



## Original Research

## Measurement properties of the Star Excursion Balance Test in patients with ACL deficiency



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## ABSTRACT

**Objectives:** To assess intrarater reliability, agreement and construct validity of the Star Excursion Balance Test (SEBT) in individuals with anterior cruciate ligament (ACL) deficiency and the ability of the SEBT to distinguish between healthy and ACL-deficient individuals.

**Methods:** Patients with ACL deficiency and healthy matched controls performed the SEBT and the One Leg Hop for Distance test (OLHD). Three consecutive trials were analyzed. Also evaluated were isokinetic thigh muscle strength and self-reported function.

**Results:** We included 33 patients and 33 matched controls. Intrarater reliability of the SEBT was good to excellent (ICC: 0.88–0.96). Agreement was estimated by the minimal detectable change (5.93–8.36 cm). Posteromedial and posterolateral direction and composite score of the SEBT were correlated with OLHD performance ( $r$ : 0.34–0.53,  $p < 0.05$ ) and thigh muscle strength ( $r$ : 0.35–0.45,  $p < 0.05$ ). Posteromedial and posterolateral direction and composite scores of the SEBT were significantly lower bilaterally for patients with ACL deficiency than controls ( $p < 0.05$ ).

**Conclusion:** The SEBT can be used in patients with ACL deficiency with good to excellent intrarater reliability. Construct validity of the SEBT versus the OLHD test and isokinetic thigh muscle strength can be confirmed. Furthermore, posteromedial and posterolateral performance of the SEBT can detect bilateral neuromuscular control deficits.

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## 1. Introduction

Anterior cruciate ligament (ACL) tear remains a frequent lower-limb injury. The recently estimated annual incidence is 68.6/100,000 person-years (Sanders et al., 2016). The practice of cutting and pivoting sports such as football, rugby, and basketball are considered related to the highest risk of ACL injury (Joseph et al., 2013). After injury, returning to the previous activity level can be hampered by knee instability, (Brandsson et al., 2002) altered

neuromuscular control, (Chmielewski, Hurd, Rudolph, Axe, & Snyder-Mackler, 2005; Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001) proprioception and muscle strength deficiency (Dhillon, Bali, & Prabhakar, 2011; Lee, Cheng, & Liau, 2009; Roberts, Andersson, & Fridén, 2004). The weaker functional outcome after ACL injury is related to thigh muscle strength deficiency (Moisala, Järvelä, Kannus, & Järvinen, 2007). Moreover, ACL tear can trigger early knee osteoarthritis, the rate varying from 24% to 84% (Wong, Khan, Jayadev, Khan, & Johnstone, 2012). Tourville et al. found that knee osteoarthritis after ACL injury is related to reduced quadriceps strength and poorer one leg hop performance compared to healthy controls (Tourville et al., 2014). However, some individuals after ACL tear can still dynamically stabilize their knee without the ACL reconstruction, so the presence and level of functional deficits can vary among individuals (Moksnes, Snyder-Mackler, & Risberg, 2008). Functional evaluation can help identify individuals who can dynamically stabilize their knee during sports

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activities and those who will lack this ability (Eitzen, Moksnes, Snyder-Mackler, & Risberg, 2010; Kaplan, 2011). Although the treatment choice can be controversial, functional evaluation is an important issue in the decision (Smith, Postle, Penny, McNamara, & Mann, 2014). Firstly, to estimate the deficits, then to administer and monitor the treatment effects and finally to provide the criteria of readiness to return to the previous activity level.

Functional evaluation is usually based on performance tests, which should possess some key measurement properties such as reliability, agreement, validity and responsiveness (Hegedus, McDonough, Bleakley, Baxter, & Cook, 2015). Otherwise, evaluation gives information of unknown meaning, and interpreting such information can be misleading. Exploring the measurement properties is a process accumulated from multiple studies and cannot be demonstrated “once and for all” by a single study (Davidson & Keating, 2014). Different population characteristics can vary the results, so good reliability of a specific measurement in healthy subjects is not necessarily the same as in, for example, individuals with ACL deficiency.

