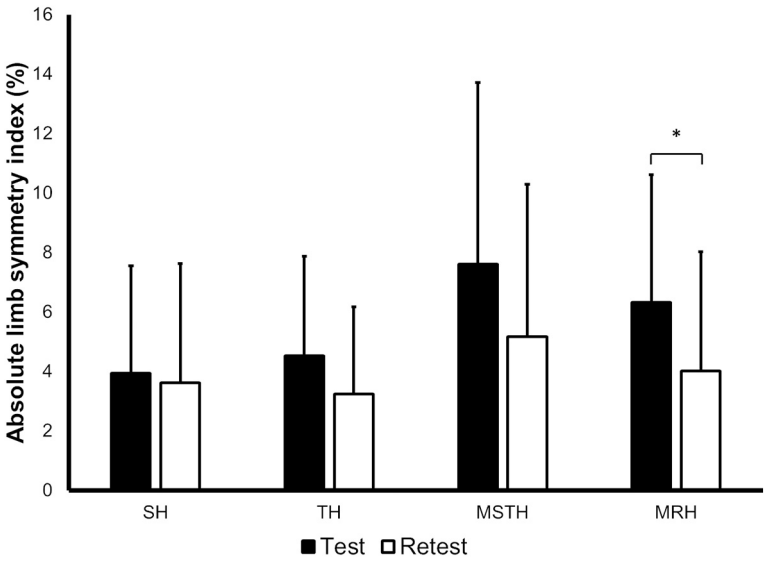

Figure 2. The absolute limb symmetry index (%) at test and retest for single hop for distance (SH), triple hop for distance (TH), medial side triple hop for distance (MSTH) and 90° medial rotation hop for distance (MRH). * Significantly different between test and retest ($P = .027$).

Table 4
Proportion of participants (%) passing different cut-off levels for the limb symmetry index and the absolute limb symmetry index at the first test session.

Limb symmetry index	≥85%	≥90%	≥95%	≥100%
Single leg hop for distance	100	100	75	50
Triple hop for distance	100	100	87.5	37.5
Medial side triple hop for distance	93.8	87.5	81.3	43.8
Medial rotation hop for distance	100	87.5	81.3	62.5
Absolute limb symmetry index	**≤15%**	**≤10%**		**≤5%**
Single leg hop for distance	100	93.8		62.5
Triple hop for distance	100	93.8		68.8
Medial side triple hop for distance	81.3	68.8		43.8
Medial rotation hop for distance	100	68.8		50

Table 4 shows the proportions of participants (%) passing different cut-off levels for the limb symmetry index and the absolute limb symmetry index at the first test session. The proportion of participants scoring ≥100% on the limb symmetry index ranged between 37.5–62.5%. Based on the limb symmetry index, all participants passed the 90% cut-off for SH and TH, while 87.5% passed the same cut-off for MSTH and MRH. For the absolute limb symmetry index, 93.8% passed the ≤10% cut-off for SH and TH, but only 68.8% passed the same cut-off for MSTH and MRH.

3.3. Discriminative ability in ACL-reconstructed participants

The hop distances of the operated leg were significantly lower compared to the non-operated leg for all hop tests within the ACL-reconstructed group ($P < .001$). The Friedman test determined no significant differences between limb symmetry indices of different hop tests ($P = .137$)(Table 5.).

Fig. 3 shows the proportions of participants (%) passing different cut-off levels for the limb symmetry index in the ACL-reconstructed group. While 62.5% and 59.4% of the ACL-reconstructed participants passed the ≥90% limb symmetry index cut-off for respectively SH and TH, only 40.6% and 46.9% passed the same cut-off for respectively MSTH and MRH.

4. Discussion

The main finding of this study was that medial and rotational hop tests have excellent test–retest reliability, similar to forward hop tests. Additionally, leg asymmetries in hop distances are more likely revealed with medial and rotational hop tests, compared to forward hop tests.

