Ph.D. in MECHANICAL ENGINEERING (30th Cycle)

JYU DISSERTATIONS 101

Valeria Rosso

Biomechanics in Paralympic Cross-Country Sit Skiing

Evidence-based Tests for Classification

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HEALTH SCIENCES

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Valeria Rosso
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ABSTRACT

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The International Paralympic Committee required the development of a new evidence-based classification system, by developing measures of performance and measures of impairment. In cross-country (XC) sit skiing, athletes compete sitting on a ski-ski and generate propulsion with upper limbs and, when possible, trunk movements. The purpose of this thesis was to develop a measure of performance and a measure of impairment of trunk that can be used for classification purposes. Firstly, biomechanics (maximal speed, generated force, cycle characteristics, and muscle activation) of skiing on snow and on an ergometer was compared (article I). The assessment of biomechanics and of trunk kinematics on the ergometer was used to develop a measure of performance (article III). Secondly, trunk kinematics during balance test performed with personal sit-ski was used to propose a measure of impairment (article II). During the process, a need for a new specific testing device was identified. A new mechanical system was designed to quantify trunk kinematics and strength respectively during balance and strength tests. Collected results allowed developing a measure of trunk impairment that can be used for classification purposes (article IV). A total of 24 elite XC sit skiers were recruited. Two separate investigations were completed during the World Cup: (1) performance tests were conducted on snow and in a laboratory (articles I, III) and balance tests with personal sit-ski were performed in the laboratory (article II); (2) strength and balance tests with the new testing device were performed in the laboratory (article IV). In addition, a cluster analysis was applied to divide athletes according to their performance and impairment and to identify the minimum set of parameters that allowed for athletes' clustering. Pushing cycle results showed that generated force or maximal speed, together with cycle time, trunk maximal backward inclination, and trunk range of motion allowed clustering athletes according to their performance (articles I, III). Results of balance test and strength test respectively showed that trunk range of motion and generated force with and without a backrest allowed clustering athletes according to their impairment (articles II, IV). In conclusion, the proposed tests and the identified set of parameters may be considered for the XC sit skiing new evidence-based classification system.

Keywords: performance, adapted ergometer, impairment, strength, trunk control, spinal cord injury

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To the persons that, seeing the sculpture in a marble block, have the patience to shape every single detail with passion

Torino, 06.06.2019
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LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following 4 original articles, which are referred in the text using Romans numbers.

Original articles:

I. Rosso, V., Gastaldi, L., Rapp, W., Lindinger, S., Vanlandewijck, Y. & Linnamo, V. 2017. Biomechanics of simulated versus natural cross-country sit skiing. Journal of Electromyography and Kinesiology, 32, 15-21.

II. Rosso, V., Gastaldi, L., Rapp, W., Lindinger, S., Vanlandewijck, Y., Äyrämö, S. & Linnamo, V. 2019. Balance perturbations as a measurement tool for trunk impairment in cross-country sit skiing. Adapted Physical Activity Quarterly, 36(1), 61-76.

III. Rosso, V., Linnamo, V., Rapp, W., Lindinger, S., Karczewska-Lindinger, M., Vanlandewijck, Y. & Gastaldi, L. 2019. Simulated skiing as a measurement tool for performance in cross-country sit skiing. Journal of Sports Engineering and Technology, doi: 10.1177/1754337119843415

IV. Rosso, V., Linnamo, V., Vanlandewijck, Y., Rapp, W., Fasel, B., Karczewska-Lindinger, M., Lindinger, S. & Gastaldi, L. Towards evidence-based classification in cross-country sit skiing: measures of impairment of strength and trunk control. Submitted for publication.

In addition to the 4 original articles, 3 conference proceedings Scopus indexed were published and the main results are presented in the thesis.

Valeria Rosso, together with the co-authors, has designed the study purposes, has prepared the test set up, and has done the data collections. Valeria Rosso has had the main responsibility of the data analysis and statistical analyses of all the four articles and the three conference proceedings. These four original articles (I-IV) and the three conference proceedings have been written by Valeria Rosso, taking into account co-authors comments.

ABBREVIATIONS

aF	average force
BT	beginning of trunk movement with respect to the poling phase
CT	cycle time
DLY1	delay between ski-ski and shoulder acceleration onset
DLY2	delay between shoulder acceleration onset and trunk inversion
EMG	electromyography
Ergo	double poling on the ergometers
ES	Erector Spinae
ET	end of trunk movement with respect to the poling phase
FET	time to complete trunk flexion during the poling phase
ICC	intraclass correlation coefficient
iF	impulse of force
IF	impact force
IPC	International Paralympic Committee
Lat	Latissimus Dorsi
LW	locomotor winter
MVC	maximal voluntary contraction
MVC_p	simulated poling by pulling ropes
MVC_{wo}	simulated bench press without the back support
MVC_w	simulated bench press with back support
Obl	Obliquus Abdominis
Pec	Pectoralis
Pert	unpredictable balance perturbations
PF	peak force
PFa_{wo}	peak of anterior force in MVC_{wo}
PFa_w	peak anterior force in MVC_w
PFp_w	peak posterior force in MVC_w
PF_p	average between peak left and peak right pulling force in MVC_p
$\frac{PFa_{wo}}{PFa_w}$	ratio between peak of anterior force in MVC_{wo} and MVC_w
PT	poling time
RT	recovery time
RecAb	Rectus Abdominis
rPT	relative poling time
SEM	standard error of measurement
TB	trunk maximal backward inclination
TF	trunk maximal forward inclination

