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

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Abstract

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

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

Introduction

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

In order to achieve maximal performance, an athlete needs to effectively generate propulsion force by means of a symmetrical double poling action and to maintain the balance on the sit-ski during pushing, in downhills and various curves. A common factor that impacts on both propulsion generation and balance maintenance is the athlete's ability to control the trunk. The complex role of the trunk in generating propulsion can be subdivided in three main contributing components: trunk momentum, trunk position, and trunk stability. An adequate use of trunk flexion and extension transfers the trunk momentum to the ski poles increasing the propulsive force component. However, in athletes with severe impairment of the lower trunk (LW10), sledge propulsion is mainly initiated by the inertial effect of the upper body region (head and arms) (Gastaldi, Mauro, & Pastorelli, 2016). The trunk position and its range of movement influence the effectiveness of the trunk momentum (Vanlandewijck, Theisen, & Daly, 2001). During the pushing phase athletes with minimal impairment (LW12) showed more forward trunk position and lower angle of poles to the ground, which would lead to more effective propulsive forces (Gastaldi, Pastorelli, & Frassinelli, 2012; Schillinger, Rapp, Hakkarainen, Linnamo, & Lindinger, 2016). During the recovery phase, LW12 athletes moved their trunk up to bend it down in the subsequent pushing phase (Gastaldi et al., 2012) taking advantage in transferring force to the poles. Skiing on the ergometer, which highly reproduces skiing on snow (Rosso et al., 2017), athletes LW12 showed more forward trunk position and had higher trunk range of motion (ROM) than athletes with more severe trunk impairment, who kept their trunk closer to the vertical (Rosso et al., 2016). The trunk plays also a major role in maintaining athlete's stability for a proper balancing on the sit-ski while skiing. Trunk stability can be defined as the equilibrium recovery after a perturbation (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007) and requires complex muscle coordination (Bergmark, 1989). Trunk stability can be achieved by increasing hip and trunk muscle stiffness, co-contracting the hip and trunk anterior and posterior muscles (Vera-Garcia, Brown, Gray, & McGill, 2006; Willson, Dougherty, Ireland, & Davis, 2005) and can be improved by strengthening the core muscles (Hibbs, Thompson, French, Wrigley, & Spears, 2008). Although trunk stability can be improved by strengthening the core muscles; athletes with high impact of impairment, such as athletes LW10, cannot increase trunk stiffness and the balance control while skiing. To overcome reduced hip and trunk muscular control and improve the stability on the sit-ski, these XC sit-skiers adopt a sitting position with the hips lower than the knees (knee high position) which assures low trunk ROM (Gastaldi et al., 2012) and limited trunk momentum. In contrast, a kneeing position with the hips higher than the knees is usually adopted by athletes with good trunk control to get benefit from increased trunk ROM and to control the force direction in order to increase the horizontal component.

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

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

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

Method

Participants

Fifteen elite Paralympic XC sit-skiers (10 male and 5 female, 30 ± 6 years, 168 ± 19 cm, 59 ± 11 kg) with different health disorders (spinal cord injury n=8, spina bifida n=2, amputee n=5) and classes (LW10 = 2, LW10.5 = 1, LW11 = 3, LW11.5 = 4, LW12 = 5) volunteered as participants. Athletes had been informed about the aim of the tests and the details of the process and signed an informed consent. Participants were free to abandon the tests at any moment. The research methods and the protocols were standard and have been approved by the ethics committee of the University of Jyväskylä. The procedures were performed in accordance with the Declaration of Helsinki.

Overall design and experimental setup

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

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

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

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

Temporal variables

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

Kinematic variables

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

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

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

Cluster Analysis

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

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

The third step was the cluster analysis validation using both internal and external criteria. Model selection for choosing the optimal number of clusters was performed using an internal validation criterion, Silhouette (Rousseeuw, 1987), which is a data-based index that measures both cluster tightness and separation. The number of clusters was a priori hypothesized to be 3 in order to divide athletes according to their impairment level in low, middle, and high (i.e. full, partial, or no trunk control). The k-means was run with different values of k (in a range between 2 and 4) and the mean silhouette for each model was calculated. The number of clusters k used for the analysis was identified as the peak in the mean silhouette. The current classes of the athletes were used as external criterion to compare clustering results to a priori information (Xu & Wunsch, 2008). However, it should be remembered that the current classification is not evidence based and thus it does not represent a gold standard.

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

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

Results

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

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

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

First step: data preprocessing and variables selection

No outliers were identified in the dataset. Coefficients of variability for DLY_1 (forward) and DLY_1 (backward) were 1.4% and 2.4%, and for DLY_2 (forward) and DLY_2 (backward) were 34.7% and 23.7%, respectively. The low variability of DLY_1 was set as criterion to not consider this variable for the applied cluster analysis. On the contrary variables DLY_2, ROM_{150}, and ROM_{inv} in both forward and backward directions were considered for the cluster analysis.