The One Leg Hop for Distance test – single hop (OLHD) aims to expose the knee joint to conditions that are similar to those existing in sports activity. Distance in the OLHD test represents the ability of the neuromuscular system to dynamically stabilize the knee joint (Reid, Birmingham, Stratford, Alcock, & Giffin, 2007). The OLHD test has been studied for reliability (intraclass correlation coefficient [ICC] 0.92), agreement (minimal detectable change [MDC] 8.09%) and construct validity ( $r = 0.48$  vs Global Rating of Change,  $r = 0.37$  vs Lower Extremity Functional Scale) in individuals with ACL reconstruction (Reid et al., 2007). Although the OLHD test is the most frequently used performance test in patients with ACL deficiency, (Hegedus et al., 2015) some authors consider its measurement properties not sufficiently studied (Hegedus et al., 2015). In some situations, the lack of confidence or severe muscle-strength deficit can disallow use of the OLHD test, but it is still required to assess neuromuscular control of the knee.

If jumping is not possible, the Star Excursion Balance Test (SEBT) can be used. In the SEBT, neuromuscular control is explored by keeping balance on one foot while the other foot is reached in specific directions. This functional test intends to measure a similar construct and was initially used as an exercise and measurement tool for chronic ankle instability (Olmsted, Carcia, Hertel, & Shultz, 2002). The SEBT is used to measure function among various conditions: patellofemoral pain syndrome, chronic low back pain and ACL injury (Aminaka & Gribble, 2008; Clagg, Paterno, Hewett, & Schmitt, 2015; Ganesh, Chhabra, & Mrityunjay, 2015; Herrington, Hatcher, Hatcher, & McNicholas, 2009). Reproducibility studies showed high reliability of the SEBT in healthy individuals (ICC: 0.84–0.92), (Munro & Herrington, 2010) and (ICC: 0.85–1.00) (Plisky et al., 2009). However, in specific patient populations, the reliability of SEBT is unknown (Hegedus et al., 2015). One study showed the predictive validity of the SEBT in relation to lower-limb injury in high school basketball players (Plisky, Rauh, Kaminski, & Underwood, 2006). Still, reports of validity of the SEBT in specific patient populations are missing (Hegedus et al., 2015). To our knowledge, no study has evaluated the construct validity and reproducibility of the SEBT in patients with ACL deficiency.

The main objective of this study was to evaluate measurement properties of the SEBT in individuals with ACL deficiency: intrarater reliability and agreement, construct validity of the SEBT versus OLHD test, and self-reported function and isokinetic strength of the thigh muscles. The secondary objective was to assess the ability of SEBT to distinguish between healthy and ACL-deficient individuals.

## 2. Methods

### 2.1. Participants

Sample size estimation was based on a previous study (Herrington et al., 2009). Our aim was to include a minimum of 30 participants per group for acceptable power for all objectives: intrarater reliability, construct validity estimation and comparisons between groups. Overall, 66 individuals participated in this study; 33 patients with ACL deficiency were recruited among patients who came for orthopedic consultation at The University Hospital of or at the nearby XXXXXX Clinic. The present analysis is a part of the study “Efficacy of preoperative re-education on patients with an anterior cruciate ligament rupture (PRELIG)” (ClinicalTrials.gov identifier: XXXXXX). All participants provided written informed consent before evaluation. The regional ethics committee approved the study (XXXXXXX, Reference no. XXXXX).