Tri	Triceps
$Trunk_{rest}$	trunk angle at rest before the first stimulus
$Trunk_{rom\text{-}pert}$	trunk range of motion at the inversion in balance test
$Trunk_{rom\text{-}poling}$	trunk range of motion during the poling phase
$Trunk_{150}$	trunk range of motion 150 ms after shoulder acceleration
TtI	time to impact
TtP	time to peak
XC	cross-country

FIGURES

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CONTENTS

1 INTRODUCTION

Paralympic cross-country (XC) skiing was introduced for the first time at the 1976 inaugural Winter Paralympic Games in Örnsköldsvik, Sweden. In this event, only amputee and athletes with visual impairment competed in two events: Alpine Skiing and Cross-Country Skiing (Vanlandewijck & Thompson 2011). Since the first event in Örnsköldvik in 1976, the number of participating nations and athletes, the number of medal events, and the included sport disciplines have increased making PyeongChang 2018 the greatest Paralympic Winter Games event in terms of size (International Paralympic Committee 2018a). Considering the number of participating nations, steady growth has occurred since 1976, almost tripling the number of nations in the last Games compared to the first. The number of sports has also increased, starting with Alpine Skiing and XC skiing in Örnsköldsvik 1976 and peaking with six sports in PyeongChang 2018. The number of medal events and the number of participating athletes are a critical point for Paralympic Winter Games due to the frequent changes that have been made throughout history in the number of categories of athletes and medals criteria assignment.

Today, athletes are divided in three categories: standing, sitting, and visual impaired. To ensure that competitions are fair and equal and the impairment effects on performance are minimized, in each category athletes are divided into classes according to their personal functional limitations (Vanlandewijck, 2006, Tweedy & Vanlandewijck 2011). All the classes of one category compete in the same event and the final time is adjusted by a percentage based on the estimated impact of the disability to the results. Therefore, only two medals are assigned to each category: one for male and one for female. This process is named classification (Van de Vliet 2013) and is one of the main challenging aspects of Paralympics.

Classification is sport-specific because impairment affects the ability to perform in different sports to a different extent. The classification process is conducted by a classification panel, a group of individuals authorized and certified by the International Paralympic Committee (IPC) Nordic Skiing

(International Paralympic Committee 2018b). This process is based both on medical criteria and on observation of expert classifiers, who conduct a physical assessment to establish if an athlete has an eligible impairment that meets the relevant minimum disability criteria and a technical assessment to perform certain tests to evaluate athletes' sitting ability and trunk stability (Pernot et al. 2011). In the particular case of XC sit skiers, athletes have impairment at lower limbs, but have different level of ability to control the trunk. Therefore, they are grouped in five different classes from LW12 (athletes who can perfectly control trunk muscles) to LW10 (who have not abdominals and trunk extensor functional activities), with three intermediate categories: LW11.5, LW11, and LW10.5 (International Paralympic Committee 2018b).

As it is now, the classification process is specific for each sport since it is governed by the different International Federations and it may be subjective since this process relies on the classifiers opinion. In order to improve the classification, the IPC requires a transparent and high standardized process across sports; therefore, it entails a process which is based on scientific evidence (International Paralympic Committee 2007). In this framework, the aim of the current Ph.D. project was to contribute to the development of an evidence-based classification process for XC sit skiing. In order to achieve the goal, measures of performance and measures of impairment were proposed and validated. Since it is desired that these measures would become a standard in the XC sit skiing classification process, controlled testing conditions, appropriate protocols, and suitable equipment have to be defined. To identify the measures of performance, biomechanics of athletes while skiing on snow was compared to athletes' biomechanics during simulated action of poling on an adapted ergometer for XC sit skiing. Because of the high biomechanical similarities between the two skiing conditions, a testing protocol consisting of simulated action of double poling on the ergometer with personal sit-ski was proposed and evaluated as measure of XC sit skiers' performance. The measures of impairment were focused on the trunk because of its key role in sitting sports, such as XC sit skiing. To assess impairment of trunk control, unpredictable balance perturbations while athletes were seated on their personal sit-ski were proposed and tested. With the purpose to have measures of impairment that can be used for the purpose of classification, a new testing device was designed. The new testing device was suitable for athletes with different impact of impairments and allowed testing both impairment of trunk strength and impairment of trunk control. A second protocol, consisting of maximal voluntary contractions and unpredictable balance perturbations, was proposed and evaluated as a measure of impairment of trunk strength and trunk control respectively.

2 REVIEW OF THE LITERATURE

2.1 Classification

Before competing, Paralympic athletes undergo a process called classification, which aims to group athletes in classes according to their impairment and to the impact of impairment on performance (Van de Vliet 2013). Therefore, classification has a fundamental role since it defines who is and who is not eligible to compete and how to group athletes in order to guarantee that the success is due to athletes' ability and not because of lower disability (International Paralympic Committee 2015).

2.1.1 History of classification

Formerly, adapted sports were prescribed by medical specialists of Stoke Mandeville hospital as a form of rehabilitation because of their good effects on physical fitness and psychology of patients (Tweedy & Howe 2011). In the Stoke Mandeville Games and then in first editions of the Paralympic Games, athletes competed divided in groups according to their disabilities: spinal cord injury, amputation, brain impairment, and other neurological or orthopedic conditions (Vanlandewijck & Thompson 2011). Once an athlete received a class, based on medical diagnosis, he/she would compete in this class in all the different sports. This form of classification was called medically based because it followed the structure of a rehabilitation hospital and it was uniquely based on medical diagnosis (Tweedy & Vanlandewijck 2011).

