Archives of Physical Medicine and Rehabilitation
journal homepage: www.archives-pmr.org
Archives of Physical Medicine and Rehabilitation 2024;105: 710−6

ORIGINAL RESEARCH

Feasibility, Reliability, and Validity of the Modified Forward Hop Test After Anterior Cruciate Ligament Reconstruction: Double-Instead of Single-legged Landing is Reliable and Results in Greater Hopping Distance

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Abstract

Objective: To investigate the feasibility, reliability, and validity of the Modified forward hop (MFH) test in participants after ACL reconstruction (ACLR).

Design: Reliability study.

Setting: Assessments were administered at different clinical locations in Germany and Switzerland by the same 2 investigators.

Participants: Forty-eight active individuals participated in this study (N=48).

Main Outcome Measures: The participants performed MFHs and Forward hops for distance in a predetermined order. The feasibility of the MFH was quantified with proportions of successfully executed attempts and Pearson's χ^2 test. Its reliability was estimated using intraclass correlation coefficient (ICC) and standard error of measurement (SEM). Test validity was explored using Pearson's product moment correlation analyses.

Results: Fewer failed attempts were recorded among the participants (age: 30 [Standard deviation 11] years; 22 women, 26 (13) months post-surgery) when compared with the Forward hop for distance test (25/288 trials; 9% vs 72/288 trials; 25%). Within-session ICC values were excellent (>0.95) for both types of Forward hop tests, independent of the side examined. The SEM values were comparable between the Modified (injured: 5.6 cm, uninjured: 5.9 cm) and the classic Forward hop (injured: 4.3 cm, uninjured: 7.2 cm).

Conclusion: The MFH is a feasible, reliable, and valid tool for judging neuromuscular performance after ACLR. If the aim of a hop for distance incorporates enhanced perceived or real landing safety, landing on both feet should be used.

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State-of-the-art rehabilitation after anterior cruciate ligament reconstruction (ACLR) is monitored and guided by test batteries on knee-related functional abilities.[1-4] An important functional ability after ACLR is the performance in classic slow stretch-shortening cycle, peak torque, and rate of torque development (ie, reactive, eccentric, rate of force development, frontal, and transverse plane control) movements.[5] Consequently, hop tests, which mirror these abilities, are a crucial part of test batteries prior to return-to-sports after ACLR.[1-4]

This study was partly supported by the German Knee Society (DKG).

Disclosures: Each author certifies that he or she has no commercial associations that might pose a conflict of interest in connection with the submitted article.

https://doi.org/10.1016/j.apmr.2023.11.008

The Single leg hop (Forward hop) for distance is the most frequently adopted hop test. Upon the single-leg landing after the Forward hop, vertical ground reaction force affects approximately the 3-fold of body mass that needs to be tolerated.[6] Patients are, consequently, likely to be limited in performing at their maximal hopping distance due to a fear of landing on the affected leg.[7] More plainly, patients can hop their maximal distance only if they do not fear the landing. It may be concluded that "a routine test used to gauge physical performance capacity may dually serve as an indicator for fear of movement".[7] One may assume that, if only the surrogate- and confounder-free sagittal plane take-off ability should be assessed, landing on both legs instead of on 1 may be more goal-leading.

The measurement properties of such a Modified forward hop (MFH) are yet unknown. The purpose of our analysis was to prove the feasibility, reliability, and validity of the MFH test in physically active participants after ACLR.

We hypothesized that (1) the MFH test is reliable (intrasession reliability), (2) valid when contrasted to the Forward hop for distance (FHD), but nevertheless (3) provides performance-based information not included in the Forward hop by reducing the contribution of kinesiophobia to the hopping performance.

Methods

Study design and ethics

Intrasession reliability study. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Albert-Ludwigs-University Freiburg (reference number: 129/17). Measurements were taken after providing detailed explanations of the risks and benefits of the study and obtaining written informed consent from each participant.

Participants

Adults with unilateral arthroscopically assisted hamstring tendon ACLR and completed formal rehabilitation were included. Exclusion criteria were any acute medical history, pre-injury Tegner activity scale (TAS) <3, injuries of the contralateral extremity, and any secondary issues that limited the participant's ability to execute the mandatory tests. Participants were recruited on a voluntary basis by calling different rehabilitation centers in Germany and Switzerland.