Patients were recruited if they had a first complete ACL rupture confirmed by MRI, were age 18–60 years, and had Tegner activity level 3 to 9 (recreational or nonprofessional competition sport activity) (Briggs et al., 2009). We excluded patients with concomitant knee injury (fracture, posterior cruciate ligament rupture, symptomatic meniscal tear based on surgeon clinical evaluation), neuropathic pain or other concurrent musculoskeletal condition in lower limbs or spine, or cardiorespiratory or neurological problems. We included 33 healthy individuals matched to patients by age, height, weight, sex and activity level who were recruited among employees and trainees of Clermont Ferrand University Hospital. Individuals with a history of surgical treatment or any dysfunction of the lower limb or the spine were not included.

### 2.2. Procedure

The study was performed in the Physical and Rehabilitation Medicine department at The University Hospital of Clermont Ferrand. To evaluate intrarater reliability and agreement of the SEBT, consecutive trials of the patients’ SEBT performance were recorded. For validity analysis of the SEBT, and the OLHD test, isokinetic measurements of the thigh muscles and self-reported function were recorded for patients. To verify the ability of the SEBT and the OLHD test to distinguish between patients with ACL deficiency and healthy individuals, the control group performed the SEBT and the OLHD test in the same manner. Since previous studies conducted with healthy subjects and indicating no effect of limb dominance on the SEBT, (Alnahdi, Alderaa, Aldali, & Alsobayel, 2015; Butler, Bullock, Arnold, Plisky, & Queen, 2016; Linek, Sikora, Wolny, & Saulicz, 2017) nor on the OLHD performance, (Hébert-Losier et al., 2015; Kockum & Heijne, 2015) only dominant limb performance of controls was used for comparison analysis. The order of these 2 tests was randomized, as was the order of the tested directions of the SEBT. All examinations were performed by the same investigator, and each individual underwent a one-examination session. After verification of inclusion and exclusion criteria and general health status, individuals performed a 5-min warm-up on a cycle ergometer at 50 W.

### 2.3. Isokinetic strength measurements

Patients performed 5 repetitions of maximal isokinetic contractions of quadriceps and hamstrings, both in concentric and eccentric mode at 60°/sec from full knee extension to 95 degrees of knee flexion using an electronic dynamometer (Humac Norm Cybex 6000™). For each mode the measurements sets were preceded by three practice contractions trials. The peak torque normalized to body mass was used for analysis (Undheim et al.,

2015).

#### 2.4. Star Excursion Balance Test

Considering previous studies, we used 3 directions of the SEBT: anterior, posteromedial and posterolateral (Clagg et al., 2015; Delahunt et al., 2013). The SEBT was performed barefoot, bilaterally. Individuals were instructed to reach the farthest possible with their non-stance limb in the above-mentioned directions. The heel of the stance limb was placed in the centre of the 3 lines marked on the floor, which indicated desired directions. No rise of the stance heel and no support with the non-stance limb were allowed. Arm movements were not restricted. All participants performed 4 practice trials for each direction, then the distance of 3 consecutive trials was recorded in centimeters by the examiner (Gribble, Hertel, & Plisky, 2012). A 30-sec rest time was allowed between each trial. The 3 recorded trials were then used for reproducibility analysis, and the mean of recorded trials was used for validity analysis. Reach distances were normalized by lower-limb length (measured from the anterior superior iliac spine to medial malleolus in the supine position). The limb symmetry index was calculated as follows: (distance reached with injured limb/distance reached with non-injured limb) x 100.

#### 2.5. One leg hop for distance - single hop test

To minimize the risk of “giving way” or additional knee damage, the OLHD test was performed only if the patient was able to jump in place without pain, quadriceps isokinetic strength deficit was <30%, full knee range of motion was present, and there was no swelling and no pain at the knee joint and no apprehension to jump on the affected limb (Eitzen et al., 2010). Participants were wearing sport shoes while performing the OLHD. The examiner instructed participants to jump on one leg as far as they could, to land on the same leg and to stabilize the landing position for at least 2 s. Arm movements were not restricted. Individuals performed one trial for each leg for familiarization with the test. Then, 3 consecutive trials were recorded in centimeters for each lower limb by the examiner. A 30-sec rest time was allowed between the trials (Reid et al., 2007). Similar to the SEBT, a limb symmetry index was calculated.

