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Abstract

The International Paralympic Committee (IPC) mandates the development of an evidence-based classification system, which requires a measure of performance. Performance in cross-country sit skiing is mainly dependent on force generated during the poling phase and is enhanced by trunk flexion-extension movements. Since all sit skiers have neuromuscular impairment, but different ability to control the trunk, this study aimed to verify if simulated action of poling on an adapted ergometer, together with a cluster analysis, could be used for grouping participants with different impairments according to their performance. On the ergometer, eight male and five female participants performed seven poling cycles at maximal speed, while sitting on personal sit-ski. Based on maximal speed, generated force, cycle characteristics, and trunk kinematic, cluster analysis divided participants into three groups showing good accuracy, sensitivity, and precision. Although a validation of this exploratory study is necessary, skiing on the ergometer could be considered as sport-specific measure of performance and may become an interesting tool in the development of an evidence-based classification system for cross-country sit skiing.

Keywords: Adapted ergometer, Performance, Spinal cord injury, Paralympics, k-means, sit skiing

Introduction

Paralympic cross-country (XC) sit skiing is a discipline in which athletes ski seated because of structural or functional impairment at the lower limbs, pelvis and/or trunk.[1] Athletes ski sitting on a sit-ski (a seat mounted on a couple of skis) and generate propulsion by means of a pair of poles. In Paralympic events, athletes are divided into classes to minimize the impact of athlete's impairment on race results[2,3] and assure that success is determined by sporting excellence.[4] In XC sit skiing, there are five classes called locomotor winter (LW), starting with LW10, which includes athletes with a high impact of impairment on performance. The subsequent classes increase by half a point (e.g. LW10.5) up to LW12 that include athletes with low impact of impairment on performance.[4] The current classification process is performed by a panel of expert classifiers who consider impact of impairment on performance, which may involve subjective decision-making.[1] To overcome this problem, the International Paralympic Committee (IPC) has mandated the development of a new evidence-based classification system.[2] Few studies have been conducted, mainly focused on measures of impairment.[5,6,7]

Independently from their impairment, all athletes use double poling technique. In this technique, propulsion is obtained by pushing symmetrically and synchronously with a pair of poles. The effectiveness of the propulsion is enhanced by trunk flexion,[8] and it is related to maximal performance.[9] Since only the horizontal component of force is useful for propulsion, a smaller angle between poles and the ground during the poling phase increases performance.[10] However, to increase pole inclination, a trunk flexion movement is required.[8] Wider forward trunk inclination and greater trunk range of motion were found in athletes with low impact of impairment (LW12), such as lower limb amputation, compared to their counterparts.[8] During the recovery phase, athletes representing LW12 brought the trunk close to vertical and bent it downward in the following poling phase, transferring force to the poles, mainly using core muscles.[8] Athletes with high impact of impairment mainly obtain trunk flexion, taking advantage of the gravity and extension using compensation mechanisms that use inertia of the upper body.[11]

XC sit skiing performance has previously been measured on snow in terms of physical fitness: aerobic power, anaerobic capacity, and upper-body muscle strength.[12] In addition, performance has been evaluated by means of cycle characteristics: cycle duration, cycle length, duty cycle[13] and by 2D-joint kinematics: elbow, shoulder, and trunk angles.[8] Finally, performance was assessed through force generated during poling phase and pole inclinations with respect to the horizontal component.[10,13] Conducting tests on snow is, however, technologically demanding due to the large volume of snow required and variable environmental conditions (temperature and humidity), therefore limiting the number of biomechanical variables that can be assessed. To overcome these limitations, previous studies proposed more controlled environments, such as a laboratory for skiing on a treadmill[14] or performing simulated action of poling on an ergometer[15]. Previous studies on the ergometer showed a good physiological agreement between sit skiing on snow and on the ergometer when comparing blood lactate and cardiorespiratory responses.[16,15] In addition, a good biomechanical agreement between the two skiing conditions was found in force generation and muscle activation.[17]

Paralympic athletes' equipment greatly impacts their performance.[18] Based on this knowledge and the good agreement in biomechanics between skiing on snow and simulating action of poling on the ergometer,[17] double poling test on an adapted ergometer for XC sit skiing with athletes seated on personal sit-ski was used in this study. Participants' performance was assessed in terms of maximal speed, generated force, cycle characteristics, and trunk kinematics. In order to develop measure of performance, the aims of this exploratory study were to verify: (i) if athletes with different impairments perform differently on a ski ergometer while ski sitting on their own sit-ski, (ii) if there is an agreement on performance between cluster analysis outcome and current athletes' classification system.

Method

Participants

Thirteen elite XC sit-skiers (8 male and 5 female, 29 ± 3 years, 167 ± 20 cm, 58 ± 12 kg) volunteered as participants. Participants had different health conditions (spinal cord injury n = 7, spina bifida n = 2, lower limb amputation n = 4) and belonged to the five classes as follows: LW10 = 1, LW10.5 = 1, LW11 = 3, LW11.5 = 4, LW12 = 4. For the test, participants used the sitting position usually adopted for training and competitions: participants in classes LW10-LW11 used knee high sitting position (hips lower than knees), whereas participants in classes LW11.5-LW12 adopted a kneeling sitting position (hips higher than knees). Participants signed an informed consent after being informed of the test aim and procedures. Research methods and protocols were 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), on a day when participants did not have to compete. An XC-ergometer (Concept2 Inc., Morrisville, Vermont, USA) was adapted to be used by athletes with physical impairment. The ergometer was fixed to the wall in a vertical position (Fig. 1). Ergometer resistance was set at 7.5 out of 10 (arbitrary units) for all participants to closely simulate skiing on snow.[17] Participants performed the test sitting on their personal sit-skis. The distance between the sit-ski and the XC-ergometer was regulated according to each athlete's feedback, in order to obtain a comparable skiing position and technique to the one usually performed on snow.[17] The ergometer was equipped with a pair of ropes, elongated from the flywheel (at the bottom) to the top of the ergometer. Each rope ended with a handle that the participant could hold while pulling. Forces were measured using custom made strain gauge sensors (University of

Jyväskylä, 4 strain gauge connected with Wheatstone bridge, operating force range 0-1000 N, supply voltage 5 V, sensitivity 5.10 mV/N)[19] that were fixed between the ropes and the handles. Due to an elastic mechanism inside the flywheel, a constant force of approximately 10 N was registered by the force sensors. Passive reflective markers were fixed on the right side of each participant on the shoulder (acromion) and hip (great trochanter) or the sit-ski corresponding to the great trochanter when the sit-ski seat did not allow fixing it directly on the hip.[20] This mostly occurred in participants who adopted a seat that enveloped the lower limbs and blocked the knees. The fixed knees position, together with the straps used to fix the pelvis to the sit-ski, allowed the authors to assume that the hip marker remained at the level of the great trochanter during the skiing test. A motion analysis system (Vicon Motion Systems Ltd., Oxford, UK) composed of eight Vicon cameras and Vicon Nexus software were used to register trunk movements during skiing tests. Both pulling forces (sample frequency 3000 Hz) and marker trajectories (sample frequency 200 Hz) were collected by the Vicon Nexus software.

