

Poor Validity of Functional Performance Tests to Predict Knee Injury in Female Soccer Players With or Without Anterior Cruciate Ligament Reconstruction

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Poor Validity of Functional Performance Tests to Predict Knee Injury in Female Soccer Players With or Without Anterior Cruciate Ligament Reconstruction

Background: Various tests have been developed to evaluate athletes' functional performance and for use as screening tools for injury prediction. Further validation of their accuracy to predict injury is needed.

Purpose: To investigate the validity of predetermined cutoffs used to differentiate between high and low-risk players in different functional performance tests to predict (1) anterior cruciate ligament (ACL) injury or (2) severe traumatic knee injury in a cohort of female soccer players with a primary unilateral ACL reconstruction and a cohort of knee-healthy players.

Study Design: Cohort study.

Methods: 117 active female soccer players (mean age \pm standard deviation, 20 \pm 2 years) 19 \pm 9 months after ACL reconstruction and 119 knee-healthy players (age 19 \pm 3 years) were prospectively followed up for 2 years for new knee injuries. At baseline, all players underwent tests to assess postural control (Star Excursion Balance Test), hop performance (1-legged hop for distance, side hop), and movement asymmetries in the lower limbs and trunk (drop vertical jump [DVJ], tuck jump). The predictive validity of the test cutoffs to identify players who would sustain an ACL injury, or a severe traumatic knee injury (absence from soccer play >28 days), was assessed. Risk ratios (RR), area under the receiver operating characteristic curve (AUC), sensitivity, and specificity were calculated.

Results: Forty-six players with ACL reconstruction (39%) sustained 48 severe knee injuries, including 28 ACL ruptures. Of the knee-healthy players, 13 (11%) sustained 14 severe knee injuries, including 8 ACL ruptures. No association was found between the predetermined functional performance test cutoffs and risk of a new ACL injury or severe knee injury in players with ACL reconstruction. In knee-healthy players, the only variable associated with future ACL injury was ≥ 6.5 cm knee valgus in the frontal plane (any knee) at DVJ (RR, 4.93; 95% CI, 1.04-23.40; $P=.045$) but with only fair predictive validity; AUC=0.7, sensitivity=0.75, specificity=0.65.

Conclusions: In our cohorts of female soccer player, the validity of commonly used functional performance tests to predict new knee injuries were poor. Only knee valgus during the DVJ was associated with new ACL injury in knee-healthy players but only with fair predictive validity.

Keywords: female; football; soccer; anterior cruciate ligament; return to sports; reinjury; predictor

What is known about the subject

Different cutoffs, to indicate a satisfactory result and to differentiate between high and low-risk players, in commonly used functional performance tests have been created from different cohorts in prospective studies. These cutoffs are often used when evaluating functional performance and to predict injuries both in injured, e.g., in players with anterior cruciate ligament (ACL) injury or reconstruction, and uninjured players. However, the validity of the cutoffs to predict injury is unclear, and the existing literature has several limitations with low numbers of participants and events included, and differences in ages, sports, test criteria, and competition levels. The cutoffs in functional performance tests need further validation in new

and relevant populations regarding their ability to predict a primary and secondary knee injury.

What this study adds to existing knowledge

The validity of predetermined cutoffs used to differentiate between high and low-risk players in commonly used functional performance tests that assess postural control, hop performance, and movement asymmetries was poor and could not predict future ACL injury or other severe knee injury. We evaluated the predictive validity of 5 different functional performance tests with a total of 10 cutoffs in 2 cohorts: female soccer players with or without ACL reconstruction. Only 1 cutoff from 1 functional performance test showed some predictive validity in 1 of the cohorts. Knee valgus ≥ 6.5 cm in any knee in the frontal plane measured during the drop vertical jump, in the cohort of knee-healthy players, was associated with 5 times higher risk for sustaining an ACL injury. However, the sensitivity and specificity of this test was only fair. Thus, the value of commonly used cutoffs in functional performance tests to predict injuries is poor.

INTRODUCTION

Different tests and test batteries have been developed to evaluate function, movement asymmetries, and to identify athletes at risk of sustaining injury to the lower extremity, especially to the knee.^{4, 28, 35, 36} The most commonly used tests to evaluate knee function are quadriceps strength tests^{14, 15, 22, 25, 39, 46} and hop tests (e.g., single hop for distance, timed hop, triple hop for distance, and cross-over hop for distance).^{14, 15, 22, 25, 39, 46} Evaluation of trunk, hip, and knee valgus motion during sport-specific activities has been in focus regarding the possibility of identifying female athletes at high risk of primary^{20, 23, 26, 35} or secondary^{23, 37} anterior cruciate ligament (ACL) injury.

Cutoffs have been proposed for the different tests to help clinicians benchmark results for their athletes, for instance as part of pre-season screening or in return to sports (RTS) after an injury. Strength and hop performance are often measured and reported with a Limb Symmetry Index (LSI) and with a cutoff of $\geq 90\%$ for a satisfactory result.^{6, 10, 16, 41} However, the validity of these cutoffs to predict injury is unclear. Two recent systematic reviews on functional performance testing after ACL reconstruction (ACLR) highlighted the poor prognostic value of reaching specific cutoffs in the tests for clearance to RTS and risk of a new ACL injury^{27, 44} and other additional knee injury.⁴⁴ Overall, RTS clearance based on results of test batteries was not associated with reduced subsequent risk of ACL or knee injury. These systematic reviews included only 4 and 5 studies, respectively (a total of 6 studies)^{14, 15, 25, 34, 39, 46} with a small number of participants. The authors^{27, 44} highlighted the need to further study the prognostic value of the test batteries to predict ACL injury^{27, 44} and new knee injury.⁴⁴

Two factors are important to validate a screening test to predict sports injuries: (1) a strong relationship between the result from a screening test and risk to sustain an injury; (2) validation of established cutoffs for different tests in relevant populations using appropriate statistical tools.³ The aim of this study (secondary analyses of a prospective cohort study) was to investigate the validity of 10 predetermined cutoffs in 5 different functional performance tests to predict (1) an ACL injury or (2) a severe traumatic knee injury in 2 different cohorts of active female soccer players, one cohort with primary unilateral ACLRs and one cohort with knee-healthy players.

MATERIALS AND METHODS

Participants

A total of 117 active female soccer players (mean age \pm standard deviation, 20 \pm 2 years) on average 19 \pm 9 months after ACLR and 119 knee-healthy players (age, 19 \pm 3 years) were included. The players with ACLR were identified from the Swedish National Knee Ligament Register (SNKLR). The registry captures over 90% of all ACLRs performed in Sweden.²⁴ We also advertised the study on 3 regional soccer district websites to include players with ACLR who were not registered in the SNKLR. The knee-healthy players were recruited by coaches from the same teams as the players with ACLR (matched to playing position and age). Teams participated at various playing levels from elite to amateur series. All players were included in the study at the same time point of the soccer pre-season (January to April) and were followed over 2 years or to the date they quit soccer if this occurred within the 2-year follow-up. Exclusion criteria in the ACLR group were additional previous ipsilateral or contralateral ACLRs, associated posterior cruciate ligament injury, and/or surgically treated injuries to either the medial or lateral collateral ligament of the knee.

All players received written and oral information about the study and signed informed consent form. The study was approved by the Swedish Ethical Review Authority (Dnr 2012/24-31 and 2013/75-32) and the SNKLR board. For a detailed description of the inclusion procedure and descriptive data for the cohort, see previously published data.^{10, 11}

Follow-up

During the 2-year follow-up, players were asked to register new traumatic (acute onset) or non-traumatic (insidious onset without any known trauma) knee injuries and absence from soccer play. Our injury definition was “any physical complaint sustained by a player

irrespective of the need for medical attention or time-loss from soccer activities.”⁹ Absence from soccer play >28 days was classified as a severe knee injury. Players also registered whether they received medical attention (e.g., emergency medical care, primary care, specialist care [e.g., orthopedics, physiotherapy]) for the knee injury or physical complaint. If the player sustained a new knee injury, she was contacted by telephone for further information, and confirmation of the diagnosis was retrieved from medical charts. Confirmation from medical charts was complete for all knee injuries.

