

1           **The single-leg sit-to-stand test is valid and reliable for assessing lower limb**  
2           **performance and asymmetry in international cross-country skiers**

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4  
5           **ABSTRACT**

6           *Objective:* To evaluate the validity and test–retest reliability of single-leg sit-to-stand  
7           (SLSTS) performance metrics derived from a mobile application in elite cross-country  
8           skiing (XCS) athletes.

9           *Design:* Cross-sectional, repeated-measures.

10          *Setting:* Laboratory, field.

11          *Participants:* 22 international-level XCS athletes (13 females, 9 males; median age: 18  
12          yrs).

13          *Main outcome measures:* SLSTS rising time, velocity, power, and inter-limb asymmetry  
14          were collected across two sessions separated by three days. Isokinetic knee extension  
15          peak torque and countermovement jump (CMJ) height were assessed to establish  
16          convergent and construct validity, respectively. Reliability was determined using  
17          intraclass correlation coefficients (ICC<sub>2,1</sub>) and coefficient of variation (CV). Validity was  
18          assessed using Pearson correlations.

19          *Results:* SLSTS metrics demonstrated good inter-day reliability (ICC<sub>2,1</sub> = 0.81–0.89; CV  
20          = 6.1–9.9%) for both limbs, with no differences in inter-limb asymmetry between  
21          sessions. These metrics showed moderate convergent validity ( $|r| = 0.34–0.54$ ) with  
22          isokinetic peak torque, and moderate–strong construct validity ( $|r| = 0.46–0.75$ ) with CMJ  
23          height. Notably, the strength of the associations with CMJ height was comparable to those  
24          observed between isokinetic torque and CMJ height (Steiger’s Z-test,  $p > 0.05$ ).

25          *Conclusion:* The app-based SLSTS is a reliable and valid alternative for assessing lower-  
26          limb performance and asymmetry in elite XCS athletes when laboratory-based  
27          assessments are not feasible.

28          **Keywords:** Cross-country skiing; isokinetic assesment, lower extremity; mobile app;  
29          rehabilitation; symmetry

## 30 **1. Introduction**

31 Cross-country skiing (XCS), first featured in the 1924 Chamonix Winter  
32 Olympics, is an Olympic endurance sport characterized by high physical, physiological,  
33 biomechanical, and technical demands (Stöggl et al., 2018). These demands involve  
34 coordinated use of both upper and lower limbs under varying intensities, durations, and  
35 environmental conditions, mostly at moderate altitude and in cold environments  
36 (Sandbakk and Holmberg, 2014). Although XCS is fundamentally an endurance-based  
37 sport, the relative importance of endurance capacity, strength, and power varies according  
38 to race distance, terrain profile, and competition format. While aerobic capacity  
39 predominates in longer-distance events, neuromuscular qualities such as lower-limb  
40 strength and power are critical during high-intensity race segments, including starts,  
41 sprint finishes, uphill skiing, and rapid accelerations, which are strongly influenced by  
42 skiing technique and terrain characteristics (Sandbakk and Holmberg, 2017).

43 Modern XCS comprises two main techniques, classical and skating, and includes  
44 various race formats (e.g., pursuit, mass start, relays) and race distances (e.g., 30–50 km),  
45 in which both male and female athletes compete (Zoppirolli et al., 2020). Due to its  
46 outdoor nature, factors such as terrain gradient and skiing speed influence muscular  
47 recruitment, particularly in the lower extremities (Losnegard, 2019). While optimal  
48 performance in both techniques requires harmonious upper-lower body movement  
49 patterns, the skating technique tends to be more asymmetrical in nature, whereas the  
50 diagonal stride of the classical technique requires symmetrical usage of both sides of the  
51 body (Björklund et al., 2017).

52 In XCS, lower-limb force output plays a significant role in actions such as push-  
53 off during strides and glides, sprinting, uphill propulsion, and rapid accelerations (Stöggl  
54 et al., 2011). A recent systematic review analyzing 12 studies indicated that both upper-  
55 and lower-limb muscle strengths are important contributors to XCS performance (Stöggl  
56 and Holmberg, 2022). Although the symmetry between the lower limbs has been  
57 consistently linked to better athletic performance outcomes (see review by Bishop et al.,  
58 2018a; Fox et al., 2023), this relationship requires cautious interpretation in skiing  
59 disciplines (Stöggl et al., 2013). Evidence from alpine skiing suggests that a symmetrical  
60 technique may enhance performance, supporting the use of symmetry-focused strategies  
61 in training (Supej et al., 2020). However, given the substantial biomechanical and  
62 technical differences between alpine skiing and XCS, findings from one discipline should

63 not be directly generalized to the other. These gaps highlight the need for discipline-  
64 specific research and emphasize the importance of developing functional assessment  
65 tools that can evaluate both lower-limb performance and inter-limb asymmetries in XCS  
66 athletes. In addition to performance implications, clinically meaningful levels of  
67 asymmetry may also increase the risk of lower-limb injuries, particularly anterior cruciate  
68 ligament (ACL) ruptures, which often require prolonged rehabilitation and may result in  
69 long-term functional limitations (Padua et al., 2015; Nielsen et al., 2020). Consequently,  
70 the early detection and monitoring of inter-limb asymmetries are crucial for both  
71 performance optimization and injury prevention, offering valuable insight for coaches,  
72 strength and conditioning professionals, and healthcare practitioners (Hughes et al.,  
73 2020).

74         Isokinetic dynamometers are widely considered the gold standard for assessing  
75 unilateral lower-limb performance and detecting inter-limb asymmetries in athletes  
76 (Menzel et al., 2013). However, their high cost and limited accessibility often hinder their  
77 use in routine athletic monitoring. For this reason, several field-based tests such as the  
78 standing heel-rise, single-leg hopping, and countermovement jump (CMJ) are commonly  
79 used as practical alternatives to evaluate lower-limb performance and asymmetry in  
80 sports settings (Smiley et al., 2024). Despite their utility, these tests may not be suitable  
81 during early rehabilitation stages due to their high physical demands (Davies et al., 2020).  
82 In contrast, the single-leg sit-to-stand (SLSTS) test has emerged as a simple and effective  
83 method for assessing lower-limb strength, particularly quadriceps function, and inter-  
84 limb asymmetry, without imposing excessive physical stress (Al Amer et al., 2018;  
85 Waldhelm et al., 2020). The SLSTS typically involves measuring either the number of  
86 repetitions performed in 30 seconds or the time taken to complete five repetitions  
87 (Thongchoomsin et al., 2020; Waldhelm et al., 2020). However, assessing strength or  
88 power output is especially important in the context of athletic performance and injury  
89 prevention, and these variables are more accurately quantified using force plates. For  
90 example, Makaracı et al. (2023) demonstrated that SLSTS-derived variables such as time,  
91 force, and sway, measured via a piezoelectric force plate, are reliable indicators of lower-  
92 limb performance in trained male athletes and shows significant correlations with  
93 unilateral CMJ performance. Despite their benefits, force plates necessitate technical  
94 proficiency, considerable time, and significant financial and logistical resources, thereby  
95 reducing their feasibility for routine use in applied sports environments.

96 To address these limitations, we developed and validated a mobile application that  
97 analyzes the SLSTS using high-speed video technology (Ruiz-Cárdenas et al., 2018;  
98 Makaracı et al., 2024). This app delivers valid and reliable kinetic and kinematic  
99 parameters from a single sit-to-stand maneuver (Ruiz-Cárdenas et al., 2018; Ruiz-  
100 Cárdenas et al., 2023), enabling a precise evaluation of SLSTS performance and inter-  
101 limb asymmetry comparable to data obtained from piezoelectric force plates (Makaracı  
102 et al., 2024). Given its unique movement pattern and the convenience of mobile-based  
103 assessment, the SLSTS represents a promising tool for application in XCS contexts,  
104 particularly when access to specialized equipment is limited and athletes face time  
105 constraints resulting from intensive training schedules. Beyond XCS, the SLSTS may  
106 also be applicable to other sports characterized by unilateral lower-limb force production  
107 and neuromuscular control, such as ski jumping and related winter sport disciplines  
108 (Cross et al., 2021).

