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Balance perturbations as a measurement tool for trunk impairment in cross-country sit skiing

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1 **Abstract**

2 In cross-country sit-skiing, the trunk plays a crucial role in propulsion generation and balance
3 maintenance. Trunk stability is evaluated by automatic responses to unpredictable
4 perturbations; however electromyography is challenging. The aim of this study is to identify a
5 measure to group sit-skiers according to their ability to control the trunk. Seated in their
6 competitive sit-ski, ten male and five female Paralympic sit-skiers received six forward and
7 six backward unpredictable perturbations in random order. k-means clustered trunk position
8 at rest, delay to invert the trunk motion, and trunk range of motion significantly into two
9 groups. In conclusion, unpredictable perturbations might quantify trunk impairment and may
10 become an important tool in the development of an evidence-based classification system for
11 cross-country sit-skiers.

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19 **Key words:** Core stability; Automatic responses; Spinal cord injury; Paralympics, k-means.

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21 **Introduction**

22 Paralympic cross-country (XC) sit skiing is a Paralympic discipline in which athletes are
23 skiing seated because they have an impairment in function or structure of the lower
24 extremities, pelvis and/or trunk. XC sit-skiers ski using a sledge mounted on a pair of XC
25 skis, named sit-ski, and a couple of poles to generate propulsion. To guarantee a fair
26 competition, in Paralympic events, seated athletes are divided into five different classes (LW
27 [locomotor winter] 10, 10.5, 11, 11.5, 12) reflecting a lower impact of the athlete's
28 impairment on XC-skiing performance (International Paralympic Committee, 2014).

29 In order to achieve maximal performance, an athlete needs to effectively generate
30 propulsion force by means of a symmetrical double poling action and to maintain the balance
31 on the sit-ski during pushing, in downhills and various curves. A common factor that impacts
32 on both propulsion generation and balance maintenance is the athlete's ability to control the
33 trunk. The complex role of the trunk in generating propulsion can be subdivided in three main
34 contributing components: trunk momentum, trunk position, and trunk stability. An adequate
35 use of trunk flexion and extension transfers the trunk momentum to the ski poles increasing
36 the propulsive force component. However, in athletes with severe impairment of the lower
37 trunk (LW10), sledge propulsion is mainly initiated by the inertial effect of the upper body
38 region (head and arms) (Gastaldi, Mauro, & Pastorelli, 2016). The trunk position and its
39 range of movement influence the effectiveness of the trunk momentum (Vanlandewijck,
40 Theisen, & Daly, 2001). During the pushing phase athletes with minimal impairment (LW12)
41 showed more forward trunk position and lower angle of poles to the ground, which would
42 lead to more effective propulsive forces (Gastaldi, Pastorelli, & Frassinelli, 2012; Schillinger,
43 Rapp, Hakkarainen, Linnamo, & Lindinger, 2016). During the recovery phase, LW12 athletes
44 moved their trunk up to bend it down in the subsequent pushing phase (Gastaldi et al., 2012)
45 taking advantage in transferring force to the poles. Skiing on the ergometer, which highly

46 reproduces skiing on snow (Rosso et al., 2017), athletes LW12 showed more forward trunk
47 position and had higher trunk range of motion (ROM) than athletes with more severe trunk
48 impairment, who kept their trunk closer to the vertical (Rosso et al., 2016). The trunk plays
49 also a major role in maintaining athlete's stability for a proper balancing on the sit-ski while
50 skiing. Trunk stability can be defined as the equilibrium recovery after a perturbation
51 (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007) and requires complex muscle
52 coordination (Bergmark, 1989). Trunk stability can be achieved by increasing hip and trunk
53 muscle stiffness, co-contracting the hip and trunk anterior and posterior muscles (Vera-
54 Garcia, Brown, Gray, & McGill, 2006; Willson, Dougherty, Ireland, & Davis, 2005) and can
55 be improved by strengthening the core muscles (Hibbs, Thompson, French, Wrigley, &
56 Spears, 2008). Although trunk stability can be improved by strengthening the core muscles;
57 athletes with high impact of impairment, such as athletes LW10, cannot increase trunk
58 stiffness and the balance control while skiing. To overcome reduced hip and trunk muscular
59 control and improve the stability on the sit-ski, these XC sit-skiers adopt a sitting position
60 with the hips lower than the knees (knee high position) which assures low trunk ROM
61 (Gastaldi et al., 2012) and limited trunk momentum. In contrast, a kneeling position with the
62 hips higher than the knees is usually adopted by athletes with good trunk control to get
63 benefit from increased trunk ROM and to control the force direction in order to increase the
64 horizontal component.

65 Given the important role of the trunk in XC-skiing propulsion generation and balance
66 maintenance, it is crucial to identify valid impairment measurements to evaluate the ability to
67 control the trunk. A widely used method to assess the ability to control the trunk is to give
68 unpredictable balance perturbations to the support surface. Therefore, inertial forces move the
69 center of mass from the equilibrium position and induce reactive responses, which tend to
70 regain the equilibrium position (Borghuis, Hof, & Lemmink, 2008; Horak, Henry, &