Functional Performance Tests

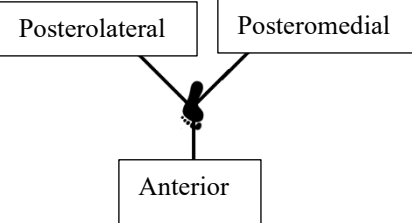
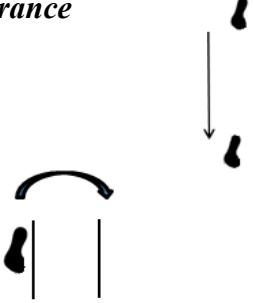
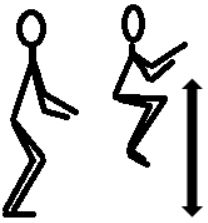
At baseline, all players performed functional performance tests to assess postural control (Star Excursion Balance Test [SEBT],³⁸), hop performance (1-legged hop for distance¹⁶ and side hop¹⁶) and movement asymmetries in the lower limbs and trunk (tuck jump²⁹ and drop vertical jump [DVJ]³⁰⁻³²). All players were tested by the same experienced tester (A.F.) according to a standardized test protocol. Indoor shoes were used in all tests except the SEBT, where players were barefoot. A detailed description of the tests is presented in Figure 1.¹⁰

Predetermined Cutoffs

Predetermined cutoffs for the different tests in the present study includes cutoffs developed in a previous study (SEBT³⁸) and guidelines to evaluate a satisfactory result in functional performance tests (LSI for the 1-legged hop for distance, and side hop^{6, 16} and tuck jump²⁹). Cutoff scores were not available for the DVJ, and therefore scores from the highest tertile (valgus motion, side difference, and pKAM measured with DVJ) from our previous data including some of the same players (77 of the 117 players with ACLR and 77 of the 119 knee-healthy players¹⁰) were used. The 10 cutoffs for the 5 different tests and the definition of players with high-risk for new injury related to the specific tests are presented in Figure 1.

The LSI was calculated for players with ACLR as $(\text{ACLR limb/uninvolved limb}) \times 100$ and for knee-healthy players as $(\text{nondominant limb/dominant limb}) \times 100$.

For the players with ACLR, 2 different LSI cutoffs were used for the 1-legged hop for distance, and side hop (i.e., 90% and 90% or 110%). For the different cutoffs; (1) players with LSI <90% and (2) players with <90% and >110% were defined as high-risk players for new injuries. For the knee-healthy players, >10% side difference independent of which limb, i.e., an LSI of <90% or >110%, was used. In addition, the number of players defined as high-risk according to the predefined cutoffs used in each of the 5 tests (SEBT; a composite score reach distance $\leq 94\%$ of limb length,³⁸ 1-legged hop for distance and side hop; an LSI of <90%,^{6, 16} tuck jump ≥ 6 flawed techniques;²⁹ and DVJ; knee valgus motion ≥ 6.5 cm in any knee¹⁰) was also calculated.

Outcome measure	Description and scoring	Cutoffs to define high-risk player
<p>Postural control</p> 	<p>The Star Excursion Balance Test (SEBT)³⁸</p> <p>The players were standing barefoot in the middle of a star reaching with the free limb as far as possible, maintaining balance, in 3 directions (anterior, posteromedial, and posterolateral). The hands were held at the back. Players had 3 practice trials and then performed 3 attempts in each direction. The best result (cm) of the 3 attempts was used and normalized to the leg length (test value/leg length × 100). A composite score was calculated for each limb as the average of the 3 normalized measurements in the different directions</p>	<p>(1) a difference between limbs in the anterior reach distance ≥ 4 cm³⁸</p> <p>(2) a composite score reach distance $\leq 94\%$ of limb length³⁸</p>
<p>Hop performance: maximum and endurance</p> 	<p>The 1-legged hop for distance¹⁶</p> <p>The players jumped with hands on the back, as far as possible, taking off and landing on the same foot, and had a controlled, balanced landing. The players had 2 practice trials and then performed 3 maximum trials. If hop lengths increased in all 3 hops, additional hops were performed until no further increase occurred. The best result of the 3 attempts was used</p> <p>The side hop¹⁶</p> <p>The players jumped from side to side on 1 limb outside two parallel strips of tape 40 cm apart. Hands were placed behind their back. Players were instructed to jump as many hops as possible for 30 seconds. A few practice jumps were performed on each limb before the test trial, and players had to rest for at least 1 minute before testing the opposite limb. If the foot touched the strips of tape, the hop was not counted. The trials were videotaped to enable analysis of successful jumps</p>	<p>(3) an LSI of $<90\%$ (only for players with ACLR)^{6, 16}</p> <p>(4) an LSI of $<90\%$ or $>110\%$¹⁰</p> <p>(5) an LSI of $<90\%$ (only for players with ACLR)^{6, 16}</p> <p>(6) an LSI of $<90\%$ or $>110\%$¹⁰</p>
<p>Movement asymmetries</p> 	<p>The tuck jump²⁹</p> <p>The players performed repeated tuck jumps for 10 seconds. The players were instructed to lift the knees to hip height and attempt to land in the same place. Two standard video cameras, 1 in the frontal plane and 1 in the sagittal plane, were used. The tuck jump was analyzed according to a clinician-friendly screening tool, which consist of 10 criteria.¹⁹ The criteria were scored as either 1 indicating flawed technique or 0 indicating no flaw, resulting in a total score ranging from 0 to 10. Flawed techniques were, e.g., lower extremity valgus at landing, thighs not equal side to side, foot placement not parallel, pause between jumps, and techniques declining during the 10 seconds.</p>	<p>(7) ≥ 6 flawed techniques²⁹</p>

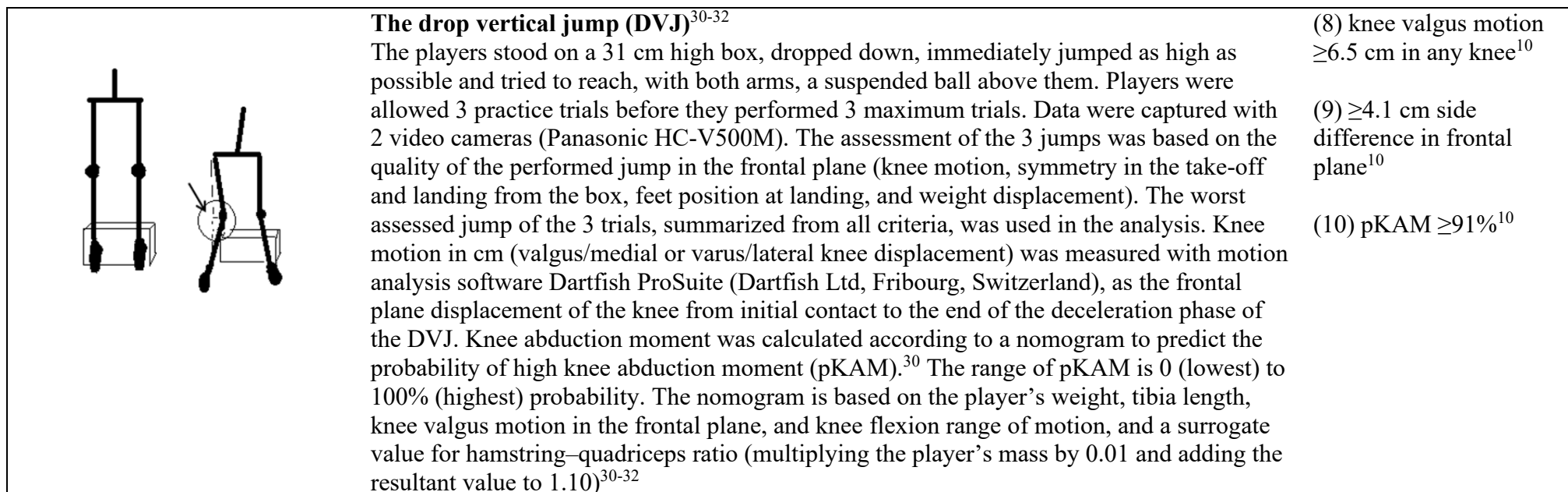


Figure 1. Description of the 5 functional performance tests with 10 different cutoffs, and the predefined definition of players with high-risk for new injury related to the specific tests and cutoffs.

Data Analysis

All statistical analyses were performed with IBM SPSS Statistics for Windows (v 24.0; IBM). Mean±standard deviation or median and interquartile range (IQR)/range were calculated with descriptive statistics. Risk ratios (RR) and 95% confidence intervals (CIs) were calculated for (1) new ACL injuries and specifically ipsi- or contralateral ruptures in the ACLR cohort, and (2) new other severe traumatic knee injuries, comparing the proportion of players in a high-risk group (as determined by the predetermined cutoffs) with the proportion of players in the referent group for each potential risk factor. The predictive validity of the tests was assessed using receiver operating characteristic (ROC) curve statistics (area under the curve [AUC]), and the sensitivity and specificity of the cutoffs. The definition of the AUC was excellent (0.90–1), good (0.80–0.89), fair (0.70–0.79), poor (0.60–0.69), or fail (<0.59). The significance level was set at $P < .05$.