109 Therefore, the primary aim of this study was to evaluate the test–retest reliability  
110 of SLSTS performance metrics (time, velocity, and power) and inter-limb asymmetry  
111 derived from our mobile app. A secondary aim was to assess the convergent and construct  
112 validity of these variables by examining their associations with isokinetic knee extension  
113 torque and CMJ performance in international XCS athletes. We hypothesized that the  
114 App-derived SLSTS performance metrics would demonstrate at least moderate test-retest  
115 reliability (intraclass correlation coefficient [ICC]  $\geq 0.50$ ), and would significantly  
116 correlate with both isokinetic measures and CMJ performance indicators.

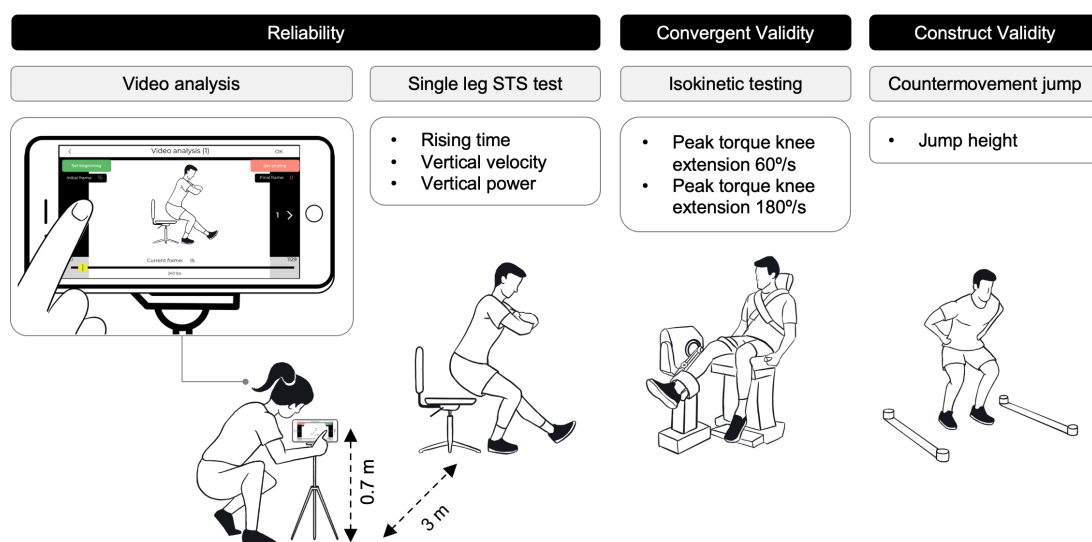
## 117 **2. Methods**

### 118 **2.1 Research Design**

119 A repeated-measures (inter-day) design was employed to evaluate the test–retest  
120 reliability of the SLSTS variables derived from our mobile app, including rising time,  
121 vertical velocity, and vertical power, in international XCS athletes. During the initial  
122 laboratory visit (Session 1), demographic and anthropometric data were collected. In the  
123 same session, a brief familiarization trial was conducted to ensure proper adaptation to  
124 the SLSTS movement pattern for both legs and to minimize potential learning effects.  
125 Although the participants were high-level competitive athletes, the SLSTS movement is  
126 not commonly performed in sport-specific contexts, which justified the need for

127 familiarization prior to the main testing sessions to ensure reliable test–retest  
128 measurements.

129 In the following week, SLSTS performance was measured across two main  
130 sessions (Sessions 2 and 3) using the *Sit to Stand* App (Lite version 1.0) installed on an  
131 iPhone 14 Pro (Apple Inc., USA). A minimum interval of three days was maintained  
132 between the two testing days to evaluate inter-day reliability. Additionally, isokinetic  
133 testing was performed on both the dominant and non-dominant legs to assess convergent  
134 validity. Construct validity was evaluated using the CMJ test, measured with the  
135 OptoJump system, to compare App-derived variables with established performance  
136 metrics, conducted 48 hours after the second SLSTS session. The schematic  
137 representation of the experimental setup for the study procedures is shown in Figure 1.



138

139 All assessments were conducted by the same researcher (XXX, first author of the  
140 study), who is affiliated with the XXXX Ski Federation. To ensure consistency across  
141 sessions, participants performed all testing procedures wearing their own running shoes.  
142 They were instructed to refrain from any moderate- to high-intensity physical activity for  
143 at least 24 hours before each session to minimize fatigue and standardize testing  
144 conditions. Additionally, participants were advised to maintain their habitual dietary  
145 routines and consume adequate fluids on all testing days to support optimal performance  
146 and hydration (Makaracı et al., 2023).

## 147 2.2 Participants

148 Sample size estimation was performed using G\*Power 3.1, based on the study's  
149 objectives. The largest calculated sample size among the analyses was adopted as the

150 minimum required to ensure adequate statistical power. For assessing test–retest  
151 reliability of SLSTS test performance metrics (i.e., time, velocity, and power), a two-  
152 tailed test with a minimum acceptable reliability ( $\rho_0$ ) of 0.50 and an expected reliability  
153 ( $\rho_1$ ) of 0.88 (Makaracı et al., 2024) indicated a required sample size of 18 participants. To  
154 examine convergent and construct validity with isokinetic variables and jump height, a  
155 required sample size of 14 participants was yielded by a minimum expected correlation  
156 of  $\rho = 0.70$  for a two-tailed test (Thongchoomsin et al., 2020).

157 Participant recruitment began with a formal meeting with the managers of the  
158 XXXX Ski Federation to identify suitable candidates. Following this, face-to-face  
159 meetings were conducted with eligible athletes. A total of twenty-two uninjured, mixed-  
160 gender international XCS athletes (n = 13 females, n = 9 males; median age: 18 years)  
161 agreed to participate in the study on a voluntary basis. All participants were members of  
162 the national XCS team and were actively competing at the international level. Given their  
163 extensive training background and competition experience, they were well-acquainted  
164 with standard strength and conditioning protocols. According to the classification by  
165 McKay et al. (2021), these athletes met the criteria for “international-level” status,  
166 defined as individuals competing on a national team at international events, a group that  
167 represents approximately 0.0025% of the global population. Participants were between  
168 17 and 23 years of age. The dominant limb for each athlete was determined as the leg  
169 they would naturally use to kick a ball, following the method described by Makaracı et  
170 al. (2023). Baseline characteristics of the participants are provided in Table 1.

171

172

**INSERT TABLE 1 HERE**

173

174 Participants were eligible for the study if they had no current musculoskeletal  
175 injuries and regularly participated in training sessions with their club and/or national team.  
176 Participants were excluded if they experienced any pain or discomfort during testing, had  
177 a lower-limb disability or functional limitation, or had undergone lower-limb surgery  
178 within the past 12 months. Additionally, the menstrual cycle phase of female athletes was  
179 monitored, and testing was scheduled accordingly to avoid the premenstrual and menstrual  
180 phases, which may influence performance outcomes (Makaracı et al., 2024). All  
181 participants were thoroughly informed about the study’s purpose, procedures, including

182 the duration of each session and the types of physical tests, and potential risks. Written and  
183 verbal informed consent was obtained prior to participation, with parental consent  
184 additionally secured for athletes under 18 years of age. The study protocol was approved  
185 by the Ethical Review Board of XXXXX XXXXX University (Approval ID: 03-2025/34)  
186 and conducted in accordance with the Declaration of Helsinki.