With the increasing participation in these events, the Paralympic Movement has changed, leading to a form of sport that is independent and no longer an extension of rehabilitation (Vanlandewijck & Thompson 2011). In this framework, also the classification process changed, becoming a functional classification system. In functional classification, athletes are grouped according to the extent of their impairment on performance. Because the same impairment may impact differently on two different sport disciplines, functional classification is sport-specific. To date, most sports adopt this kind of classification system. The only exception is for the International Blind Sports Federation, which still adopts a medically based classification system (Tweedy & Vanlandewijck 2011).

Although the advantage to be sport-specific, current classification is performed by a small panel of expert classifiers rather than on empirical evidence, this leads to two threats to the validity that are related to the measurement of impairment and to the dependence of classes allocation on expert opinion for decision-making (Tweedy & Vanlandewijck 2011). For example, athletes with a complex situation of impairment belong to the first case of threats, while athletes with more than one impairment type belong to the second one. In both cases, athletes can be classified in more than one class at the same time. To overcome these difficulties, the IPC mandates the development of an evidence-based classification system. Guidelines for the development of this new classification system are described in the document "Classification Code and International Standards" (International Paralympic Committee 2007) and following (Tweedy & Vanlandewijck 2011).

2.1.2 Current classification system

At present, functional classification is the classification system used by the majority of sports. Functional classification is conducted by a panel of expert classifiers on medical diagnoses and functional tests. It is composed of three steps: (i) evaluate if the athlete has an eligible impairment, (ii) assess if the eligible impairment meets the minimum impairment criteria, (iii) identify the class which most describe athlete's impairment limitation (International Paralympic Committee 2015). Since it is sport-specific, each sport defines its eligible impairments, minimum impairment criteria, and classes. To date, 10 eligible impairments are accepted by the IPC: impaired muscle power, impaired range of motion, limb deficiency, leg length difference, short stature, hypertonia, ataxia, athetosis, and visual and intellectual impairment. For each sport, those impairments that provide limitations for the sport performance are identified. In cross-country skiing, the following impairments are eligible: impaired muscle power, impaired range of motion, limb deficiency, leg length difference, hypertonia, ataxia, athetosis, and visual impairment (International Paralympic Committee 2017a). Then, there are sports such as athletics that include all impairments and others, such as goalball, which are specific to one impairment only (International Paralympic Committee 2015). A definition of the eligible physical impairment for cross-country skiing is reported in Table 1. For each impairment, there are rules that define how severe it has to be in order to consider the athlete eligible. This is defined as minimum impairment criteria. For cross-country skiing, minimum impairment criteria for all the physical eligible impairments are described in the World Para Nordic Skiing Classification Rules and Regulations document (International Paralympic Committee 2017a).

TABLE 1 Impairment definition for physical eligible impairments

Physical eligible impairments	Impairment definition
Impaired muscle power	Athletes with Impaired Muscle Power have a Health Condition that either reduces or eliminates their ability to voluntarily contract their muscles in order to move or to generate force
Impaired range of motion	Athletes with Impaired Passive Range of Movement have a restriction or a lack of passive movement in one or more joints
Limb deficiency	Athletes with Limb Deficiency have total or partial absence of bones or joints as a consequence of trauma
Leg length difference	Athletes with Leg Length Difference have a difference in the length of their legs
Hypertonia	Athletes with hypertonia have an increase in muscle tone and a reduced ability of a muscle to stretch caused by damage to the central nervous system
Ataxia	Athletes with Ataxia have uncoordinated movements caused by damage to the central nervous system
Athetosis	Athletes with Athetosis have continual slow involuntary movements

Once an athlete has been judged to be eligible to compete, he / she is allocated in a specific class. Each class includes athletes with similar impact of impairment on performance, but not necessarily athletes with the same impairment. Classes are named “Locomotor Winter” (LW). Number of classes varies among sports; however, there are some sports, such as Para Ice Hockey, which has only one class (International Paralympic Committee 2017a). In cross-country skiing, there are 8 classes for athletes with physical impairment who compete standing: LW2-LW4 for athletes with impairment at the lower limbs, LW5-LW8 for athletes with impairment at the upper limbs, and LW9 for athletes with combined impairment at the lower and upper limbs. There are 5 classes for athletes who compete sitting, from LW10 (high impact of impairment) increasing to half a point to LW12 (low impact of impairment). Finally, there are 3 classes for athletes with visual impairment (B1-B3). A detailed description of categories and classes for XC sit skiing is reported in Figure 1.

Standing	**LW2-LW4:** Athletes with impairment at the lower limbs	**LW2:** Skiers with impairment affecting one leg (i.e. an amputation above the knee). They will use a prosthesis and ski with two skis. **LW3:** Skiers with an impairment in both legs (i.e. muscle weakness in both legs). **LW4:** Skiers with impairments in the lower parts of one leg, but with less impact on skiing compared to LW2 (i.e. amputations above the ankle or loss of muscle control in one leg).
	LW5-LW8: Athletes with impairment at the upper limbs	**LW 5/7:** Skiers with impairments in both arms that prohibit them to use ski poles (i.e. athletes with no hands or cannot grip firmly). They ski without poles. **LW6:** Skiers with impairment in one arm (i.e. a missing arm above the elbow). This arm is fixed to the body and may not be used during the races; whereas the other hand they use a ski pole. **LW8:** Skiers with impairments affecting one arm (i.e. no elbow or finger flexion allowed on one side or they have a below elbow amputation). They will use one ski pole only.
	LW9: Athletes with combined impairment at the lower and upper limbs	Skiers with mild coordination problems in all extremities or amputations affecting at one arm and one leg. Depending on their abilities, they will ski with one or two ski poles.
Sitting		**LW10:** Skiers with an impairment that limits their leg and trunk function. They would be unable to sit without supporting himself or herself with the arms, (i.e. due to paraplegia).
		LW10.5: Skiers in this sport class also have limited trunk control, but they can keep their sitting balance when not moving sideways.
		LW11: Skiers have a leg impairment and fair trunk control, which enables them to balance even when moving sideways.
		LW11.5: Skiers in this sport class have near to normal trunk control.
		LW12: Skiers in this sport class have impairments similar to those described for the sport classes LW2-4: They have a leg impairment, but normal trunk control. They are eligible to compete standing or sitting and can chose their preferred way of skiing at their first Classification.
Visual impairment		**B1:** Skiers in this sport class are either blind or have very low visual acuity. By way of explanation, their level of visual acuity is such that the athlete cannot recognize the letter "E" (15x15cm in size) from a distance of 25cm. During the race they wear eyeshades.
		B2: This sport class profile includes athletes with a higher visual acuity than athletes competing in the B1 class, but they are unable to recognize the letter "E" from a distance of 4m. Moreover, athletes with a visual field of less than 10 degrees diameter are eligible for this sport class.
		B3: The B3 sport class profile describes the least severe visual impairment eligible for Nordic Skiing. Eligible athletes either have a restricted visual field of less than 40 deg diameter or a low visual acuity.