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

The protocol consisted of five to ten minutes on the XC-ergometer to warm up and become familiar with the equipment.[21] Afterwards, the participant was directed to perform a maximal skiing test in which he/she, using double poling technique, had to reach his/her maximal speed on the XC-ergometer and continue for at least seven cycles.[22] The operator assessed when the maximal speed was reached using the XC-ergometer display and gave information on cycle number to the participants. Maximal speed was chosen for the test because of its relevance to race performance: in races sit skiers adopt a sort of "all out" strategy, starting with a high speed and maintaining it as long as they can.[13] After two minutes of recovery, a second maximal skiing test was conducted. For the analysis, the test in which the participants reached the highest speed was considered.

Data analysis

To evaluate maximal speed reached during the test, information provided by the ergometer software was used. In particular, maximal speed was calculated using the time required to cover a theoretical distance of 500 m (pace given by the ergometer) and theoretical distance of 500 m. This time was expected to be almost constant over the seven cycles.

Force acquired from rope sensors was used to determine cycle phases: cycle time (CT), poling and recovery time. Poling cycle was defined from the start of one poling to the subsequent poling start; poling phase corresponds to the time during which a force was generated, whereas in recovery phase force was negligible (Fig. 2, panel A). A threshold equal to 10% of the maximum value of force was used to identify the beginning and the end of the poling phase. The CT and the relative poling time (rPT), calculated as the ratio between poling and cycle time, were considered.

Generated force, impact force (IF), peak force (PF), average force (aF), and impulse of force (iF) were calculated for each of the seven poling cycles. The IF corresponded to the first peak of the force signal during the poling phase, whereas the PF, being related to propulsion generation, was identified as the second highest peak during the poling phase (Fig. 2, panel A). The aF and the iF were calculated, respectively, as the average value and the integral of the force curve during the poling phase.

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

The shoulder and hip markers were used to calculate trunk flexion-extension angle with respect to a vertical plane (considered as 0 deg), considering the trunk as a single rigid segment.[23] To evaluate trunk motion, during each poling cycle, trunk maximal backward inclination (TB) and trunk maximal forward inclination (TF) were evaluated. Inclinations were reported as positive when participants' shoulder moved anterior from the vertical plane (considered as 0 deg) and negative when they moved posterior (Fig. 2, panel B). Trunk range of motion (ROM) of the poling phase was calculated for each poling cycle as the difference between TF and TB (Fig. 2, panel B). The beginning (BT) and the end (ET) of trunk flexion were calculated, respectively, as the time when the trunk flexion started and finished with respect to the beginning of the poling phase (considered as 0 s). These times were reported as positive when the trunk movement occurred after the beginning of the poling phase and as negative when it occurred before (Fig. 2, panel A). Time to complete a trunk flexion during the poling phase (FET) was calculated as the difference in time between ET and BT (Fig. 2, panel A).

For each participant, data collected from the seven poling cycles were averaged for the subsequent analysis.

Cluster analysis

Cluster analysis is a method used to group data, maximizing similarity of elements within a cluster and differences between clusters.[24] Cluster analysis has already been used in the field of Paralympic sport classification to identify a measure of impairment.[6,7,20] In the current study, to identify a measure of performance, cluster analysis was composed of four steps[20]:

(i) Data pre-processing: method of the mean and three standard deviations was used to discard outliers and the method of coefficient of variability (ratio between standard deviation and mean value) was used to select variables that could be considered for the cluster analysis (coefficient of variability > 5%).

(ii) k-means: cluster analysis was used to empirically group participants[7] according to their performance (expressed in terms of maximal speed, generated force, cycle characteristics, and trunk kinematics). Data were normalized using the z-score, the number of clusters (k) can be defined a priori or estimated from the data. A priori was hypothesized to have three clusters of participants aggregated according to their impairment level (i.e. no, partial, or full trunk control); however, the optimal number of clusters was defined from the data using internal validation results.

(iii) Cluster analysis validation: internal and external criteria were used to validate cluster analysis output. The k-means was run with values of k = 2, 3, and 4. The optimal number of clusters for each model was chosen using the internal validation criterion called Silhouette.[25] For each k, the overall mean Silhouette coefficient was calculated to assess the strength of the class structure.[25] Coefficients ≤ 0.25 indicated no substantial structure, 0.26 – 0.5 weak structure, 0.51 – 0.7 reasonable structure, and ≥ 0.71 strong structure.[26] In addition, the principal component analysis (PCA)[24] was used to represent data in the space of the first two principal components in order to visualize formation of clusters. The k used for the subsequent analysis was identified as the peak in mean Silhouette coefficient if the strength was identified from reasonable to strong and if the same number of groups was visible in the PCA scatter plot. The external validation compared clustering results to a priori information in order to quantify the decision of the k-means classifier.[27] The a priori information used to group participants was based on real participants' classes and participants' ability to control the trunk (defined by the current classification system). For the external validation, if the number of clusters identified by the k-means classifier was lower than the number of real participants' classes, the five classes were aggregated into a number of groups equal to k according to their trunk control.[28] The k-means classifier[7] performance was quantified using the confusion matrix in terms of accuracy, precision, and sensitivity.[29] Accuracy was the total number of participants classified coherently with the current classification system. Precision was the percentage of participants classified as belonging to a group among all the cases that the k means classify as belonging to that group. Sensitivity was the percentage of participants classified as belonging to a group among all the cases that truly belong to that group.