RESULTS

Forty-six players with ACLR (39%) sustained 48 severe knee injuries, including 28 new ACL injuries; 21 ipsilateral and 7 contralateral ruptures, during soccer. Of the knee-healthy players, 13 (11%) sustained 14 severe traumatic knee injuries including 8 ACL injuries (Table 1).¹¹

TABLE 1

Severe (>28 Days Absence from Soccer Play) Traumatic Knee Injuries Reported from Baseline up to 2-Year Follow-Up in Players With ACL Reconstruction and Previously Knee-Healthy Players^a

	Players With ACL Reconstruction (n=117)		Knee-Healthy Players (n=119)	
Total players with severe knee injury	46 (39)		13 (11)	
New ACL injuries ^b	28 (24)		8 (7)	
Other severe knee injuries ^b	20 (17)		6 (5)	
	ACL reconstructed knee	Contra-lateral knee	Non-dominant leg	Dominant leg
No. of new severe traumatic knee injuries				
ACL total rupture	14 ^c	7 ^d	3 ^e	4 ^e
ACL partial rupture	7 ^f			1 ^g
Meniscus lesion	6 ^e		1 ^g	
Cartilage lesion	2 ^h			
Medial or lateral collateral ligament injury	2 ⁱ	1 ⁱ	2	
Patella subluxation	1	1 ⁱ		
Joint sprain unspecified	4			
Contusion	1		1	1 ⁱ
Graft problems (fixation, scar tissue)	2 ^e			
Wound			1	

^aValues are reported as n (%). ACL, anterior cruciate ligament.
^b2 players with ACL reconstruction reported 2 severe knee injuries. 1 further ACL re-rupture occurred when skiing and was not included in the analysis; 1 player in the knee-healthy cohort had 2 severe knee injuries.
^c12 surgically diagnosed/treated, 1 diagnosed with magnetic resonance imaging, and 1 clinically.
^d6 surgically diagnosed/treated, 1 diagnosed with magnetic resonance imaging.
^eAll surgically treated.
^f5 surgically diagnosed/treated, 2 diagnosed clinically.
^g1 surgically diagnosed/treated.
^h1 surgically diagnosed/treated, 1 diagnosed with magnetic resonance imaging.
ⁱ1 diagnosed with magnetic resonance imaging.

26 **Functional performance Tests**

27 Scores, LSI values, and the number of players with functional performance test results
28 defining a high-risk player related to the cutoffs, are presented in Table 2. The proportion of
29 players who had scores defining a high-risk player ranged from 13% (side difference ≥ 4 cm in
30 SEBT anterior direction) to 65% ($\leq 94\%$ of limb length in SEBT composite score) for players
31 with ACLR and 14% to 61% for knee-healthy players (Table 2).

TABLE 2
Scores, LSI Values, and the Numbers of Players Defined as High-risk According to the Predefined Cutoffs in the
Different Functional Performance Tests for the Reconstructed and Uninvolved Limbs of Female Soccer Players
With ACLR and the Nondominant and Dominant Limbs of Knee-Healthy Players^a

Test	Players With ACLR (n=117)		Knee-Healthy Players (n=119)		
	No new ACL injury (n=89)	New ACL injury (n=28)		No ACL injury (n=111)	ACL injury (n=8)
Star Excursion Balance Test – anterior reach distance, % ^b					
ACLR limb	84±6	83±6	Nondominant limb	85±6	87±3
Uninvolved limb	85±6	83±7	Dominant limb	84±6	86±2
LSI ^c	99±3	101±3		101±3	101±3
Side difference ≥4 cm	14 (16)	1 (4)		16 (14)	1 (13)
Star Excursion Balance Test – composite score, % ^b					
ACLR limb	92±6	92±7	Nondominant limb	93±5	95±3
Uninvolved limb	93±6	92±6	Dominant limb	93±6	95±2
LSI ^c	100±3	100±2		101±3	100±2
≤94% of limb length	59 (66)	17 (61)		68 (61)	4 (50)
1-legged hop for distance, cm					
ACLR limb	120±19	127±23	Nondominant limb	125±17	140±13
Uninvolved limb	122±18	128±21	Dominant limb	124±18	139±18
LSI ^c	98±8	98±9		101±8	101±7
LSI ^c <90%	12 (13)	3 (11)		n.a.	n.a.
LSI ^c <90% or >110%	17 (19)	6 (21)		18 (16)	1 (13)
Side hop, n					
ACLR limb	32±14	41±17	Nondominant limb	37±14	49±11
Uninvolved limb	36±13	42±15	Dominant limb	38±13	48±12
LSI ^c	92±22	98±19		98±17	105±15
LSI ^c <90%	36 (40)	6 (21)		n.a.	n.a.
LSI ^c <90% or >110%	50 (56)	11 (39)		46 (41)	3 (38)
Tuck jump, total score (0–10)					
≥6 flawed techniques	5±2	5±2		5±2	4±1.5
	38 (43)	12 (43)		36 (32)	1 (13)
Drop vertical jump, knee motion in frontal plane (cm) ^d					
ACLR limb	3 (4; –8 to 9)	3 (6; –3 to 11)	Nondominant limb	5 (4; –5 to 17)	7 (4; 0–11)
Uninvolved limb	3 (6; –10 to 11)	4 (4; –1 to 9.0)	Dominant limb	4 (4; –7 to 13)	4 (7; 0–9)
≥6.5 cm valgus in any knee	21 (24)	8 (29)		40 (36)	6 (75)
≥4.1 cm side difference	28 (31)	12 (43)		33 (30)	3 (38)
Probability of a high knee abduction moment, pKAM (%)					
ACLR limb	67 (40; 10–98)	60 (46; 14–99)	Nondominant limb	78 (12; 7–100)	86 (19; 40–99)
Uninvolved limb	71 (37; 15–98)	67 (40; 21–96)	Dominant limb	70 (44; 7.4–98.7)	71 (50; 13–95)
pKAM ≥91%	21 (24)	7 (25)		38 (34)	4 (50)

^aValues are reported as means±SD, medians (interquartile range; range), or n (%). ACLR, anterior cruciate ligament reconstruction; LSI, limb symmetry index; n.a., not applicable.

^bReach distance in centimeters was normalized to the leg length ([test value/leg length] × 100). The composite score is the average of the 3 normalized measurements in the different directions.

^cLSI was calculated as (ACL – reconstructed limb/uninvolved limb) × 100 or (nondominant limb/dominant limb) × 100.

^dPositive values refers to valgus (medial) motion; negative values refers to varus (lateral) motion.

Validation of Predetermined Cutoffs

Prediction of New ACL Injury

The validity of the 5 tests with 10 different test cutoffs to predict an ACL injury are presented in Figure 2 (postural control), Figure 3 (hop performance, endurance, and maximum), and Figure 4 (hop performance, movement asymmetries). There were no

significant associations between predetermined cutoffs on any of the tests and the risk of sustaining an additional ACL injury in players with ACLR. In knee-healthy players, the only variable associated with new ACL injury was ≥ 6.5 cm knee valgus in the frontal plane (in any knee) in the DVJ (RR, 4.93; 95% CI, 1.04–23.40; $P=.045$), but with only fair predictive validity (AUC=0.7, sensitivity=0.75, specificity=0.65) (Figure 4). Six of the 46 knee-healthy players that had ≥ 6.5 cm valgus in any knee in the DVJ and who sustained an ACL injury during follow-up had ≥ 6.5 cm in their nondominant limb, and 2 also had >6.5 cm valgus in their dominant limb. All new ACL injuries occurred in the dominant limb except in one player (valgus ≥ 6.5 cm in both limbs).

Separate analyses of association between cutoffs in the 5 different functional tests and risk of sustaining a rerupture or contralateral rupture specifically showed that the risk for a contralateral rupture was almost 5 times higher with a side difference in valgus ≥ 4.1 cm (AUC=0.8, 71% sensitivity and 69% specificity), but did not reach statistical significance (RR, 4.813; 95% CI, 0.977–23.711; $P=.053$) (Supplemental Appendix, Figure 9c).