### 187 **2.3 Single-Leg Sit to Stand (SLSTS) Test**

188 Prior to performing the SLSTS test, femur length (cm) was measured using a  
189 flexible, inelastic tape. Femur length was defined as the distance between the superior  
190 aspect of the greater trochanter. Participants then completed a standardized 10-minute  
191 warm-up consisting of active and passive stretching exercises and SLSTS movement  
192 rehearsals.

193 The test began with participants seated on an adjustable chair without armrests, feet  
194 flat on a hard surface. Chair height was adjusted to ensure 90° knee flexion of the tested  
195 leg, while the non-tested leg was lifted just above the floor to maintain correct positioning,  
196 following the protocol (Makaracı et al., 2024). Participants were instructed to rise as  
197 quickly as possible to a fully standing position with full knee extension on their preferred  
198 (tested) leg, keeping hands on hips. Each trial was visually monitored to ensure strict  
199 adherence to test instructions. The researcher concluded and recorded the correctly  
200 executed trials. The test was performed on both dominant and nondominant legs, with  
201 three trials each leg. The best values for rising time, vertical velocity, and vertical power  
202 were used for analysis. Trials were separated by 30-second rest periods. Participants  
203 repeated the second trial (retest) after at least three days under identical testing conditions  
204 to assess reliability.

205 A smartphone (iPhone 14 Pro, iOS 18.3) mounted horizontally on a 0.7-m-high  
206 tripod positioned 3 m to the participant's right or left side recorded all trials at 240 frames  
207 per second. Recordings were analyzed using the *Sit to Stand App* (Lite version 1.0) by an  
208 independent observer blinded to both isokinetic and CMJ outcomes. A visual marker was  
209 placed on the participant's greater trochanter to identify the rising phase, defined as  
210 starting when the marker moved forward and upward beyond a reference square on the  
211 app screen and ending when it reached its highest vertical point (see Figure 1 in Makaracı  
212 et al., 2024). The elapsed time during this phase was recorded as the rising time. The app  
213 automatically calculated vertical velocity (m/s) as vertical displacement (i.e., femur

214 length) divided by rising time, and vertical power relative to body mass (W/kg) using the  
215 validated regression equation:

$$216 \quad \text{Vertical power (W/kg)} = 2.773 - 6.228 \times t + 18.224 \times d$$

217 Where t is the rising time as calculated by the two selected frames and d is the femur  
218 length which is matched with the vertical displacement when the participant is seated at  
219 90 degrees of knee joint (Orange et al., 2020; Ruiz-Cárdenas et al., 2018; Ruiz-Cárdenas  
220 et al., 2023).

221 Inter-limb asymmetry in rising time, vertical velocity, and power during the SLSTS  
222 was calculated using the formula proposed by Bishop et al. (2018b):

$$223 \quad \text{Symmetry} = \frac{(\text{Stronger limb} - \text{Weaker limb})}{\text{Stronger limb}} \times 100$$

#### 224 **2.4 Isokinetic Assessment**

225 Prior to isokinetic testing, all participants completed a standardized warm-up  
226 protocol consisting of 5 minutes of submaximal cycling on a stationary ergometer,  
227 followed by self-selected dynamic stretching exercises targeting the lower extremities.  
228 As the final component of the warm-up, participants performed several submaximal  
229 familiarization trials using the isokinetic dynamometer at the testing angular velocities  
230 (60°/s and 180°/s) to prepare neuromuscular function for maximal effort. Isokinetic knee  
231 extensor peak torque was assessed using an ISOMED 2000 isokinetic dynamometer (D.&  
232 R. Ferstl GmbH, Hemau, Germany). The dynamometer was calibrated according to the  
233 manufacturer's specifications by a one of the study researchers with over five years of  
234 experience in isokinetic testing to ensure consistent and accurate measurements. Verbal  
235 and visual instructions were provided to each participant before testing commenced  
236 (Baumgart et al., 2021).

237 Participants were seated on the dynamometer with the hip flexion angle set at 70°,  
238 a position found to be optimal for allowing full range of motion during knee extension  
239 while maintaining participant comfort and stabilization. The trunk, pelvis, and tested limb  
240 were securely stabilized using Velcro straps and padded bands at the shoulders, waist,  
241 distal thigh, and femur to minimize extraneous movements. Testing was performed on  
242 both the dominant and non-dominant legs unilaterally in a randomized order. Concentric  
243 knee extension peak torque was assessed at angular velocities of 60°/s and 180°/s, with a  
244 minimum rest period of 2 minutes between velocity conditions to minimize fatigue. The

245 range of motion was set between 10° and 100° of knee flexion, and gravity correction  
246 was applied for each limb in accordance with standard procedures. Participants were  
247 instructed to exert maximal effort throughout the testing and received strong verbal  
248 encouragement during each trial. In addition, real-time visual feedback was provided via  
249 the computer screen connected to the dynamometer to enhance motivation and effort  
250 consistency (Lategan, 2012). Each participant completed five maximal repetitions at each  
251 velocity, and the highest peak torque value was selected for further analysis.

## 252 **2.5 Countermovement Jump (CMJ) Test**

253 Following a general warm-up lasting approximately five minutes, which included  
254 dynamic stretching and mobility exercises targeting the major muscle groups of the lower  
255 extremities, participants proceeded to the main testing phase. They were instructed to  
256 perform bilateral CMJ with maximal effort during each trial. In accordance with  
257 standardized guidelines, participants dipped to a visually assessed knee flexion angle of  
258 approximately 90°, then immediately extended upward without pausing at the bottom of  
259 the movement to optimize explosive force production (Comyns et al., 2023). To eliminate  
260 the influence of arm swing, hands were kept firmly on the hips throughout all phases of  
261 the jump. Any extraneous movements such as swinging or shifting the legs outside the  
262 intended countermovement were prohibited and closely monitored by a member of the  
263 research team.

264 CMJ performance was recorded using the Optojump Next system (Microgate,  
265 Bolzano, Italy), which consists of two parallel photoelectric bars (each measuring 100 ×  
266 4 × 3 cm, 1.5 kg) positioned on the floor with the transmitter and receiver units facing  
267 each other. The system detects flight time by measuring interruptions in the light beams  
268 during take-off and landing, and calculates jump height using validated algorithms  
269 (Glatthorn et al., 2011). The units were connected to a computer via USB, and data were  
270 collected and analyzed using the manufacturer's software (Optojump software interface).  
271 Each participant completed three successful CMJ trials, with a passive rest period of 30  
272 seconds between attempts to reduce fatigue. The mean jump height from the three trials  
273 was used for statistical analysis.

## 274 **2.6 Statistical Analyses**

275 Statistical analyses were performed using JASP software version 0.19.3 (JASP  
276 Team, Amsterdam, Netherlands) and a custom spreadsheet implemented in Microsoft

277 Excel 365 (Microsoft Corp., Redmond, WA, USA). To determine the reliability of the  
278 SLSTS test variables (rising time, vertical velocity, and power) derived from the app  
279 across two separate sessions, the ICCs two-way mixed effects absolute agreement (ICC<sub>2,1</sub>)  
280 was calculated as a measure of relative reliability. The ICC<sub>2,1</sub> was interpreted as poor  
281 (< 0.5), moderate (0.50–0.74), good (0.75–0.89), or excellent (≥ 0.90) (Koo and Li, 2016).  
282 Absolute reliability was addressed using the coefficient of variation (CV) and the Bland–  
283 Altman analysis. Additionally, the minimal detectable change at the 95% confidence level  
284 (MDC<sub>95</sub>) was calculated using the formula  $SEM_{\text{agreement}} \times \sqrt{2} \times 1.96$ . Differences in inter-  
285 limb asymmetry between test sessions were assessed using paired-sample t-tests. Cohen’s  
286 d was reported as an estimate of effect size and interpreted as trivial (0–0.2), small (>0.2–  
287 0.6), moderate (>0.6–1.2), and large (>1.2) effects.