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

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

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

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

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

Fourth step: Variable relevance to the new model

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

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

Three of the selected variables were of most importance in determining the clusters (Table 3). Concerning the temporal variables, DLY_2 was higher for cluster 1 in both forward (p=0.003, r=0.77) and backward (p=0.01, r=0.64) directions (Figure 3).

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

Regarding the kinematic variables, REST (p=0.006, r=0.71) and trunk ROM_{inv} in both forward (p=0.02, r=0.59) and backward (p=0.004, r=0.74) perturbations were higher for cluster 1 (Figure 4). In contrast, ROM_{150} in both forward (p = 1) and backward (p = 0.9) directions was not important in determining the clusters.

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

Discussion

Considering the determinant role of the trunk in propulsion generation and balance maintenance in XC sit-skiing, the aim of this study was twofold: (a) Do sit-skiers, sitting as in competitive events, perform perturbation test differently?, and (b) Is the clusters outcome from the perturbation test coherent with the actual classes of the athletes? The variables collected in perturbation test: trunk angle at rest, time to invert the trunk motion, and trunk ROM at the inversion significantly divided athletes into two clusters (cluster 1 with high impact of impairment and cluster 2 with low impact of impairment). The clusters matched the actual classification of the athletes in 80% of the cases.

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

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

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

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

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

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

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

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

Limitations

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

Conclusion

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

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

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Table 1. Temporal and kinematic variables results during forward and backward stimuli. Timing variables: DLY$_1$ (ms), delay between the onset of the sledge acceleration and the onset of the shoulder acceleration; DLY$_2$ (ms), delay between the onset of the shoulder acceleration and the time when the trunk inverted the motion. Kinematic variables: REST (deg), trunk angle before the perturbation; ROM$_{150}$ (deg), trunk range of motion 150 ms after the onset of the shoulder acceleration; ROM$_{inv}$ (deg), trunk range of motion when the trunk inverted the motion. Trunk flexions are reported positive, while trunk extensions are reported negative. For each athlete, the values were obtained averaging twelve perturbations for 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

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

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

Stimuli type	Variable	Cluster 1	Cluster 2	p-value	Effect size
	REST (deg)	-11.6±4.2	-1.4±5.2	0.006	0.71
Forward	DLY$_2$ (ms)	401.8±93.2	193.3±57.3	0.003	0.77
	ROM$_{150}$ (deg)	4.9±1.7	4.9±1.4	1	-
	ROM$_{inv}$ (deg)	8.0±1.2	5.8±1.0	0.02	0.59
Backward	DLY$_2$ (ms)	624.8±104.6	374.3±134.3	0.01	0.64
	ROM$_{150}$ (deg)	6.3±1.0	6.2±0.6	0.9	-
	ROM$_{inv}$ (deg)	18.9±5.2	8.9±1.7	0.004	0.74

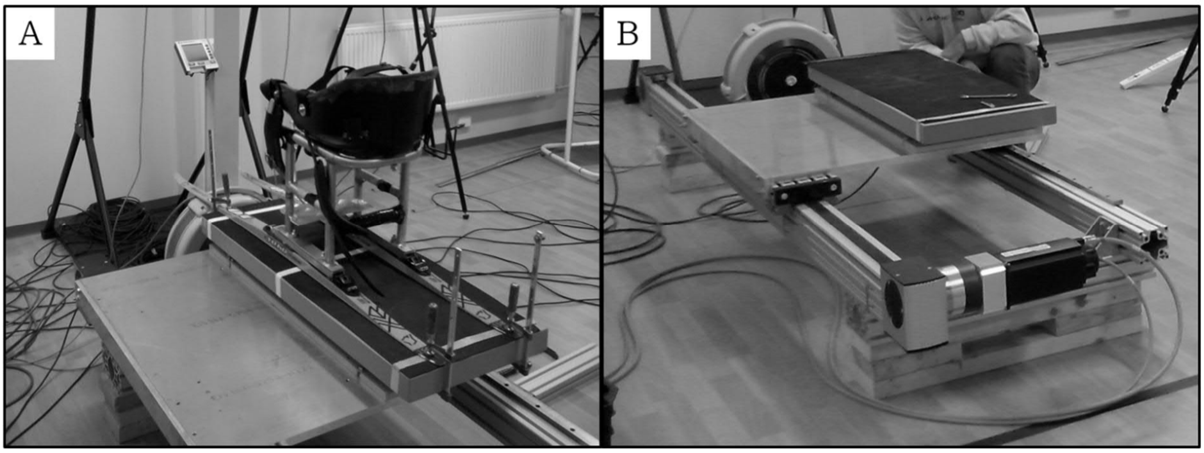

Figure 1. Setup used for unpredictable stimuli. (A) Athlete's sit-ski was fixed on a movable plate by four clamps. Athlete was sitting on his/her personal sit-ski strapped as for a competitive event. (B) The movable plate (0.94 m long and 0.84 m wide) can be moved along a couple of parallel tracks 1.4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

