



Preliminary Scoring Template of a Modified Landing Error Scoring System

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Abstract

Background: The Landing Error Scoring System (LESS) identifies participants displaying potentially high-risk movement patterns during a double-leg jump-landing (DLJL) task. However, the DLJL has been criticized for not reflecting injury-prone situations in sport. The biomechanics and perceived difficulty of a rotated single-leg jump-landing (SLJL_{rot}) task have shown stronger associations with sport-specific cutting maneuvers than DLJL. Therefore, the SLJL_{rot} may be a better suited task than the DLJL to assess landing “errors”.

Objectives: Present a preliminary scoring template of a modified LESS applied to a SLJL_{rot} task.

Design: Cross-sectional study.

Methods: Whole-body motion was recorded for 42 young active participants (25 males and 17 females) using a three-dimensional infrared camera system during DLJL and SLJL_{rot} tasks. Ankle, knee, hip, and trunk angles corresponding to the original LESS items were extracted for dominant and non-dominant legs from both tasks. Based on the differences in kinematic values between tasks, original LESS thresholds, and current scientific evidence, the original LESS items from the DLJL were modified to suit the SLJL_{rot} task.

Results: A preliminary scoring template of a modified LESS applied to a SLJL_{rot} task was developed, including operational definitions of errors and relevant thresholds. The preliminary template consists of 13 items. The minimum and maximum scores are 0 and 12 errors, respectively, with higher scores indicating poorer landing biomechanics.

Conclusions: The modified LESS may be an appropriate clinical screening tool for assessing sport-related non-contact lower extremity injury risk in athletes. The proposed template and thresholds require further scientific validation.

Keywords: Injury Risk; Screening Tool; Sport Injuries; Anterior Cruciate Ligament

Highlights

- Preliminary scoring template of modified LESS applied to SLJL_{rot} task was developed
- Modified LESS may be an appropriate clinical sport-related injury risk screening tool
- The proposed template of modified LESS require further scientific validation

Introduction

The Landing Error Scoring System (LESS) is a movement-based injury risk screening tool first proposed by Padua and colleagues in 2009 [1]. The LESS was designed to identify participants displaying potentially high-risk biomechanical patterns for Anterior Cruciate Ligament (ACL) injury [1]. Clinicians evaluate frontal and sagittal plane videos of a double-leg jump-landing (DLJL) task and visually evaluate aberrant lower extremity and trunk kinematics between

initial ground contact and peak knee flexion instances. Several studies have criticized the DLJL task used in the LESS, stating it is neither sport-specific nor sufficiently challenging to reveal movement patterns linked to non-contact lower-extremity injuries, and is poor for predicting ACL injuries [2,3]. Hanzlíková, Richards, Athens, Hébert-Losier [4] associated trunk and lower extremity kinematics between sport-specific unanticipated side-step cutting and jump-landing variations and compared perceived difficulty levels between tasks in young active individuals. The authors concluded that due to its subjective difficulty ratings and biomechanical associations with cutting movements, the rotated single-leg jump-landing (SLJL_{rot}) task might be a more appropriate screening task for detecting at risk athletes involved in landing and cutting sports than the traditional DLJL task [4]. Hence, the SLJL_{rot} may be better suited than the DLJL task to assess landing “errors” and more ecologically valid to identify athletes displaying movement patterns placing them at greater risk of lower-extremity injury during challenging sporting maneuvers. The original LESS scoring criteria need modifications to suit a SLJL_{rot} task. This technical report presents a preliminary modified LESS scoring template applied to a SLJL_{rot} task based on three-dimensional (3D) data collected in our laboratory, the original LESS thresholds [1,5], and current scientific evidence.

Methods

Forty-two physically active participants (25 males and 17 females) volunteered. A Health Research Ethics Committee approved the study protocol [HREC(Health)2018#27], which adhered to the Declaration of Helsinki. All participants signed a written informed consent document before participating that explained the potential risks (i.e., delayed onset muscle soreness or risk of injury performing sport-related tasks).

Participants performed DLJL and SLJL_{rot} tasks. The DLJL followed the original LESS protocol [1], requiring participants to jump forward from a 30-cm high box with both feet, landing to a distance equal to 50% of their body height, and then immediately jumping upwards for maximal height (Figure 1). For the SLJL_{rot}, the protocol was similar to the DLJL one, but participants rotated 90° in the air before landing on one leg to a distance equal to 25% of their body height (Figure 1). After a familiarization period of on average two attempts per task, each participant completed three successful repetitions of DLJL and SLJL_{rot} tasks in a randomized order. The SLJL_{rot} was performed three times on the right and left lower extremity. The order of lower extremities was also randomized.



