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Beyond Distance: A Simple Qualitative Assessment of the Single-Leg Hop Test in Return-to-Play Testing

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Beyond distance. A Simple Qualitative Assessment of the Single Leg Hop test in the return to play testing

Running Title: Implications for secondary ACL injury prevention

Abstract

Background: Limb symmetry index in the Single Leg Hop (SLH) test has been questioned for its low predictive value in identifying secondary Anterior Cruciate Ligament (ACL) injury. The purpose of this study was to describe a qualitative 2D scoring system for the assessment of the SLH test and associate it with the vertical Ground Reaction Forces (vGRF) and sagittal plane biomechanics evaluated through gold standard 3D motion analysis.

Hypothesis: Stiff landings would be associated with low 2D scores.

Study Design: Descriptive Laboratory Study

Level of Evidence: Level 4

Methods: Thirty-four competitive football (soccer) players (age 22.8 ± 4.1 , 16 females) were enrolled. Each athlete performed a series of SLH tests. 3D motion analysis was recorded using 10 stereophotogrammetric cameras, a force platform, and three high-speed cameras. The 2D qualitative assessment was performed through a scoring system based on the video-analysis of sagittal plane joint kinematics. A score of 0/2 (non-adequate), 1/2 (partially adequate), or 2/2 (adequate) was attributed to the movement, based on objective measurements. The vGRF was extracted from the force platform and grouped according to the results of the 2D evaluation.

Results: Significantly higher vGRF (stiffer landing) was found for athletes obtaining a 0/2 score compared to those obtaining a 2/2 score (up to 0.8 BW higher, $P < 0.01$). A significant negative rank correlation was found between the vGRF and the total score ($\rho = -0.17$, $P = 0.03$).

Conclusions: The qualitative scoring system effectively identified stiff landings in the SLH for distance test.

Clinical relevance: The qualitative scoring system could be a user-friendly standardized method to assess athletes' movement quality in Return to Sport (RTP) clearance decision after ACL injury.

Keywords: ACL, single leg hop test, 2D video-analysis, return to sport, injury prevention

Introduction

Hop tests are the most used functional evaluations to clear patients to Return to Play (RTP) after an Anterior Cruciate Ligament (ACL) reconstruction.¹ The hop distance ratio between injured and contralateral leg is the election criteria for RTP clearance, and a Limb Symmetry Index (LSI) >90% is the recommended threshold.¹⁹ Although passing the LSI has been associated with a higher rate of RTP at the pre-injury level, such a distance-based approach has been questioned for its limited predictiveness of knee functional deficits and identifying secondary ACL injury.^{7,13,26,28}

A stronger focus on movement quality is therefore needed to establish patients' RTP readiness. Poor biomechanical and neuromuscular control has been already ascribed as a risk factor for landings and pivoting movements.^{12,14,15} In the Single Leg Hop (SLH) test, a stiff landing pattern (i.e., limited knee flexion with high vertical ground reaction forces – vGRF) has been detected in ACLR patients when compared to controls and has been related to an increased risk for ACL injury.^{12,13,16}

3D motion analysis with force platform is predominant in the investigation of hop tests biomechanics. Such an analysis requires advanced technologies and large processing time and is not applicable to quick and large screenings. From a clinical point of view, a user-friendly standardized method to qualitatively evaluate hop tests does not exist.

The aim of the present study was to describe a qualitative 2D scoring system for the assessment of the SLH test and to associate it with the vGRF and sagittal plane biomechanics evaluated through gold standard 3D motion analysis. The hypothesis was that stiff landings would be associated with low 2D scores.

53

54 **Methods**

55 **Participants**

56 The analysis was conducted in the Education and Research Department of the Isokinetic Medical
57 Center of Bologna (Italy). Overall, 34 recreational and elite athletes were recruited for the study
58 (Table 1). Inclusion criteria were age between 18 and 50 years old and Tegner activity level at least
59 7. Exclusion criteria were: (1) evidence of musculoskeletal disorders or functional impairment; (2)
60 body mass index (BMI) > 35; (3) previous surgery to lower limbs; (4) cardiopulmonary or
61 cardiovascular disorders; (5) inability to perform the required tasks. All the subjects signed informed
62 consent before starting the acquisition protocol. The rights of the subjects were protected. The
63 research study was approved by the Institutional Review Board (IRB approval: 555/2018/Sper/IOR
64 of 12/09/2018) of Area Vasta Emilia Romagna Centro (AVEC, Bologna, Italy) and registered on
65 ClinicalTrials.gov (Identifier: NCT03840551).