List of abbreviations:

ACL	**anterior cruciate ligament**
ACLR	**anterior cruciate ligament reconstruction**
FHD	**Forward hop for distance**
ICC	**intraclass correlation coefficient**
LYS	**Lysholm score**
MDC	**Minimal detectable change**
MFH	**Modified forward hop**
SEM	**standard error of measurement**
SEM%	**relative standard error of measurement**
TAS	**Tegner activity scale**
TSK	**Tampa scale of kinesiophobia**

Procedures

Three questionnaires were completed: The German versions of the TAS,[8] and the Lysholm score (LYS[9]) were used to determine participants' activity level (TAS: 0-10) and knee-specific symptoms (LYS: 0-100), respectively. The shortened 11-item German version of the Tampa scale of kinesiophobia (TSK[10-13]) was applied to uncover participants' fears of movement or reinjury (TSK: 11-44), with higher values reflecting greater kinesiophobia.

All participants completed the following performance tests in a predetermined order: the MFH and the FHD. Participants starting position was on 1 leg for both tests. In contrast to the FHD, the MFH requires double-legged landing (fig 1).

For both hop tests, the participants were asked to hop as far as possible and to land in a controlled manner. The tests were performed with the same athletics shoes for each test. Participants were allowed to move their arms in a natural fashion during the tests. Beginning with the uninjured side, participants performed at least 2 familiarization trials for each limb and test.[14,15] Three measured and recorded trials followed. The time between the trials was approximately 30 seconds. The 2 best trials were used for intrasession reliability estimation.[16] The hopping distance was measured from the start line to the heel of the landing leg in centimeters. In the case of asymmetrical double-legged landings, the shorter distance was recorded. For each test, the best trial was selected for further analysis. Data were normalized to participants' lower limb length (LLL). For that purpose, the distance from the greater trochanter to the medial malleolus on participants' right side was measured.

The measurement properties for the FHD are excellent, the relative reliability is intraclass correlation coefficient (ICC)=0.97 (95% CI: 0.89-0.99), and the absolute reliability, that is, the standard error of measurement (SEM), is 5 cm.[17]

Sample size estimation

The calculation was made based on the suggestions in Bonett, 2002.[18] The ICC for the comparative Forward hop was found to be >0.93. We expect at least the same reliability coefficients for the modified test. Assuming a minimal acceptable reliability of ICC = 0.85, a tolerable alpha-error of 5% and a beta error of 20%, we had to include 56 participants to, with a suggested dropout rate of 10%, analyze 50 participants.

Statistical analyses

Data are presented as mean with standard deviation (SD), and as minimum and maximum values. Prior to any inference statistical analysis, data and residuals distribution were checked visually and

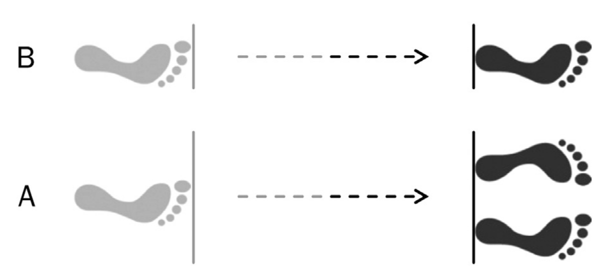

Fig 1 Examined forward hop tests. (A) Modified forward hop test where landing is performed bilaterally. (B) Commonly used Forward (single leg) hop test for distance.

using Shapiro-Wilk testing. Both demonstrated normal distribution of the data and residuals ($P>.2$).

Test feasibility was quantified with the proportion of successfully executed attempts and Pearson's χ^2 test.

Relative reliability was estimated using a 2-way mixed-effects model with absolute agreement on the 2 best trials. Absolute reliability estimates are given as SEM and 95% minimal detectable change (MDC). Further, the SEM was expressed as a percentage of the mean for the 2 trials (SEM%[19]). As an absolute measure of consistency between repeated measurements, the difference was calculated between the 2 best trials.