#### 2.6. Self-reported knee function

Self-reported knee function was evaluated with the International Knee Documentation Committee (IKDC2000) subjective knee form and Lysholm score, both frequently used in patients with ACL deficiency (Briggs et al., 2009; Higgins et al., 2007).

#### 2.7. Statistical analysis

Statistical analysis involved use of Stata v13 (StataCorp, College Station, TX, USA) and  $p < 0.05$  was considered significant for all analysis. Continuous data are presented with mean ( $\pm$ SD). The assumption of normal distribution was verified by the Shapiro-Wilk test. Intrarater reliability was estimated by the intraclass correlation coefficient ( $ICC_{3,1}$ ) with 3 consecutive trials of the SEBT. Then, to determine absolute measurement error/agreement, the standard error of measurement (SEM) and the minimal detectable change with 95% confidence bound ( $MDC_{95}$ ) were calculated (de Vet, Terwee, Knol, & Bouter, 2006). Construct validity was evaluated by the Pearson product-moment correlation coefficient or Spearman rank-order correlation coefficient, depending on statistical distribution. Finally, to compare injured limb and non-injured limb for patients with the controls participants, mixed model was carried out to take into account the between and within patient

variability (as random effect). A Sidak's type I error correction was applied to adjust p-values due to multiple comparisons. When appropriate, the results were expressed with Cohen's  $d$  effect size, classified as follows: small, 0.2–0.49; medium, 0.5–0.79; and large,  $\geq 0.8$  (Cohen, 1977).

### 3. Results

#### 3.1. Patients and controls did not differ (Table 1)

The results of the SEBT and OLHD test are presented in Fig. 1 and Fig. 2, respectively. Posteromedial and posterolateral direction and composite score (sum of the three measured directions) of the SEBT for both deficient and non-deficient limb were significantly lower in patients than controls ( $p < 0.05$ ). These differences showed moderate effect size (Cohen's  $d$ : 0.54–0.69). The anterior direction of the SEBT was slightly lower in the deficient limb than for the non-deficient limb, ( $p = 0.045$ ,  $d = 0.14$ ). There were no significant differences in the anterior SEBT performance between patients and controls, ( $p > 0.05$ ). Patient's deficient and non-deficient limbs did not differ in the posteromedial, posterolateral direction and composite score of the SEBT ( $p > 0.05$ , Fig. 1).

Consequently, all indexes of symmetry for the SEBT are close to 100 percent, specifically  $98.06 \pm 9.37$  for the anterior direction,  $100.22 \pm 8.08$  for the posteromedial direction,  $98.06 \pm 9.37$  for the posterolateral direction and  $99.10 \pm 7.33$  for the composite score, (mean  $\pm$  SD). The OLHD test performance was significantly lower for the deficient limb than for controls ( $p < 0.002$ ,  $d = 0.95$ ) (Fig. 2). There were no significant differences between non-deficient limb and controls ( $p > 0.05$ ) for the OLHD test. The deficient limb performance was significantly lower than non-deficient limb performance for the OLHD test ( $p = 0.006$ ,  $d = 0.49$ ). The corresponding OLHD test limb symmetry index was  $76.27 \pm 29.18$  (mean  $\pm$  SD).

Isokinetic thigh muscle strength results are presented in the Appendix. Patients scored  $63.1 \pm 12.6$  on the IKDC2000 subjective knee form and  $76.3 \pm 13.0$  on the Lysholm score.

Intrarater reliability of the SEBT was excellent for all directions ( $ICC$ : 0.88–0.96). The agreement estimation was  $MDC_{95}$ : 5.93–8.36 cm (Table 2).

Correlation analysis for patients ( $n = 33$ ) is presented in Table 3.