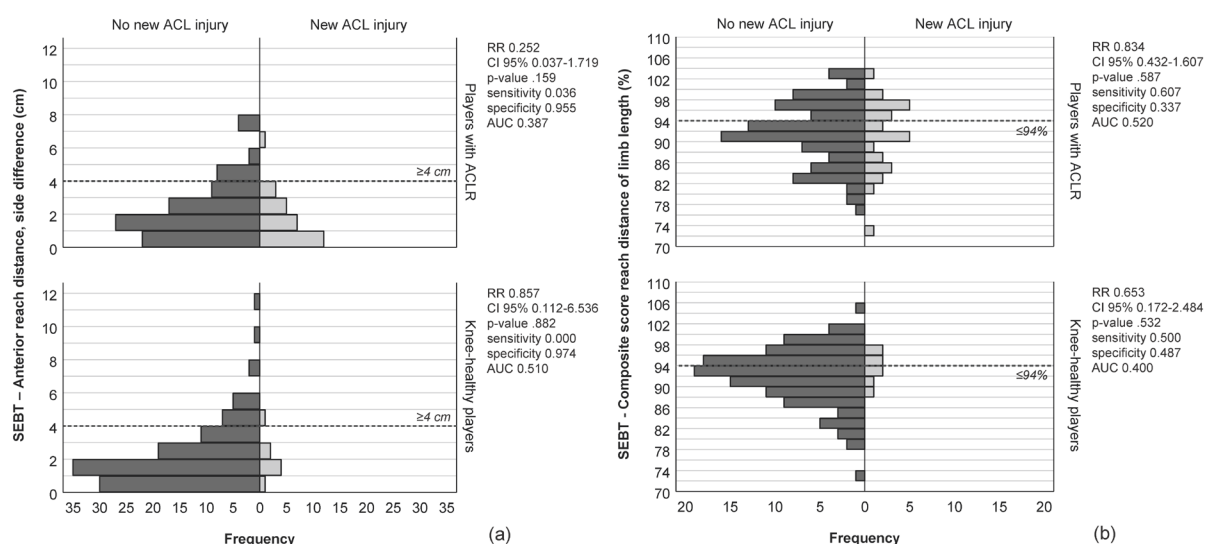


Figure 2. Postural control: risk ratio (RR), 95% confidence interval (CI), P value for the 2 cohorts, players with ACLR and knee-healthy players, comparing the proportion of

players with cutoffs defining a high or low-risk player, and sustaining a new ACL injury: (a) ≥ 4 cm side difference in anterior reach distance and (b) $\leq 94\%$ of limb length in composite score in the Star Excursion Balance Test (SEBT). The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

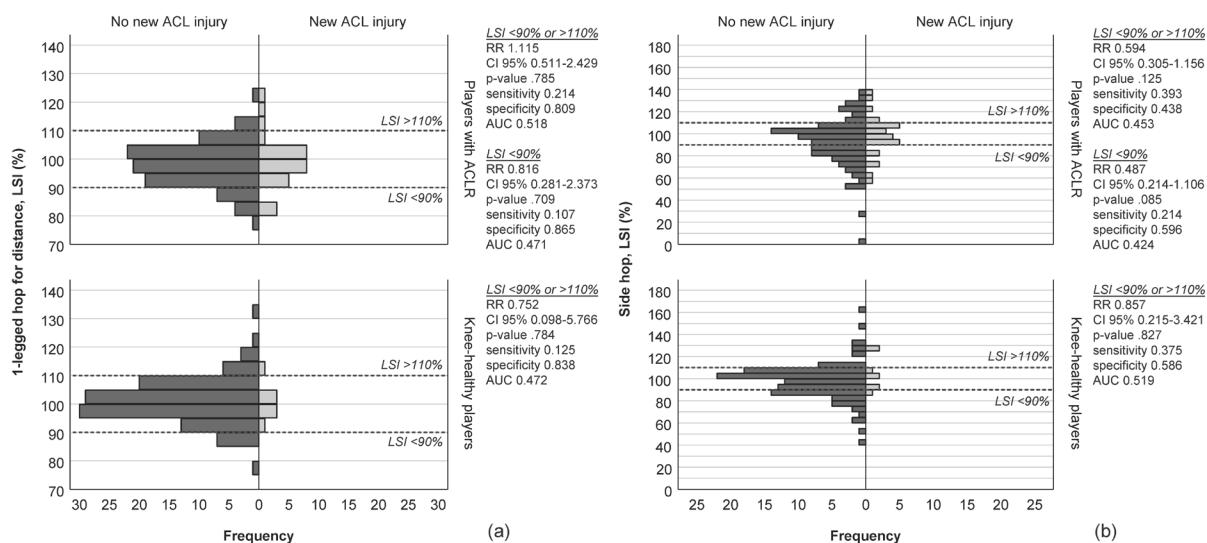


Figure 3. Hop performance: risk ratio (RR), 95% confidence interval (CI), *P* value for the 2 cohorts, players with ACLR and knee-healthy players, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a new ACL injury: (1) Limb Symmetry Index (LSI) < 90%, (2) < 90% or > 110%, i.e., the ACLR limb should neither not be 10% weaker or stronger compared with the non-reconstructed leg in (a) 1-legged hop for distance and (b) side hop. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

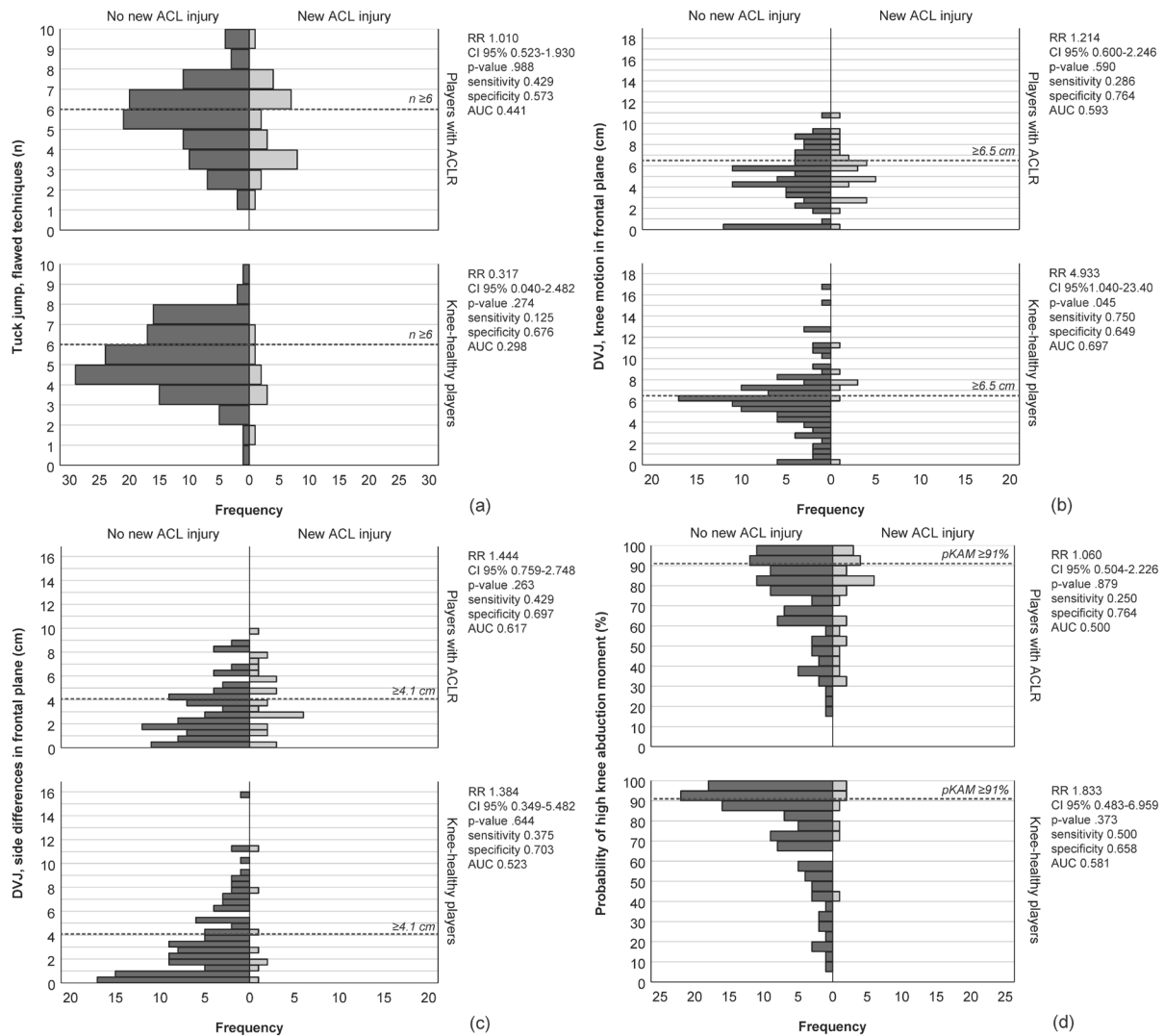


Figure 4. Movement asymmetries in the lower limbs and trunk: risk ratio (RR), 95% confidence interval (CI), *P* value for the 2 cohorts, players with ACLR and knee-healthy players, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a new ACL injury; (a) ≥ 6 flawed techniques in the tuck jump, (b) knee valgus motion ≥ 6.5 cm in any knee, (c) ≥ 4.1 cm side difference in frontal plane, (d) probability of high knee abduction moment (pKAM) $\geq 91\%$ in drop vertical jump (DVJ) and sustaining a new ACL injury. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

Prediction of New Severe Traumatic Knee Injury

There was no significant association between predetermined cutoffs for the different tests and risk of sustaining a severe traumatic knee injury in players with ACLR or in knee-healthy players (Supplemental Appendix, Figures 1–3).