Criterion-related validity of the MFH was explored on the one hand, using Pearson's product moment correlation to find associations between the 2 hop tests. On the other hand, we calculated a multiple linear regression with the independent variables MFH for distance and kinesiophobia as well as with the dependent variable FHD. This was done to determine the contributions of the MFH test hopping ability and of kinesiophobia on the Forward hop performance. Therefore, collinear relations among the independent variables were verified using Pearson product moment correlation. Furthermore, the deviation of both forward hop tests (MFH, FHD) was visually displayed with the Bland-Altman plot and corresponding upper and lower limits (1.96 SD) of agreement. Relations between different interval or ordinal scaled outcome measures were proven using Pearson's or Spearman's correlation coefficients. Potential differences between sexes were verified using Student unpaired *t* or Mann-Whitney *U* tests.

All statistical analyses were carried out with SPSS 28.0 (IBM SPSS Statistics Inc, Chicago, IL). The significance cut-off was set at 5%, all *P* values below are considered as significant.

Results

Participant characteristics

Initially, 63 participants were screened for eligibility (fig 2). None of the enrolled participants withdrew consent. Six participants were excluded because of ipsilateral (4) ACL graft retears or contralateral (2) ACL injuries. Seven participants were excluded because of bone-patella tendon-bone autografts. One participant dropped out because of an ingrown toenail that limited his ability to hop. Finally, 48 active participants (M/F: 26/22; age: 30 [SD 11] years) were examined; at 26 (SD 13, 11-79) months post-surgery.

The current TAS ranged between 3 and 10 (men: 3-10, women: 3-9). The median LYS was 95 with at least 76 in men and women, respectively. Participants' fear of movement or reinjury ranged between 11 and 29 in men and 13 and 27 in women. In 54% of the participants the injured leg was their dominant (eg, leg used to kick a ball) lower limb. The demographic and injury-specific characteristics of the participants are listed in table 1.

Participants' fear of movement or reinjury was not related to the time since their surgery (ρ=-0.04, P=.77).

Feasibility of the Modified forward hop

For the modified test version fewer failed attempts were recorded (25/288 error trials, 9%) than for the FHD (72/288 error trials, 25%). The relation between the type of hop test and successful attempts was significant ($\chi^2 = 27.4$, $P<.001$). Executing FHD was more likely to fail than MFH.

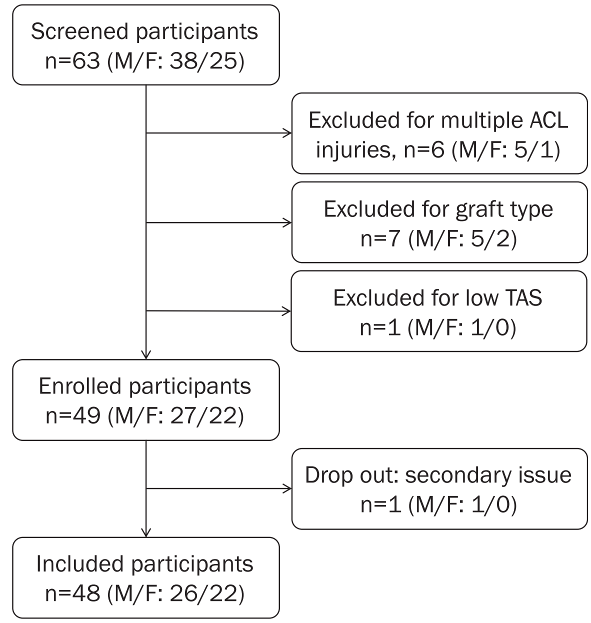

Fig 2 Flow chart of the study population stratified by sex.

For detailed absolute as well as normalized results of the MFH, and FHD, both in the total sample and separated for the men and women, please refer to table 2.

Reliability of the Modified forward hop

Within-session ICC values were all larger than 0.94, independent of the test or side examined (table 3). The SEM values and the MDC based on the confidence level of 95% were smaller for the injured as compared with the uninjured sides. To be 95% confident that differences reflect real changes at the injured side, the MFH and the FHD need to exceed 16 and 12 centimeters, respectively.