Figure 1: Double-leg jump-landing (DLJL) and rotated single-leg jump-landing (SLJL_{rot}) tasks. BH, body height.

Whole-body motion was recorded at 200 Hz during both tasks using an 8-camera 3D motion capture system (Oqus 700+ cameras) and software (Qualisys Track Manager v.2019.1, Qualisys AB, Gothenburg, Sweden). Forty-two 12.5mm retroreflective markers and five clusters were taped onto the skin and shoes based on the Calibrated Anatomical System Technique [6], with one of the clusters positioned on the right side of the pelvis to improve segment tracking [4]. Data were exported to the .c3d format and processed using Visual3D Professional™ (v.6.01.36, C-Motion Inc., Germantown, Maryland, USA). A 13 rigid segment biomechanical model with six degrees of freedom at each joint was constructed. The local coor-

dinates of all segments were derived from a static trial captured prior to the dynamic trials. Any marker data gaps, up to 10 frames (20 ms), were interpolated using a third order polynomial fit algorithm. A fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz was then applied to the data. Kinematic parameters were calculated using an XYZ cardan sequence, equivalent to the joint coordinate system [7]. Ankle, knee, hip, and trunk angles relevant to both the DLJL and SLJL_{rot} items (Table 1) were extracted for the dominant and non-dominant leg. Inertial measurement units were placed above the lateral malleoli to define initial contact based on the peak vertical acceleration.

Items ^a	Dominant leg		Non-dominant leg	
	DLJL	SLJL _{rot}	DLJL	SLJL _{rot}
Knee flexion: IC	33.7 ± 8.3	18.3 ± 5.6	34.2 ± 7.9	17.6 ± 5.4
Hip flexion: IC	38.9 ± 13.1	25.2 ± 9.9	38.7 ± 12.3	19.3 ± 12.6
Trunk flexion: IC	16.4 ± 7.5	4.5 ± 5.6	16.2 ± 7.4	2.0 ± 6.5
Ankle plantar flexion: IC	-13.1 ± 7.9	-18.8 ± 7.5	-12.0 ± 8.1	-16.9 ± 6.6
Medial knee position: IC	1.4 ± 4.6	-1.6 ± 3.8	-0.9 ± 4.9	-2.9 ± 4.3
Lateral trunk flexion: IC	-0.7 ± 2.9	7.3 ± 4.7	-0.7 ± 3.0	7.5 ± 5.3
Foot position: external rotation ^b	-12.4 ± 6.6	-16.9 ± 5.7	-9.8 ± 6.7	-14.1 ± 6.3
Foot position: internal rotation ^b	-0.8 ± 6.1	-3.1 ± 6.4	2.6 ± 7.0	0.0 ± 6.7
Knee flexion displacement ^b	74.4 ± 14.9	53.6 ± 7.8	72.0 ± 14.2	51.6 ± 6.2
Hip flexion displacement ^b	38.3 ± 12.4	27.5 ± 9.1	38.0 ± 12.7	31.3 ± 10.3
Trunk flexion displacement ^b	22.8 ± 11.4	28.7 ± 10.9	22.7 ± 11.6	28.9 ± 12.4
Medial knee displacement ^{b, c}	-9.4 ± 7.8	-8.0 ± 6.5	-13.3 ± 9.1	-11.2 ± 7.4
Lateral trunk flexion displacement ^b	3.3 ± 1.2	8.6 ± 3.8	3.3 ± 1.4	8.8 ± 4.2

Table 1: Mean ± standard deviation of angle values (°) of the Landing Error Scoring System items for the double-leg jump-landing (DLJL) and rotated single-leg jump-landing (SLJL_{rot}) tasks.

IC: Initial Contact.

a. Positive values indicate flexion, dorsiflexion, knee varus, trunk lateral flexion to the tested leg, internal rotation

b. From initial contact to maximal knee flexion.

c. According to the Landing Error Scoring System definition, medial knee displacement represents the maximal knee valgus position (-).

Angle data from the three trials of each task were averaged for each participant. Means and standard deviations for dominant and non-dominant legs were calculated for each LESS item. Based on the kinematic differences between DLJL and SLJL_{rot} tasks, original LESS thresholds [1,5], and current scientific evidence [3,8-18], the original LESS items from the DLJL task were modified to suit the SLJL_{rot} task.