FIGURE 1 Description of Cross-country skiing categories and classes (https://www.paralympic.org/nordic-skiing/rules-and-regulations/classification)

2.1.3 Towards an evidence-based classification system

In many sports, research has already started to move towards an evidence-based classification according to principles described by the IPC in the " IPC Classification Code and International Standards" (International Paralympic Committee 2007) and following documents (Tweedy & Vanlandewijck, 2011, Tweedy, Mann, & Vanlandewijck 2016). It is stated that evidence-based classification has 3 requirements:

(I) to develop measures of impairment,

(II) to develop standardized and sport-specific measures of performance determinants,

(III) to assess the relative strength between measures of impairment and sport-specific measures of performance determinants (Tweedy, Beckman, & Connick 2014, Tweedy et al. 2016).

The main characteristics of each requirement are the following:

(I) Measures of impairment: in order to be used for classification purposes, measures of impairment should be impairment specific (measure effect of one impairment type without influence of other impairments), parsimonious (smallest number of measures that account for greatest performance variance), reliable, precise, quantitative, ratio scaled, and training resistant (Tweedy et al. 2016). Ten are the eligible impairment that should be assessed: impaired muscle power, impaired range of motion, hypertonia, ataxia, athetosis, limb deficiency, leg length difference, short stature, vision impairment, and intellectual impairment. Overall, physical impairment can be summarized in three groups: impairment of strength, impairment of range of motion, and impairment of coordination. Impairment of strength is the most studied since it is fundamental in 16 out of the 27 Paralympic sports (Beckman, Connick, & Tweedy 2017).

(II) Sport-specific measures of performance: To be sport-specific, performance measures should be highly predictive of the overall performance of a sport, sensitive to differences in the measures of impairment, and minimize the effect of factors that are not classified (Tweedy et al. 2016). For each activity that is predictive of overall performance, a single test should be proposed. In addition to specific tests also a rigorous and reproducible protocol must be developed (Tweedy et al. 2016). Since the protocol must be the same for all athletes with an eligible impairment, it should be the least restrictive as possible.

(III) Relationship between impairment and performance: The stronger this association is, the more suitable is the measure of impairment for the evidence-based classification in this sport (Tweedy et al. 2016). Once the relationship between measures of impairment and measures of performance is assessed, it is possible to create a classification system that has a method for determining minimum impairment criteria, number of classes, and method for allocating classes, which is based on scientific evidence.

Some studies concerning the development of an evidence-based classification for athletes with physical impairment have already been conducted in different sports. IPC Athletics has required great attention (Tweedy & Bourke 2009), with specific scientific research on the different disciplines. In particular, physical impairment and its effect on performance have been evaluated in wheelchair racing (Vanlandewijck, Verellen, Beckman, Connick, & Tweedy 2011, Vanlandewijck, Verellen, & Tweedy 2011, Connick et al. 2017), running (Beckman & Tweedy 2009), and throwing (Frossard, 2012, Burkett et al. 2017, Hyde et al. 2017). Among sitting sports, wheelchair rugby has obtained a good outcome investigating measures for trunk impairment of strength, range of motion, and coordination (Altmann, Groen, Van Limbeek, Vanlandewijck, & Keijsers 2013). In this sport also the relationship impairment-performance was assessed (Altmann et al. 2017, Altmann, Groen, Hart, Vanlandewijck, & Keijsers 2018). For the first time, attention was also given to athletes' priorities with regard to classification (Altmann, van Limbeek, Hart, & Vanlandewijck 2014). Recently, also Para swimming has been of matters of interest (Burkett et al. 2018) evaluating impairment of range of motion (Nicholson et al. 2018), limb deficiency (Hogarth, Payton, Van de Vliet, Connick, & Burkett 2018), and strength (Hogarth et al. 2018).

Due to its importance in the majority of sports, measures of impairment of strength have been the most studied, pointing out general suggestions applicable for all sports. The literature suggests that isometric contractions are identified as the most suitable to assess impairment of strength because in this condition muscles are able to generate the maximal level of force (Cormie, McGuigan, & Newton 2011). In addition, the literature highlights the fact that the measures should be: multi-joint to include all key muscles involved to enhance the validity of the measure (Tweedy et al. 2014) and training resistance since the weaker the relationship is between strength and performance the more suitable the test is (Beckman et al. 2017). In accordance with these guidelines, a novel strength test battery for upper and lower limbs was proposed (Beckman, Newcombe, Vanlandewijck, Connick, & Tweedy 2014). These tests, being multi-joint, were parsimonious and comprehensive because they assess the majority of muscles that span the involved joints reducing the number of tests needed.