Validity of the Modified forward hop

Linear correlations revealed strong positive associations (injured: $r = 0.88$ 95% CI [0.79, 0.93], uninjured: $r = 0.92$ 95% CI [0.86, 0.96], $P<.001$, fig 3) between the FHD and the MFH. There were differences between the normalized distances achieved (injured: $t = 10.5$, $P<.001$, d = 1.5; uninjured: $t = 11.4$, $P<.001$, d = 1.6) between both hop tests. Men reached the highest relative values, irrespective of the type of hop test. With regard to the MFH at the injured side, women shared almost 85% of the value range of men (fig 4).

The systematic variation of both forward hop tests is displayed in figure 5. On average, the FHD revealed 27 cm shorter hopping distance than the MFH. The Shapiro-Wilk test on the differences between MFH and FHD did not show evidence of non-normality ($P>.05$). However, the variability is larger between 110 and 170 cm average hopping distance and lower at the edges.

How can the Forward hop for distance performance be explained?

The Pearson product moment coefficient among the independent variables was −0.086 (95% CI [−0.361, 0.203], $P>.5$), indicating that multicollinearity was not a problem in our sample. Multiple

Table 1 Demographic and injury-specific characteristics of the participants

	Men (n=26)	Women (n=22)	*P* Value	Total Sample (n=48)
Age [years]	29.1 (9.8, 17.0-52.0)	30.9 (12.2, 19.0-55.0)	.566	29.9 (10.9, 17.0-55.0)
Body height [cm]	181 (7, 172-196)	169 (6, 159-183)	<.001	176 (9, 159-196)
Body mass [kg]	80.8 (8.9, 62.5-98.1)	64.4 (6.9, 52.0-84.0)	<.001	73.3 (11.5, 52.0-98.1)
Body mass index [kg/m^2]	24.7 (2.8, 18.8-31.2)	22.5 (2.1, 18.0-25.3)	.002	23.7 (2.7, 18.0-31.2)
Lower limb length [cm]	96.8 (5.6, 88.0-109.0)	88.6 (4.2, 82.0-97.0)	<.001	93.0 (6.4, 82.0-109.0)
Time post-surgery [months]	22.0 (9.3, 11.0-56.6)	31.3 (15.0, 13.3-78.8)	0.011	26.3 (13.0, 11.0-78.8)

NOTE. Values presented as mean (SD, minimum and maximum).
P values are based on Student unpaired *t* tests.

Table 2 Absolute and relative results of the MFH and FHD as well as the TSK

	Men (n=26)	Women (n=22)	Total Sample (n=48)
	Mean (SD, minimum and maximum)		
MFH injured [cm]	175.0 (27.0, 120.0-226.0)	135.9 (27.4, 88.0-192.0)	157.1 (33.3, 88.0-226.0)
MFH uninjured [cm]	176.9 (23.4, 122.0-211.5)	137.2 (31.7, 83.0-207.0)	158.7 (33.8, 83.0-211.5)
MFH injured [%LLL]	181.2 (29.0, 124.4-245.7)	153.3 (29.3, 95.7-211.0)	168.4 (32.1, 95.7-245.7)
MFH uninjured [%LLL]	183.2 (25.9, 127.5-229.9)	154.6 (33.8, 90.2-227.5)	170.1 (32.8, 90.2-229.9)
FHD injured [cm]	146.3 (30.9, 81.0-203.0)	110.8 (35.9, 39.5-181.0)	130.0 (37.5, 39.5-203.0)
FHD uninjured [cm]	154.6 (23.1, 112.0-199.5)	118.6 (34.4, 54.0-192.0)	138.1 (33.8, 54.0-199.5)
FHD injured [%LLL]	151.7 (34.0, 86.2-220.7)	125.1 (40.5, 48.2-198.9)	139.5 (39.1, 48.2-220.7)
FHD uninjured [%LLL]	160.1 (25.4, 119.1-216.8)	133.8 (37.7, 58.7-211.0)	148.1 (34.0, 58.7-216.8)
	Median (Quartiles)		
TSK (11-44)	18 (15/21)	19 (15/20)	18 (15/21)

Abbreviation: %LLL, percentage lower limb length.