Results

The age, height, and mass (mean ± standard deviation) of the 25 male volunteers were 23.6 ± 4.1 years (range 17 to 32 years), 182.2 ± 6.4 cm, and 85.0 ± 11.9 kg; and of the 17 female volunteers were 22.2 ± 5.7 years (range 16 to 35 years), 169.1 ± 6.0 cm, and 63.7 ± 6.8 kg. Ninety-three percent of participants were right-leg domi-

nant based on the preferred leg to kick a ball. All participants were physically active, involved in sport activity three times per week (median) on average for 6.7 ± 4.4 hours per week.

Kinematic parameters related to the LESS items extracted from 3D capture during DLJL and SLJL_{rot} are summarized in Table 1. Table 2 presents the operational definitions of the original and modified LESS items with rationale for the suggested thresholds. The original LESS items (a) stance width: wide, (b) stance width: narrow, and (c)

symmetric initial foot contact¹ are not applicable for the SLJL_{rot} and were removed from the modified LESS scoring sheet template. The original LESS items joint displacement and overall impression are subjective in nature, which is an obstacle for the automated quantification of the LESS [15]. Furthermore, the purely subjective rating or ranking of human movement to define performance [16] or injury risk [3] has been criticized and shown inaccurate. Therefore, these items were also removed from the modified LESS with a premise to yield higher sensitivity and predictive value.

Items	Operational definition of original LESS errors ^a	Suggested operational definition of modified LESS errors	Rational
Knee flexion: IC	The knee is flexed less than 30° at IC	The knee is flexed less than 15° at IC	VA of ACL injuries report between 5° to 30° of knee flexion at IC [8-11]. Based on our data, knee flexion at IC is almost 50% lower for SLJL _{rot} vs DLJL. Therefore, 50% of the original threshold is proposed.
Hip flexion: IC	The thigh is in line with the trunk at IC	The thigh is in line with the trunk at IC	According to our data, hip flexion at IC is lower for SLJL _{rot} compared to DLJL. The threshold for error is already set at 0° of hip flexion. A hip extension threshold would be functionally irrelevant.
Trunk flexion: IC	The trunk is vertical or extended on the hips at IC	The trunk is vertical or extended on the hips at IC	VA of ACL injuries report 4° of trunk flexion at IC [13]. Upright and extended positions of the trunk have been associated with ACL loading [18]. Based on our data, trunk flexion at IC is lower during SLJL _{rot} than DLJL. However, the threshold for error is already set at 0° of trunk flexion.
Ankle plantar flexion: IC	The foot lands heel to toe or with flat foot at IC	The foot lands with less than 5° of plantar flexion	VA of ACL injuries report less than 10° of plantar flexion during injury [10,12]. Based on our data, plantar flexion at IC is greater during SLJL _{rot} than DLJL (~5°). Therefore, the threshold was conservatively set to 5° of plantar flexion.
Medial knee position: IC	The center of the patella is medial to the midfoot at IC	The line connecting the hip and the center of the patella is medial to the ankle joint center at IC	Due to the nature of the single-leg jump-landing task, the line connecting the hip and patella is needed to estimate knee valgus. The ankle joint center may be a more accurate term than the midfoot.
Lateral trunk flexion: IC	The midline of the trunk is flexed to the left or the right side of the body at IC	The trunk lateral flexion is more than 10°	VA of ACL injuries report 11° of lateral trunk flexion at IC [14]. Based on our data, lateral trunk flexion at IC is greater during SLJL _{rot} than DLJL (~8°). Therefore, the threshold was rounded to 10° of lateral trunk flexion.
Stance width: wide	The feet are positioned greater than shoulder width apart (acromion processes) at initial contact.	Item removed	Not applicable for SLJL _{rot} .
Stance width: narrow	The feet are positioned less than shoulder width apart (acromion processes) at initial contact.	Item removed	Not applicable for SLJL _{rot} .