In order to interpret differences during and/or following an intervention appropriately, an indication of the test–retest reliability is necessary. This is the first study to determine relative and absolute test–retest reliability of forward, medial and rotational single-leg hop tests. In line with previous studies, excellent test–retest reliability was found for SH and TH [2,11–15]. Furthermore, the results of our study show that medial and rotational single-leg hop tests also have excellent test–retest reliability, similar to forward hop tests, despite the inherent biomechanical differences. Excellent test–retest reliability of MSTH was previously also reported in non-injured male hockey players [37] and female dancers with unilateral hip pain [36].

The absolute measures of reliability SEM and SDD allow clinicians or athletic trainers to determine whether a change in hop distance reflects a true change, rather than irrelevant fluctuations when repeatedly testing an individual. Typically, the SDD reported in this study were seven to 11% of the mean of the group, and similar across the different hop tests (Table 1). This means that an improvement of approximately 10% of the hop distance reflects a true change in performance when retesting an individual. These percentages are in line with previous studies focusing of SH and TH [2,12].

The limb symmetry index can be used as an outcome measure to quickly assess the difference between legs within the same athlete. Most studies calculate the limb symmetry index in non-injured participants by dividing the distance of the dominant leg by the distance of the non-dominant leg [2,40]. Munro et al. [2] found that all recreational athletes included in their study

Table 5
Hop test outcomes for the ACL-reconstructed group.

	Operated leg (cm) (mean (SD))	Non-operated leg (cm) (mean (SD))	Limb symmetry index (%)	*P* value
Single leg hop for distance	178.5 (35.8)	199.1 (27.1)	89.4 (11.9)	<.001[a]
Triple hop for distance	499.4 (124.9)	564.9 (75.4)	87.8 (18.3)	<.001[a]
Medial side triple hop for distance	368.4 (108.7)	426.8 (65.1)	85.2 (19.2)	<.001[a]
Medial rotation hop for distance	160.6 (36.6)	184.0 (25.0)	86.6 (13.6)	<.001[a]

SD: standard deviation.
[a] Significant difference between operated and non-operated leg.

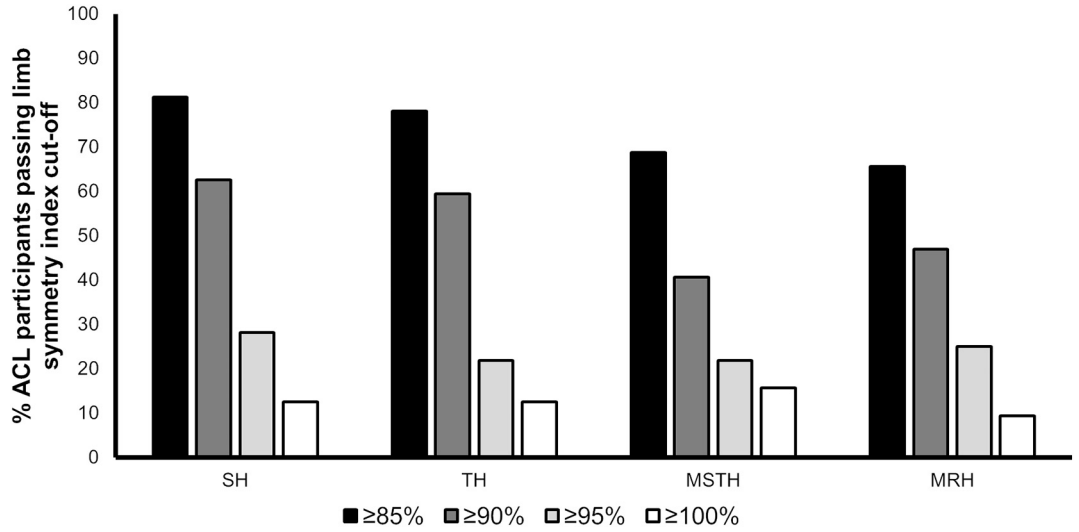

Figure 3. The proportion (%) of ACL-reconstructed participants passing different limb symmetry index cut-off values for single hop for distance (SH), triple hop for distance (TH), medial side triple hop for distance (MSTH) and 90° medial rotation hop for distance (MRH).