71 Shumway-Cook, 1997; Nashner, 1976; Thigpen et al., 2009). In such a test, the automatic
72 postural responses of the core muscles activation are usually measured (Enoka, 2008; Jones,
73 Henry, Raasch, Hitt, & Bunn, 2012). In people with damage to proprioceptive tissue in the
74 lumbar spine, a correlation was found between the trunk muscle response time and the
75 balance performance, suggesting that longer muscles activation latency may contribute to
76 impaired trunk control (Borghuis et al., 2008; Cholewicki et al., 2002; Radebold, Cholewicki,
77 Polzhofer, & Greene, 2001). The recruitment pattern is also altered inducing a loss of
78 stability (Borghuis et al., 2008; Comerford & Mottram, 2001; Radebold, Cholewicki, Panjabi,
79 & Patel, 2000). The core muscle response is assessed by using electromyography; however
80 this technique is quite demanding for practical issue (Borghuis et al., 2008), especially in
81 people with spinal cord injury. An alternative method for assessing trunk stability during a
82 sitting balance task is to evaluate reactions to perturbations of the center of pressure
83 (Hendershot & Nussbaum, 2013; Thrasher et al., 2010).

84 In the present study, a perturbation device was used to move towards a kinematic
85 quantification of trunk stability in people with physical impairment. Kinematic results were
86 used in order to answer the following questions: (a) Do sit-skiers, positioned and strapped as
87 in competition, perform different in a perturbation test? and (b) Is a clustered perturbation
88 outcome compatible with the current classes of the athletes?

89 **Method**

90 *Participants*

91 Fifteen elite Paralympic XC sit-skiers (10 male and 5 female, 30 ± 6 years, 168 ± 19 cm, $59 \pm$
92 11 kg) with different health disorders (spinal cord injury $n=8$, spina bifida $n=2$, amputee $n=5$)
93 and classes (LW10 = 2, LW10.5 = 1, LW11 = 3, LW11.5 = 4, LW12 = 5) volunteered as
94 participants. Athletes had been informed about the aim of the tests and the details of the
95 process and signed an informed consent. Participants were free to abandon the tests at any

96 moment. The research methods and the protocols were standard and have been approved by
97 the ethics committee of the University of Jyväskylä. The procedures were performed in
98 accordance with the Declaration of Helsinki.

99 *Overall design and experimental setup*

100 All the tests were conducted during the IPC World Cup in December 2014 in Vuokatti,
101 Finland. The set up consisted of a motorized plate (0.94 m long and 0.84 m wide) on which
102 the athlete's sit-ski was fixed using four clamps as it is shown in Figure 1A (University of
103 Jyväskylä, Finland). The plate was driven by an electro-mechanical servo-actuator (IndraDyn
104 S MSK, Bosh Rexroth, Lohr am Main, Germany) along a couple of parallel tracks 1.4 m long
105 (Figure 1B). The plate was controlled by a LabVIEW custom-made script (LabVIEW 8.5;
106 National Instruments, Austin, Texas, USA). The maximum acceleration and maximum
107 velocity were set at $\pm 2.5 \text{ m/s}^2$ and $\pm 0.5 \text{ m/s}$ respectively. The direction and the duration of
108 each stimulus were arbitrary decided by the operator. A maximum of two perturbations in the
109 same direction were allowed because of the length of the tracks.

110

111 *****Figure 1 near here*****

112

113 The protocol consisted of twelve unpredictable balance perturbations (6 forward and 6
114 backward, in antero-posterior direction) while athletes were sitting on their personal sit-ski
115 strapped as for a competitive event. According to the rules and regulation document
116 (International Paralympic Committee, 2016), maximum sitting height (between the top of the
117 cushion and the top of the ski) was 40 cm; however athletes may use lower sledges.
118 Perturbations were given in random order with varying inter-trial intervals to prevent athletes
119 from anticipating platform movements, which affects the perturbation response (Gilles,
120 Wing, & Kirker, 1999). Athletes were instructed to keep the upper limbs in a neutral position

121 and maintain the stability as much as possible during the perturbation. Time was given to
122 athletes to recover the initial position on the sit-ski before the following perturbation was
123 initiated.

124 A motion analysis system composed of 8 Vicon cameras and the Vicon Nexus software
125 (Vicon Motion Systems Ltd., Oxford, UK) was used to register trunk movements. A passive
126 reflective marker was fixed on the posterior right corner of the plate. In addition, five markers
127 were placed on the right side of each athlete; on the shoulder (acromion), the elbow (lateral
128 epicondyle), the wrist (ulnar styloid process), on the hip (great trochanter), and on the knee
129 (lateral epicondyle). When the sit-ski seat did not allow fixing the marker directly on the hip,
130 the marker was fixed on the sit-ski in correspondence to the great trochanter. In this study,
131 only the acromion and hip markers were used to evaluate trunk angle with respect to a
132 vertical line (trunk angle). The trunk movement onset was identified as an increase in the
133 acceleration of the acromion marker along the anteroposterior direction.

134 *Temporal variables*

135 To assess the temporal response to unpredictable balance perturbations, two different
136 delays were calculated for each stimulus: the delay between the onset of the sledge
137 acceleration and the onset of the shoulder acceleration (DLY_1) and the delay between the
138 onset of the shoulder acceleration and the time when the trunk inverted the motion (DLY_2).

139 *Kinematic variables*

140 To evaluate the kinematic response, the trunk ROM was assessed. The trunk angle was
141 calculated at three specific times: at rest before the first stimulus (REST), 150 ms after the
142 onset of the shoulder acceleration, and when the trunk inverted the motion. The time span of
143 150 ms was chosen since it represents the interval of possible reflex contribution before
144 voluntary activation (Enoka, 2008), considering the electromechanical delay (Cavanagh &

145 Komi, 1979; Howatson, Glaister, Brouner, & van Someren, 2009; Szpala, Rutkowska-
146 Kucharska, & Drapala, 2014). Trunk flexions and extensions are reported positive and
147 negative, respectively. For each perturbation two trunk ROMs were calculated: ROM₁₅₀
148 between REST and 150 ms, and ROM_{inv} between REST and when the trunk inverted the
149 motion.