Numbers of Players Who Had Predefined Cutoffs Defining a High-Risk Player in Each of the 5 Tests

Overall, only 9% of the players with ACLR (10 of 117) and 8% of the knee-healthy players (9 of 119) were classified as a low-risk players based on all 5 predetermined cutoffs in the test battery. There was no difference in the risk of new ACL injury between players who were classified as high-risk players according to the 5 predetermined cutoffs and those who did not, neither in players with ACLR (RR, 0.561; 95% CI, 0.243–1.295; $P=.176$) nor in knee-healthy players (RR, 0.573; 95% CI, 0.079–4.157; $P=.582$). Similarly, there was no difference in the risk of other severe knee injury in players with ACLR (RR, 0.623; 95% CI, 0.355–1.093; $P=.099$) or knee-healthy players (RR, 0.981; 95% CI, 0.143–6.720; $P=.985$).

DISCUSSION

The main finding was that none of the 10 cutoffs in the 5 different functional performance tests had any predictive validity for new knee injuries in the ACLR cohort. In knee-healthy players, only 1 cutoff from 1 functional performance test (knee valgus ≥ 6.5 cm in any knee in the frontal plane measured during DVJ) showed an association with a 5 times higher risk of sustaining an ACL injury, but only with fair combined sensitivity and specificity. Thus, the predetermined cutoffs evaluated in this study has questionable value in identifying risk factors and helping clinicians in the goal of preventing a severe knee injury in female soccer players.

The cutoffs used for postural control measures, i.e., SEBT, have previously been described by Plisky et al.³⁸ They reported an association between (1) side-to-side differences in the anterior reach distance, and (2) a composite score reach distance $\leq 94\%$ of limb length, and risk of injury to the lower extremities in high school basketball players. These results could not be confirmed in our cohorts regarding severe knee injuries, and further validation of the SEBT and these 2 cutoffs is needed.

The cutoffs of an LSI $< 90\%$, defining a high-risk player, used for the 1-legged hop for distance and side hop did not show any association with sustaining a severe knee injury. The most commonly used cutoff for hop performance tests,^{7,41} is an LSI of 90% .^{6,44} There is, to our knowledge, only 1 study showing any relationship with reaching an LSI $\geq 90\%$ and sustaining fewer knee injuries. Grindem et al.¹⁵ showed that reaching an LSI $\geq 90\%$ in quadriceps strength before return to sport after ACLR was associated with a lower knee reinjury rate, but, in line with our results, this association was not reported for the 1-legged hop for distance, 6 m timed hop, triple hop for distance, and cross-over hop for distance. However, the validity of the specific LSI cutoffs in different hop performance tests for evaluating the risk of sustaining an injury has been questioned.^{41,46} LSI can overestimate performance due to bilateral deficits and poor performance of the non-ACLR limb.^{13,46} The cutoff is sometimes proposed to be 100% of LSI as a more precise and demanding criteria for athletes who will return to cutting and pivoting sports.⁴¹ On the other hand, there is a 3 times increased risk for contralateral ruptures in athletes with ACLR who passed return-to-sport criteria.⁴⁴ A hypothesis is that side-to-side asymmetries may increase injury risk to both limbs.³⁷ Therefore, a cutoff of an LSI of $> 110\%$, defining a high-risk player, was also analyzed in the cohort of players with ACLR. However, asymmetries indicating stronger ACLR leg (LSI $> 110\%$) were not associated with sustaining a secondary knee injury.

The results in our study did not show any association between <6 flawed techniques in the tuck jump and sustaining a primary or secondary knee injury. The cutoff of 6 or more flaws during the tuck jump is based on empirical evidence and is associated with poor performance, identifying players who might be at risk for ACL injury.^{2, 29} However, no relationship was reported between tuck jump assessment and knee valgus measured with DVJ, one-legged hop for distance, the International Knee Documentation Committee 2000 Subjective Knee Form and the Knee injury Osteoarthritis Outcome Score.² Still, this cutoff has not been previously validated, and the test needs further validation.^{2, 8} It may be more valuable clinically to use the individual tuck jump assessment items than assessing the total score.²

We found no association between movement asymmetries in the DVJ and a secondary knee injury. Only 1 of 3 cutoffs (≥ 6.5 cm knee valgus in any knee in frontal plane) showed an association with primary ACL injury, albeit only with fair combined sensitivity and specificity. Our hypothesis was that knee valgus ≥ 6.5 cm in any knee could represent movement asymmetries associated with an increased risk for a new knee injury in that athlete. This is supported by the fact that Hewett et al²⁰ reported that ACL-injured females had 6.4 times greater side-to-side knee abduction moment difference in DVJ test compared to uninjured females.

There are conflicting results and limited evidence on whether knee valgus motion, as a part of movement asymmetries evaluation, is associated with an increased risk of sustaining a primary or secondary ACL injury. For primary injury prediction, Hewett et al²⁰ reported that increased dynamic valgus and high abduction loads in female athletes could predict an ACL injury with 78% sensitivity and 73% specificity. In contrast, Goetschius et al¹² and Krosshaug et al²³ did not show that high valgus motion was predictive for sustaining an ACL injury for previously uninjured female athletes. For secondary injury prediction, some associations with increased knee valgus pattern during a DVJ and sustaining an ACL re-injury have been

reported.^{23, 37} In addition, many ACL injury prevention programs that have been proven to decrease primary ACL injuries by 53%²¹ target movement asymmetries, such as avoiding knee valgus motion and using proper landing mechanics.²¹ Still, the cause in relation to prevention in these programs is still unknown,⁴⁰ and the predictive value of dynamic knee valgus motion pattern for a primary and secondary ACL injury is still not confirmed.

Our results showed that analyzing all tests as a test battery, i.e., players who were defined as high-risk players in each of the 5 tests, was not associated with an increased risk of new ACL injury or severe knee injury. These results are in line with most of the previous studies evaluating different test batteries, mainly including strength and hop performance tests.^{5, 27, 44,}⁴⁵ However, 2 previous studies found an association between results in test batteries and sustaining a second ACL injury, but each test alone in the test batteries did not predict a second ACL injury.^{25, 43} Although there is no objective criteria,¹⁷ or test after an ACLR that can predict who will sustain a new injury,¹⁸ it is considered best approach to evaluate different components and use a battery of tests to inform the return-to-sport decision.^{1, 25, 41} Test batteries also discriminate better between involved and uninvolved limbs than single tests.^{16, 41} In our study, only 9% of the players with ACLR and 8% of knee-healthy players were classified as low-risk players based on all 5 tests. This is in line with previous studies showing that only 11%–23% of the athletes with ACLR^{10, 44, 45} and 19% of knee-healthy players passed all criteria in test batteries.¹⁰ The likelihood of passing a full test battery is dependent on the number of tests used and the cutoffs, the more tests and cutoffs included, the more difficult it is for patients to pass the full test battery.⁴⁴ Therefore, how many and which tests and cutoffs should be included in a test battery requires further evaluation.

Another question is whether the functional performance tests commonly used in clinic capture the risk factors related to common knee injury mechanisms. The drop vertical jump and tuck jump tests both aim to capture the valgus mechanism involved in many non-contact

and indirect contact ACL injuries in soccer.^{7, 42} It is possible that more soccer-specific functional tests should be used, but these are often more difficult to standardize and to perform in many clinics because of limited space. The used cutoffs for the different tests could also be inappropriate, but in our data no other cutoff could be used to predict a new ACL or severe knee injury.