Table 3 Agreement (ICC, Difference) and measurement error (SEM, MDC, SEM%) characteristics of the MFH and FHD for the total sample (n=48)

	ICC (95% CI)	Difference (95% CI)	SEM	MDC	SEM%
Injured					
MFH	0.97 (0.94-0.99)	-3.0 (-5.1, -0.9)	5.7	±15.7	3.7
FHD	0.99 (0.97-0.99)	-2.4 (-4.1, -0.7)	4.3	±11.8	3.3
Uninjured					
MFH	0.97 (0.94-0.98)	-2.8 (-5.1, -0.5)	6.0	±16.7	3.9
FHD	0.95 (0.91-0.98)	-3.9 (-6.8, -1.1)	7.2	±20.1	5.4

Abbreviations: CI, confidence interval; Difference, mean absolute difference between the 2 trials.

regression analysis revealed that the interaction of the independent variables (MFH, TSK) explained 78% ($F(2, 45) = 82.7$, $P<.001$) of the FHD.

Both MFH ($\beta = 0.86$, 95% CI [0.88, 1.22], $P<.001$) and TSK ($\beta = -0.14$, 95% CI [−2.63, −0.03], $P<.05$) significantly predicted the FHD.

Discussion

Statements of principal findings

With the aim of determining the feasibility, reliability, and validity of the MFH test, we found that the classic FHD led to a larger number of errors than the modified counterpart landing double legged. Patients felt safer during the MFH; the test can thus be rated as feasible. Furthermore, the test was excellently reliable when a retest was performed: the ICC values were comparable with and the standard error values lower than their counterpart in the FHD. Association analysis showed that the MFH is, generally, valid. Nevertheless, the limits of agreement indicate considerable differences between the values of the 2 hop test results. This suggests that the MFH test depicts different performance characteristics which are not interchangeable with those of the classic forward hop test.

Is the tested sample representative?

Our sample consisted of athletes and physically active non-athletes. The TAS ranged from 3 to 10. The time since ACLR ranged between 1 and 5 years. This time span is, at the beginning, associated with the end of rehabilitation and return-to-sport phase,[20] followed by excessive secondary prevention. Our sample and thus

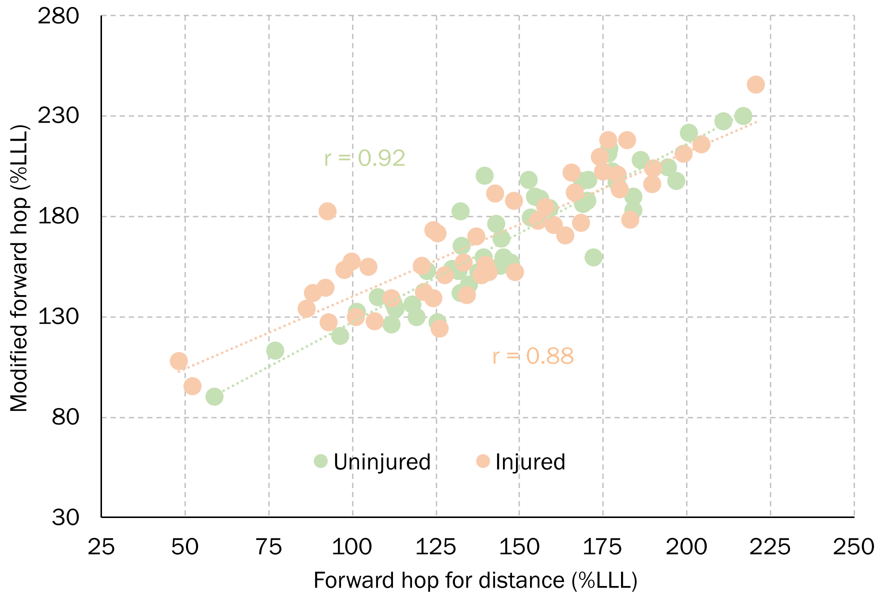

Fig 3 Linear relations between the normalized values of the Forward hop and the Modified forward hop for distance tests performed at the uninjured and injured sides. Values are normalized to participants' lower limb length (LLL).

also the measurements and results are likely to be representative (external validity) for this sample and time-span post-surgery.

Is the Modified forward hop test reliable?