150 For each athlete, temporal and kinematic results for the six forward stimuli were averaged;
151 the same was done for the backward stimuli.

152 *Cluster Analysis*

153 The first step dealt with data preprocessing and variables selection. The data was checked for
154 outliers using the method of the mean plus or minus three standard deviations. The
155 coefficients of variability for temporal and kinematic variables were calculated to select those
156 variables to be considered for the subsequent cluster analysis.

157 In a second step, a k-means cluster analysis was performed in order to empirically group
158 athletes according to their ability to control the trunk, ensuring minimal difference within a
159 cluster and maximum difference between clusters (Altmann, Groen, Hart, Vanlandewijck, &
160 Keijsers, 2017). k-means was performed defining distances by means of the squared
161 Euclidean and defining the initial seed by means of the k-means++ algorithm. Since the
162 variables were measured in different scales, they were normalized using the z-score. k-means
163 method requires a defined number of clusters (k) a priori or it can be estimated from data.

164 The third step was the cluster analysis validation using both internal and external criteria.
165 Model selection for choosing the optimal number of clusters was performed using an internal
166 validation criterion, Silhouette (Rousseeuw, 1987), which is a data-based index that measures
167 both cluster tightness and separation. The number of clusters was a priori hypothesized to be
168 3 in order to divide athletes according to their impairment level in low, middle, and high (i.e.
169 full, partial, or no trunk control). The k-means was run with different values of k (in a range

170 between 2 and 4) and the mean silhouette for each model was calculated. The number of
171 clusters k used for the analysis was identified as the peak in the mean silhouette. The current
172 classes of the athletes were used as external criterion to compare clustering results to a priori
173 information (Xu & Wunsch, 2008). However, it should be remembered that the current
174 classification is not evidence based and thus it does not represent a gold standard.

175 In the fourth step, Mann-Whitney test was applied to the clustering input variables in order to
176 assess how strongly they contribute to the discrimination between the clusters and, thereby,
177 evaluate their relevance to the new model. The effect size was calculated as correlation
178 coefficient r (Tomczak & Tomczak, 2014) to determine the meaningfulness of the strength.
179 Statistical significance was set at $p < 0.05$ for all analyses.

180 The analyses and the statistics were performed using custom-made code prepared in MatLab
181 Software (MatLab and Release 2015, The MathWorks, Inc., Natick, Massachusetts, United
182 States).

183 **Results**

184 During the perturbation stimuli, the plate movements ranged between 15 cm to 30 cm and in
185 all cases the athletes were able to invert the trunk motion before the sledge stopped moving.
186 For all athletes, forward perturbations induced a backward trunk motion, while backward
187 perturbation moved the trunk forward.

188 The results for REST, DLY_1 , DLY_2 , ROM_{150} , and ROM_{inv} are reported as mean \pm standard
189 deviation in Table 1 for all athletes in both forward and backward perturbations. For each
190 athlete, the reported values are the average value of 12 perturbations for REST and 6
191 perturbations for the other variables.

192

193

****Table 1 near here****

194

195 *First step: data preprocessing and variables selection*

196 No outliers were identified in the dataset. Coefficients of variability for DLY₁ (forward) and
197 DLY₁ (backward) were 1.4% and 2.4%, and for DLY₂ (forward) and DLY₂ (backward) were
198 34.7% and 23.7%, respectively. The low variability of DLY₁ was set as criterion to not
199 consider this variable for the applied cluster analysis. On the contrary variables DLY₂,
200 ROM₁₅₀, and ROM_{inv} in both forward and backward directions were considered for the
201 cluster analysis.

202 *Second and third steps: k-means analysis and clusters validation*

203 The k-means was run with two to four clusters. Internal validation criterion (Silhouette)
204 results are given in figure 2. Even though three clusters would be the optimal number in order
205 to divide athletes in full, partial, and no trunk control; the highest silhouette was reached for a
206 number of clusters equals to 2 (mean silhouette = 0.52). According to the highest silhouette
207 the athletes were divided in 2 clusters: high and low impact of impairment.

208

209 ****Figure 2 near here****

210

211 Results for the external validation criterion were reported in the confusion matrix (Table 2).
212 An agreement equal to 80% was found between the two identified clusters (cluster 1 with
213 high impact of impairment and cluster 2 with low impact of impairment) and the real
214 athletes' classes (group 1: LW10 – LW10.5 – LW11 and group 2: LW11.5 – LW12). In
215 addition, sensitivity equal to 67% and 89% was found for group 1 and group 2 respectively
216 and precision equal to 80% for both clusters.

217

218 ****Table 2 near here****

219

220 *Fourth step: Variable relevance to the new model*

221 For all variables, the means \pm standard deviation for both clusters and their relevance to the
222 new model are reported in Table 3, Figure 3, and Figure 4.

223

224 *****Table 3 near here*****

225

226 Three of the selected variables were of most importance in determining the clusters (Table 3).
227 Concerning the temporal variables, DLY₂ was higher for cluster 1 in both forward (p=0.003,
228 r=0.77) and backward (p=0.01, r=0.64) directions (Figure 3).