66 **SLH acquisition protocol**

67 As part of a multi-movement assessment, each athlete was asked to perform an SLH for distance
68 (Figure 1). Before the test, the athletes performed a 10-minute dynamic warm-up and few repetitions
69 of the movement to get confident with the environment and the motor task. To determine the proper
70 distance for the hop, each athlete jumped from the center of the force plate in backward direction and
71 the landing point was chosen as the start for the trials. A sport & exercise medicine physician
72 specialized in sports biomechanics (FDV) instructed each subject on the movements to perform and
73 verified the validity of each trial. Full foot contact on the force platform with at least 2 seconds of
74 holding the landing position was required to consider a trial valid. All subjects performed three valid
75 repetitions per lower limb.

76 3D motion analysis was recorded through a set of 10 stereophotogrammetric cameras, a force
77 platform embedded in the floor (AMTI 400*600, Watertown, MA USA), and three high-speed
78 cameras placed frontally and bilaterally towards movement direction (VICON Nexus, Vicon Motion

79 Systems Ltd, Oxford, UK). The sampling frequency of cameras and force platform was 120 Hz, while
80 the sampling frequency of the high-speed cameras was 100 Hz. The systems were synchronized for
81 direct data comparison.

82 A total of 42 retroreflective markers were placed on each subject according to the full-body Plug-in
83 Gait protocol. After marker positioning, subjects' model calibration was performed before each
84 acquisition.

85 **Data Processing – 3D analysis**

86 Regarding the 3D analysis, VICON Nexus was used to quantify the GRF and the joint kinematics.
87 Marker trajectories were collected through the stereophotogrammetric cameras, and GRFs were
88 collected through the force platform. The peak vGRF value was extracted for each trial and
89 normalized by the body weight (BW) of the subjects.

90 **Data Processing – 2D analysis**

91 Regarding the 2D analysis, a scoring system was adopted based on the frontal and sagittal plane
92 joint kinematics. Such a scoring system is included in a clinical multiple movements evaluation for
93 RTP decision making after ACL reconstruction.^{2,3} The test, a qualitative movement evaluation, is
94 aimed to identify biomechanical and neuromuscular control deficits providing an intuitive and quick
95 response to the patient. The evaluation is performed in a simplified VICON software environment
96 through the recordings of the three high-speed cameras and the resultant GRF vector of the force
97 platform. Joint kinematics are evaluated at the frame of maximal knee flexion angle after the foot
98 contact with the force platform.

99 For the present study, each SLH trial was evaluated through five scoring criteria, *shock absorption*
100 (SA), *movement strategy* (MS), *limb stability* (LS), *pelvis stability* (PS), *trunk stability* (TS). For each
101 criterion, a sub-score of 0/2 (non-adequate), 1/2 (partially adequate), or 2/2 (adequate) is attributed to
102 the movement, based on objective measurements detailed in Figure 2. A single sports physician
103 specialized in sports biomechanics (FDV) evaluated each SLHT trial. The maximum total score for
104 each trial is 10/10.

105 **Statistical analysis**

106 The peak vGRF extracted from each trial was grouped according to the results of the 2D
107 evaluation. Three groups – Group 0, 1, 2 – were generated for each of the SA and the MS sub-scores,
108 i.e., the two sub-scores assessing the athlete's sagittal plane kinematics. The normal distribution of
109 the data was verified through the Shapiro-Wilk test. The categorical variables were presented as a
110 percentage over the total, while the continuous variables were presented as mean $\pm$ standard deviation
111 (95% Confidence Interval – CI). The Kruskal-Wallis H test was used to investigate the statistical
112 differences among the three groups, and the Mann-Whitney U test with the Bonferroni correction for
113 multiple comparisons was used to investigate the differences between the single groups.

114 Furthermore, the Spearman's coefficient ρ was used to investigate the rank correlation between
115 the 2D Total Score and the peak vGRF, while the Pearson's coefficient r was used to investigate the
116 linear correlation between the α and β angles⁶ and the peak knee and hip flexion angles, respectively,
117 and between the α angle and the peak vGRF.

118 Differences were considered statistically significant for $p < 0.05$. All the statistical analyses were
119 performed in SPSS (v26, IBM, Armonk, NY, US).