(iv) Variables relevance: to identify variables that mostly contributed in clusters discrimination. Since data did not show normal distribution (Kolmogorov-Smirnov test), non-parametric statistic was used. Variable relevance was assessed using Kruskal Wallis test (Fisher's least significant difference post hoc) and the effect size was calculated as correlation coefficient $r = \sqrt{\chi 2/N}$, where $\chi 2$ is the chi-squared and N is the total number of participants in the study.[30] The effect size was interpreted using Cohen's d: ≤ 0.40 small, 0.41 - 0.70 moderate, and ≥ 0.71 large.[31] Once the most relevant variables were selected, the Spearman correlation was used in order to identify redundant variables. Spearman correlations were interpreted using Cohen.[31]

The analyses and statistics were performed using custom-made scripts in MatLab Software (MatLab and Release 2015, The MathWorks, Inc., Natick, Massachusetts, United States). Statistical significance was set at an alpha of 0.05 for the analysis.

Results

Results for maximal speed, force generation, cycle characteristics, and trunk kinematic variables are reported for all participants as mean (standard deviation) and median (interquartile rage) in Table 1. For each athlete, reported values are the average value of the seven poling cycles.

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

Cluster analysis

(i) No outliers were found in generated data for force and kinematics. The coefficients of variability among participants for all variables are reported in the last column of Table 1. Since the coefficients of variability were generally high to very high, all variables were included in the cluster analysis.
(ii) and (iii) Internal validation showed a peak in mean silhouette for k = 3 (Fig. 3, panel A), which corresponded to the a priori hypothesis. For k = 3, the mean silhouette was 0.51, indicating reasonable overall class structure. Three clusters were also visible by a visual inspection of the PCA scatter plot (Fig. 3, panel B). Therefore, three clusters were identified: cluster_1 (high impact of impairment), cluster_2 (middle impact of impairment), cluster_3 (low impact of impairment).

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

Since three clusters were identified, for the external validation participants were grouped in three groups according to their ability to control the trunk:[28] group_1 (LW10 – LW10.5) participants with no or limited trunk control and no ability to keep the balance, group_2 (LW11) participants with fair trunk control and ability to keep the balance, and group_3 (LW11.5 – LW12) participants with normal or near to normal trunk control and ability to keep balance. Results for the external validation are reported in Table 2. Precision and sensitivity for the three clusters showed precision between 50% and 100% and sensitivity between 62.5% and 100% (Table 2). The classification showed an overall accuracy of 69%.

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

(iv) For all the selected variables, means (standard deviations) and median (interquartile range), Kruskal Wallis, and the effect size (variable relevance) for the three clusters are reported in Table 3. Results for Kruskal Wallis post hoc test are reported in Figs. 4 and 5.

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

Cluster_1 (high impact of impairment) and cluster_3 (low impact of impairment) significantly differed in maximal speed ($p < 0.01$, $r = 0.86$), showing lower speed for cluster_1 (3.6 m/s) than cluster_3 (4.8 m/s). Cluster_1 and cluster_3 differed also in force, showing lower PF ($p < 0.01$, $r = 0.91$), aF ($p < 0.01$, $r = 0.88$), and iF ($p = 0.01$, r =

0.81) for cluster_1 than cluster_3 (Fig. 4, panel A). Lower iF was also found for cluster_2 than cluster_3. A longer CT ($p < 0.01$, $r = 0.88$) was found for cluster_1 than cluster_2 (Fig. 4, panel B).

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

TB ($p = 0.05$, $r = 0.69$) significantly differed between cluster_1 and cluster_2 and between cluster_1 and cluster_3, showing trunk close to the vertical for cluster_1 and a flexed trunk for cluster_2 and cluster_3 (Fig. 5, panel A). ROM ($p < 0.05$, $r = 0.77$) and FET ($p < 0.05$, $r = 0.78$) significantly differed between cluster_2 and cluster_1 and between cluster_2 and cluster_3, showing higher values for cluster_1 and cluster_3 than cluster_2 (Fig. 5, panel B). Finally, cluster_1 showed longer BT ($p < 0.05$, $r = 0.76$) than cluster_2 (Fig. 5, panel B).

****Figure 5 near here****

Results for Spearman correlation are reported in Table 4. Significant correlation was found between maximal speed and force variables ($0.64 < r < 0.96$). Significant correlations were also found between cycle characteristics and trunk kinematics variables. In particular, CT correlated with TB ($r = -0.67$), BT ($r = -0.86$), and FET ($r = 0.81$); whereas rPT correlated with TF ($r = -0.62$) and ROM ($r = -0.64$). BT and ET correlated, respectively, with TB ($r = 0.71$) and TF ($r = 0.64$); whereas FET correlated with ROM ($r = 0.73$) and BT ($r = -0.63$).

****Table 4 near here****

Discussion

Considering the determinant role of propulsion generation in cross-country sit skiing performance, this study aimed to verify the hypothesis that sit skiers performed double poling differently on an adapted XC ergometer depending on the impairment level, and to assess the agreement between cluster analysis outcome and current participants' classification. Overall, maximal speed and force variables differed between participants with high and low impact of impairment, whereas cycle characteristics and trunk kinematics allowed differentiating between participants with high and middle impact of impairment. An effect size of Fisher's post hoc tests comprised between 0.81 and 0.91 for maximal speed, force variables, and cycle characteristics suggests higher relevance of these variables in clustering participants compared to trunk kinematic variables. However, the high correlation between maximal speed and force variables and between cycle characteristics and trunk kinematics suggests that a smaller set of variables may be considered in future studies to validate current results.

To evaluate how much impairments impact performance (single variable or group of variables), differences among the three clusters highlighted by clusters analysis are discussed in relation to the literature in the following paragraphs.
During the poling phase, participants with high impact of impairment (cluster_1) reached 25% lower maximal speed and generated 49% lower peak force, 45% lower average force, and 32% lower impulse of force compared to participants with low impact of impairment (cluster_3) (Fig. 4, panel A). These results were expected since force generated during poling phase is of primary importance for skiing performance in terms of speed.[14,32,33] Generated force during poling phase is also related to sitting position.[9] Non-disabled athletes, skiing on the ergometer using a knee-high sitting posture (similar to the position of cluster_1 participants), generate lower impulse of force compared to the kneeling posture (similar to the position of cluster_3 participants).[34]

Current results on cycle time are in line with literature that identify higher poling frequency (lower cycle time) as primary method for increasing skiing speed in non-disabled athletes.[14,35,36] The longer cycle time of athletes with high impact of impairment (cluster_1) could be attributable to the lack in trunk core muscles, which make their trunk movement slower, as well as confirm the longer time to complete trunk flexion movements. Unexpectedly, no difference was observed in cycle time between cluster_3 and cluster_2 (Fig. 4, panel B), which may be due to the small sample size. Although no statistically significant, on average slightly longer cycle time was found for cluster_3 compared to cluster_2, whichis in line with what was previously found in athletes with low impact of impairment when double poling on a flat terrain.[10] This could be due to the fact that in the poling phase of participants in cluster_3 who had complete trunk muscle control, they may have had greater forward trunk inclination that allowed them to cover longer distance with trunk and poles and increase cycle absolute poling and swing time.[37]