Our results showed that commonly used functional performance tests did not predict new severe knee injuries. However, functional testing of players and patients is positive in many aspects because these give valuable information about the players' progress in the rehabilitation after injury, identify deficits, for goalsetting, feedback, and engagement with the medical team for each player.³³

A strength of the present study is the homogeneous cohort of female soccer players with ACLR and knee-healthy players from the same soccer teams. Another strength is the prospective design of the data collection with relatively frequent follow-up to reduce the risk of recall bias. All severe knee injuries were also verified from medical charts. Some limitations other than the ones already discussed should be acknowledged. We were not aware of the amount of match or training soccer exposure, and this is probably the most important risk factor for new injury. Hypothetically, players who do not meet the cutoffs and have worse performance could have less soccer exposure with less stress and forces on the knee and thus be less likely to sustain a new injury, and vice versa. To evaluate tests to predict injuries in future the risk exposure for the athletes is important.

CONCLUSIONS

Previously predetermined cutoffs used to differentiate between high and low-risk players on commonly used functional tests to assess postural control, hop performance, and movement asymmetries in the lower limbs and trunk showed poor validity to predict new

knee injuries in female soccer players. Ten cutoffs for 5 functional tests in two different cohorts of female soccer players were tested, and the predictive validity for both cohorts in players with a previous ACLR and in previously knee-healthy players was poor.

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Supplementary Appendix.

The validity of the 5 tests with 10 different test cut-offs to predict a new traumatic severe knee injury are presented in Figure 1 (postural control), Figure 2 (hop performance, endurance and maximum) and Figure 3 (hop performance, movement asymmetries).

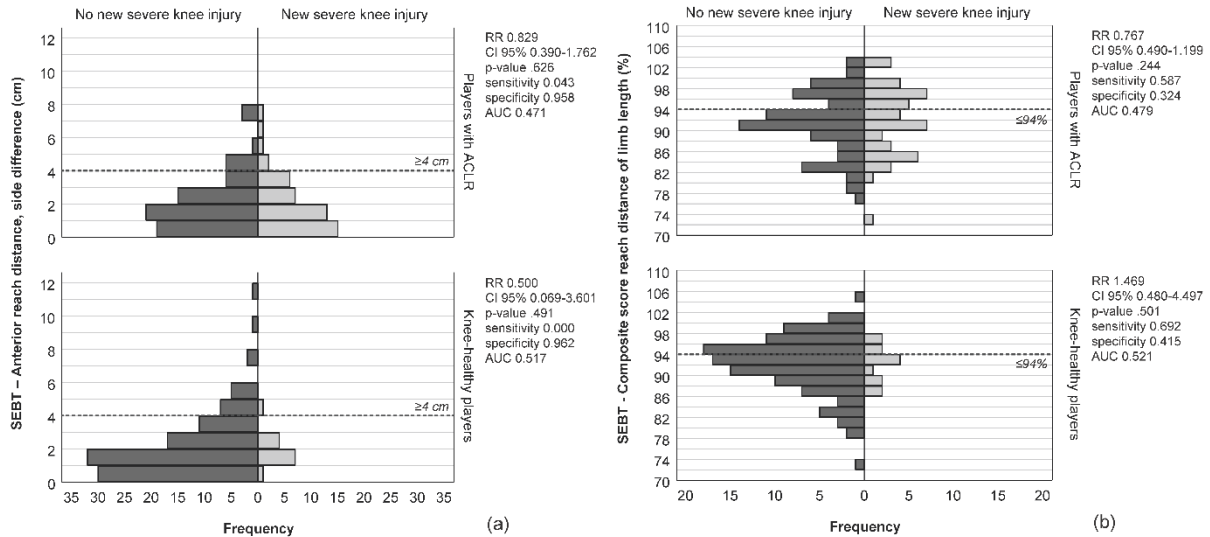


Figure 1. Postural control: risk ratio (RR), 95% confidence interval (CI), *P* value for the 2 cohorts, players with ACLR and knee-healthy players, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a new traumatic severe knee injury: (a) ≥ 4 cm side difference in anterior reach distance and (b) $\leq 94\%$ of limb length in composite score in the **Star Excursion Balance Test (SEBT)**. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

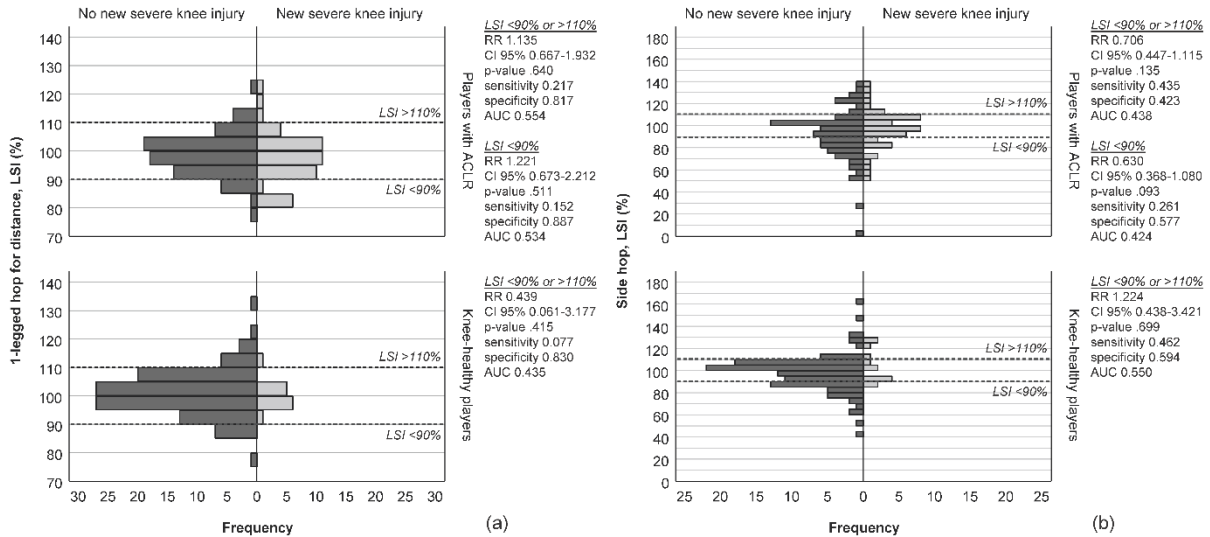


Figure 2. Hop performance: risk ratio (RR), 95% confidence interval (CI), *P* value for the 2 cohorts, players with ACLR and knee-healthy players, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a new traumatic severe knee injury: (1) Limb Symmetry Index (LSI) <90%, (2) <90% or >110%, i.e., the ACLR limb should neither not be 10% weaker or stronger compared with the non-reconstructed leg in (a) **1-legged hop for distance** and (b) **side hop**. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