Foot position: external rotation	The foot is externally rotated more than 30° between IC and MKF	The foot is externally rotated more than 35° between IC and MKF	According to our data, foot external rotation is greater during SLJL _{rot} than DLJL (~5°). Therefore, the threshold was changed to 35° of foot external rotation.
Foot position: internal rotation	The foot is internally rotated more than 30° between IC and MKF	The foot is internally rotated more than 30° between IC and MKF	Our data showed similar foot internal rotation between SLJL _{rot} and DLJL. Therefore, the original threshold for error was kept.
Symmetric initial foot contact: IC	One foot lands before the other foot or one foot lands heel to toe and the other foot lands toe to heel.	Item removed	Not applicable for SLJL _{rot} .
Knee flexion displacement	The knee flexes less than 45° between IC and MKF	The knee flexes less than 30° between IC and MKF	According to our data, the knee flexion displacement is 70% lower during SLJL _{rot} than DLJL. Therefore, 70% of the original threshold was used.
Hip flexion displacement	The thigh does not flex more on the trunk between IC and MKF	The thigh does not flex more on the trunk between IC and MKF	Based on our data, hip flexion displacement is lower during SLJL _{rot} than DLJL. However, the threshold for error is already set at 0° of hip flexion displacement.
Trunk flexion displacement	The trunk does not flex more between IC and MKF	The trunk does not flex more than 5° between IC and MKF	According to our data, trunk flexion displacement is greater during SLJL _{rot} than DLJL (~5°). Therefore, the threshold was changed to 5° of trunk flexion displacement.
Medial knee displacement	At the point of maximum medial knee position, the center of the patella is medial to the midfoot	At the point of maximum medial knee position, the center of the patella is medial to the ankle joint center	The ankle joint center may be a more accurate term than the midfoot. The original threshold was kept.
Joint displacement	Soft: the participant demonstrates a large amount of trunk, hip, and knee displacement. Average: the participant has some, but not a large amount of, trunk, hip, and knee displacement. Stiff: the participant goes through very little, if any, trunk, hip, and knee displacement.	Item removed	This item is subjective in nature. The purely subjective rating or ranking of human movement to define performance [16] or injury risk ³ has been criticized and has been shown to be inaccurate. Furthermore, this item is an obstacle for the automated quantification of the LESS [15].
Overall impression	Excellent: the participant displays a soft landing with no frontal-plane or transverse-plane motion. Average: all other landings. Poor: the participant displays large frontal-plane or transverse-plane motion, or the participant displays a stiff landing with some frontal-plane or transverse-plane motion.	Item removed	See the rationale above.
Lateral trunk flexion displacement		The trunk lateral flexion increases between IC and MKF	This item was added to the modified LESS given the important role of trunk displacement in ACL injuries [14,17].

Table 2: Preliminary operational definitions of errors proposed for a modified Landing Error Scoring System applied to a rotated single-leg jump-landing with rationale for the suggested thresholds.




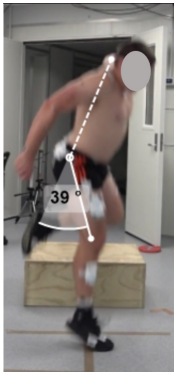
ACL, Anterior Cruciate Ligament; DLJL, double-leg jump-landing; IC, Initial Contact; LESS, Landing Error Scoring System; MKF, Maximal Knee Flexion; SLJL_{rot}, Rotated Single-leg Jump-landing; VA, Video Analysis.







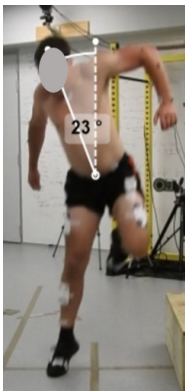
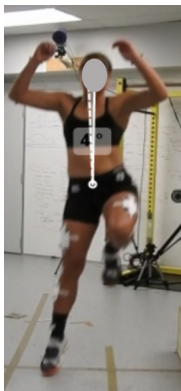
a. Adapted from Padua, *et al.* 2015.

A scoring sheet template of the proposed modified LESS is presented in Table 3, as well as in Table 4 with pictorial representations of errors. The preliminary template consists of 13 items. The minimum score is 0 and maximum score is 12 errors, as it is not possible to score item 7 (i.e., foot external rotation) and 8 (i.e., foot internal rotation) at the same time. A higher score indicates a greater number of landing errors and poorer landing biomechanics.