288 To assess convergent validity between the SLSTS variables and isokinetic knee  
289 extensor peak torque measures, as well as concurrent validity with CMJ performance, the  
290 Pearson’s correlations were calculated and interpreted as weak (< 0.30), moderate (0.30  
291 to < 0.60), strong (0.60 to 0.80), or almost perfect (≥ 0.90) (Hopkins et al., 2009). To  
292 compare the strength of the correlations between SLSTS variables and isokinetic  
293 measures with jump performance, Steiger’s Z-test was applied, considering the nested  
294 structure of the data due to repeated measures from each participant. Statistical  
295 significance was set at  $p \leq .05$ .

296

297 **3. Results**

298 **3.1 Inter-day Reliability of the SLSTS Variables**

299 The dominant limb showed good reliability for rising time (ICC<sub>2,1</sub>: 0.813; 95% CI:  
300 0.6–0.92), vertical velocity (ICC<sub>2,1</sub>: 0.83; 95% CI: 0.64–0.93), and vertical power (ICC<sub>2,1</sub>:  
301 0.87; 95% CI: 0.72–0.95). The coefficient of variation was 7.3%, 8.9%, and 6.1%,  
302 respectively. Likewise, the non-dominant limb showed good reliability for rising time  
303 (ICC<sub>2,1</sub>: 0.82; 95% CI: 0.62–0.92), vertical velocity (ICC<sub>2,1</sub>: 0.85; 95% CI: 0.67–0.94),  
304 and vertical power (ICC<sub>2,1</sub>: 0.89; 95% CI: 0.76–0.95) with coefficient of variation slightly  
305 higher for time (8.9%), velocity (9.9%), and power (6.8%) compared to the dominant  
306 limb. No evidence of systematic bias was observed during the SLSTS test in any of the  
307 App-derived variables (rising time, velocity, and power), irrespective of limb dominance  
308 (**Table 2**). Moreover, inter-limb asymmetry did not differ across sessions with trivial  
309 effect sizes (**Table 3**).

310 **INSERT TABLE 2 HERE**

311

312

313 **INSERT TABLE 3 HERE**

314

315 **3.2 Convergent Validity of the SLSTS variables with Isokinetic Measures**

316 Moderate correlations were found between the SLSTS variables derived from the  
317 app (rising time, vertical velocity and power) and isokinetic knee extension torque at both  
318 60°/s and 180°/s, for both the dominant and non-dominant limbs. Rising time showed  
319 inverse correlations with knee extension peak torque at 60°/s ( $r = -0.44$  and  $-0.54$ ;  $p <$   
320  $0.05$ ) and at 180°/s ( $r = -0.45$  and  $-0.34$ ;  $p < 0.05$ ), for the dominant and non-dominant  
321 limbs, respectively. Vertical velocity was positively correlated with peak torque at 60°/s  
322 for dominant ( $r = 0.37$ ;  $p = 0.04$ ) and non-dominant limb ( $r = 0.44$ ;  $p = 0.02$ ), and at 180°/s  
323 only for the dominant limb ( $r = 0.37$ ;  $p = 0.04$ ), while the non-dominant limb showed a  
324 non-significant trend ( $r = 0.31$ ;  $p = 0.08$ ). Vertical power also showed significant  
325 correlations at 60°/s ( $r = 0.48$ ;  $p < 0.05$ ) for both limbs, and at 180°/s for the dominant  
326 limb ( $r = 0.43$ ;  $p < 0.05$ ), but not for the non-dominant limb ( $r = 0.28$ ;  $p = 0.107$ ).

327 **3.3 Construct Validity of the SLSTS Variables and Isokinetic Measures in**  
328 **Relation to Jump Performance**

329 SLSTS variables derived from the app were significantly associated with jump  
330 height. In the dominant limb, strong correlations were observed for rising time ( $r = -0.70$ ;  
331  $p < 0.001$ ), velocity ( $r = 0.74$ ;  $p < 0.001$ ), and power ( $r = 0.75$ ;  $p < 0.001$ ). In the non-  
332 dominant limb, the associations were slightly weaker, showing moderate correlations for  
333 jump height with rising time ( $r = -0.53$ ;  $p = 0.013$ ), velocity ( $r = 0.46$ ;  $p = 0.035$ ), and  
334 power ( $r = 0.52$ ;  $p = 0.016$ ).

335 Similarly, isokinetic variables were also associated with jump height. Knee  
336 extension peak torque showed associations at  $60^\circ/s$  ( $r = 0.69$ ;  $p < 0.001$ ) and  $180^\circ/s$  ( $r =$   
337  $0.57$ ;  $p = 0.007$ ) for dominant limb, and at  $60^\circ/s$  ( $r = 0.56$ ;  $p = 0.008$ ) and  $180^\circ/s$  ( $r = 0.51$ ;  
338  $p = 0.017$ ) for non-dominant limb. Moreover, the strength of the associations between  
339 isokinetic variables and jump height did not significantly differ from those observed  
340 between SLSTS variables and jump height (Steiger's Z test,  $p > 0.05$ ). Finally, inter-limb  
341 asymmetry was not associated with jump performance in either the SLSTS or the  
342 isokinetic variables.

343 **4. Discussion**

344 The main findings of this study indicate that the SLSTS test, assessed via a mobile-  
345 based application, provides reliable and valid measures of lower-limb performance in  
346 international-level XCS athletes. Specifically, SLSTS-derived metrics of rising time,  
347 velocity, and power demonstrated good-to-excellent test-retest reliability and showed  
348 significant associations with isokinetic knee extensor peak torque and CMJ performance.  
349 These results support the construct and convergent validity of the SLSTS as a functional  
350 assessment of neuromuscular performance. Importantly, the simplicity and accessibility  
351 of the mobile-based SLSTS make it a practical tool for routine athlete monitoring,  
352 offering potential value for tracking lower-limb function, identifying inter-limb  
353 asymmetries, and informing return-to-training or return-to-competition decisions when  
354 access to laboratory-based equipment is limited.

355 **4.1 Reliability of the SLSTS Variables: Results from App-Based Testing**

356 In many sports, the optimization of sport-specific performance outcomes has been  
357 closely associated with lower extremity function. Moreover, the presence of asymmetries  
358 in the lower limbs can limit the effective application of force and thus negatively impact

359 performance (Fox et al., 2023). Due to the inherent nature of winter sports, and more  
360 specifically XCS, certain movements such as strides, glides, sprinting, and rapid  
361 accelerations are directly influenced by the interaction of forces within the lower  
362 extremities (Stöggl et al., 2013). Consequently, in situations where traditional field-based  
363 functional performance tests are not feasible, alternative assessments conducted under  
364 controlled conditions may offer more reliable insights into neuromuscular function and  
365 power production (Bucher et al., 2023). Notably, no specific tests have yet been  
366 developed or validated to assess lower-extremity strength and power specifically within  
367 the context of XCS athletes. Although the *Sit to Stand* App was originally designed to  
368 assess bilateral lower-limb performance (Ruiz-Cárdenas et al., 2018), recent evidence  
369 supports its use for unilateral assessments as well. Specifically, it has demonstrated high  
370 test–retest reliability (ICC = 0.88–0.92) across three consecutive sessions (48 hours apart)  
371 in trained female adults during SLSTS testing, with inter-limb asymmetry remaining  
372 stable across sessions (Makaracı et al., 2024). Our results extend these findings to  
373 international-level XCS athletes, showing good test–retest reliability (ICC = 0.81–0.89)  
374 regardless of limb dominance, and consistent inter-limb asymmetry measures between  
375 sessions.