2.2 Para cross-country skiing

Paralympic XC skiing is the adapted version of XC skiing for athletes with disabilities. There are three categories of disabilities included in this sport: standing, sitting, and visual impaired. Standing athletes have impairment at upper limbs or lower limbs (such as amputations), but still ski standing using a pair of skis similar to the ones used by able bodied athletes. Sitting athletes have impairment at the lower limbs that do not allow them to ski standing and they have different ability to control trunk. Sitting athletes compete using a sit-ski mounted on a pair of regular XC skis (Figure 2). Athletes with visual impairment have limited vision or are blind; therefore compete with a guide. Since they do not have physical impairment, they can ski using a pair of skis that can also be used by able bodied athletes. Both male and female athletes can participate in short, middle, and long distances events.

FIGURE 2 Cross-country sit skiing (https://www.paralympic.org/news-5125)

2.2.1 Double poling

Independently from their impairment, XC sit athletes ski sitting on a sit-ski and obtain propulsion by pushing synchronously a pair of poles in a technique called double poling (Rapp, Lappi, Lindinger, Ohtonen, & Linnamo 2014). To generate propulsion, the poles are pushed by shoulder and arm muscles and it is increased using trunk flexion-extension movements. Poling cycle (Figure 3) is composed of a poling phase in which force is exerted while poles are in contact with the ground and a recovery phase in which force is negligible since it involves arms and poles swing forward in preparation for the following poling phase (Smith, Fewster, & Braudt 1996). Poling time and recovery time are respectively the duration of the poling phase and the recovery phase.

Many studies have been conducted to assess physiology, biomechanics, and muscle activation of double poling technique performed by able bodied athletes, e.g. (Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller 2005, Holmberg, Lindinger, Stöggl, Björklund, & Müller 2006, Bojsen-Møller et al. 2010, Pellegrini et al. 2013, Zoppirolli, Pellegrini, Bortolan, & Schena 2015). Double poling technique is usually used in flat or moderate slope when high speed is reached while other techniques are preferred for steeper slope (Pellegrini et al. 2013). Nowadays, however, some athletes use double poling throughout even longer races. Double poling is the technique with the highest level of force generated through the poles and the lowest cost of transport (Pellegrini et al. 2013). Concerning the generation of force in able bodied athletes, an initial peak occurred when the poles tip impact with the ground and it is followed by a second active force peak, which was higher and is associated to impulse force for propulsion (Holmberg et al. 2005). Double poling is mostly an upper body exercise with a defined muscles coordination pattern. Core muscles (Rectus Abdominis and Obliquus), hip flexors (Rectus Femoris), shoulder extensors (Pectoralis, Latissimus, Deltoids, and Teres Major), and elbow extensor (Triceps) are mostly activated during the first half of the poling phase; whereas lower body extensors (Gluteus and Biceps Femoris) are used to keep the balance during trunk flexion movements (Holmberg et al. 2005, Bojsen-Møller et al. 2010). Even though these results are not directly transferable to athletes with physical impairment because of their lack in core and lower limbs muscles, they may be used as a reference when double poling of XC sit skiers is evaluated.

Limited literature exists concerning the evaluation of double poling technique performed on snow by athletes with physical impairment. Skiing strategy usually adopted by sit skiers is a sort of “all-out” performance in which athletes attempted to keep speed as high as possible during the whole race, from the start to the end (Bernardi & Schena 2011). The use of “all-out” strategy led, however, to fatigue during the race and speed decreases from the first to the last lap of the race in both flat and uphill terrains (Bernardi et al. 2013). Performance variation during a race was pointed out also by the correlation between speed and cycle length. These findings were corroborated by an increase in duty cycle that, reducing time for recovery, leads to more fatigue between the first and the last lap in flat terrain (Bernardi et al. 2013). Flat terrain showed also longer cycle duration and greater pole inclination than uphill terrain; whereas no differences were found in trunk inclination when the poles tip impact with the ground (Bernardi et al. 2013). However, trunk inclination showed an inverse correlation with cycle length and speed, suggesting that trunk inclination is used to compensate for performance reduction (Bernardi et al. 2013). Concerning the physiology measured during field test, higher values of heart rate, oxygen uptake, and blood lactate were found for cross-country sit skiing compared to indoor sports (wheelchair basketball or wheelchair tennis), especially towards the end of a race (Bernardi et al. 2010). In laboratory test (maximal incremental arm cranking test), cross-country sit skiers showed higher oxygen uptake compared to other winter sport (alpine skiing and Para ice hockey) (Bernardi et al. 2012). In contrast, cross-country sit skiers showed lower oxygen uptake than Paralympic standing skiers during 3-minutes trial at the ergometer (Bhambhani et al. 2012).