229

230 *****Figure 3 near here*****

231

232 Regarding the kinematic variables, REST (p=0.006, r=0.71) and trunk ROM_{inv} in both
233 forward (p=0.02, r=0.59) and backward (p=0.004, r=0.74) perturbations were higher for
234 cluster 1 (Figure 4). In contrast, ROM₁₅₀ in both forward (p = 1) and backward (p = 0.9)
235 directions was not important in determining the clusters.

236

237 *****Figure 4 near here*****

238

239 **Discussion**

240 Considering the determinant role of the trunk in propulsion generation and balance
241 maintenance in XC sit-skiing, the aim of this study was twofold: (a) Do sit-skiers, sitting as in
242 competitive events, perform perturbation test differently?, and (b) Is the clusters outcome
243 from the perturbation test coherent with the actual classes of the athletes? The variables

244 collected in perturbation test: trunk angle at rest, time to invert the trunk motion, and trunk
245 ROM at the inversion significantly divided athletes into two clusters (cluster 1 with high
246 impact of impairment and cluster 2 with low impact of impairment). The clusters matched the
247 actual classification of the athletes in 80% of the cases.

248 At rest, the effect size was equal to 71% (Table 3) suggesting the meaningful effects of
249 this variable in grouping athletes according to their impact of impairment. Athletes with low
250 impact of impairment (cluster 2) had the trunk very close to the vertical (-1.4 deg, Figure 4).
251 This posture is typical of kneeling position, because of the voluntary control of core muscles.
252 In contrast, athletes with high impact of impairment (cluster 1) had on average a more
253 extended trunk position (-11.6 deg). This posture is common in knee high position, to limit
254 the trunk range of motion and to stabilize the trunk between the sit-ski backrest and the thighs
255 (Rapp, Lappi, Lindinger, Ohtonen, & Linnamo, 2014). In this study athletes used their own
256 sit-ski strapped as for a competitive event to better simulate a realistic skiing situation.

257 At the inversion of the trunk motion, the delay during forward perturbations ($r = 0.77$)
258 and the trunk ROM during backward perturbations ($r = 0.74$) had meaningful effects than the
259 same variables in the opposite stimuli directions (Table 3). Athletes with low impact of
260 impairment (cluster 2) showed a 52% and 40% shorter delay to invert the trunk motion
261 (Figure 3) and 28% and 53% lower trunk ROM in forward and backward perturbations
262 respectively (Figure 4). The shorter delay and the smaller trunk ROM registered at the
263 inversion of the trunk motion in cluster 2 compared to cluster 1 could be due to faster and
264 stronger neuromuscular activation. Co-contraction of trunk muscles plays a major role in
265 increasing the trunk strength and stiffness and therefore, to assist trunk passive stabilizer,
266 such as bones and ligaments (Borghuis et al., 2008; Panjabi, 1992). Trunk muscles include
267 abdominal and back muscles. Abdominal muscles, especially Transversus Abdominis and
268 Oblique, contribute to the trunk stability increasing the intra-abdominal pressure (Akuthota &

269 Nadler, 2004; Borghuis et al., 2008). From the back side the Erector Spinae, which spans
270 many spinal segments, provides general trunk stabilization and balance external loads
271 (Bergmark, 1989; Borghuis et al., 2008). Athletes with high impact of impairment have a
272 limited or absent voluntary control of these muscles, which may explain the longer delay to
273 invert the trunk motion and the greater trunk ROM at the inversion.

274 Other than the voluntary muscle activation to increase the trunk stiffness, the reflex
275 contributes up to 42% in stabilizing the trunk (Moorhouse & Granata, 2007). In people with
276 spinal cord injury, the reflex arc is intact below the lesion level (Crewe & Krause, 2009;
277 Ditunno, Little, Tessler, & Burns, 2004). Because of the disrupted connection to the brain
278 (supraspinal pathways), the lack of inhibition might evoke a hypertonic response (Mukherjee
279 & Chakravarty, 2010). This might explain why no differences in trunk range of movement
280 were observed after 150 ms, explaining why the reflex component had no meaningful effects
281 in divided athletes in the two clusters (Table 3).

282 Comparing the two perturbation directions, both clusters needed a longer time to invert
283 the trunk motion and had greater trunk ROM in backward than in forward perturbations. This
284 could suggest that perturbations in backward direction are more challenging to be managed
285 than forward with the used perturbation setup and perturbation parameters of acceleration and
286 velocity. Athletes were tested in their own sit-ski, which was equipped with a backrest in
287 those in the knee-high position. The backrest may support athletes during forward
288 perturbations facilitating the trunk inversion and thus reducing the ROM. Overall, due to fine
289 postural adjustment in the sagittal plane, perturbation in anterior-posterior direction may be
290 the best to discriminate between healthy individuals and those with low back pain (Radebold
291 et al., 2001). In particular, a previous study showed that voluntary forward trunk movement
292 can better predict stability limits in individuals with spinal cord injury (Gauthier et al., 2012).