376 Previous studies have also reported excellent reliability for repetition-based SLSTS  
377 protocols (Thongchoomsin et al., 2020; Waldhelm et al., 2020). For example, Waldhelm  
378 et al. (2020) showed high test–retest reliability (ICC = 0.87–0.94) for both the 30-second  
379 and the five-repetition SLSTS protocols in healthy young adults. While these approaches  
380 offer valuable functional insight, they typically rely on simple repetition counts or total  
381 completion time. In contrast, the present study evaluated kinetic and kinematic variables  
382 (rising time, velocity, and power) extracted from a single SLSTS movement using a  
383 mobile app. Although these biomechanical variables provide a more nuanced assessment  
384 of unilateral lower-limb function, they are also more susceptible to biological variability  
385 and technical measurement error, which can make achieving high test–retest reliability  
386 more challenging. Nevertheless, our findings demonstrate that these variables can be  
387 consistently and reliably measured in elite endurance athletes using accessible, mobile-  
388 based technology. This supports the feasibility of integrating high-resolution SLSTS  
389 metrics into performance monitoring and asymmetry evaluation protocols, particularly  
390 when laboratory-grade equipment is unavailable. Furthermore, previous validation  
391 studies have shown that rising time, velocity, and power data obtained from the app

392 during the SLSTS test exhibit excellent agreement with force plate measurements, the  
393 gold standard in performance assessment (Maloney and Fletcher, 2021), with correlation  
394 coefficients  $\geq 0.95$  and ICC values ranging from 0.96 to 0.97 (Makaracı et al., 2024).  
395 These findings suggest that the mobile app may offer a viable complement to laboratory-  
396 based assessments for monitoring lower-limb performance in field settings.

397 In addition to providing reliable data, the SLSTS test, which serves as a functional  
398 performance assessment for trained athletes (Makaracı et al., 2023), has also been  
399 reported as a potential clinical marker for monitoring postoperative recovery in  
400 individuals following ACL reconstruction (Nielsen et al., 2020). When assessing strength  
401 imbalances, unilateral performance tests are generally more sensitive and precise than  
402 bilateral assessments, as they minimize compensation effects, better replicate unilateral  
403 task demands, and provide a more detailed understanding of limb-specific neuromuscular  
404 capacity (Bishop et al., 2018b; Thongchoomsin et al., 2020). Our findings revealed that  
405 the SLSTS test variables exhibited good inter-day reliability (Table 2). Notably, these  
406 results were consistent regardless of leg dominance, further underscoring the app's  
407 reliability across limbs (Table 3). Importantly,  $MDC_{95}$  ranged from 5.5% to 9.5%,  
408 depending on the variable analyzed (rising time, velocity, and power), indicating that  
409 changes surpassing these thresholds are likely to reflect genuine improvements rather  
410 than random measurement variation. This reinforces the test's potential usefulness for  
411 monitoring meaningful functional changes, particularly in early rehabilitation phases.  
412 Supporting this, Kamiike et al. (2023) found that incorporating progressive SLSTS  
413 exercises in a home-based rehabilitation program after ACL reconstruction led to greater  
414 gains in knee extension and flexion peak torque and functional performance compared to  
415 standard care. Taken together, these findings support the potential utility of the app-based  
416 SLSTS as a reliable monitoring tool for athletic performance and suggest it may also hold  
417 promise in rehabilitation contexts. However, future studies are needed to evaluate its  
418 responsiveness and clinical applicability in post-injury recovery programs.

419 This is particularly relevant in ski-based sports, where lower-limb strength and  
420 asymmetries have been associated with performance outcomes and injury risk in previous  
421 research. Jordan et al. (2018) reported that adolescent alpine ski racers and ski cross  
422 athletes showed lower eccentric deceleration impulse and decreased systematic lower  
423 limb stiffness during CMJ compared to elite and reconstructed skier groups. These  
424 findings suggest specific targets for training interventions, such as improving eccentric

425 strength and addressing asymmetries, to enhance performance and reduce injury risk.  
426 Additionally, ski racers with a history of ACL reconstruction displayed increased bilateral  
427 asymmetry indices in kinetic impulse during specific phases of CMJ and squat jump (SJ)  
428 movements, particularly in the concentric phase of CMJ and mid-to-late phases of SJ,  
429 when compared to uninjured peers (Jordan et al., 2015). Such asymmetries may  
430 detrimentally affect performance and elevate the risk of re-injury or new injuries.  
431 Therefore, tools that provide valid, reliable, and accessible assessment of limb-specific  
432 strength and asymmetry may be especially valuable in this population. Our findings  
433 further support the SLSTS test as a practical tool for this purpose, particularly within the  
434 context of XCS.

#### 435 **4.2 Convergent and Construct Validity of the SLSTS Test Variables**

436 Due to the outdoor and endurance-based nature of XCS, the extensive involvement  
437 of the lower extremities plays a crucial role in neuromuscular activation and,  
438 consequently, skiing speed (Losnegard, 2019). Double poling, one of the most commonly  
439 used techniques in XCS, demands explosive power from the lower limbs, particularly at  
440 the hip, knee, and ankle joints, to enhance propulsion and efficiency, contrary to its  
441 reputation as an upper-body-dominant technique (Stöggl et al., 2011). This highlights the  
442 critical importance of lower extremity functional power in modern XCS. Our findings  
443 confirmed the moderate correlation between the SLSTS variables (i.e., rising time,  
444 velocity, and power) and isokinetic knee extension torque at both 60°/s and 180°/s, for  
445 both the dominant and non-dominant limbs. Carlsson et al. (2012) examined the  
446 relationship between competition performance and the results of seven different  
447 physiological tests, including isokinetic knee extension peak torque and vertical jump  
448 performance, in 12 national-level male XCS athletes. The findings indicated that  
449 performance demands may vary depending on the type of race. The authors concluded  
450 that, particularly for skiers competing in long-distance events, the selection of specific  
451 test parameters and the use of regression models are more appropriate for identifying key  
452 performance indicators. We assessed convergent validity with the isokinetic testing, a  
453 commonly used laboratory-based method for evaluating lower extremity muscle strength  
454 (Parraca et al., 2022). Therefore, the SLSTS test variables analyzed in our study may be  
455 used for determining lower extremity power of XCS athletes as well as competition  
456 performance.

457 Lower-limb maximal force production and power output are fundamental physical  
458 attributes across many sports and are commonly evaluated using vertical jump tests, such  
459 as the CMJ (Cross et al., 2021). Vertical jump performance is particularly useful for  
460 identifying neuromuscular deficits, including those related to ACL injury or reinjury, as  
461 it allows for the direct comparison of mechanical muscle function and inter-limb  
462 asymmetries (Paterno et al., 2007). In this context, Jordan et al. (2015) emphasized that  
463 vertical jump tests (e.g., CMJ and SJ) offer valuable insights into functional asymmetries  
464 during stretch-shortening cycle muscle actions, movements that are not only essential in  
465 alpine skiing but also are highly relevant for XCS athletes. Given the dynamic and  
466 cyclical loading patterns involved in XCS, especially under conditions of fatigue,  
467 monitoring vertical jump performance (i.e. jump height) can serve as both a performance  
468 indicator and a neuromuscular screening tool. Supporting this perspective, Makaracı et  
469 al. (2023) reported a correlation between force plate-derived metrics (i.e., STS time and  
470 postural sway velocity) related to the SLSTS test and CMJ performance (i.e., mean  
471 power, force, and velocity) in trained male athletes. Their findings suggest that the SLSTS  
472 test may have broader implications for evaluating functional performance in sport-  
473 specific contexts. Similarly, Stöggl et al. (2011) identified positive associations between  
474 SJ performance and peak velocity in key XCS sub-techniques, including G3 skating,  
475 double poling, and diagonal stride, among elite male athletes, with correlation  
476 coefficients (r value) ranging from 0.55 to 0.75. These relationships underscore the value  
477 of jump-based assessments in evaluating lower-limb force production relevant to XCS-  
478 specific performance. Our findings further support the construct validity of this approach.  
479 Specifically, the SLSTS test variables, derived from a mobile app, were significantly  
480 correlated with jump height, showing stronger associations for the dominant leg and  
481 moderate associations for the non-dominant leg. This is a notable observation, as the  
482 dominant limb is generally characterized by superior force output and postural stability,  
483 especially under fatigue-induced conditions common in prolonged XCS bouts (Cignetti  
484 et al., 2010).