120 An a-priori power-analysis was performed in G*Power (v3.1, Brunsbüttel, Germany) based on
121 the results of a previous similar study analyzing the SLH for distance.²⁸ Considering a standard
122 deviation of 0.6 N/BW (Newton / Body Weight) and a mean group difference of 1 N/BW (Effect size
123 1.7), at least 18 subjects were required to have a power of 0.9 and a type I error of 0.05.

124

125 **Results**

126 Overall, 172 valid trials were included in the analysis. The peak vGRF was 4.0 ± 0.9 N/BW and
127 3.5 ± 0.6 N/BW for male and female athletes, respectively ($P < 0.01$).

128

129 **Vertical GRF based on the 2D scoring system**

130 A statistically significant difference was found in terms of peak vGRF among the three groups
131 based on the SA and MS scores ($P<0.01$, for both) (Table 2, Supplementary A). For the SA score, the
132 peak vGRF in the trials score as 0 was significantly higher than in the trials score as 1 ($P=0.03$) and
133 in the trials score as 2 ($P<0.01$) (Supplementary B). For the MS score, the peak vGRF in the trials
134 score as 0 was significantly higher than in the trials score as 2 ($P<0.01$) (Supplementary B).

135 A significant negative rank correlation was found between the Total Score and the peak vGRF
136 ($\rho=-0.17$, $P=0.03$) (Supplementary C).

137 **Correlation between 2D and 3D angles**

138 A statistically significant positive correlation was found between the peak knee flexion angle and
139 the α angle ($r=0.80$, $P<0.01$) and between the peak hip flexion angle and the β angle ($r=0.55$, $P<0.01$)
140 (Supplementary D). Furthermore, a statistically significant negative correlation was found between
141 the peak vGRF and the α angle ($r=-0.28$, $P<0.01$).

143 **Discussion**

144 The main finding of the present study was a strong association between the peak vGRF and the
145 qualitative 2D scoring system for the SLH test. Excellent intra-rater and inter-rater reliability were
146 also found for the 2D criteria and the total score. Overall, the athletes exhibiting stiffer landings
147 (higher vGRF) obtained lower 2D scores (Figure 3 A-B), confirming the hypothesis. Since stiff
148 landings in hop tests is associated with higher knee forces (stress on the ACL) and potentially
149 increased risk for ACL injury,^{12,13,16} the scoring system here described could be an effective method
150 to support the RTP clearance decision. Indeed, the identification of stiff landing patterns offers a
151 stronger insight on movement quality than standard distance-based symmetry indices.^{12,13,28} Such an
152 approach is crucial to recognize at-risk patients and set up additional targeted preventative
153 training.^{10,21}

154 A significantly higher vGRF (up to 0.8 BW) was found for both the SA and the MS sub-scores in
155 the athletes scoring 0/2 compared to those scoring 2/2. Both sub-scores have been obtained through

one single high-speed camera and a dedicated user-friendly software interface (Figure 2). The discriminative power reached with such a simplified setting could be easily replied to in the daily clinical practice of RTP assessment.

A significant negative rank correlation was found between the vGRF and the total score. Although mainly based on frontal plane kinematics (Figure 2), the total score could be indicative of patients' knee joint overload during hop tests. Such a parameter could serve to track patients' progress during the rehabilitation phase and clearing the RTP.

The identification of clinically relevant altered movements through 2D evaluations has been previously advocated^{20,24,27} and represents a practical surrogate of laboratory 3D motion analysis. The latter aspect was further confirmed by the high correlation between the 3D knee and hip flexion angles and the α and β angles, respectively. The α angle was also significantly correlated with vGRF, thus further confirming the effective approximation of sagittal plane kinematics in the 2D scoring system.⁴ A stiffer landing in presence of limited knee and hip flexion is indicative of knee overloading and limited lower-limb power absorption during the landing. The achievement of good range of motion is often targeted in rehabilitation programs after an ACL injury and used as a criterion for RTP clearance.¹⁶

No previous studies defined a standardized method for the qualitative assessment of the SLH test. The bipodalic tests, e.g., the vertical drop jump, have been investigated more from a qualitative point of view, and both frontal and sagittal plane biomechanical indices have been developed.^{9,18,23} Although such indices showed potential validity in discriminating ACL-reconstructed and controls, they are not applicable to the single-leg landings. Moreover, ACL injury mechanisms mainly occur in single support,^{5,17} thus corroborating the need for qualitative assessment of such movements.