293 The second question regarded coherence between the clusters outcome from the
294 perturbation test and the actual classification of the athletes. Analyses were done for k equal
295 to 2 because of the highest mean silhouette; however the mean silhouette for k equal to 3 was
296 high too. The possibility to consider three clusters would also be interesting as it would
297 divide athletes among total, partial, and no trunk control; nevertheless, considering only two
298 clusters allowed dividing athletes in significant clusters according to their trunk control.
299 Lower number of clusters compared to what expected could be due to the small sample size,
300 which should be increased in future studies maybe including athletes with comparable
301 impairment who practice similar sports. Actual results showed accuracy between clusters and
302 the current classes of 80%, very high precision in defining clusters (80%) and high to very
303 high sensitivity for both groups (67% and 89% for group 1 and group 2, respectively). These
304 results were very good considering that the current classification system is not evidence-
305 based. In order to contribute to the development of evidence-based classification, future
306 research should compare perturbation test results with sport-specific measurements, such as
307 poling force generation and the effectiveness of taking a curve.

308 In general the findings are well in line with other sports where the trunk momentum is
309 expected to be greater for those athletes who can control the trunk. A transfer of momentum
310 was previously found in wheelchair racing, in which athletes increased propulsive force by
311 imparting trunk momentum to the handrim (Cooper, 1990). During the recovery phase
312 wheelchair racers move their trunk up vertically, in order to exploit the gravity acceleration
313 during the subsequent pushing phase increasing the force applied to the handrim and enhance
314 propulsion (O'Connor, Robertson, & Cooper, 1998). In wheelchair racing, also a more
315 anterior position of the trunk is adopted. Moving the trunk forward allows athletes to apply
316 the force beyond the top of the handrim, diminishing the trunk horizontal reaction force
317 (Gehlsen, Davis, & Bahamonde, 1990), but enhancing the trunk vertical reaction force

318 (Sanderson & Sommer, 1985). The trunk vertical reaction force can be countered by the
319 impact of the gravity on the trunk and some residual abdominal muscle strength (Sanderson
320 & Sommer, 1985).

321 *Limitations*

322 A limitation of this study is the small sample size. It would be important to get a
323 representative number of athletes with different impairment levels to corroborate actual
324 results and to verify if the highest mean silhouette would increase. Overall the number of elite
325 athletes who compete in XC sit skiing is low and this will be a challenge also in all future
326 studies. One possibility would be to invite athletes with physical impairment (spinal cord
327 injury and amputation) from other but similar sports to increase the sample. Using athletes'
328 own sit-ski during the test allows assessing their movement competitions; however
329 perturbations responses are influenced by both neuromuscular factors as well as sitting
330 constraints. Indeed, sitting constrains such as sit-ski backrest and straps may enhance
331 athletes' stability reducing the trunk ROM and limiting the necessity of control abilities.
332 Performing the test using a standard sitting position and binding for all athletes would allow
333 excluding sitting constrains effects on athletes' responses to unpredictable perturbations.
334 Moreover, the standard sitting position for all athletes would allow fixing markers directly on
335 the joints for all athletes, instead of on the sit-ski seat, increasing the precision in marker
336 positioning. In addition, since the athletes' sitting height and athletes' trunk length were not
337 always the same, the height of the center of mass was not similar. Although no differences
338 were observed between clusters in the time between the onset of the sledge and shoulder
339 acceleration or within the 150 ms after shoulder acceleration, the height of the center of mass
340 could have affected the inversion of the trunk and this should be taken into account in future
341 studies.

342 **Conclusion**

343 This study aimed to assess if sit-skiers equipped as in competition perform different on a
344 perturbation test and if the clustered perturbation outcome is coherent with the actual
345 athletes' classification. The skier-specific perturbation test showed very high accuracy,
346 sensitivity, and precision in clustering sit-athletes by using variables such as time to stop the
347 trunk and the trunk ROM.

348 Despite some limitations, the unpredictable balance perturbations test together with cluster
349 analysis appears to be a promising addition for the evidence-based classification process in
350 the future because it seems to group the athletes in a valid way due to their impairment level.
351 Therefore, the suggestion for a further study would be testing this clustering method while
352 athletes are sitting in a position not compensated by straps and comparing results with sport-
353 specific measurements. This suggestion would also allow inviting athletes with spinal cord
354 injury and amputee from other but similar sports to increase the sample size.

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492 **Table 1. Temporal and kinematic variables results during forward and backward**
493 **stimuli.** Timing variables: DLY₁ (ms), delay between the onset of the sledge acceleration and
494 the onset of the shoulder acceleration; DLY₂ (ms), delay between the onset of the shoulder
495 acceleration and the time when the trunk inverted the motion. Kinematic variables: REST
496 (deg), trunk angle before the perturbation; ROM₁₅₀ (deg), trunk range of motion 150 ms after
497 the onset of the shoulder acceleration; ROM_{inv} (deg), trunk range of motion when the trunk
498 inverted the motion. Trunk flexions are reported positive, while trunk extensions are reported
499 negative. For each athlete, the values were obtained averaging twelve perturbations for
500 REST, and six stimuli for the other variables.