Test familiarization is crucial for conducting reliable forward hop distances.[14,15] The inter-session test-retest reliability coefficients of the FHD were excellent (ICC > 0.9) in healthy active populations[14,21-24] and were shown to be 0.89[25] or 0.92[26,27] in patients after unilateral ACLR. The SEM results ranged between 4.6[14,22] and 7.7 cm[23] in uninjured individuals. The SEM values determined in our setting were, considering the FHD, within this reported ranges. For the injured side, the SEM was even lower than for the uninjured side. As the same reliability outcomes were found in different populations, reliability may thus be independent of the sample. The reliability values we determined for the MFH were, both compared trial-internally as well as in comparison with the literature, even better than the coefficients for the FHD. Although studies warrant from using the symmetry achieved through the FHD as a discharge criterion in men athletes after ACLR,[28] the results may be helpful to judge rehabilitation progression in stages before return-to-sports clearance. Accordingly, the MFH test can be used in earlier rehabilitation stages to prepare patients for more demanding single-leg landings.

The Forward hop was modified to assess the surrogate- and confounder-free sagittal plane take-off ability. We found differences between the injured and contralateral sides in the hopping distance performance only in the Forward hop but not in the MFH.

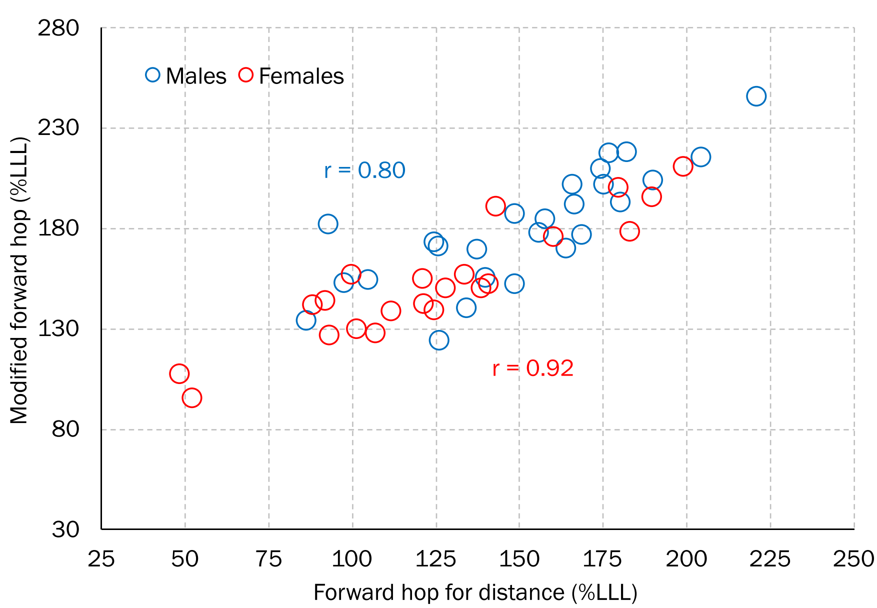

Fig 4 Relation between the Forward hop for distance and the Modified forward hop for distance tests performed at the injured side and stratified by sex. Values are normalized to participants' lower limb length (LLL).

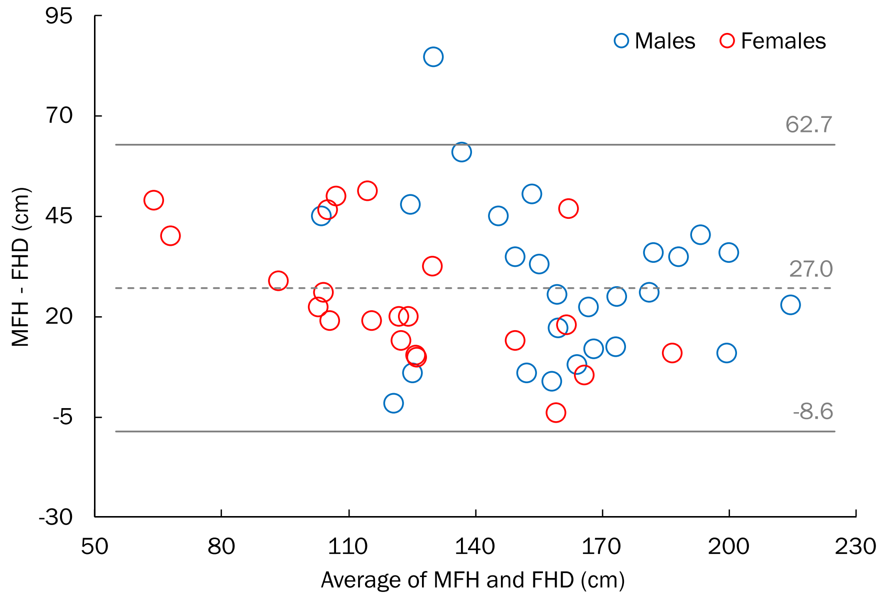

Fig 5 Bland-Altman plot between the MFH and the FHD at the injured side stratified by sex. The dashed and continuous lines indicate the bias and the 95% limits of agreement.