485 Importantly, Steiger's Z-test revealed no significant differences in the strength of  
486 associations between App-based and isokinetic variables in relation to jump height ( $p >$   
487 0.05). These results indicate that our mobile app is not only a valid assessment tool but  
488 also a practical and less resource-intensive alternative to traditional laboratory-based  
489 methods (e.g., isokinetic dynamometry) for evaluating lower-limb neuromuscular

490 function in athletic populations. The broader utility of the SLSTS test itself is further  
491 supported by recent evidence showing that SLSTS performance reflects knee muscle  
492 strength and inter-limb asymmetry as measured by isokinetic devices (Kamiike et al.,  
493 2023). Our findings extend this understanding by confirming the reliability and validity  
494 of App-derived SLSTS variables in XCS athletes. Notably, inter-limb asymmetry was not  
495 significantly associated with jump performance, regardless of whether it was assessed  
496 using the App or isokinetic device. This suggests that, in this population, performance  
497 monitoring should prioritize overall functional capacity rather than asymmetry alone.  
498 However, it is worth considering that the high mechanical demands inherent in certain  
499 sport-specific movements may reduce the sensitivity of asymmetry-based assessments,  
500 particularly in the early stages of injury rehabilitation (Buckthorpe and Della Villa, 2021).  
501 While previously validated applications such as My Jump2 and COD Timer have  
502 demonstrated feasibility in assessing jump performance and change-of-direction ability  
503 (Barbalho et al., 2020; Bishop et al., 2022), the *Sit to Stand App* may offer a unique  
504 advantage. Specifically, its reliance on a closed kinetic chain movement sets it apart from  
505 other commonly used tests such as unilateral hopping, CMJ, or drop jumps which are  
506 based on open kinetic chain or plyometric actions (Davies et al., 2020). This  
507 biomechanical distinction may enhance the App's applicability for evaluating lower-limb  
508 function and symmetry during both performance monitoring and early rehabilitation  
509 phases.

#### 510 **4.1. Limitations**

511 Several limitations of this study should be acknowledged. First, the sample  
512 comprised a mixed-gender group of international-level XCS athletes. While this provides  
513 insight into a high-performance and relatively underrepresented population, it precludes  
514 gender-specific analyses and limits conclusions regarding potential sex-related  
515 differences in SLSTS performance and asymmetry. Second, the findings may not be  
516 directly generalizable to athletes competing at lower performance levels or to individuals  
517 undergoing rehabilitation following sports-related injuries, as neuromuscular demands  
518 and functional capacity may differ in these populations. Future studies should therefore  
519 examine the applicability of the SLSTS in sex-specific cohorts, across different  
520 competitive levels, and in clinical or post-injury contexts.

521

522

523 **5. Conclusion**

524 Our findings demonstrate that the SLSTS test is a reliable tool for assessing lower-  
525 limb function in international mixed-gender XCS athletes. We also confirmed the  
526 feasibility of using a mobile app to accurately measure rising time, vertical velocity,  
527 power, and lower-limb asymmetry during SLSTS performance. The App-derived  
528 variables showed strong correlations with established gold-standard measures, including  
529 isokinetic assessment (peak torque during knee extension) and vertical jump  
530 performance, supporting their concurrent and construct validity. Overall, these results  
531 highlight the potential of the SLSTS test as an accessible and practical alternative for  
532 performance monitoring and rehabilitation in XCS athletes. Given the known sex-related  
533 differences in neuromuscular control, muscle function, and fatigue responses, future  
534 research should include sufficiently powered samples of both male and female athletes to  
535 explore possible sex-specific differences.

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540 **References**

- 541 Al Amer, H. S., Sabbahi, M. A., Alrowayeh, H. N., Bryan, W. J., and Olson, S. L. (2018).  
542 Electromyographic activity of quadriceps muscle during sit-to-stand in patients  
543 with unilateral knee osteoarthritis. *BMC Research Notes*, 11(1), 356.  
544 <https://doi.org/10.1186/s13104-018-3464-9>
- 545 Barbalho, M., Kleiner, A. F. R., Callegari, B., de Lima, R. C., da Silva Souza, G., et al.  
546 (2020). Assessing interlimb jump asymmetry in young soccer players: The My  
547 Jump 2 App. *International Journal of Sports Physiology and Performance*, 16(1),  
548 19–27. <https://doi.org/10.1123/ijsp.2019-0981>
- 549 Baumgart, C., Kurz, E., Freiwald, J., and Hoppe, M. W. (2021). Effects of hip flexion on  
550 knee extension and flexion isokinetic angle-specific torques and HQ-ratios. *Sports*  
551 *Medicine–Open*, 7(1), 41. <https://doi.org/10.1186/s40798-021-00330-w>

- 552 Bishop, C., Read, P., Lake, J., Chavda, S., and Turner, A. (2018b). Interlimb asymmetries:  
553 Understanding how to calculate differences from bilateral and unilateral tests.  
554 *Strength and Conditioning Journal*, 40(4), 1–6.  
555 <https://doi.org/10.1519/SSC.0000000000000371>
- 556 Bishop, C., Rubio, M. P. H., Gullon, I. L., Maloney, S., and Balsalobre-Fernandez, C.  
557 (2022). Jump and change of direction speed asymmetry using smartphone apps:  
558 Between-session consistency and associations with physical performance. *The*  
559 *Journal of Strength and Conditioning Research*, 36(4), 927–934.  
560 <https://doi.org/10.1519/JSC.00000000000003567>
- 561 Bishop, C., Turner, A., and Read, P. (2018a). Effects of inter-limb asymmetries on  
562 physical and sports performance: A systematic review. *Journal of Sports Sciences*,  
563 36(10), 1135–1144. <https://doi.org/10.1080/02640414.2017.1361894>
- 564 Björklund, G., Alricsson, M., and Svantesson, U. (2017). Using bilateral functional and  
565 anthropometric tests to define symmetry in cross-country skiers. *Journal of Human*  
566 *Kinetics*, 60, 9–16. <https://doi.org/10.1515/hukin-2017-0107>
- 567 Bucher, E., Millet, G. P., Wehrin, J. P., and Steiner, T. (2023). Test-retest reliability of  
568 ski-specific aerobic, sprint, and neuromuscular performance tests in highly trained  
569 cross-country skiers. *Scandinavian Journal of Medicine and Science in Sports*,  
570 33(12), 2482–2498. <https://doi.org/10.1111/sms.14473>
- 571 Buckthorpe, M., and Della Villa, F. (2021). Recommendations for plyometric training  
572 after ACL reconstruction – A clinical commentary. *International Journal of Sports*  
573 *Physical Therapy*, 16(3), 879. <https://doi.org/10.26603/001c.23549>
- 574 Carlsson, M., Carlsson, T., Hammarström, D., Tiivel, T., Malm, C., and Tonkonogi, M.  
575 (2012). Validation of physiological tests in relation to competitive performances in  
576 elite male distance cross-country skiing. *The Journal of Strength and Conditioning*  
577 *Research*, 26(6), 1496–1504. <https://doi.org/10.1519/JSC.0b013e318231a799>
- 578 Cignetti, F., Schena, F., Mottet, D., and Rouard, A. (2010). A limit-cycle model of leg  
579 movements in cross-country skiing and its adjustments with fatigue. *Human*  
580 *Movement Science*, 29(4), 590–604. <https://doi.org/10.1016/j.humov.2010.03.001>