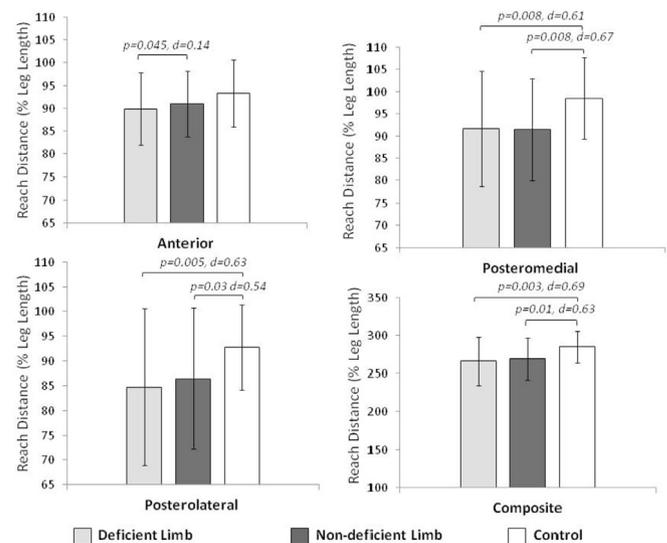
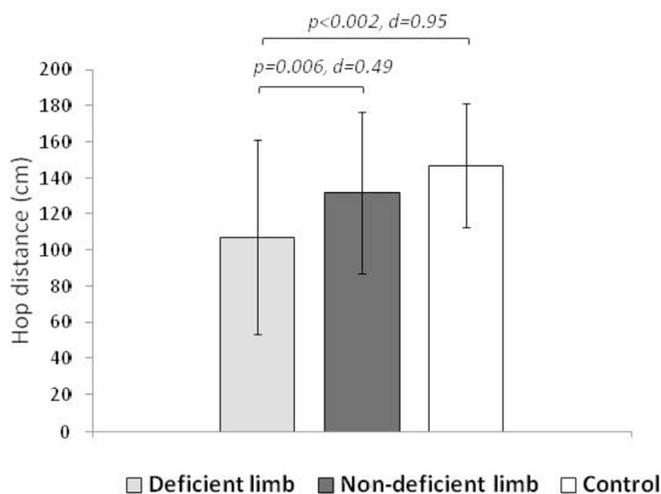


Fig. 1. Normalized Star Excursion Balance Test (SEBT) performance in patients with ACL-deficiency ( $n = 33$ ) and controls (dominant limb performance,  $n = 33$ ). Composite score represents the sum of the three measured SEBT directions. Data are mean  $\pm$  SD.



**Fig. 2.** One Leg Hop for Distance test (OLHD) performance in patients with ACL deficiency ( $n = 33$ ) and controls (dominant limb performance,  $n = 33$ ). Data are mean  $\pm$  SD.

**Table 1**  
Participants demographics.

	Patients ( $n = 33$ )	Controls ( $n = 33$ )	<i>P</i> value
Age [years]	36.8 $\pm$ 10.4	36.8 $\pm$ 11.0	0.98
Height [m]	1.73 $\pm$ 0.08	1.71 $\pm$ 0.10	0.48
Mass [kg]	73.8 $\pm$ 14.8	70.1 $\pm$ 12.4	0.28
BMI [kg/m <sup>2</sup> ]	24.5 $\pm$ 3.7	23.8 $\pm$ 3.3	0.44
Men/women	20/13	17/16	0.46
Lower-limb length [cm]	88.4 $\pm$ 5.9	87.5 $\pm$ 5.9	0.56
Dominant limb R/L	24/9	28/5	0.23
Tegner activity level			0.22
3	19	17	
4	12	8	
5	0	1	
6	2	4	
7	0	3	
Deficient limb R/L	19/14	NA	
Time since injury [weeks]	159.1 $\pm$ 296.6	NA	

Data are no. or mean  $\pm$  SD. BMI, body mass index; R, right; L, left; NA, not applicable.