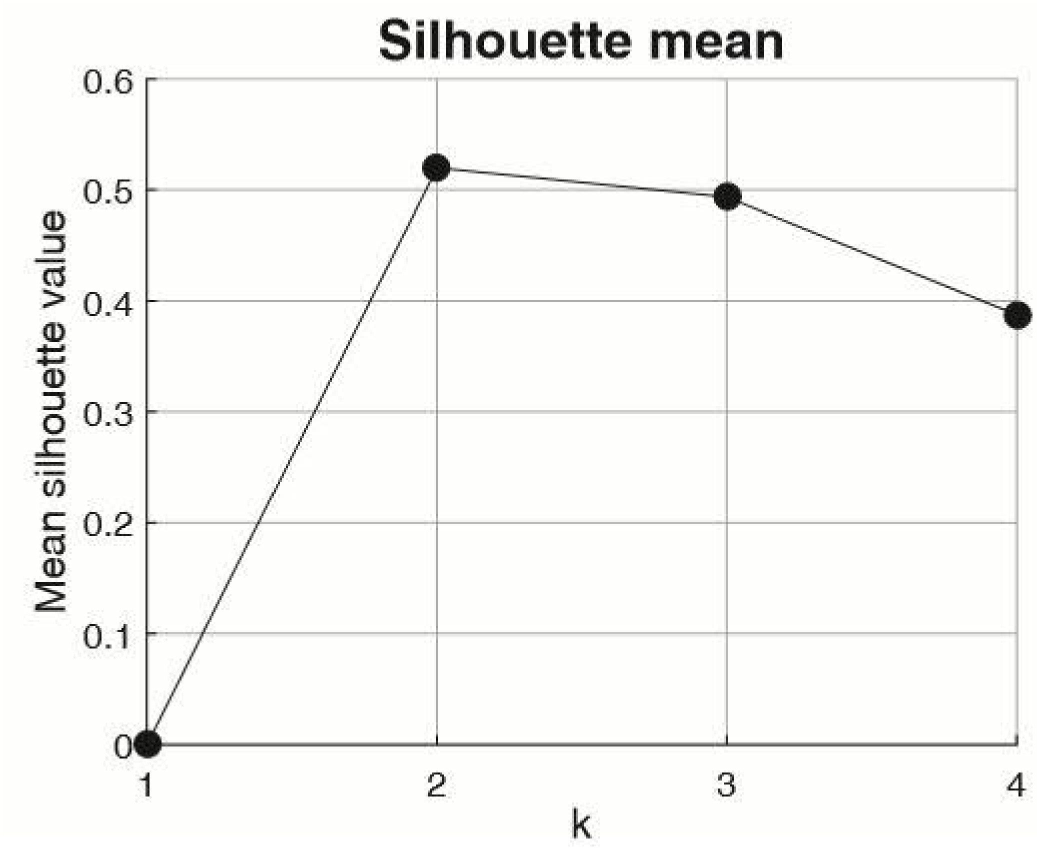

Figure 2. Mean silhouette graph. To define the number of clusters (k) for the analysis, the k-means was run with three different k (from 2 to 4) and the mean silhouette for each k was calculated. The k = 2 was chosen for the analysis because of it showed the highest mean silhouette value (0.52).