		Athletes and Classes														
Stimuli type	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		10	10	10.5	11	11	11	11.5	11.5	11.5	11.5	12	12	12	12	12
	REST (deg)	-18.1 ±1.6	-11.6 ±0.9	-4.1 ±0.6	-6.5 ±4.7	-11.6 ±1.5	-7.7 ±1.6	-10.2 ±0.7	2.4 ±0.9	0.3 ±1.6	-7.4 ±0.9	-1.1 ±0.7	2.7 ±0.8	-6.4 ±0.8	8.8 ±1.5	-1.9 ±0.8
Forward	DLY ₁ (ms)	47 ±1.6	47 ±2.6	45 ±1.1	47 ±3.7	47 ±2.8	48 ±2.8	47 ±2.1	49 ±1.6	47 ±2.3	48 ±2.6	47 ±2.1	49 ±2.3	47 ±2.1	48 ±2.4	47 ±2.5
	DLY ₂ (ms)	338 ±88	544 ±20	158 ±36	359 ±168	447 ±280	223 ±30	321 ±45	140 ±81	159 ±14	107 ±3.0	258 ±96	240 ±32	287 ±62	167 ±10	194 ±27
	ROM ₁₅₀ (deg)	4.9 0.3	6.0 ±0.6	4.7 ±0.4	2.0 ±4.1	5.5 ±0.6	6.0 ±0.4	6.0 ±0.6	2.1 ±1.1	5.2 ±0.1	2.8 ±0.3	5.2 ±0.5	5.6 ±0.2	5.3 ±0.3	6.1 ±0.3	6.1 ±0.4
	ROM _{inv} (deg)	5.9 ±0.9	8.2 ±0.7	4.8 ±0.5	9.1 ±6.3	8.4 ±2.4	6.8 ±0.5	8.5 ±1.9	4.2 ±0.7	5.2 ±0.1	4.2 ±0.1	6.8 ±1.7	6.2 ±0.5	6.5 ±0.8	6.3 ±0.5	6.6 ±0.8
Backward	DLY ₁ (ms)	47 ±0.6	49 ±1.7	45 ±1.8	49 ±2.1	46 ±1.4	49 ±3.5	49 ±1.9	49 ±2.1	49 ±1.4	51 ±2.0	48 ±2.0	48 ±2.2	47 ±1.6	49 ±1.4	47 ±0.8
	DLY ₂ (ms)	698 ±71	693 ±112	271 ±32	651 ±124	638 ±82	133 ±14	443 ±48	361 ±42	398 ±43	333 ±61	445 ±170	378 ±46	357 ±31	666 ±93	402 ±102
	ROM ₁₅₀ (deg)	5.6 ±0.3	6.8 ±0.6	7.3 ±0.9	4.9 ±2.4	7.5 ±0.4	5.8 ±0.4	6.5 ±0.4	5.6 ±0.3	5.8 ±0.1	6.1 ±0.2	6.9 ±0.2	5.7 ±0.2	5.8 ±0.1	6.7 ±0.3	6.5 ±0.3
	ROM _{inv} (deg)	24.5 ±2.4	18.8 ±6.0	8.4 ±1.3	15.6 ±4.5	23.4 ±2.9	6.1 ±0.2	12.2 ±1.1	8.9 ±0.6	8.5 ±0.5	8.2 ±1.0	8.9 ±0.6	8.0 ±1.6	9.0 ±1.0	12.3 ±1.5	10.7 ±1.9

501

502

503 **Table 2. External validation results.** The number of elements grouped coherently with the
 504 actual classification is reported on the main diagonal of the confusion matrix. For athletes
 505 belong to classes from LW10 to LW11 (high level of impairment), the alternative variables
 506 grouped four out of six elements coherently with the actual classification; whereas for
 507 athletes belong to classed from LW11.5 to LW12 (low level of impairment) athletes
 508 coherently grouped are eight out of nine. Therefore, the accuracy is equal to 0.8, which
 509 means that a total of 80% of athletes are grouped coherently with the actual classification.

	Group 1 (LW10-LW11)	Group 2 (LW11.5-LW12)	Total	Precision
Cluster 1 (high impairment)	4	1	5	80%
Cluster 2 (low impairment)	2	8	10	80%
Total	6	9	15	
Sensitivity	67%	89%		

510

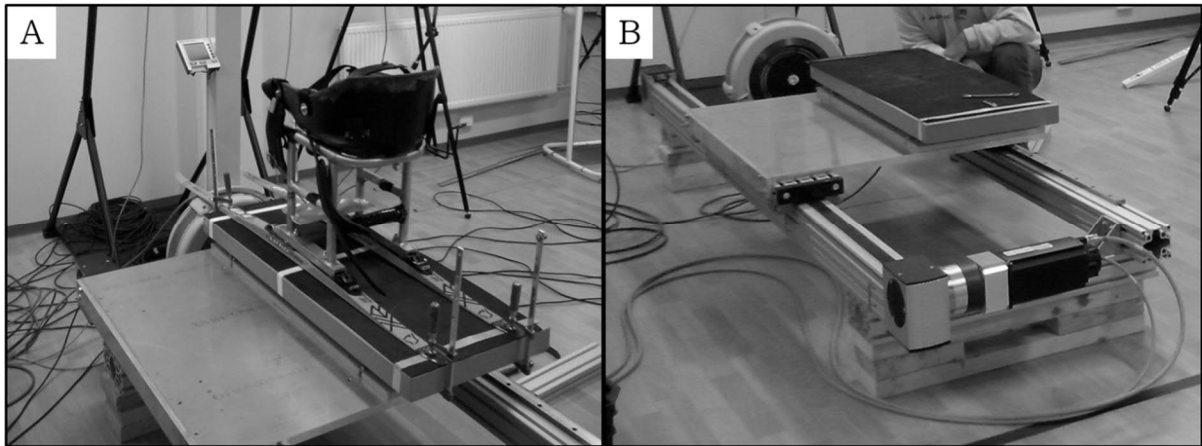
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512 **Table 3. Relevance of variables.** The mean \pm the standard deviation were reported for the
 513 two clusters on all the selected variables used in the cluster analysis. In addition, it was
 514 reported the strength of each variable in contributing to the discrimination between the
 515 clusters (Mann-Whitney test results).