Concerning trunk maximal backward inclination, cluster_1 showed trunk close to the vertical, whereas cluster_2 and cluster_3 had a forward trunk inclination (Fig. 5, panel A). These results are in line with literature on cross-country sit skiing[8,38] and wheelchair racing[39]: athletes with high impact of impairment, using a deeper sitting position and straps to increase stability on the sit-ski and on the wheelchair, showed trunk flexion-extension movements close to vertical. In contrast, wheelchair athletes with low impact of impairment lean their trunk forward to increase the power transferred from the trunk to the pushrim.[40] Results of trunk maximal backward inclination were in line with the time of starting trunk flexion movement: participants with high impact of impairment, who had the trunk close to vertical, started trunk motion earlier than those with middle impact of impairment, which had a forward trunk inclination. The greater trunk range of motion found for cluster_3 (LW11.5-LW12) than cluster_2 (LW11) was expected since it was in line with a previous study on cross-country sit skiing on snow.[38] In contrast, comparable trunk range of motion for cluster_1 and cluster_3 was not expected because the literature reports reduced trunk range of motion when impact of impairment increased.[8,10,38] However, in those studies, trunk kinematics were assessed while athletes were skiing on snow. The only study that compared biomechanics of skiing on snow and simulated action of poling on the ergometer did not evaluate trunk kinematics[17]; therefore to confirm this unexpected result, additional studies are needed. The trunk range of motion result may be influenced by the model used to calculate trunk angle (based on a single, rigid segment) that did not consider spinal flexion, especially in the upper part, and shoulder retraction/protraction movements.[23] This result may affect cluster analysis coherence with actual classification system (Table 2). Only cluster_3 showed a precision of 100% and only group_1 showed a sensitivity of 100%, suggesting that participants with high impact of impairment (group_1) were correctly located to cluster_1, whereas participants with middle (group_2) and low (group_3) impact of impairment were identified as they have higher impairment being located in cluster_1 and cluster_2. In addition to the model used to calculate trunk angle, other factors may affect cluster analysis precision, such as inclusion in the study of both genders, which may have different levels of force, fitness levels, and training volumes. Additional research would need to be conducted to address the potential impacts resulting from physiological differences.

In order to contribute to an evidence-based classification, sport-specific measures of performance determinants are mandatory.[41] Skiing on the adapted ergometer accomplished this requirement; but test precision for high impact of impairment could be improved, for example considering gender influence or including other variables related to performance determinants. Effect size results (Table 3) showed large value for all the variables with an exception for trunk maximal backward inclination, which had a moderate effect size. Overall, kinematic variables had lower effect size than generated force, cycle characteristics, and maximal speed variables, suggesting that trunk kinematics may be slightly less relevant to classify participants with different impact of impairment according to their performance compared to others variables. Among the variables that showed relevance in clustering, the high positive correlation found between maximal speed and force variables (impact force, peak force, average force, and impulse of force) suggest that selecting one of these variables could be enough for the cluster analysis. Concerning cycle characteristics and trunk kinematic variables, cycle time, trunk maximal backward inclination, and trunk range of motion are the three variables that showed the lowest correlations with other variables, making them more advisable for the cluster analysis and excluding the beginning time and the time to complete a trunk flexion. This smaller set of variables should be considered in a future study in order to validate findings of the present exploratory study.

In general, results are in line with other sitting sports, such as wheelchair racing and wheelchair basketball. In wheelchair racing, performance expressed in terms of force applied to the wheelchair push rims decreased and cycle time increased when the sitting position was lower and tilted backward.[42] Similar results were found in wheelchair basketball, in which performance expressed in term of acceleration from standstill, decreased when a deeper sitting position was used.[39,43] In that study, it was also demonstrated that during poling phase able bodied athletes that assume a deeper sitting position had the trunk more vertical compared to the others, who had an anterior trunk inclination.[39]

Limitations

The small sample size, especially considering participants with high impact of impairment, the inclusion of both male and female participants, and considering trunk as a single, rigid segment may influence cluster analysis results and be responsible for unexpected results on trunk range of motion. Since the number of XC sit-ski athletes worldwide competing at the elite level is small, it may be beneficial to include novice athletes to increase the sample size. However, since poling action is specific to cross-country skiing and training dependent, a period of training on the ergometer is necessary before conducting the test.

Conclusion

Simulated action of poling on an adapted ergometer together with a cluster analysis was used to assess if cross-country sit skiers perform differently based on their impairment. Results of the current study showed good sensitivity and an overall acceptable precision and accuracy in clustering cross-country sit skiers in three clusters according to performance determinants by using variables such as maximal speed or generated force, cycle time, trunk maximal backward inclination, and trunk range of movement. Some unexpected results were found, likely due to the low number of elite sit skiers who participated in the current study, especially those with high impact of impairment. Therefore, to validate the current results, future research should include participants from similar sports (such as wheelchair racing and wheelchair basketball) to increase the sample size, and consider gender effects and additional variables related to performance determinants to improve the outcome precision. In conclusion, simulated action of poling on the ergometer, together with cluster analysis, seems to be a promising development in cross-country sit skiing for an evidence-based classification based on measured performance, accounting for impairment severity that impacts performance.

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Figure 1. Maximal speed test setup. An adapted ergometer was fixed to the wall in a vertical position with a couple of ropes elongated from the top. Each rope ended with a handle that the participant held while pulling. Participant's sit-ski was fixed in front of the ergometer at a distance that allows the participant skiing technique used on snow.