Items	Suggested operational definition of modified LESS errors	View	Scoring
Knee flexion: IC	The knee is flexed less than 15° at IC	Side	Yes = 1; No = 0
Hip flexion: IC	The thigh is in line with the trunk at IC	Side	Yes = 1; No = 0
Trunk flexion: IC	The trunk is vertical or extended on the hips at IC	Side	Yes = 1; No = 0
Ankle plantar flexion: IC	The foot lands with less than 5° of plantar flexion	Side	Yes = 1; No = 0
Medial knee position: IC	The line connecting the hip and the center of patella is medial to the ankle joint center at IC	Front	Yes = 1; No = 0
Lateral trunk flexion: IC	The trunk lateral flexion is more than 10°	Front	Yes = 1; No = 0
Foot position: external rotation	The foot is externally rotated more than 35° between IC and MKF	Front	Yes = 1; No = 0
Foot position: internal rotation	The foot is internally rotated more than 30° between IC and MKF	Front	Yes = 1; No = 0
Knee flexion displacement	The knee flexes less than 30° between IC and MKF	Side	Yes = 1; No = 0
Hip flexion displacement	The thigh does not flex more on the trunk between IC and MKF	Side	Yes = 1; No = 0
Trunk flexion displacement	The trunk does not flex more than 5° between IC and MKF	Side	Yes = 1; No = 0
Medial knee displacement	At the point of maximum medial knee position, the center of the patella is medial to the ankle joint center	Front	Yes = 1; No = 0
Lateral trunk flexion displacement	The trunk lateral flexion increases between IC and MKF	Front	Yes = 1; No = 0
Maximal score			12 errors ^a

Table 3: Scoring sheet template of the proposed modified Landing Error Scoring System applied to a rotated single-leg jump-landing. IC, Initial Contact; LESS; Landing Error Scoring System; MKF, Maximal Knee Flexion.
a. It is not possible to score error 7 and 8 at the same time. Therefore, the maximal score is 12 errors.

Items	Suggested operational definition of modified LESS errors	Error present (1)	Error absent (0)
Knee flexion: IC	The knee is flexed less than 15° at IC		
Hip flexion: IC	The thigh is in line with the trunk at IC		

Trunk flexion: IC	The trunk is vertical or extended on the hips at IC		
Ankle plantar flexion: IC	The foot lands with less than 5° of plantar flexion		
Medial knee position: IC	The line connecting the hip and the center of the patella is medial to the ankle joint center at IC		
Lateral trunk flexion: IC	The trunk lateral flexion is more than 10°		

Foot position: external rotation	The foot is externally rotated more than 35° between IC and MKF		
Foot position: internal rotation	The foot is internally rotated more than 30° between IC and MKF		
Knee flexion displacement	The knee flexes less than 30° between IC and MKF		
Hip flexion displacement	The thigh does not flex more on the trunk between IC and MKF		

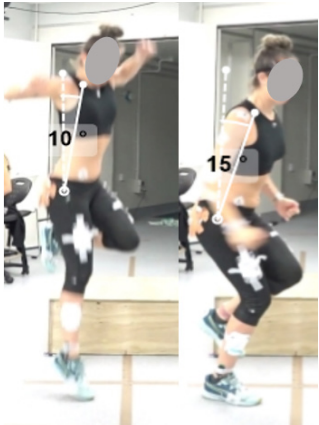



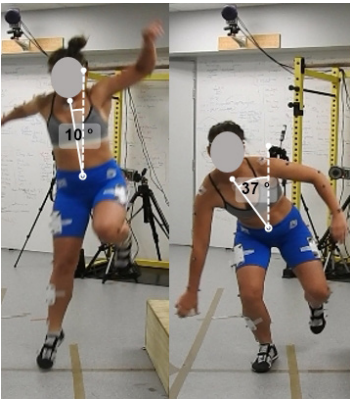
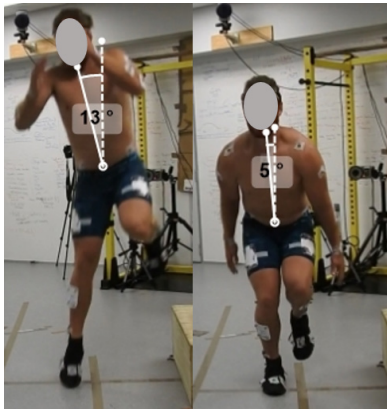
Trunk flexion displacement	The trunk does not flex more than 5° between IC and MKF		
Medial knee displacement	At the point of maximum medial knee position, the center of the patella is medial to the ankle joint center		
Lateral trunk flexion displacement	The trunk lateral flexion increases between IC and MKF		

Table 4: Alternative scoring template for the proposed modified Landing Error Scoring System applied to the rotated single-leg jump-landing task with pictorial representation of errors.