Stimuli type	Variable	Cluster 1	Cluster 2	p-value	Effect size
	REST (deg)	-11.6 \pm 4.2	-1.4 \pm 5.2	0.006	0.71
Forward	DLY ₂ (ms)	401.8 \pm 93.2	193.3 \pm 57.3	0.003	0.77
	ROM ₁₅₀ (deg)	4.9 \pm 1.7	4.9 \pm 1.4	1	-
	ROM _{inv} (deg)	8.0 \pm 1.2	5.8 \pm 1.0	0.02	0.59
Backward	DLY ₂ (ms)	624.8 \pm 104.6	374.3 \pm 134.3	0.01	0.64
	ROM ₁₅₀ (deg)	6.3 \pm 1.0	6.2 \pm 0.6	0.9	-
	ROM _{inv} (deg)	18.9 \pm 5.2	8.9 \pm 1.7	0.004	0.74

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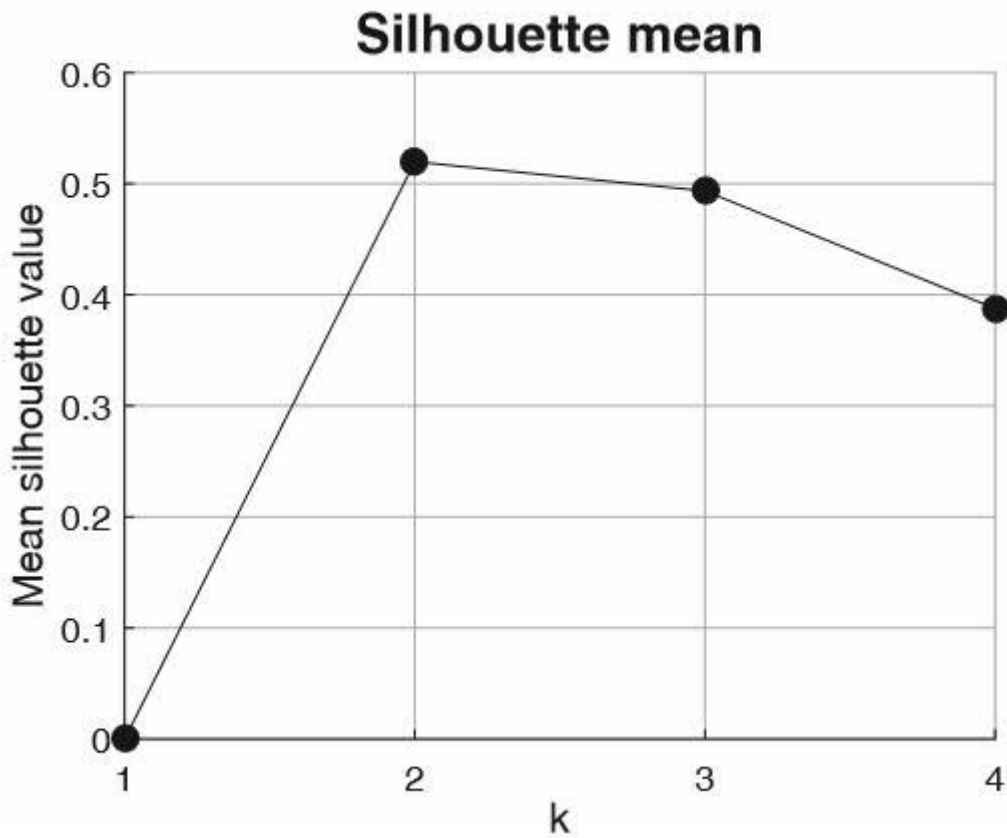
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519 **Figure 1. Setup used for unpredictable stimuli.** (A) Athlete's sit-ski was fixed on a
520 movable plate by four clamps. Athlete was sitting on his/her personal sit-ski strapped as for a
521 competitive event. (B) The movable plate (0.94 m long and 0.84 m wide) can be moved along
522 a couple of parallel tracks 1.4 m long by an electro-mechanic servo-actuator that was
523 controlled by custom-made software.