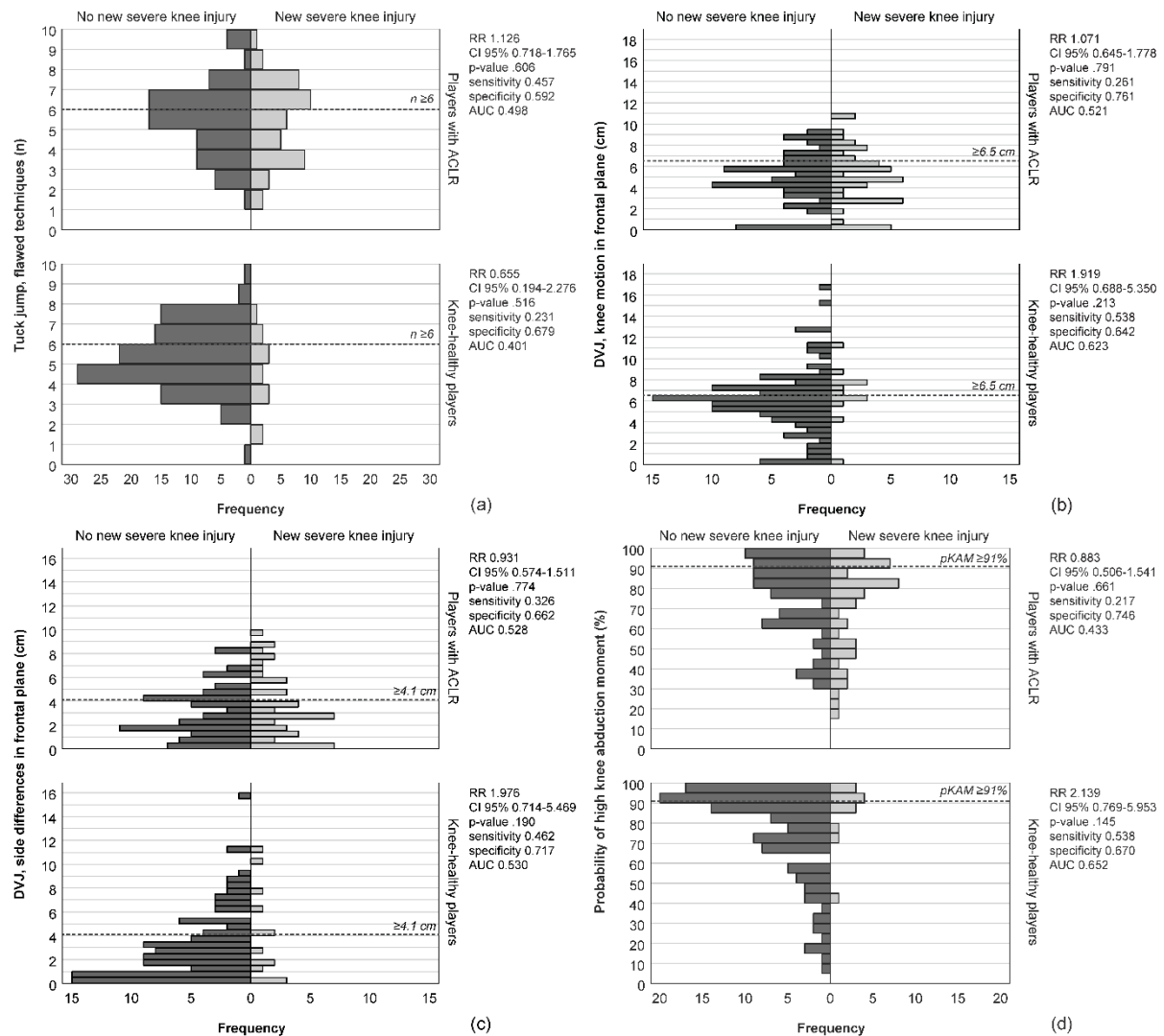


Figure 3. Movement asymmetries in the lower limbs and trunk: risk ratio (RR), 95% confidence interval (CI), *P* value for the 2 cohorts, players with ACLR and knee-healthy players, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a new traumatic severe knee injury; (a) ≥ 6 flawed techniques in the **tuck jump**, (b) knee valgus motion ≥ 6.5 cm in any knee, (c) ≥ 4.1 cm side difference in frontal plane, (d) probability of high knee abduction moment (pKAM) $\geq 91\%$ in **drop vertical jump (DVJ)** and sustaining a new ACL injury. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

The validity of the 5 tests with 10 different test cut-offs to predict a **rerupture of the ACL graft** are presented in figure 4 (postural control), figure 5 (hop performance, endurance and maximum) and figure 6 (hop performance, movement asymmetries).

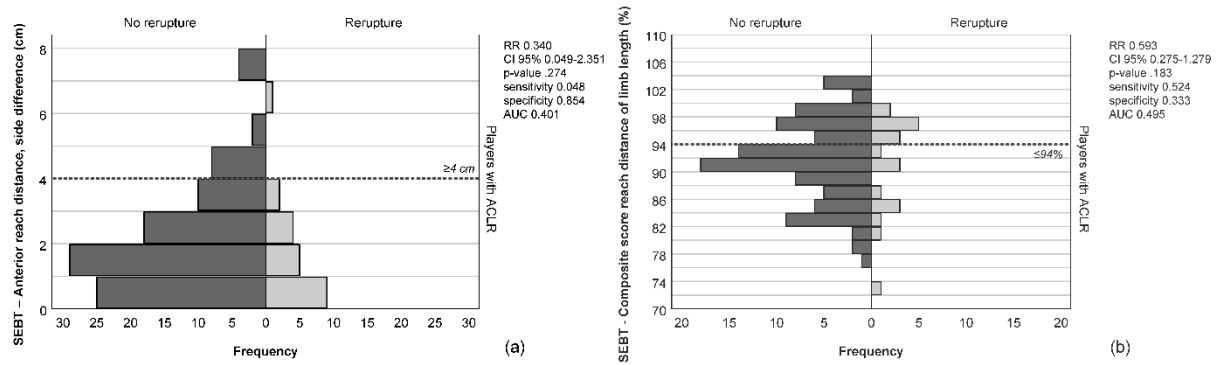


Figure 4. Postural control: risk ratio (RR), 95% confidence interval (CI), *P* value for players with ACLR, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a rerupture of the ACL graft: (a) ≥ 4 cm side difference in anterior reach distance and (b) $\leq 94\%$ of limb length in composite score in the **Star Excursion Balance Test (SEBT)**. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

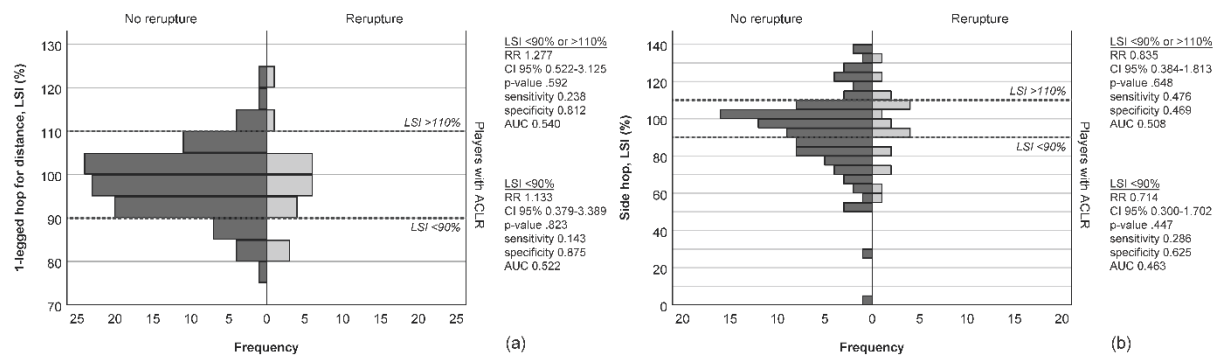


Figure 5. Hop performance: risk ratio (RR), 95% confidence interval (CI), *P* value for the players with ACLR, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a rerupture of the ACL graft: (1) Limb Symmetry Index (LSI) <90%, (2) <90% or >110%, i.e., the ACLR limb should neither not be 10% weaker or stronger compared with the non-reconstructed leg in (a) **1-legged hop for distance** and (b) **side hop**. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

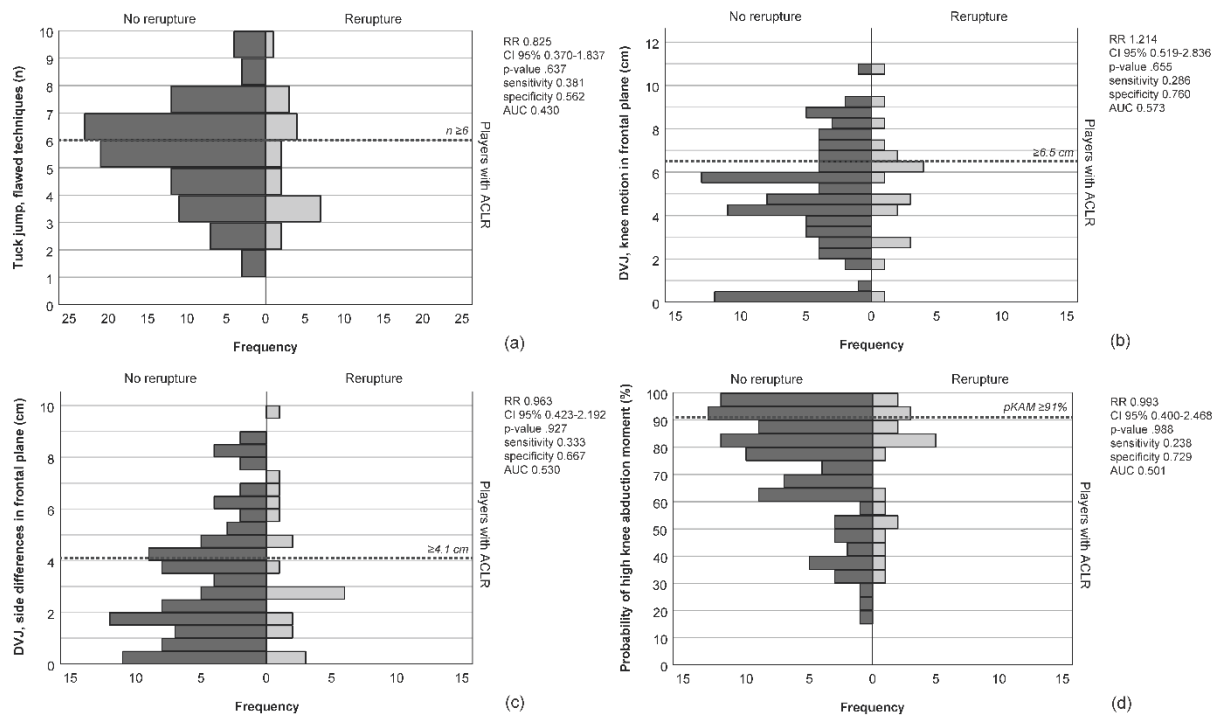


Figure 6. Movement asymmetries in the lower limbs and trunk: risk ratio (RR), 95% confidence interval (CI), *P* value for the players with ACLR, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a rerupture of the ACL graft; (a) ≥ 6 flawed techniques in the **tuck jump**, (b) knee valgus motion ≥ 6.5 cm in any knee, (c) ≥ 4.1 cm side difference in frontal plane, (d) probability of high knee abduction moment (pKAM) $\geq 91\%$ in **drop vertical jump (DVJ)** and sustaining a new ACL injury. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