IC, Initial Contact; LESS, Landing Error Scoring System; MKF, Maximal Knee Flexion.

Discussion

The aim of this technical report was to present a preliminary scoring template of a modified LESS applied to a SLJL_{rot} task that is

likely to be more sport-specific and ecologically valid for screening for injury risk than the original LESS applied to a DLJL task [1]. Based on our 3D motion data, original LESS thresholds [1,5], and current scientific evidence [3,8-18], we propose a modified LESS scoring tem-

plate. This proposed template and associated thresholds require further scientific validation.

Similar to the original LESS, the modified LESS requires basic equipment for testing. More specifically, a 30 cm-high box, a stadiometer to measure height, a measuring tape to set the landing distance to 25% of body height, and two standard video cameras are required, all of which are low-cost compared to other laboratory-based equipment used to evaluate movement. The SLJL_{rot} task can be performed in a small area, and can be implemented in laboratories, clinics, gymnasiums, or outdoors. The time required to test is minimal given that participants are able to perform three repetitions of SLJL_{rot} on both lower extremities in less than five minutes. Therefore, the modified LESS is feasible to conduct movement screening on large cohorts with limited time, space, and equipment. Furthermore, based on Hanzlíková, *et al.* [4], the SLJL_{rot} may be better suited than the DLJL to reveal movement patterns present during more challenging sport situations and therefore have a greater association with injury risk profiles specific to ACL and other non-contact lower extremity injuries in sport. On the other hand, due to its perceived level of difficulty [4], the SLJL_{rot} may result in kinesiphobia in some individuals and an inability to perform this task. Hence, the SLJL_{rot} may be inappropriate when screening older individuals or less physically active populations. Accurately determining angular measures from visual observations is challenging, with studies concluding that subjective ratings or rankings of human movement to define performance [16] or injury risk [3] are inaccurate. Therefore, we recommend assessing the modified LESS using a video analysis software for a more accurate quantification of angles and frame-by-frame analysis. There are a number of free or low-cost software available shown to be valid and reliable for this purpose, suitable for clinical use [19].

To determine the thresholds for the modified LESS applied to the SLJL_{rot}, we compared lower extremity and trunk angles between DLJL and SLJL_{rot} tasks using 3D motion analysis. This method is considered the “gold standard” tool for quantifying human movement non-invasively. We also based the new thresholds on previous studies [3,8-18], mainly video analyses, reporting joint angles during ACL injury situations. Finally, we also relied on the original LESS items and thresholds [1,5]. This three-pronged approach has several limitations. Even though the original LESS is a commonly used clinical and research tool shown to predict non-contact ACL injury in elite youth soccer players [5], the original LESS thresholds were based on clinical opinions rather than high-quality scientific evidence. Another

limitation to our approach in setting the modified LESS thresholds is that the underpinning video analysis studies explored various injury situations, such as cutting, pivoting, and jump-landings [8-12,14]. These injury situations may not correspond to “risky” biomechanics during the SLJL_{rot}. The ideal approach would be to base the modified LESS template and thresholds on high-quality prospective studies; however, such studies are currently not available and difficult to perform. Therefore, the suggested thresholds and individual items may change with new evidence.

It is essential that testing methods provide outcomes that are reproducible and valid so that changes in scores reflect meaningful changes in function of individuals and are able to identify individuals with differing abilities. Therefore, it is necessary to evaluate reliability and validity of the modified LESS. A systematic review exploring reliability and validity of the original LESS [20] concluded that the LESS is a reliable screening tool with moderate-to-excellent validity against 3D motion capture data for most of the items. Therefore, we expect the modified LESS screening tool to have similar levels of validity and reliability. Padua, DiStefano, Beutler, de la Motte, DiStefano, Marshall [5] identified 5 errors in the original LESS as an optimal cut point for distinguishing between athletes with low and high risk of ACL injury. The predictive value of this threshold in the context of ACL injury has not been confirmed by other studies [20]. Prospective studies are needed to assess the predictive ability of the modified LESS to detect non-contact ACL and other lower-extremity injury incidence and identify adequate thresholds for these injuries.

Conclusion

The modified LESS may be an appropriate clinical screening tool for assessing sport-related non-contact lower extremity injury risk in athletes. However, further research needs to evaluate the psychometric properties, specificity and sensitivity of the thresholds, and clinical merit of the modified LESS presented in this technical report.

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