**Table 2**  
Intrarater reliability and agreement of the Star Excursion Balance Test (SEBT) for patients ( $n = 33$ ).

SEBT direction	ICC <sub>3,1</sub>	SEM [cm]	SEM [%]	MDC <sub>95</sub> [cm]	MDC <sub>95</sub> [%]
Anterior					
Deficient limb	0.91	2.14	2.70	5.93	7.47
Non-deficient limb	0.88	2.38	2.95	6.59	8.18
Posteromedial					
Deficient limb	0.96	2.55	3.15	7.08	8.74
Non-deficient limb	0.94	2.79	3.45	7.72	9.56
Posterolateral					
Deficient limb	0.96	3.02	4.03	8.36	11.16
Non-deficient limb	0.96	2.88	3.76	7.98	10.43

ICC, intraclass correlation coefficient; SEM, standard error of measurement; MDC<sub>95</sub>, minimal detectable change.

Posteromedial and posterolateral direction and composite score of the SEBT showed weak to moderate positive correlations with OLHD test scores ( $r: 0.34$ – $0.53$ ,  $p < 0.05$ ). We found a weak positive correlation between isokinetic strength of thigh muscles and SEBT score ( $r: 0.35$ – $0.45$ ,  $p < 0.05$ ). The anterior direction of the SEBT was not correlated with any considered variable. Furthermore, we found no correlation between SEBT and self-reported function

(IKDC2000 and Lysholm score). All limb symmetry indexes of SEBT were not correlated with any considered variable.

#### 4. Discussion

The aim of this study was to evaluate the measurement properties of the SEBT in patients with ACL deficiency, namely, to estimate intrarater reliability and agreement, construct validity and ability of the SEBT to distinguish between healthy and ACL-deficient subjects.

##### 4.1. Intrarater reliability and agreement

To our knowledge, this is the first study evaluating measurement properties of the SEBT in patients with ACL deficiency. We found good to excellent intrarater reliability of the SEBT (ICC: 0.88–0.96). Similar findings were previously reported with healthy individuals (Munro & Herrington, 2010; Plisky et al., 2009). Regarding agreement estimation, the difference that should be considered real and not due to measurement error should be  $> 6.59$  cm for the anterior, 7.72 cm posteromedial and 8.36 cm posterolateral direction of the SEBT. These values should be taken into account in interpreting the change in repeated measures. Comparing the measurement error with the difference related to the treatment effect could be used to determine whether this measurement error is clinically acceptable or not.

The difference reported in the literature after training in the posteromedial and posterolateral but not anterior SEBT direction seems close to our agreement estimation (Hale, Hertel, & Olmsted-Kramer, 2007; McKeon et al., 2008). However, these were studies of individuals with chronic ankle instability and not those with ACL deficiency. Whether the estimated agreement is acceptable, it depends on the amount of change possible with a specific intervention in patients with ACL deficiency. This question could be considered in further studies.

##### 4.2. Construct validity

The construct validity of the SEBT versus OLHD test can be confirmed for the posteromedial and posterolateral but not anterior direction and for the composite score. The correlations we found were weak to moderate, which indicates these 2 tests evaluate a similar construct, but other factors simultaneously contribute to each test result independently. The nature of the challenge for neuromuscular control differs among the 2 tests. The more dynamic OLHD test demands maximal acceleration following deceleration and stabilization of the subject's centre of mass. The SEBT requires stabilizing the centre of mass during movements of the non-stance limb but no dynamic center of mass acceleration. Some authors state that smaller changes in position or motion can be more challenging for the sensory system to detect and less challenging for the motor system to counteract (Lawrence et al., 2015). Conversely, large changes in position or motion would be more easily detected but would be more challenging to the motor system (Lawrence et al., 2015). This observation may explain the weak to moderate correlations we found between the 2 tests.