achieved a limb symmetry index of 90% on the original set of four single-leg hop tests. The mean limb symmetry index ranged between 98.4–101.6%, which is in line with the results of our study (99.1–102.1%) (Table 3). However, this percentage may underestimate the prevalence of limb asymmetries within a group of athletes as the dominant leg during a mobilizing task where both legs are involved such as kicking a ball, is not necessary the dominant leg during unilateral tasks such as jumping and landing [41]. This can be observed in Table 4, where the proportion of participants having a limb symmetry index of ≥100% was 37.5–62.5%. A mean limb symmetry index of 100% may therefore mask the asymmetry of an individual within a non-injured group [42]. To overcome this limitation of the limb symmetry index, we introduced the absolute limb symmetry index. The higher this value, the more asymmetry between legs. Using this absolute limb symmetry index, we observed that more participants failed to pass the ≤10% and ≤ 5% absolute limb symmetry index cut-off, compared to the ≥90% and ≥95% classic limb symmetry indices, respectively. Hence, we believe that calculating the absolute limb symmetry index better reflects the presence of limb asymmetry within a non-injured group, compared to the classic limb symmetry index. Future studies should therefore be interpreted with caution when only using the classic limb symmetry index within a non-injured group of athletes. Clinicians are advised to use the absolute limb symmetry index in non-injured individuals, and to interpret asymmetries within an individual sport-specific context. In addition, exclusively relying on limb symmetry indices (absolute or classic) should be avoided, as an individual may present with bilateral deficits compared to age- and sex-matched non-injured individuals [43]. As a consequence, limb symmetry indices may underestimate performance deficits [43,44].

Interestingly, the results of our study show that the amount of limb asymmetry can be dependent on the tests being performed. Although the (absolute) limb symmetry indices were statistically not different between hop tests in both the non-injured and ACLR group, clinically relevant differences could be observed in the proportion of participants passing different cut-off values. In the non-injured group, no less than 93.8% passed the ≤10% absolute limb symmetry cut-off for SH and TH, but only 68.8% passed the same cut-off for MSTH and MRH. When using the ≤5% cut-off value, 62.5% passed for SH, 68.8% for TH, but only 43.8% for MSTH and 50% for MRH. An increased asymmetry of MSTH in non-injured participants was also observed in the study of Hardesty et al. [35]. These results imply that some degree of asymmetry may be normal in non-injured athletes, but also that leg asymmetries may become more apparent when athletes are exposed to hop tests in the medial and rotational direction, compared to the forward direction. In the ACL-reconstructed group, the same tendency could be observed. While the hop distance of the injured leg was significantly less compared to the non-injured leg for all hop tests, the proportion of the ACL-reconstructed participants passing the ≥90% limb symmetry index cut-off was lower for MSTH and MRH compared to SH and TH. Clinically, this has important implications, as the ≥90% limb symmetry index cut-off is for SH and TH is traditionally used within return to sport decision-making processes [6]. If a clinician would select the medial or rotational hop tests instead of forward hop tests, a larger group of patients would fail to pass towards a next phase within a return to sport continuum. A systematic review on functional performance testing after ACL reconstruction also concluded that limb asymmetry increased when more demanding tests that required increased stamina of the operated leg were included [8]. Based on these findings, we hypothesize that medial and rotational single-leg hop tests can be used to complement evaluations focusing on movements in the forward direction to track progress during an athlete's road to recovery or optimization of performance. Researchers, clinicians and athletic trainers are advised to vary the selection of hop tests based on the individual they are testing and phase within the continuum of an intervention. The decision when to start multidirectional hop tests within an intervention remains dependent on the individual (clinical) presentation. Nevertheless, future prospective studies are needed to validate whether multidirectional hop tests can improve return to activity, return to sport or return to performance decision-making. Current return-to-sport approaches emphasize

that passing hop tests is only one of the factors allowing athletes to progress towards more sport-specific late-stage rehabilitation phases, including on-field rehabilitation and physical reconditioning with progressively increased workloads [6,45,46]. The final decision to return to sport is multifactorial and should be considered within a multifactorial biopsychosocial perspective [6].