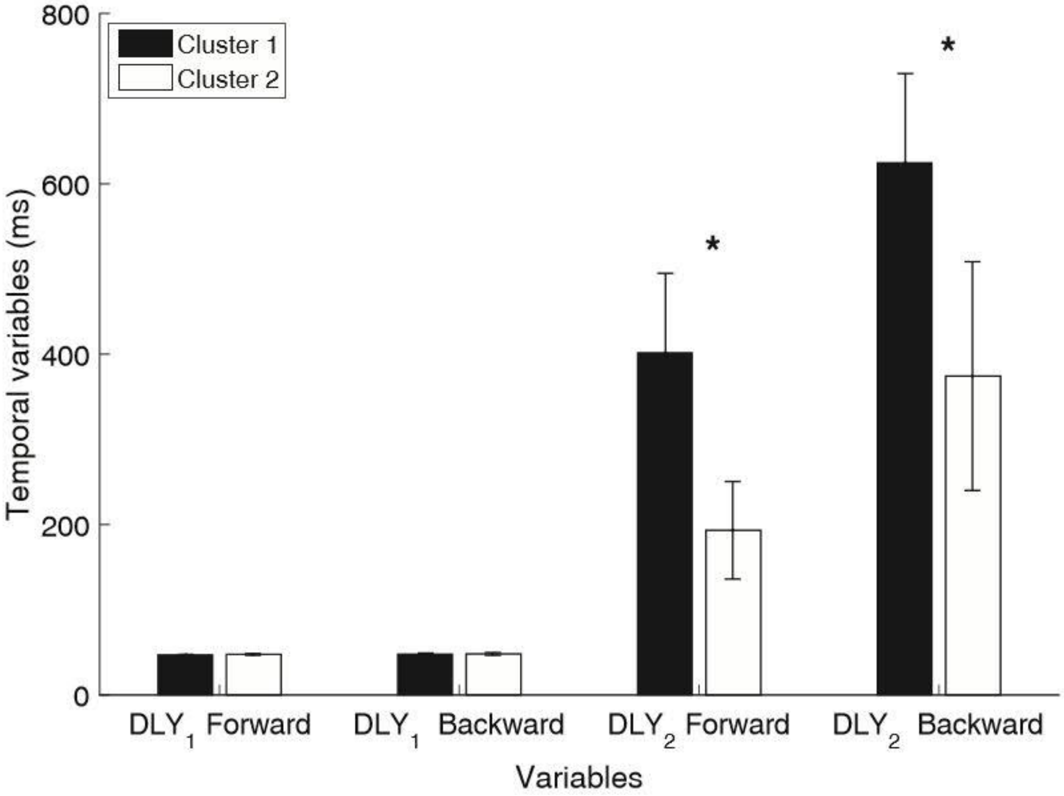

Figure 3. Temporal variable. The delay between the onset of the sledge acceleration and the onset of the shoulder acceleration (DLY_1) and the delay between the onset of the shoulder acceleration and the time when the trunk inverted the motion (DLY_2) in both forward and backward perturbations were represented for the two clusters. The DLY2 showed a difference between the two clusters in both forward and backward perturbations (*). Cluster 2 (athletes with low impact of impairment) showed a lower delay in both perturbation directions than cluster 1 (athletes with high impact of impairment). During forward perturbations shorter time was necessary to invert the trunk motion than in backward direction.

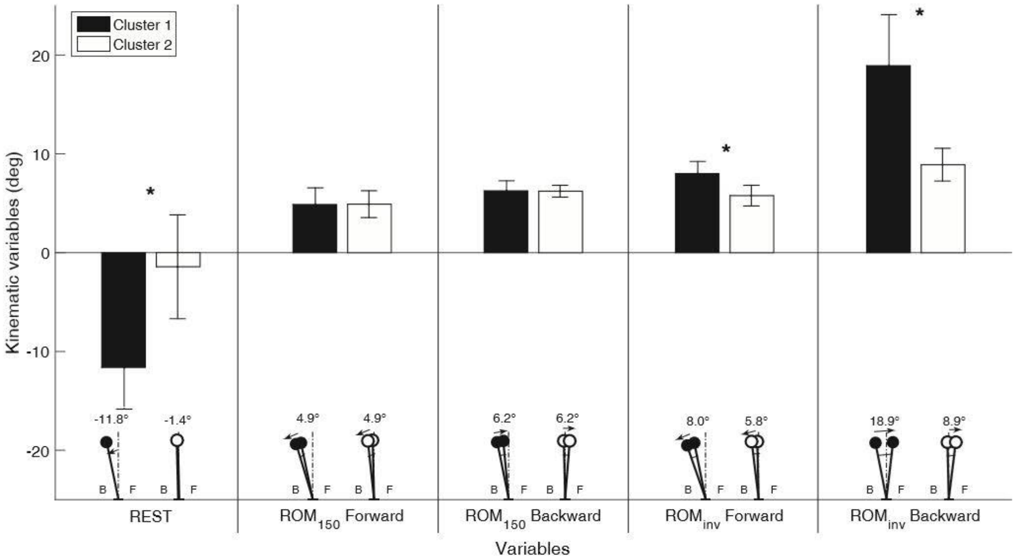

Figure 4. Kinematic variables. The trunk angle with respect to the vertical at rest (REST), the trunk range of motion 150 ms after the shoulder acceleration (ROM_{150}) and trunk range of motion when the trunk inverted the motion (ROM_{inv}) in forward and backward perturbations were reported in upper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