On the one hand, this could be another indication that the modification was successful in terms of the test application at an earlier rehabilitation phase. On the other hand, these suggestions can only be approved if future studies show that the MFH performance uncovers such side asymmetries at an earlier stage of the rehabilitation process.

What contributes to the hopping distance?

Kinesiophobia is related to knee function after ACLR[29] and was reported by approximately 50% of those who did not return to sports.[30] Most of the variance in the classic FHD can be explained by the MFH values, with a minor share explained by kinesiophobia. One may speculate that the contribution of kinesiophobia to the FHD may lead to a certain misleading interpretation of the classic Forward hop when kinesiophobia is present but not statistically partialized. The MFH is able to counteract this potential measurement uncertainty. The somewhat higher reliability coefficients in comparison with the single-legged landings may be a result of the reduction in these degrees of freedom. Generally, although the Forward hop and the MFH have major variance in common, they do not assess congruent abilities.

Practical relevance

If the aim is to enhance safety, presumably in earlier phases after injury, one may consider landing on both feet. One advantage of the MFH is a safer and less compromised landing. Accordingly, the MFH requires less balance control and provides a better landing shock absorption. Patients who are unafraid to touch down with the affected leg can easily progress with single-leg landings. Unless newer or more population-fitting values are published, one may consider our values for the SEM of 5.7 to 6.0 cm (3.7%-3.9%) for the reconstructed and the uninjured leg, respectively, as valid cut-off values for the clinical relevance of between-group comparisons and within-group change scores. On an individual level, changes above 16.0 cm represent an increase or decrease in the MFH performance above or below the MDC.

The simple quantification of jumping distances of the affected leg[31] or side-to-side asymmetries [1] were found to be predictive for a second ACL injury.[4] In contrast, compensatory movement patterns cannot sufficiently be identified by a simple hop or jump distance quantification. Beyond such distance quantifications, the quality of jumping and cutting maneuvers is crucial for the rating of an athlete's function after an ACLR.[32] Qualitative assessments, however, are only applied infrequently after ACLR.[33] Future study is, thus, warranted to develop and validate qualitative outcomes of the MFH test.

Strengths and limitations

We performed an adequately powered study and showed that the Modified front hop is a feasible, reliable, and valid tool for judging neuromuscular performance after ACLR. However, there are a few limitations that one must keep in mind when our findings are interpreted or adopted. As the time between attempts was quite short, we have only assessed intrasession reliability. Inter-session reliability needs to be determined in future investigations. A certain volunteer bias cannot be excluded. This study considered quantitative results only; movement quality was not assessed. The time period since reconstruction was considerable. The MFH test is explicitly designed to prepare for the classic FHD. Thus, the target population is confronted with more in an early rehabilitation after lower extremity injuries. Consequently, the feasibility found is not necessarily transferable to the target population. Although a comparison with other populations' reliability for the FHD test showed no or only minor differences in the reliability values between uninjured and ACLR sides, it remains unknown if this generalizability of the results is also given for the MFH for distance.

Conclusions

A MFH, where participants land with both instead of 1 leg as during the classic FHD, is feasible, valid for testing neuromuscular performance after ACLRs, and reliable. The results of the Modified test are not interchangeable with those of the classic Forward hop test. The MFH may act as a complementary or additive measurement tool to the traditional Forward hop. Rehabilitation and assessment staff may use this test to guide early rehabilitation progressions and to prepare participants for single-leg landings.

Key words

ACL; Exercise; Function; Physiotherapy; Rehabilitation; Single-leg hop for distance; Validity

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Acknowledgments

The authors would like to thank Ms. Tara Russell for language assistance.

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