Double poling kinematics of athletes with different impact of impairment were also evaluated (Gastaldi, Pastorelli, & Frassinelli 2012, Gastaldi, Pastorelli, & Frassinelli 2013, Gastaldi, Mauro, & Pastorelli 2016). Independently from impairment, all athletes started the poling phase with wrist joints at the maximum elevation (Gastaldi et al. 2013). However, at the end of the poling phase, greater wrist joints extension with respect to the hip was reached by athletes with low impact of impairment (LW12) compared to athletes with high impact of impairment (LW10 and LW11) (Gastaldi et al. 2012). During the poling phase, athletes with trunk control ability performed trunk flexion and extension movements using core muscles (as able bodied athletes); whereas those with limited or absent abdominal muscles control perform trunk flexion taking advance of gravity force and trunk extension by compensation mechanisms, which involve head, arms, and upper trunk inertia (Gastaldi et al. 2012). Especially, athletes LW10 used a second mechanism to increase propulsion: at the very beginning of the poling phase (when the poles are not yet in contact with the ground), inertial effects due to a quick lowering of both arms was used to increase propulsive force; thereby the sledge had a positive acceleration (Gastaldi et al. 2016). Compared to athletes with absent trunk control (LW10) or complete trunk control but bilateral amputation, athletes with partial (LW11) to full (LW12) trunk control had greater trunk range of motion during the poling phase (Gastaldi et al. 2012). Those athletes took advantage from greater trunk range of motion since it allows shoulder and elbow not to work in an extreme position, thus to generate higher propulsive force limiting fatigue (Gastaldi et al. 2012).

2.2.2 Skiing on snow vs simulated action of poling on an ergometer

To test athletes skiing on snow and to obtain accurate and repeatable results is demanding due to varying environmental conditions, such as temperature, humidity, and track profiles. Therefore, it became necessary to identify standardized procedures, which can be conducted in a controlled environment, such as a laboratory. Previous studies have assessed able bodied athletes biomechanics and physiology during roller skiing on a large treadmill (Holmberg et al. 2005, Holmberg et al. 2006, Stöggl, Björklund, & Holmberg 2013, Pellegrini et al. 2013). Other than a treadmill, an ergometer was used for training able bodied athletes (Nilsson, Holmberg, Tveit, & Hallén 2004, Alsobrook & Heil 2009). The ergometer showed good reliability for power output and peak oxygen uptake and good validity for monitoring performance compared to skiing on snow (Holmberg & Nilsson 2008).

Biomechanics of able bodied athletes during simulated action of poling on an ergometer was evaluated in comparison to skiing on snow at maximal and submaximal speed (Halonen et al. 2014). Skiing at the maximum speed, longer cycle time and poling time, but lower cycle length were found during simulated action of poling on the ergometer than skiing on snow. When submaximal speeds were used, longer cycle time and shorter cycle length on the ergometer occurred compared to snow (Halonen et al. 2014). Higher impulse of force was generated on the ergometer compared to skiing on snow at maximal speed; however, no differences were found in peak force. Nevertheless, when athletes were skiing at slow speed, lower peak force was found on the ergometer than skiing on snow (Halonen et al. 2014). No differences in Triceps, Pectoralis, and Latissimus muscles activity were observed when skiing at maximal speed; whereas at submaximal speed lower activation for all muscles was found on the ergometer compared to snow. Although Rectus Abdominis was activated earlier on snow than on the ergometer, in both skiing conditions it was activated earlier than the Triceps, which was important for better use of core muscles

(Halonen et al. 2014). The lack of difference in muscle activation at maximum speed together with the absence of difference in peak force suggested similar performance between skiing on snow and simulated action of poling (Halonen et al. 2014).

Concerning the physiology of simulated action of poling on the ergometer and skiing on snow, higher level of blood lactate and heart rate were found in able bodied athletes after ergometer test, compared to skiing on snow (Halonen et al. 2014). Higher heart rate and blood lactate together with higher peak respiratory exchange ratio were also found in athletes with physical impairment during simulated action of poling on the ergometer than skiing on snow (Forbes, Chilibeck, Craven, & Bhambhani 2010). In contrast, no difference in peak oxygen consumption was found between ergometer and snow (Forbes et al. 2010) and a relationship was found in oxygen uptake between field and laboratory test (incremental arm cranking test) (Bernardi et al. 2010). It is suggested that higher cardiorespiratory and metabolic responses in laboratory test may be due to a continuous resistance of the ergometer compared to the intermittent effort during variable slopes in field, which allows for recovery (Forbes et al. 2010). A second reason that leads to a higher response in laboratory can be related to the different temperature between laboratory and field (Forbes et al. 2010).

2.2.3 Effect of sitting position

All XC sit athletes compete sitting on a sit-ski. The sit-ski is composed of a seat mounted on a pair of XC skis by a metallic frame. No spring or flexible parts that can store energy are allowed, all the elements must be rigidly connected to each other (International Paralympic Committee 2017b). In addition, a maximum height between the contact point of the buttock with the seat (including cushion) and the top of the ski is 40 cm (International Paralympic Committee 2017b). During races, athletes' buttock must always remain in contact with the seat, therefore straps of non-flexible material are used to fix athletes' tight and pelvis to the seat (International Paralympic Committee 2017b). In contrast, there are no rules and regulation on sit-ski design; therefore different sitting positions are used by athletes (Figure 3), (Rapp et al. 2014):

(A) long sit: in which athletes' lower limbs are elongated in front, almost extended, and the feet are fixed to the front extremity of the sit-ski (Figure 4-A). Pelvis, thigh, and ankle joints are strapped to the sit-ski.
(B) normal: in which athletes are sitting with hip and knee joints at almost 90 degree and feet almost under the knees (Figure 4-B). Pelvis, thigh, and ankle joints are strapped to the sit-ski.
(C) knee high: in which athletes are sitting with hip joints lower than knee joints and feet are usually aligned with knees (Figure4-C). A backrest can be used to support athlete's back; pelvis, thigh, and ankle joints are strapped to the sit-ski.
(D) kneeling: in which athletes are sitting with hip joints higher than knee joints. Usually, only tights are strapped to the sit-ski leaving the hip joints free to

make flexion and extension movements, but keeping constant contact with the seat.