The reasons why limb asymmetries are more prevalent with medial and rotational hop tests remain speculative based on the measurements within this study. Each of the hop tests required a different challenge to the individual. From a biomechanical perspective, jump-landing direction significantly influences lower extremity biomechanics [47–49] and dynamic postural stability outcomes [50,51]. It could be hypothesized that MSTH and MRH are more likely to provoke a movement pattern including hip adduction, hip medial rotation and knee valgus during landing [36]. This movement pattern has previously been related with several pathologies of the lower extremity, such as patellofemoral pain or ACL injuries [52]. Another possible explanation for the side-to-side asymmetries could be that medial and rotational hop tests are thought to challenge more the hip abductor and external rotator muscles compared to forward hop tests [37]. However, the correlations between isokinetic measures of hip abduction and adduction strength and single-leg medial and lateral single-hop tests are slight to low [37]. Therefore, it is reasonable that other factors such as balance, coordination, power, muscle recruitment, skill level, agility, confidence and training factors (predominantly in the forward direction, and less in the medial and rotational directions) might also be related to differences in hop performance [36,37]. Future studies combining performance, kinematic, kinetic, muscle activation and psychological measures could help to unravel the role of each of these potential contributing factors.

An important inherent limitation of the hop tests used in the current study is that these tests are planned, predictable, performed within a "closed" environment with minimal neurocognitive involvement [6]. Athletes participating in multidirectional sports often have to multitask, move quickly in unpredictable open environments with complex visual–spatial processing, often in a fatigued state. Millikan et al. [53] were the first to incorporate neurocognitive aspects within the traditional hop test protocol. Future studies should further evaluate performance measures within open environments, including aspects of neurocognition, quick decision-making and fatigue [6]. It could be hypothesized that adding more of these components within a multidirectional hop test battery would even further increase the likelihood to detect functional deficits. For example, previous studies have shown more pronounced differences in limb symmetry indices after ACL reconstruction between SH and the 30-s side hop test, a hop test including aspects of both directionality and fatigue [17,25,26].

Only four hop tests were included in this study. The MSTH and MRH were chosen to challenge the participants especially in the frontal and transversal plane. Including other hop tests in other directions would have increased the effect of fatigue, which was not the aim of this study. Nevertheless, other hop tests in other directions (e.g. lateral) have previously been described [9,35,36,42,54] and might offer additional options for a clinician or athletic trainer to add complexity within functional performance evaluations.

Hop distance and limb symmetry were the only outcome measures in this study, as a surrogate for physical performance. Biomechanical outcomes related to quality of movement were not captured. Clinically relevant altered movement patterns can be present, even in the absence of physical performance deficits [55]. Furthermore, a vast difference between protocols being used to perform hop tests exists in current literature. For example, some studies measure the distance of a hop test from toe at push-off to heel at landing [2,17], while others measure the distance from toe to toe [3]. Other discrepancies can be found in the instructions, arm positioning, rest periods between consecutive hops, rest periods between different hop tests, the number of familiarization hops, the number of hops during testing and the calculation of the outcome (mean versus maximum distance). We believe that a standardization of test procedures across different studies, but also in clinical practice, is necessary to be able to interpret hop test distances appropriately and achieve optimal reliability. Finally, the test–retest reliability was only studied in non-injured participants. The results should therefore be carefully interpreted within other populations. Within the ACL-reconstructed group, rehabilitation was not controlled. A strong association has been shown between rehabilitation and hop test symmetry after ACL reconstruction [56]. In addition, the majority of the ACL-reconstructed group (28 of 32) were males, and only participants with a hamstring autograft were included. Future studies should investigate whether other populations with predominantly females and other graft types would score similarly across the different hop tests.

5. Conclusion

Excellent test–retest reliability of forward, medial and rotational hop tests was reported in this study. These results allow clinicians to make informed interpretations of changes in hop test distances when retesting athletes. Medial and rotational hop tests are more likely to elicit limb asymmetries compared to forward hop tests in non-injured and ACL-reconstructed participants.

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Declaration of Competing Interest

None.

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