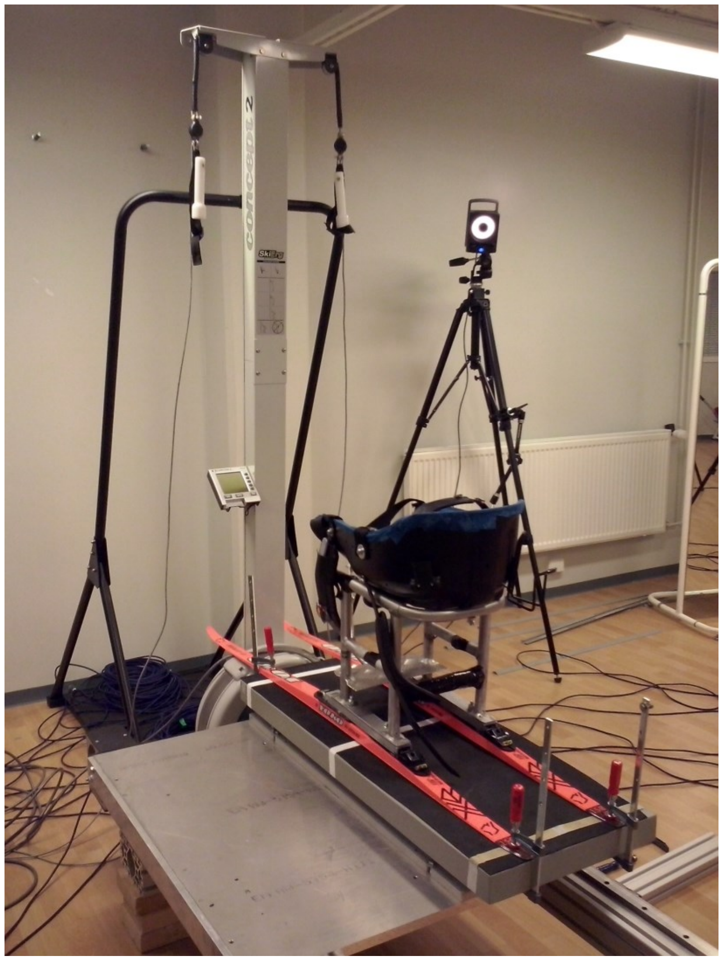

Figure 2. Cycle characteristic and kinematic variables. (A) On generated force, the start and end of the poling phase were identified to calculate cycle phases. On trunk angle, maximal backward and forward inclinations were used to calculate trunk range of motion. (B) Trunk maximal backward (TB) and forward (TF) inclinations were considered positive when the trunk moved anterior the vertical plane (0 deg) and negative when it moved posterior. Trunk range of motion (ROM) was calculated as a difference between TF and TB.

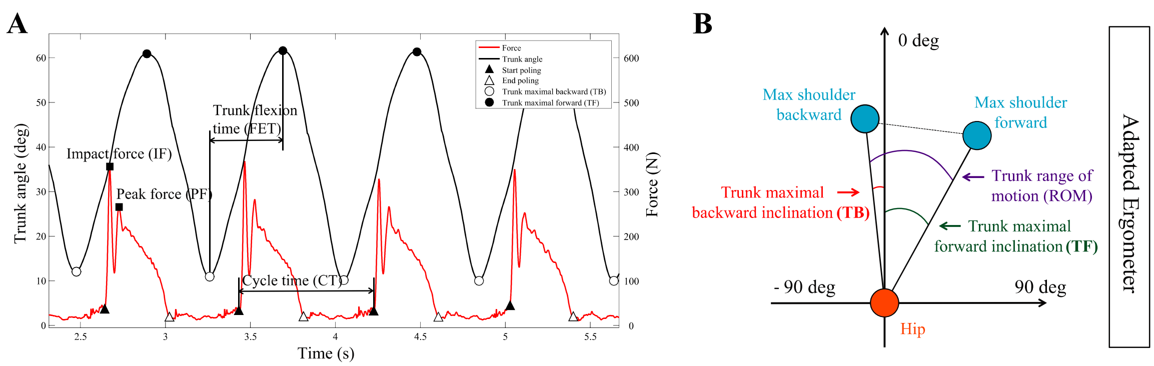

Figure 3. Mean silhouette and principal component analysis. (A) Number of clusters (k) was defined running k-means with different k=2, 3, and 4 and calculating the mean silhouette for each k. For the analysis, k=3 was chosen because of the peak in mean silhouette. (B) Representation of normalized data in the space of the first two principal components: three groups were visible.

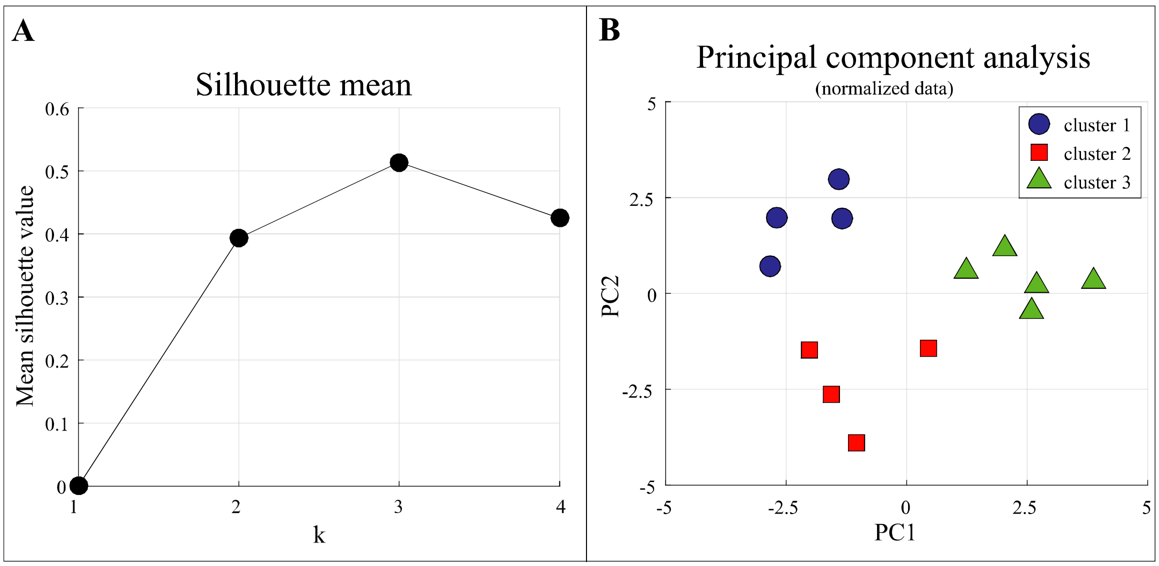

Figure 4. Force and cycle characteristic variables. (A) Impact force (IF), peak force (PF), average force (aF), and impulse of force (iF) were represented as mean ± standard deviation for the three clusters. Cluster_3 showed higher PF, aF, and iF than cluster_1. (B) Cycle time (CT) and relative poling time (rPT) were reported as mean ± standard deviation for the three clusters. Cluster_1 showed longer CT than cluster_2. Statistical difference between clusters are reported, * = $p < 0.05$, ** = $p < 0.01$