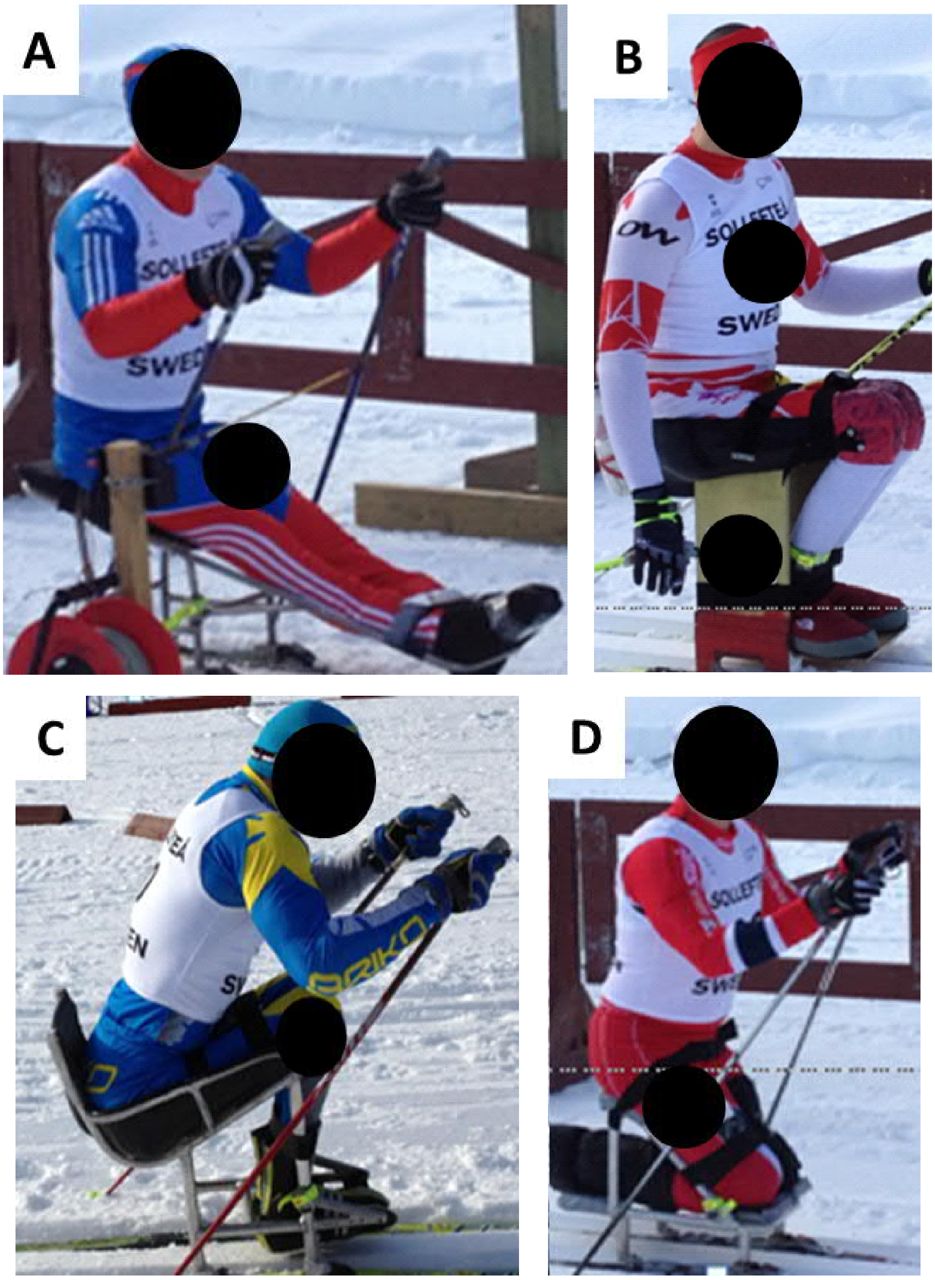


FIGURE 3 Cross-country sitting positions: (A) long sit, (B) normal, (C) knee high, and (D) kneeling (Rapp et al. 2014)

The biomechanics and performance of skiing in the different sitting position have been previously evaluated. When simulated action of poling on the ergometer was performed by able bodied athletes in the four sitting positions, the highest velocity and generated force were obtained for kneeling position whereas the lowest for knee high position (Lappi 2014, Rapp et al. 2014). Higher velocity and generated force for kneeling position compared to knee high position was also found for sit skiers while skiing on snow (Karczewska-Lindinger et al. 2016). In contrast, no difference in the level of force generated by able bodied athletes while poling on the ergometer was found comparing kneeling position provided with a frontal support and knee high position, meaning that the frontal support impeded the performance (Lund Ohlsson & Laaksonen 2017). Concerning the activation of core and propulsive muscles, a difference was found between kneeling and long sit positions (Rapp et al. 2016) and between kneeling and knee high sitting position (Lajunen 2014, Lappi 2014, Lund Ohlsson & Laaksonen 2017), showing higher muscle activity when athletes were sitting in kneeling position compared to the others. Comparing kneeling position provided with a frontal support and knee high position no differences were found in cycle characteristics (Lund Ohlsson & Laaksonen 2017). However, the frontal support may influence these results since previous studies showed lower cycle rate for athletes in kneeling position compared to the knee high while skiing on the ergometer (Lajunen 2014, Hofmann, Ohlsson, Höök, Danvind, & Kersting 2016). To increase the cycle rate in knee high sitting position, athletes reduce recovery time (Lajunen 2014). Trunk range of motion during simulated action of poling on the ergometer using a kneeling position with frontal support for the trunk was smaller than when athletes used a knee high position probably because the trunk fixation keeps shoulders more in position (Lund Ohlsson & Laaksonen 2017). Indeed, greater upper body range of motion was found when kneeling position was used compared to knee high sitting position during simulated action of poling on the ergometer (Lajunen 2014) and on snow (Gastaldi et al. 2012, Schillinger, Rapp, Hakkarainen, Linnamo, & Lindinger 2016). Concerning the physiological response to simulated action of poling on the ergometer at different submaximal intensities, comparison between sitting positions showed higher oxygen consumption, pulmonary ventilation, and blood lactate in knee high sitting position compared to kneeling position; whereas no differences were found in heart rate and respiratory exchange ratio (Lajunen 2014). These results suggest that kneeling position is more economical than knee high sitting position (Lajunen 2014, Rapp et al. 2014).