- 581 Comyns, T. M., Murphy, J., and O'Leary, D. (2023). Reliability, usefulness, and validity  
582 of field-based vertical jump measuring devices. *The Journal of Strength and*  
583 *Conditioning Research*, 37(8), 1594–1599.  
584 <https://doi.org/10.1519/JSC.0000000000004436>
- 585 Cross, M. R., Rivière, J. R., Van Hooren, B., Coulmy, N., Jiménez-Reyes, P., Morin, J.  
586 B., and Samozino, P. (2021). The effect of countermovement on force production  
587 capacity depends on extension velocity: A study of alpine skiers and sprinters.  
588 *Journal of Sports Sciences*, 39(16), 1882–1892.  
589 <https://doi.org/10.1080/02640414.2021.1906523>
- 590 Davies, W. T., Myer, G. D., and Read, P. J. (2020). Is it time we better understood the  
591 tests we are using for return of sport decision making following ACL  
592 reconstruction? A critical review of the hop tests. *Sports Medicine*, 50, 485–495.  
593 <https://doi.org/10.1007/s40279-019-01221-7>
- 594 Fox, K. T., Pearson, L. T., and Hicks, K. M. (2023). The effect of lower inter-limb  
595 asymmetries on athletic performance: A systematic review and meta-analysis.  
596 *PLOS One*, 18(6), e0286942. <https://doi.org/10.1371/journal.pone.0286942>
- 597 Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., and  
598 Maffiuletti, N. A. (2011). Validity and reliability of Optojump photoelectric cells  
599 for estimating vertical jump height. *The Journal of Strength and Conditioning*  
600 *Research*, 25(2), 556–560. <https://doi.org/10.1519/JSC.0b013e3181ccb18d>
- 601 Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J. (2009). Progressive  
602 statistics for studies in sports medicine and exercise science. *Medicine & Science*  
603 *in Sports & Exercise*, 41(1), 3-12. <https://doi.org/10.1249/MSS.0b013e31818cb278>
- 604 Hughes, G., Musco, P., Caine, S., and Howe, L. (2020). Lower limb asymmetry after  
605 anterior cruciate ligament reconstruction in adolescent athletes: A systematic  
606 review and meta-analysis. *Journal of Athletic Training*, 55(8), 811.  
607 <https://doi.org/10.4085/1062-6050-0244-19>
- 608 Jordan, M. J., Aagaard, P., and Herzog, W. (2015). Lower limb asymmetry in mechanical  
609 muscle function: A comparison between ski racers with and without ACL

- 610 reconstruction. *Scandinavian Journal of Medicine and Science in Sports*, 25(3),  
611 e301–e309. <https://doi.org/10.1111/sms.12314>
- 612 Jordan, M. J., Aagaard, P., and Herzog, W. (2018). A comparison of lower limb stiffness  
613 and mechanical muscle function in ACL-reconstructed, elite, and adolescent alpine  
614 ski racers/ski cross athletes. *Journal of Sport and Health Science*, 7(4), 416–424.  
615 <https://doi.org/10.1016/j.jshs.2018.09.006>
- 616 Kamiike, K., Mori, T., Yoshiya, S., Kawaguchi, K., and Fukunishi, S. (2023).  
617 Effectiveness of single leg standing up exercise for recovery of knee muscle  
618 strength and lower extremity motion function following anterior cruciate ligament  
619 reconstruction. *Journal of Joint Surgery and Research*, 1(1), 179–185.  
620 <https://doi.org/10.1016/j.jjoisr.2023.07.006>
- 621 Koo, T. K., and Li, M. Y. (2016). A guideline of selecting and reporting intraclass  
622 correlation coefficients for reliability research. *Journal of Chiropractic Medicine*,  
623 15(2), 155-163. <https://doi.org/10.1016/j.jcm.2016.02.012>
- 624 Lategan, L. (2012). Differences in knee flexion and extension angles of peak torque  
625 between men and women. *Isokinetics and Exercise Science*, 20(2), 71–76.  
626 <https://doi.org/10.3233/IES-2012-0443>
- 627 Losnegard, T. (2019). Energy system contribution during competitive cross-country  
628 skiing. *European Journal of Applied Physiology*, 119(8), 1675–1690.  
629 <https://doi.org/10.1007/s00421-019-04158-x>
- 630 Makaracı, Y., Nas, K., Gündüz, K., Uysal, A., Orange, S. T., and Ruiz-Cárdenas, J. D.  
631 (2024). Validity and test-retest reliability of a smartphone app for measuring rising  
632 time, velocity, power, and inter-limb asymmetry during single-leg sit-to-stand test  
633 in female-trained athletes. *Measurement in Physical Education and Exercise  
634 Science*, 28(4), 391–400. <https://doi.org/10.1080/1091367X.2024.2377096>
- 635 Makaracı, Y., Nas, K., Ruiz-Cárdenas, J. D., Gündüz, K., Aydemir, M., and Orange, S.  
636 T. (2023). Test-retest reliability and convergent validity of piezoelectric force plate  
637 measures of single-leg sit-to-stand performance in trained adults. *The Journal of*

- 638        *Strength and Conditioning Research*, 37(12), 2373–2380.  
639        <https://doi.org/10.1519/JSC.0000000000004489>
- 640        Maloney, S. J., and Fletcher, I. M. (2021). Lower limb stiffness testing in athletic  
641        performance: A critical review. *Sports Biomechanics*.  
642        <https://doi.org/10.1080/14763141.2018.1460395>
- 643        McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey,  
644        V. L., et al. (2021). Defining training and performance caliber: A participant  
645        classification framework. *International Journal of Sports Physiology and*  
646        *Performance*, 17(2), 317–331. <https://doi.org/10.1123/ijsp.2021-0451>
- 647        Menzel, H. J., Chagas, M. H., Szmuchrowski, L. A., Araujo, S. R., de Andrade, A. G.,  
648        and de Jesus-Moraleida, F. R. (2013). Analysis of lower limb asymmetries by  
649        isokinetic and vertical jump tests in soccer players. *The Journal of Strength and*  
650        *Conditioning Research*, 27(5), 1370–1377.  
651        <https://doi.org/10.1519/JSC.0b013e318265a3c8>
- 652        Nielsen, J. L., Arp, K., Villadsen, M. L., Christensen, S. S., and Aagaard, P. (2020). Rate  
653        of force development remains reduced in the knee flexors 3 to 9 months after  
654        anterior cruciate ligament reconstruction using medial hamstring autografts: A  
655        cross-sectional study. *The American Journal of Sports Medicine*, 48(13), 3214–  
656        3223. <https://doi.org/10.1177/0363546520960108>
- 657        Orange, S. T., Metcalfe, J. W., Liefeyth, A., and Jordan, A. R. (2020). Validity of various  
658        portable devices to measure sit-to-stand velocity and power in older adults. *Gait*  
659        *and Posture*, 76, 409–414. <https://doi.org/10.1016/j.gaitpost.2019.12.003>
- 660        Padua, D. A., DiStefano, L. J., Beutler, A. I., De La Motte, S. J., DiStefano, M. J., and  
661        Marshall, S. W. (2015). The landing error scoring system as a screening tool for an  
662        anterior cruciate ligament injury-prevention program in elite-youth soccer athletes.  
663        *Journal of Athletic Training*, 50(6), 589–595. [https://doi.org/10.4085/1062-6050-](https://doi.org/10.4085/1062-6050-50.1.10)  
664        50.1.10