To our knowledge, this is the first study analyzing the correlation between the SEBT and OLHD test. Furthermore, we included isokinetic thigh muscle strength in the construct validity analysis. Again, posteromedial and posterolateral direction and composite score of the SEBT showed weak to moderate correlation with thigh muscle strength. Such relations suggest that the strength of thigh muscles contribute to SEBT performance. This finding agrees with a study finding considerable muscle activation (21–77% of maximum voluntary isometric contraction) in the lower limb during

**Table 3**  
Correlation analysis for Star Excursion Balance Test (SEBT) scores for patients (n = 33).

SEBT		Anterior		Posteromedial		Posterolateral		Composite	
		D	N	D	N	D	N	D	N
OLHD test	D	ns	ns	0.45	0.52	0.49	0.44	0.47	0.47
	N	ns	ns	0.45	0.53	0.40	0.34	0.41	0.43
Isokinetic strength: Quadriceps CON	D	ns	ns	ns	ns	0.37	0.37	ns	ns
	N	ns	ns	ns	ns	ns	ns	ns	ns
Quadriceps EXC	D	ns	ns	ns	ns	ns	ns	ns	ns
	N	ns	ns	ns	ns	ns	ns	ns	ns
Hamstring CON	D	ns	ns	ns	ns	ns	0.37	ns	ns
	N	ns	ns	ns	0.45	0.35	0.38	ns	0.39
Hamstring EXC	D	ns	ns	ns	ns	ns	ns	ns	ns
	N	ns	ns	ns	0.40	ns	0.37	ns	0.35
IKDC2000		ns	ns	ns	ns	ns	ns	ns	ns
Lysholm score		ns	ns	ns	ns	ns	ns	ns	ns

Only significant  $r$  values are shown ( $p < 0.05$ ); ns, non-significant ( $p > 0.05$ ); D, deficient limb; N, non-deficient limb; OLHD, one leg hop for distance; CON, concentric; EXC, eccentric; IKDC2000, International Knee Documentation Committee subjective knee form.

performance of the SEBT (Norris & Trudelle-Jackson, 2011). Clagg et al. also found weak positive correlations between quadriceps strength and posterolateral direction of the SEBT ( $r = 0.28$ ,  $p = 0.03$ ) as well as hamstring strength and posterolateral direction of the SEBT ( $r = 0.29$ ,  $p = 0.02$ ). Similarly, no significant correlation was found between the anterior direction of the SEBT and thigh muscle strength in individuals with a reconstructed ACL (Clagg et al., 2015). These results are similar to our findings considering the posterolateral and anterior direction of the SEBT. However, the posteromedial direction of the SEBT showed weak to moderate correlations with thigh muscle strength. Altogether, the correlations we found confirm that thigh muscle strength contributes in the construct measured by the posteromedial and posterolateral but not anterior SEBT in individuals with ACL deficiency. However, self-reported function was not correlated with SEBT, so subjective declaration of knee function represents a construct other than SEBT performance. Our findings support the use of the posteromedial and posterolateral direction of the SEBT to evaluate objective knee function in ACL deficiency, but self-reported function should complete the evaluation because it seems to represent a different construct.

#### 4.3. Patients versus controls comparison

Patients showed lower performance in both, the deficient and non-deficient limb in the posteromedial and posterolateral direction and composite score of the SEBT compared to controls. For the anterior direction, the performance was only slightly lower for the deficient limb, than for the non-deficient limb and there were no significant differences compared to controls. Consequently, all limb symmetry indexes of the SEBT were close to 100 percent, which casts doubt on the clinical utility of the limb symmetry index of the SEBT in individuals with ACL deficiency. Herrington et al. also found poorer bilateral reach distance in the medial and lateral direction of the SEBT in patients with ACL deficiency. Furthermore, the authors found poorer anterior, lateral, posteromedial and medial direction distance in the deficient limb as compared with controls (Herrington et al., 2009). Delahunt et al. compared females undergoing ACL reconstruction and healthy individuals by only unilateral evaluation and found poorer posteromedial and posterolateral SEBT performance in females undergoing surgery (Delahunt et al., 2013). Recently, Clagg et al. compared patients undergoing ACL reconstruction and healthy individuals. Similar to our results, symmetry indexes of the SEBT did not differ between