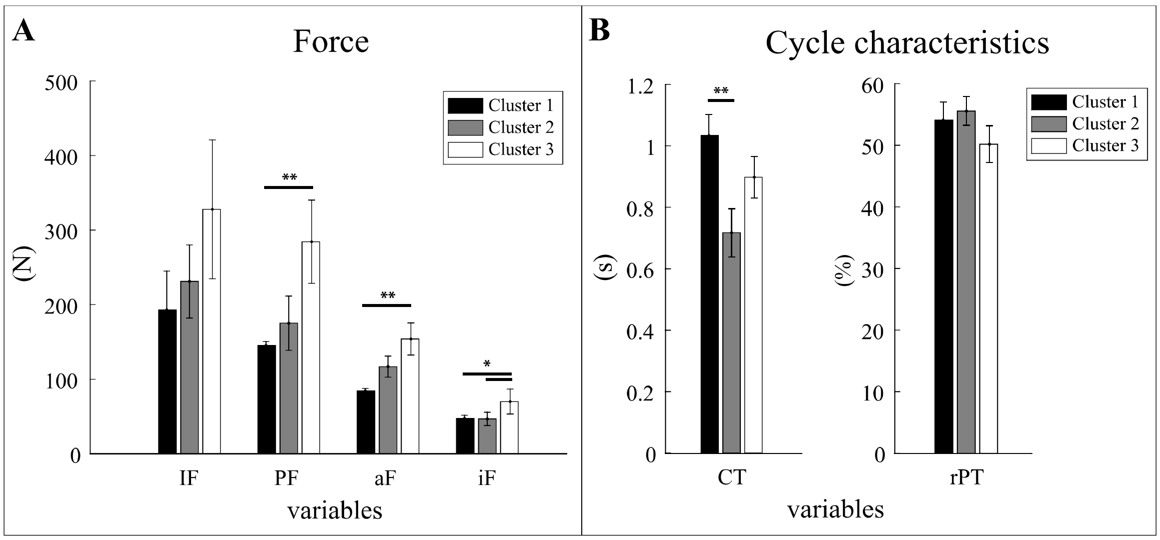

Figure 5. Kinematic variables. (A) Trunk maximal backward inclination (TB), trunk maximal forward inclination (TF), and trunk range of motion (ROM) were reported as mean ± standard deviation for the three clusters. Cluster_1 showed negative TB compared to cluster_2 and cluster_3. Cluster_2 showed lower ROM compared to cluster_1 and cluster_3. (B) The beginning (BT) and end (ET) of the trunk movement and the time to complete trunk flexion (FET) were represented as mean ± standard deviation for the three clusters. Cluster_1 had greater BT than cluster_2. Cluster_2 showed lower FET than cluster_1 and cluster_3. Statistical difference between clusters are reported, * = $p < 0.05$

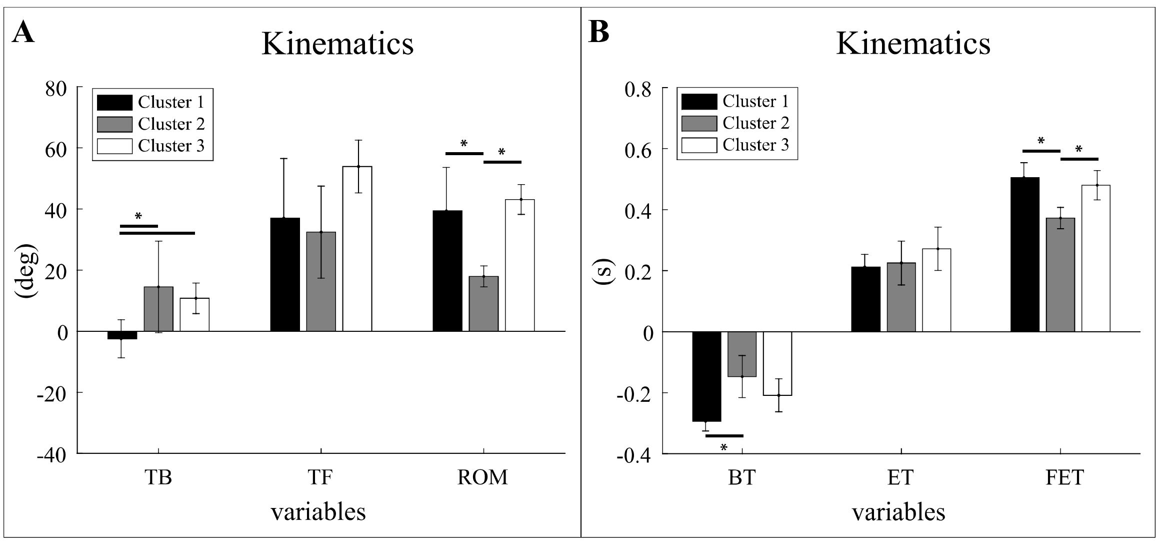

Table 1. Maximal speed, force, cycle characteristics, and kinematic results. For each participant and variable, the mean (standard deviation) and median (interquartile range) among the seven poling cycles are reported in the first and in the second row respectively. The coefficient of variability of each variable is reported in the last column.