- 665 Parraca, J. A., Adsuar, J. C., Domínguez-Muñoz, F. J., Barrios-Fernandez, S., and Tomas-  
666 Carus, P. (2022). Test-retest reliability of isokinetic strength measurements in lower  
667 limbs in elderly. *Biology*, *11*(6), 802. <https://doi.org/10.3390/biology11060802>
- 668 Paterno, M. V., Ford, K. R., Myer, G. D., Heyl, R., and Hewett, T. E. (2007). Limb  
669 asymmetries in landing and jumping 2 years following anterior cruciate ligament  
670 reconstruction. *Clinical Journal of Sport Medicine*, *17*(4), 258–262.  
671 <https://doi.org/10.1097/JSM.0b013e31804c77ea>
- 672 Ruiz-Cárdenas, J. D., Montemurro, A., del Mar Martínez-García, M., and Rodríguez-  
673 Juan, J. J. (2023). Concurrent and discriminant validity and reliability of an Android  
674 App to assess time, velocity and power during sit-to-stand test in community-  
675 dwelling older adults. *Aging Clinical and Experimental Research*, *35*(8), 1631–  
676 1640. <https://doi.org/10.1007/s40520-023-02451-6>
- 677 Ruiz-Cárdenas, J. D., Rodríguez-Juan, J. J., Smart, R. R., Jakobi, J. M., and Jones, G. R.  
678 (2018). Validity and reliability of an iPhone App to assess time, velocity and leg  
679 power during a sit-to-stand functional performance test. *Gait and Posture*, *59*, 261–  
680 266. <https://doi.org/10.1016/j.gaitpost.2017.10.029>
- 681 Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic  
682 cross-country skiing. *International Journal of Sports Physiology and Performance*,  
683 *9*(1), 117–121. <https://doi.org/10.1123/ijsp.2013-0373>
- 684 Sandbakk, Ø., and Holmberg, H. C. (2017). Physiological capacity and training routines  
685 of elite cross-country skiers: approaching the upper limits of human endurance.  
686 *International Journal of Sports Physiology And Performance*, *12*(8), 1003-1011.
- 687 Smiley, T., Dallman, J., Long, R., Kapple, M., Aldag, L., Mok, A., et al. (2024). Lower  
688 extremity return of sport testing: A systematic review. *The Knee*, *50*, 115–146.  
689 <https://doi.org/10.1016/j.knee.2024.07.021>
- 690 Stöggl, T., and Holmberg, H. C. (2022). A systematic review of the effects of strength  
691 and power training on performance in cross-country skiers. *Journal of Sports  
692 Science and Medicine*, *21*(4), 555. <https://doi.org/10.52082/jssm.2022.555>

- 693 Stöggl, T., Hébert-Losier, K., and Holmberg, H. C. (2013). Do anthropometrics,  
694 biomechanics, and laterality explain V1 side preference in skiers? *Medicine and*  
695 *Science in Sports and Exercise*, 45(8), 1569–1576.  
696 <https://doi.org/10.1249/MSS.0b013e31828b815a>
- 697 Stöggl, T., Mueller, E., Ainegren, M., and Holmberg, H. C. (2011). General strength and  
698 kinetics: Fundamental to sprinting faster in cross country skiing? *Scandinavian*  
699 *Journal of Medicine and Science in Sports*, 21(6), 791–803.  
700 <https://doi.org/10.1111/j.1600-0838.2009.01078.x>
- 701 Stöggl, T., Pellegrini, B., and Holmberg, H. C. (2018). Pacing and predictors of  
702 performance during cross-country skiing races: A systematic review. *Journal of*  
703 *Sport and Health Science*, 7(4), 381–393.  
704 <https://doi.org/10.1016/j.jshs.2018.09.005>
- 705 Supej, M., Ogrin, J., Šarabon, N., and Holmberg, H.-C. (2020). Asymmetries in the  
706 technique and ground reaction forces of elite alpine skiers influence their slalom  
707 performance. *Applied Sciences*, 10(20), 7288.  
708 <https://doi.org/10.3390/app10207288>
- 709 Thongchoomsin, S., Bovonsunthonchai, S., Joseph, L., and Chamnongkich, S. (2020).  
710 Clinimetric properties of the one-leg sit-to-stand test in examining unilateral lower  
711 limb muscle strength among young adults. *International Journal of Clinical*  
712 *Practice*, 74(9), e13556. <https://doi.org/10.1111/ijcp.13556>
- 713 Waldhelm, A., Gubler, C., Sullivan, K., Witte, C., Buchheister, D., and Bartz-Broussard,  
714 J. (2020). Inter-rater and test-retest reliability of two new single leg sit-to-stand  
715 tests. *International Journal of Sports Physical Therapy*, 15(3), 388.  
716 <https://doi.org/10.26603/ijsp20200388>
- 717 Zoppirolli, C., Hébert-Losier, K., Holmberg, H. C., and Pellegrini, B. (2020).  
718 Biomechanical determinants of cross-country skiing performance: A systematic  
719 review. *Journal of Sports Sciences*, 38(18), 2127–2148.  
720 <https://doi.org/10.1080/02640414.2020.1775375>
- 721

722 **Tables**723 **Table 1.** Sample characteristics (n = 22)

	Mean (SD)	Minimum	Maximum
Age (years) <sup>a</sup>	18 (17–18)	16	23
Female (%)	12 (57%)	-	-
Right dominance (%)	20 (95%)	-	-
Height (m)	1.66 (0.07)	1.57	1.84
Body mass (kg)	59.8 (8.4)	42	80
Femur length (m)	0.51 (0.03)	0.45	0.57
<i>SLSTS-derived variables</i>			
Dominant limb			
Rising time (s)	0.883 (0.19)	0.592	1.425
Vertical velocity (m/s)	0.607 (0.13)	0.365	0.913
Vertical power (W/kg)	6.636 (1.36)	3.374	8.929
Non-dominant limb			
Rising time (s)	0.866 (0.19)	0.567	1.246
Vertical velocity (m/s)	0.628 (0.17)	0.394	0.935
Vertical power (W/kg)	6.746 (1.59)	3.863	9.112
<i>Isokinetic peak torque</i>			
Dominant limb			
Knee extension 60°/s (N·m/kg)	3.13 (0.49)	2.17	4.1
Knee extension 180°/s (N·m/kg)	2.2 (0.32)	1.69	2.77
Non-dominant limb			
Knee extension 60°/s (N·m/kg)	2.97 (0.37)	2.25	3.63
Knee extension 180°/s (N·m/kg)	2.16 (0.23)	1.71	2.71
Jump height (m)	0.34 (0.09)	0.193	0.544

724 Notes. <sup>a</sup>Data reported as median and interquartile range due to absence of normality. Single-leg sit-to-  
725 stand (SLSTS)–derived variables is reported for session 1.

726 **Table 2.** Bland-Altman analysis and the minimal detectable change (MDC<sub>95</sub>) for the  
 727 single-leg sit-to-stand test variables

	Dominant limb				Non-dominant limb			
	Bias	+1.96 SD	-1.96 SD	MDC <sub>95</sub>	Bias	+1.96 SD	-1.96 SD	MDC <sub>95</sub>
Rising time (s)	-0.018	0.195	-0.232	0.08 (9%)	0.026	0.246	-0.194	0.07 (8%)
Vertical velocity (m/s)	0.016	0.165	-0.134	0.06 (9%)	-0.014	0.158	-0.187	0.06 (9.5%)
Vertical power (W/kg)	0.114	1.445	-1.218	0.43 (6.5%)	-0.199	1.162	-1.56	0.37 (5.5%)

728 Notes. SD: Standard deviation. The minimal detectable change is expressed as absolute and percentage  
 729 of change (%).

730 **Table 3.** Comparison of inter-limb asymmetry in the single-leg sit-to-stand test variables  
 731 across test sessions

Inter-limb asymmetry	Session 2	Session 3	$\Delta$ Sessions (95% CI)	Cohen's <i>d</i>
Rising time (%)	21.5 (20.9)	17.2 (15.13)	4.37 (-4.2 to 13)	0.2
Vertical velocity (%)	15.3 (12.4)	13.1 (10.1)	2.16 (-3.1 to 7.4)	0.18
Vertical power (%)	12.7 (10.4)	10.9 (7.8)	1.82 (-3.1 to 6.7)	0.16

732 Notes. Data are reported as mean and standard deviation (SD), along with 95% confidence intervals (95%  
 733 CI) for the differences.