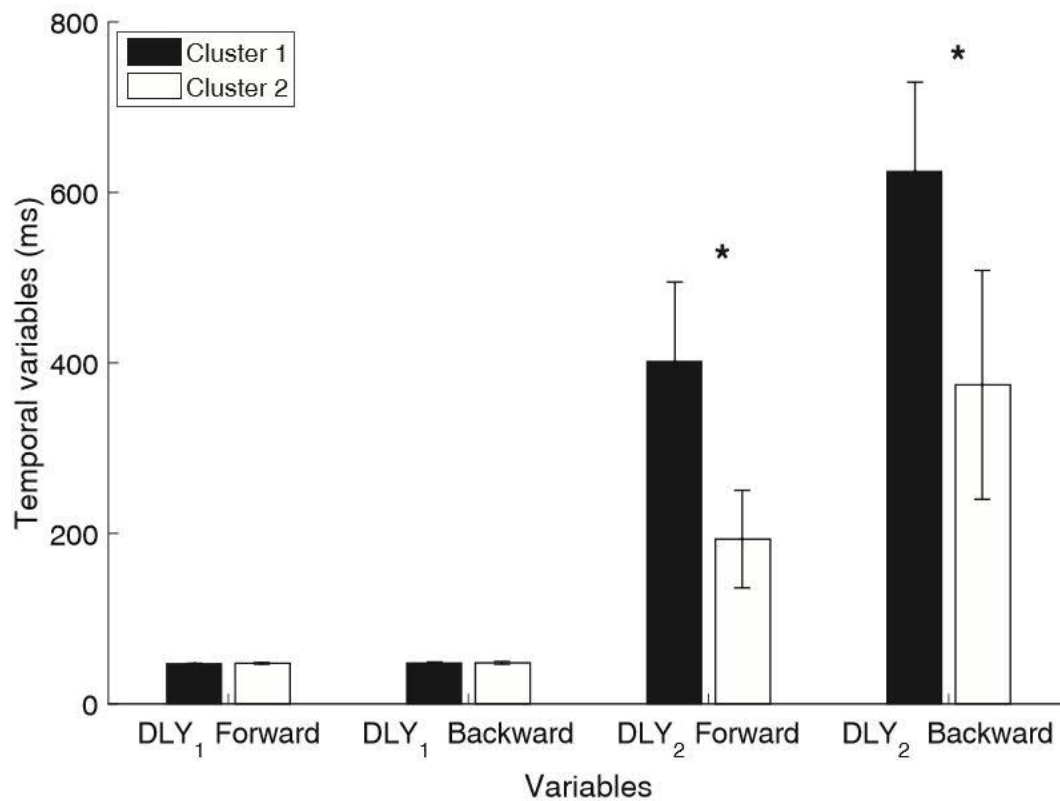
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526 **Figure 2. Mean silhouette graph.** To define the number of clusters (k) for the analysis, the
527 k-means was run with three different k (from 2 to 4) and the mean silhouette for each k was
528 calculated. The k = 2 was chosen for the analysis because of it showed the highest mean
529 silhouette value (0.52).

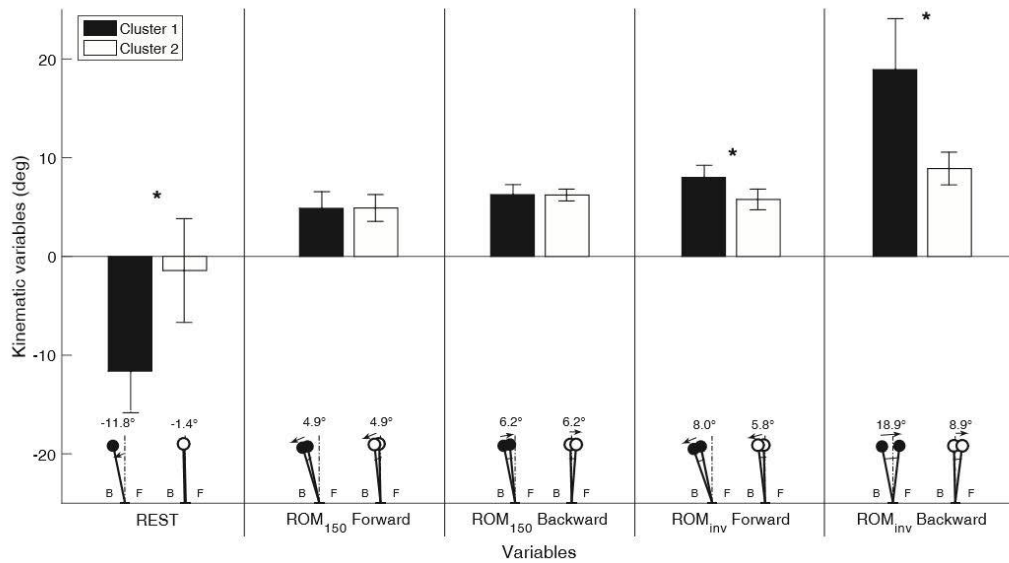
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531

532 **Figure 3. Temporal variable.** The delay between the onset of the sledge acceleration and the
 533 onset of the shoulder acceleration (DLY₁) and the delay between the onset of the shoulder
 534 acceleration and the time when the trunk inverted the motion (DLY₂) in both forward and
 535 backward perturbations were represented for the two clusters. The DLY₂ showed a difference
 536 between the two clusters in both forward and backward perturbations (*). Cluster 2 (athletes
 537 with low impact of impairment) showed a lower delay in both perturbation directions than
 538 cluster 1 (athletes with high impact of impairment). During forward perturbations shorter
 539 time was necessary to invert the trunk motion than in backward direction.

540



541

542 **Figure 4. Kinematic variables.** The trunk angle with respect to the vertical at rest (REST),
 543 the trunk range of motion 150 ms after the shoulder acceleration (ROM₁₅₀) and trunk range of
 544 motion when the trunk inverted the motion (ROM_{inv}) in forward and backward perturbations
 545 were reported in upper part of the figure using an histogram. Under the histogram an
 546 illustration of REST, ROM₁₅₀, ROM_{inv} is reported for both directions and clusters. The letter
 547 “B” stands for backward direction, whereas the letter “F” stands for forward direction. The
 548 numbers reports the mean values for each variable. REST and ROM_{inv} showed a difference
 549 between the two clusters in both forward and backward perturbations (*). Cluster 2 (athletes
 550 with low impact of impairment) had the trunk closer to the vertical at rest, whereas cluster 1
 551 (athletes with high impact of impairment) showed an extended position for the trunk. Cluster
 552 2 had greater trunk ROM in both perturbation directions than cluster 1. Overall, backward
 553 perturbation direction showed higher trunk ROM than forward direction.

554