Variables	Participants and Classes													Coefficient of variability
	1	2	3	4	5	6	7	8	9	10	11	12	13	
	10	10.5	11	11	11	11.5	11.5	11.5	11.5	12	12	12	12	
Speed (m/s)	3.8	3.3	3.6	3.9	4.5	4.6	4.4	4.8	5.4	4.3	4.6	3.6	5	14.7%
IF (N)	174.0 (21.3)	255.9 (14.3)	132.9 (7.7)	234.5 (25.4)	207.2 (15.9)	298.1 (13.9)	319.0 (16.9)	322.8 (33.7)	446.6 (15.3)	184.8 (19.9)	188.9 (7.7)	208.4 (12.9)	361.9 (23.4)	34.6%
	182.7 (36.2)	252.1 (18.0)	131.3 (5.4)	226.4 (31.9)	210.2 (24.3)	302.7 (24.4)	320.6 (27.3)	321.9 (54.4)	450.0 (15.9)	187.4 (28.2)	191.2 (14.6)	207.9 (23.1)	361.7 (21.1)	
PF (N)	145.1 (7.9)	138.1 (7.9)	150.3 (10.8)	152.7 (11.3)	153.1 (3.7)	228.9 (3.6)	251.1 (13.2)	284.7 (17.0)	379.3 (34.7)	165.8 (8.0)	238.9 (5.6)	147.5 (6.7)	267.8 (9.9)	35.6%
	146.1 (7.4)	139.2 (12.9)	150.7 (14.2)	152.8 (21.6)	153.6 (3.0)	229.1 (3.0)	254.8 (12.9)	281.6 (17.6)	382.8 (44.7)	165.7 (16.0)	240.5 (8.8)	147.5 (10.6)	267.2 (9.3)	
aF (N)	85.2 (3.0)	88.3 (9.0)	80.3 (3.4)	108.8 (6.6)	116.4 (2.6)	137.0 (6.5)	131.1 (3.1)	153.3 (2.7)	188.5 (20.9)	105.5 (3.5)	142.7 (1.9)	83.6 (2.8)	154.1 (3.4)	27.5%
	84.9 (4.5)	85.8 (9.0)	80.5 (4.0)	110.8 (9.5)	115.8 (4.6)	135.3 (9.4)	131.5 (4.3)	153.5 (3.3)	181.4 (18.9)	105.1 (4.7)	143.0 (1.1)	84.6 (1.5)	153.7 (5.5)	
iF (Ns)	48.7 (2.0)	52.4 (14.6)	46.0 (2.5)	42.6 (4.8)	47.1 (2.4)	59.1 (5.8)	59.5 (2.4)	63.7 (2.6)	99.6 (15.3)	38.3 (1.5)	65.3 (2.1)	42.2 (1.6)	62.0 (2.3)	28.4%
	48.5 (2.9)	47.4 (18.3)	46.0 (2.3)	43.0 (7.2)	47.0 (4.4)	56.8 (5.0)	60.5 (2.8)	62.5 (4.4)	98.4 (15.1)	37.9 (2.3)	65.5 (2.5)	42.6 (2.4)	61.5 (2.2)	
CT (s)	0.99 (0.02)	1.06 (0.10)	1.12 (0.02)	0.71 (0.04)	0.74 (0.03)	0.80 (0.02)	0.93 (0.02)	0.87 (0.02)	0.96 (0.06)	0.62 (0.01)	0.94 (0.01)	0.97 (0.03)	0.79 (0.01)	16.4%
	0.99 (0.03)	1.02 (0.14)	1.12 (0.02)	0.71 (0.05)	0.74 (0.05)	0.81 (0.02)	0.92 (0.03)	0.87 (0.03)	0.96 (0.06)	0.62 (0.02)	0.94 (0.01)	0.97 (0.05)	0.80 (0.01)	
rPT (%)	57.8 (0.7)	55.1 (9.2)	51.3 (2.0)	54.9 (3.7)	54.8 (2.0)	53.6 (2.7)	49.0 (1.9)	47.5 (1.5)	55.1 (3.9)	58.9 (1.1)	48.5 (1.1)	52.3 (1.4)	50.8 (0.9)	6.6%
	58.1 (0.5)	54.2 (5.3)	50.5 (2.6)	55.4 (3.0)	54.9 (0.6)	52.3 (2.6)	48.8 (1.0)	47.6 (0.5)	55.7 (2.1)	58.8 (1.6)	48.6 (1.0)	52.6 (0.8)	50.5 (0.4)	
TB (deg)	-5.4 (2.1)	-8.5 (0.5)	6.0 (5.0)	19.9 (3.5)	-1.2 (1.4)	6.6 (1.0)	4.9 (1.2)	10.3 (1.8)	8.7 (7.3)	32.7 (1.8)	18.5 (0.9)	-2.0 (2.3)	11.4 (1.7)	144.2%
	-5.4 (2.9)	-8.5 (0.8)	7.7 (8.4)	19.6 (3.0)	-1.1 (1.3)	6.7 (1.8)	5.1 (1.8)	9.8 (3.1)	9.7 (7.2)	32.9 (2.2)	18.8 (1.7)	-2.0 (2.6)	11.5 (2.6)	

TF (deg)	24.4 (1.4)	16.3 (2.0)	56.6 (3.2)	37.5 (2.9)	13.5 (0.8)	29.4 (1.4)	44.0 (1.7)	53.7 (1.5)	46.9 (1.1)	49.4 (1.6)	63.2 (1.6)	50.5 (3.0)	61.8 (2.2)	39.4%
	24.2 (2.5)	16.1 (2.6)	57.1 (5.6)	38.6 (3.4)	13.7 (1.6)	29.4 (1.9)	43.2 (1.2)	53.4 (2.6)	46.8 (1.4)	49.2 (2.4)	63.5 (1.8)	50.1 (4.5)	62.0 (3.3)	
ROM (deg)	29.8 (1.9v	24.8 (2.1)	50.6 (3.7)	17.6 (4.4)	14.7 (2.0)	22.8 (1.1)	39.0 (2.4)	43.3 (1.3)	38.2 (7.4)	16.6 (1.6v	44.6 (2.0)	52.5 (3.7)	50.4 (3.6)	40.4%
	29.8 (3.0)	25.1 (3.7)	50.0 (4.6)	16.8 (5.3)	14.9 (1.6)	23.0 (1.6)	38.1 (3.4)	43.2 (1.1)	37.5 (13.0)	16.2 (2.8)	44.8 (3.4)	52.3 (3.8)	50.9 (4.3)	
BT (s)	-0.28 (0.02)	-0.33 (0.01)	-0.31 (0.03)	-0.15 (0.02)	-0.24 (0.10)	-0.14 (0.01)	-0.20 (0.01)	-0.16 (0.01)	-0.30 (0.02)	-0.07 (0.05)	-0.21 (0.01)	-0.26 (0.02)	-0.17 (0.01)	36.0%
	-0.28 (0.03)	-0.33 (0.02)	-0.30 (0.04)	-0.15 (0.04)	-0.19 (0.02)	-0.14 (0.01)	-0.20 (0.01)	-0.16 (0.01)	-0.29 (0.04)	-0.08 (0.04)	-0.21 (0.03)	-0.26 (0.03)	-0.18 (0.01)	
ET (s)	0.16 (0.04)	0.19 (0.06)	0.24 (0.02)	0.19 (0.03)	0.14 (0.01)	0.28 (0.02)	0.27 (0.01)	0.33 (0.03)	0.17 (0.03)	0.29 (0.02)	0.35 (0.02)	0.25 (0.01)	0.25 (0.01)	27.1%
	0.16 (0.05)	0.18 (0.01)	0.24 (0.03)	0.18 (0.03)	0.15 (0.01)	0.29 (0.03)	0.27 (0.01)	0.32 (0.03)	0.16 (0.05)	0.30 (0.02)	0.34 (0.03)	0.25 (0.02)	0.25 (0.01)	
FET (s)	0.44 (0.06)	0.52 (0.07)	0.56 (0.05)	0.33 (0.04)	0.37 (0.10)	0.42 (0.01)	0.47 (0.01)	0.48 (0.02)	0.46 (0.05)	0.36 (0.05)	0.59 (0.02)	0.50 (0.02)	0.43 (0.01)	15.6%
	0.44 (0.08)	0.51 (0.02)	0.56 (0.09)	0.33 (0.06)	0.34 (0.03)	0.42 (0.02)	0.47 (0.01)	0.48 (0.04)	0.46 (0.11)	0.38 (0.04)	0.56 (0.02)	0.51 (0.03)	0.43 (0.01)	