The validity of the 5 tests with 10 different test cut-offs to predict a **contralateral ACL injury** are presented in figure 7 (postural control), figure 8 (hop performance, endurance and maximum) and figure 9 (hop performance, movement asymmetries).

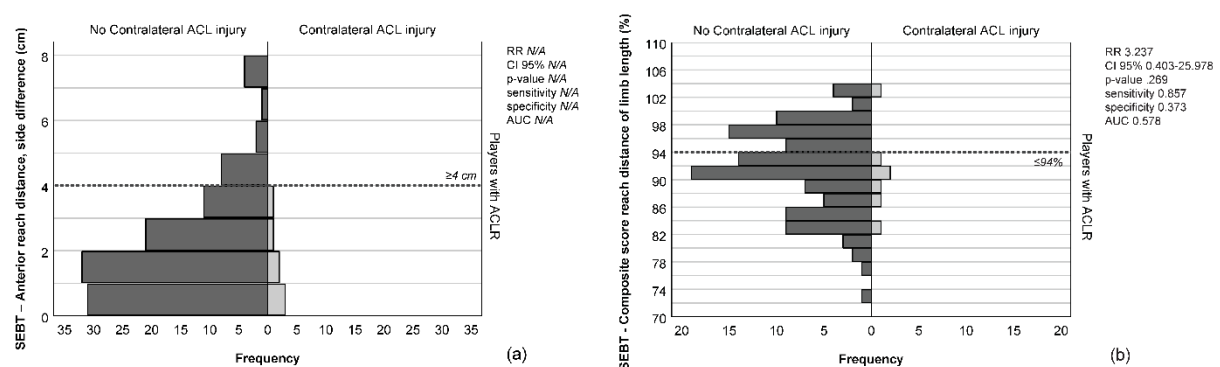


Figure 7. Postural control: risk ratio (RR), 95% confidence interval (CI), *P* value for the players with ACLR, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a contralateral ACL injury: (a) ≥ 4 cm side difference in anterior reach distance and (b) $\leq 94\%$ of limb length in composite score in the **Star Excursion Balance Test (SEBT)**. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

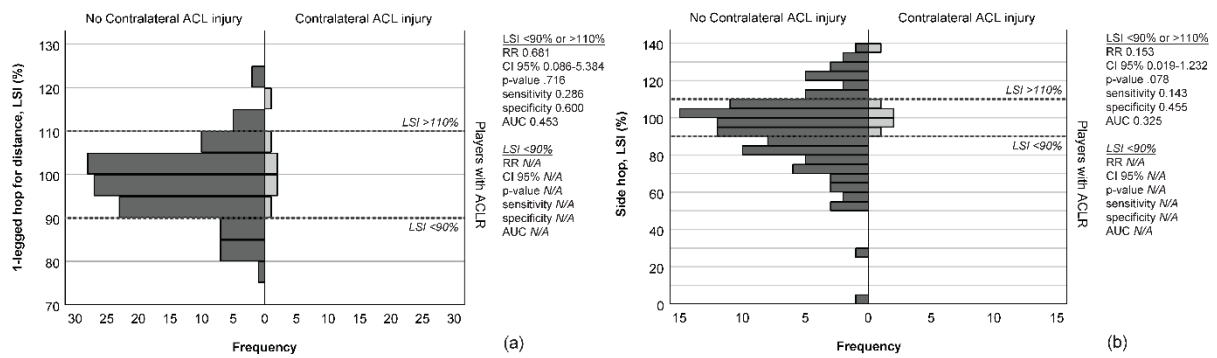


Figure 8. Hop performance: risk ratio (RR), 95% confidence interval (CI), *P* value for the players with ACLR, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a contralateral ACL injury: (1) Limb Symmetry Index (LSI) <90%, (2) <90% or >110%, i.e., the ACLR limb should neither not be 10% weaker or stronger compared with the non-reconstructed leg in (a) **1-legged hop for distance** and (b) **side hop**. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.

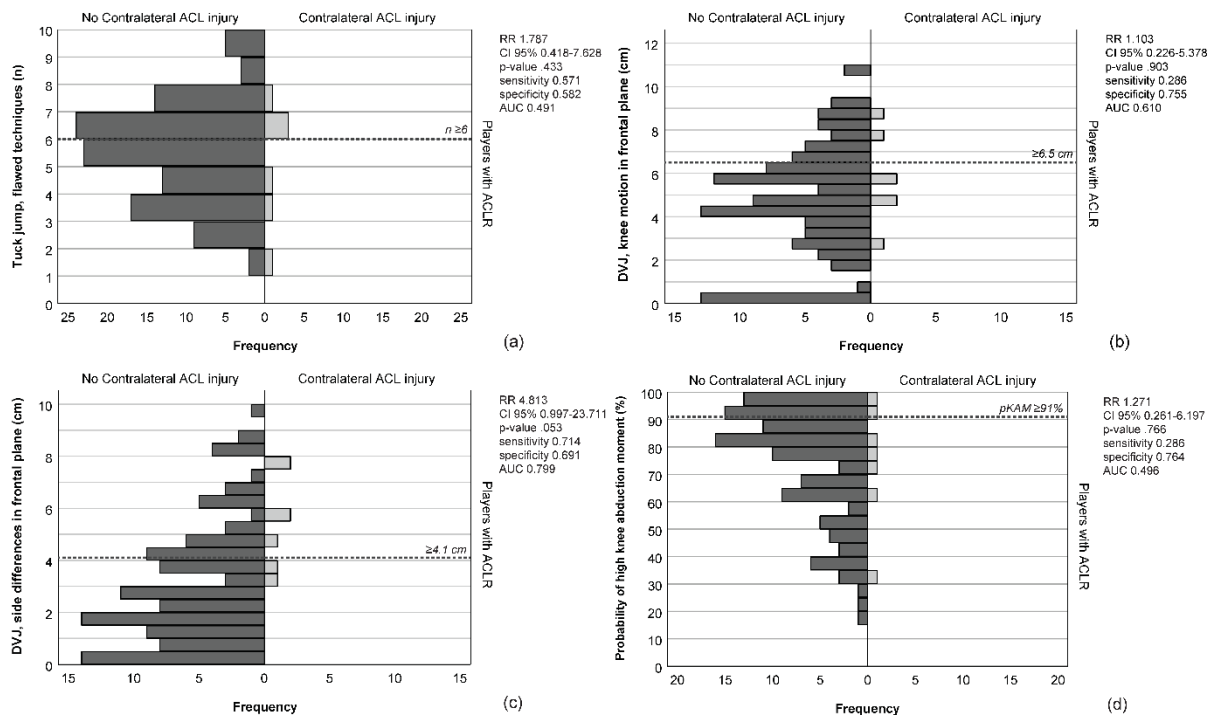


Figure 9. Movement asymmetries in the lower limbs and trunk: risk ratio (RR), 95% confidence interval (CI), *P* value for the players with ACLR, comparing the proportion of players with cutoffs defining a high or low-risk player, and sustaining a contralateral ACL injury; (a) ≥ 6 flawed techniques in the **tuck jump**, (b) knee valgus motion ≥ 6.5 cm in any knee, (c) ≥ 4.1 cm side difference in frontal plane, (d) probability of high knee abduction moment (pKAM) $\geq 91\%$ in **drop vertical jump (DVJ)** and sustaining a new ACL injury. The predictive validity of the cutoffs was assessed with receiver operating characteristic curve statistics with area under the curve (AUC), sensitivity, and specificity.