the groups (Clagg et al., 2015). However, contrary to our results, only anterior direction was bilaterally poorer for patients undergoing ACL reconstruction. Poor bilateral SEBT performance has been also observed in patients with lateral ankle trauma (Wikstrom, Naik, Lodha, & Cauraugh, 2010). These results are not all identical to our findings regarding specific direction deficit. Yet, patients with lateral ankle trauma and those undergoing ACL reconstruction have different clinical characteristics than our patient group. Furthermore, our patients were older than previous study participants (Clagg et al., 2015; Delahunt et al., 2013; Herrington et al., 2009). Nevertheless, despite differences in population characteristics, the existence of bilateral deficits detected with the SEBT seems interesting. Pietrosimone et al. evaluated patients undergoing ACL reconstruction in terms of corticomotor and spinal-reflex excitability. The authors reported lower bilateral quadriceps central activation ratio and higher bilateral Hoffmann reflex in patients undergoing surgery versus controls (Pietrosimone et al., 2015). Such a modification in functioning of the central nervous system seems consistent with the hypothesis that higher level motor control alteration disturbs neuromuscular control in a more global manner. Explaining this concern could be considered in future studies. Regarding OLHD test comparison, only performance in the deficient limb was significantly lower in patients than controls. Also, side-to-side difference in patients was significant, which is consistent with previous studies (Reid et al., 2007).

#### 4.4. Study limitations

We acknowledge some limitations of this study. First, the participant characteristics age span, time since injury and activity level could be considered heterogenic and could prevent the generalization of our findings. However, such variability of characteristics is real in the Physical and Rehabilitation Medicine department in our hospital. Also, sample size could have been greater to improve study power, but we recruited the number of subjects estimated *a priori*. Intrarater reliability was calculated from 3 consecutive trials. Some could consider that a greater time interval between measures would be more appropriate. Only three of the eight directions of the SEBT were analyzed, so different results may be possible for the directions not included in this study. Furthermore, the study did not explore all measurement properties, interrater reproducibility and responsiveness were not studied. The validity analysis was not exhaustive. These elements can be explored in further studies.

## 5. Conclusion

The SEBT can be used in patients with ACL deficiency and has good to excellent intrarater reliability. The change in repeated measurements that can be considered real should be > 6.59 cm for the anterior, 7.72 cm posteromedial and 8.36 cm posterolateral direction of the SEBT. Construct validity of the SEBT versus the OLHD test and isokinetic thigh muscle strength but not self-reported knee function is confirmed. Furthermore, posteromedial and posterolateral performance of SEBT can detect bilateral neuromuscular control deficits and can be administered if jumping is not possible. However, the OLHD test can detect side-to-side deficits. Application of the SEBT in addition to the OLHD test could improve assessment of functional deficits in patients with ACL deficiency.

## Conflicts of interest

None declared.

## Ethical approval

All participants signed written informed consent. The regional ethics committee approved the study (CPP Sud-Est 6, Reference no. AU1163).

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## Clinical trial registry

The present manuscript is a part of the study “Efficacy of pre-operative re-education on patients with an anterior cruciate ligament rupture (PRELIG)” (ClinicalTrials.gov identifier: NCT02505659).

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## Appendix. Isokinetic thigh muscle strength in patients group (n = 33).

	Deficient limb	Non-deficient limb
Quadriceps CON	172.1 ± 56.5	197.5 ± 54.8
Quadriceps EXC	230.3 ± 68.0	246.5 ± 73.1
Hamstring CON	92.5 ± 34.4	104.8 ± 36.4
Hamstring EXC	124.2 ± 37.6	147.6 ± 42.0

Values are peak troque normalized to body mass [(Nm/kg)×100]; CON, concentric; EXC, eccentric.

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