Notes: Speed: maximal speed (m/s). Force and cycle characteristics: IF (N), impact force; PF (N), peak force; aF (N), average force; iF (Ns), impulse of force; CT (s), cycle time; rPT (%), relative poling time. Kinematic: TB (deg), trunk maximal backward inclination; TF (deg), trunk maximal forward inclination; ROM (deg), trunk range of motion; BT (s) and ET (s), start and end of the trunk movement with respect to the beginning of the poling phase; FET (s), time to complete the trunk flexion movements. Trunk inclinations are positive when athletes moved anterior the vertical plane and negative when they moved posterior. Trunk times are reported positive when trunk movements occurred after the start of the poling phase and negative when it occurred before.

Table 2. External validation: comparison between clusters and real classes. The number of athletes grouped coherently with the actual classification is reported on the main diagonal, whereas precision and sensitivity are reported in the last column and the last row respectively.

	Group_1 (LW10-LW10.5)	Group_2 (LW11)	Group_3 (LW11.5-LW12)	Precision
Cluster_1 (high impact of impairment)	2	1	1	50%
Cluster_2 (middle impact of impairment)	0	2	2	50%
Cluster_3 (low impact of impairment)	0	0	5	100%
Sensitivity	100%	66.7%	62.5%	

Table 3. Variables relevance. The mean ± standard deviation are reported for the three clusters and all variables used in the cluster analysis. Results of Kruskal Wallis test and corresponding effect size for the selected variables are reported. For variables with $p > 0.05$, the effects size was not calculated.

Variable	Cluster_1	Cluster_2	Cluster_3	p-value	Effect size
Speed (m/s)	3.5 ± 0.2	4.3 ± 0.3	4.8 ± 0.4	0.008	0.86
IF (N)	192.8 ± 52.1	231.2 ± 49.0	327.8 ± 93.1	0.07	-
PF (N)	145.3 ± 5.2	175.1 ± 36.4	284.4 ± 55.8	0.005	0.91
aF (N)	84.3 ± 3.3	116.9 ± 14.1	153.9 ± 21.5	0.006	0.88
iF (Ns)	47.3 ± 4.3	46.8 ± 8.9	70.0 ± 16.7	0.01	0.81
CT (s)	1.03 ± 0.07	0.72 ± 0.08	0.90 ± 0.07	0.006	0.88
rPT (%)	54.1 ± 2.9	55.6 ± 2.3	50.2 ± 3.0	0.08	-
TB (deg)	-2.4 ± 6.2	14.5 ± 15.0	10.8 ± 5.0	0.05	0.69
TF (deg)	36.9 ± 19.6	32.4 ± 15.1	53.9 ± 8.6	0.1	-
ROM (deg)	39.4 ± 14.2	17.9 ± 3.4	43.1 ± 4.9	0.02	0.77
BT (s)	-0.29 ± 0.03	-0.15 ± 0.07	-0.21 ± 0.05	0.02	0.76
ET (s)	0.21 ± 0.04	0.22 ± 0.07	0.27 ± 0.07	0.3	-
FET (s)	0.51 ± 0.05	0.37 ± 0.04	0.48 ± 0.05	0.02	0.78

Notes: Speed: maximal speed (m/s). Force and cycle characteristics: IF (N), impact force; PF (N), peak force; aF (N), average force; iF (Ns), impulse of force; CT (s), cycle time; rPT (%), relative poling time. Kinematic: TB (deg), trunk maximal backward inclination; TF (deg), trunk maximal forward inclination; ROM (deg), trunk range of motion; BT (s) and ET (s), start and end of the trunk movement with respect to the beginning of the poling phase; FET (s), time to complete the trunk flexion movements.

Table 4. Variables redundance. Spearman correlation coefficient for all the variables included in the cluster analysis. * Significant correlation at 0.05, ** Significant correlation at 0.01.

	Speed	IF	PF	aF	iF	CT	rPT	TB	TF	ROM	BT	ET	FET
Speed	1.00	**0.64***	**0.93****	**0.96****	**0.74****	-0.44	-0.38	0.52	0.33	0.02	0.39	0.29	-0.19
IF		1.00	**0.68***	**0.77****	**0.64***	-0.20	-0.29	0.12	0.04	0.08	0.16	0.11	-0.10
PF			1.00	**0.91****	**0.71****	-0.39	-0.49	0.57	0.45	0.13	0.41	0.43	-0.09
aF				1.00	**0.82****	-0.40	-0.38	0.47	0.25	-0.02	0.35	0.30	-0.14
iF					1.00	0.16	-0.48	0.09	0.26	0.26	-0.12	0.24	0.35
CT						1.00	-0.05	**-0.67****	0.06	0.57	**-0.86****	-0.20	**0.81****
rPT							1.00	-0.16	**-0.62***	**-0.64***	-0.13	-0.56	-0.48
TB								1.00	0.54	-0.10	**0.71****	0.52	-0.35
TF									1.00	**0.75****	0.14	**0.64***	0.45
ROM										1.00	-0.34	0.31	**0.73****
BT											1.00	0.55	**-0.63***
ET												1.00	0.28
FET													1.00

Notes: Speed: maximal speed (m/s). Force and cycle characteristics: IF (N), impact force; PF (N), peak force; aF (N), average force; iF (Ns), impulse of force; CT (s), cycle time; rPT (%), relative poling time. Kinematic: TB (deg), trunk maximal backward inclination; TF (deg), trunk maximal forward inclination; ROM (deg), trunk range of motion; BT (s) and ET (s), start and end of the trunk movement with respect to the beginning of the poling phase; FET (s), time to complete the trunk flexion movements.