In the context of functional recovery following injury, e.g., ACL injury and reconstruction, it is recommended to use a set of tests both to progress and decide when an athlete is ready to RTP^{8,20}. The hop tests for distance have been suggested as part of these assessments in the current clinical practice guidelines.¹⁹ Although the LSI may be highly informative in this scenario, the clinicians may

182 also benefit from an easy qualitative movement evaluation.^{7,13,28} Also, detailed information could be
183 provided to the patient regarding the knee joint loading, according to the association found between
184 the score and the vGRF. In conjunction with quadriceps strength testing and psychological readiness
185 scores,^{11,22,25} in the authors' view and practical experience, a qualitative movement evaluation is key
186 to better evaluate the neuromuscular function before RTP.

187 The present study has limitations. First, the data collection was performed in one single session
188 on healthy athletes. A repeated evaluation after preventative training or during rehabilitation after
189 ACL injury could have provided information regarding the sensibility of the 2D score. Second, no
190 muscle activation data were collected, thus making it impossible to investigate potential lower limb
191 deficits towards the 2D evaluation. Third, the validity of the trial was considered if patients could
192 obtain a stable landing. This is a common assumption in the SLH test assessment. Nonetheless, the
193 analysis of sub-optimal landings could give further insights into patients' movement quality and
194 should be considered in future studies.

195

196 **Conclusion**

197 The qualitative scoring system described in the present study effectively identified stiff landings
198 in the SLH for distance test and could be a user-friendly standardized method to assess athletes'
199 movement quality in RTP clearance decision after ACL injury.

200

201 **Clinical Recommendations**

202 Although the LSI is predominantly used to clear patients for RTP after ACL injury, it showed a low
203 predictive value in identifying secondary ACL injury. For this reason, a stronger focus on movement
204 quality is needed rather than a distance-based approach. The scoring system here described could be
205 an effective method to identify patients exhibiting stiff landing, claimed as a risk factor for ACL
206 injury. Professionals could benefit from a user-friendly qualitative method to better evaluated
207 athletes' neuromuscular function in the RTP decision making.

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312 Tables

313

TABLE 1. Demographic data ^a

Number of subjects	34
Gender (M/F)	18/16
Dominant limb (R/L) ^b	30/4
Age (y)	22.8 ± 4.1 [18 - 31]
Height (cm)	174.8 ± 10.2 [157 – 191]
Weight (Kg)	68.6 ± 12.7 [51 – 94]
BMI	22.6 ± 2.6 [18 - 27]
Tegner	8.6 ± 1.0 [7- 9]

314 ^a Data are expressed as mean ± standard deviation [range].

315 ^b Dominant limb is meant as the preferred one used to kick a ball.

316

317

TABLE 2. Peak vertical Ground Reaction Force based on the 2D scoring system ^a

2D score	0	1	2	P Value
SA	4.3 ± 0.7 [3.9 - 4.6]	3.8 ± 0.8 [3.7 – 4.0]	3.5 ± 0.9 [3.2 - 3.8]	<.01 ^b
MS	4.0 ± 0.6 [3.8 - 4.1]	3.9 ± 0.8 [3.6 - 4.1]	3.6 ± 1.0 [3.4 - 3.9]	<.01 ^b

318 Abbreviations: SA, Shock Absorption; MS, Movement strategy.

319 ^a Data are expressed in Newton/Bodyweight as mean ± standard deviation [95% CI].

320 ^b Statistically significant differences between the three groups evaluated through the Kruskal-Wallis
321 test (P<0.05).

322

323

324 **Figure Legends**

325 **Figure 1.** Example of the Single Leg Hop test.

326 **Figure 2.** Detailed scoring system for 2D video-analysis of the Single Leg Hop test.

327 Abbreviations: FPKPA: frontal plane knee projection angle; GRF: ground reaction forces; KJC: knee
328 joint center; AJC: ankle joint center; ASIS: antero-superior iliac spine; LM: lateral malleolus; LFC:
329 lateral femoral condyle; GT: great trochanter; SJC: shoulder joint center, CL: contralateral; OL:
330 Omolateral; KFA: knee flexion angle.

331 **Figure 3.** (A) Example of Single Leg Hop performed with high vertical Ground Reaction Force (stiff
332 landing) and corresponding low 2D score; (B) Example of Single Leg Hop performed with low
333 vertical Ground Reaction Force (smooth landing) and corresponding high 2D score.

334