2.2.4 Role of trunk control

Trunk control plays a key role in propulsion generation and balance on the sit-ski, which are both important in order to achieve maximal skiing performance. The trunk is crucial in propulsion generation and balance by means of three contributions: trunk momentum, trunk position, and trunk stability. Upper body flexion and extension movements can transfer momentum to the poles increasing the propulsive force. Depending on different trunk control ability, athletes transfer momentum to the poles using different strategies. Athletes with more severe trunk impairment (LW10-LW10.5) took advantage of gravity (Gastaldi et al. 2012) and used mostly head and upper limb movements to increase propulsion (Gastaldi et al. 2016). In contrast, athletes with normal or near to normal trunk control (LW11.5-LW12) mainly used trunk movements to increase propulsion. During the recovery phase, those athletes moved their trunk up vertically to bend it down in the following poling phase (Gastaldi et al. 2012). As in XC sit skiing, wheelchair athletes with high mobility severity used a strategy that involves upper limbs and head movements in order to increase propulsion (Cooper 1990). Whereas, wheelchair athletes with high trunk control, use downward trunk movements in push-rim contact preparation in order to transfer higher force and, thereby, to increase propulsion (O'Connor, Robertson, & Cooper 1998).

Trunk position at the beginning of the poling phase highly influences the effectiveness of the trunk momentum (Sanderson & Sommer 1985), especially in terms of direction of force application. A more forward trunk position is associated with greater pole inclination with respect to the ground and, thereby, with greater horizontal pushing force component. Horizontal pushing force is the only component that contributes to generate propulsion (Smith 2002, Holmberg et al. 2005, Gastaldi et al. 2012). During the poling phase, athletes with high trunk control, by bending their trunk more forward, kept the poles close to the ground; whereas athletes with high impact of impairment due to the lack in core muscles kept the trunk and the poles close to vertical (Schillinger et al. 2016). Similarly, wheelchair athletes leaned the trunk forward to facilitate push rims contact and, thus, increased the propulsion. Moving the point of force application after the top of the wheel, generated force with downward and backward direction increasing the ground reaction force and reducing trunk and chair reaction force (Gehlsen, Davis, & Bahamonde 1990).

Trunk stability, being the ability to recover the equilibrium after a perturbation (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki 2007), plays an important role in balance on the sit-ski. Trunk stability requires great stiffness and coordination of hip muscles and anterior and posterior trunk muscles (Bergmark 1989, Vera-Garcia, Brown, Gray, & McGill 2006) and can be improved by strengthening core muscles (Hibbs, Thompson, French, Wrigley, & Spears 2008). Due to the importance of core muscles in increasing trunk stability, athletes with high impact of impairment overcome this limitation by using different strategies to keep their balance on the sit-ski. Athletes with high impact of impairment adopt a sitting position with the hip joints in a lower position than the knee joints and use straps at the level of pelvis and thigh to assure a more vertical and stable position with the trunk (Gastaldi et al. 2012). Because of these constraints, limited trunk range of motion is allowed for these athletes (Gastaldi et al. 2012). In contrast, athletes with low impact of impairment, having normal or near to normal trunk control, can use a sitting position with the hip joints in a higher position compared to the knee joints. This sitting position allows these athletes to freely move trunk in forward and backward directions, increasing the range of motion (Gastaldi et al. 2012). Therefore, other than control of core muscles, also trunk position and poles inclination affect athletes' trunk stability during the poling phase. Similarly, for wheelchair racing athletes, trunk forward lean, abdominal muscles, and contact point between hands and the push rims contributed to trunk stability (Gehlsen et al. 1990).

3 PURPOSE OF THE THESIS

To date, classification process has the advantage to be specific for each sport, but being performed by classifiers it might be subjective. In order to improve the classification, the IPC requires a transparent and standardized process; therefore it mandates the development of a classification process based on scientific evidence. In order to move towards an evidence-based classification system in this sport, the present thesis was designed to investigate cross-country sit skiers' biomechanics in order to develop standardized and sport-specific measure of performance. In addition, the thesis was planned to develop measures of trunk impairments, which can be used for the purpose of classification.

The thesis is based on 4 original articles in international journals and 3 conference proceedings with Scopus index. Specific aims of the thesis were:

1. To compare biomechanics of XC sit skiers while skiing on snow and during simulated action of poling on an adapted ergometer (Original article I). In addition, to evaluate trunk kinematics of XC sit skiers with different impact of impairment during simulated action of poling on the ergometer.

   Because the ergometer is widely used for indoor training by XC skiers and an agreement between skiing on snow and on the ergometer was found for able-bodied athletes, it was hypothesized a biomechanical agreement between the two skiing conditions for sit skiers (Halonen et al. 2014). Trunk plays a main role in sit skiing propulsion, therefore it was hypothesized that trunk kinematics is related to XC sit athletes impact of impairment (Gastaldi et al. 2012).

2. To develop a new measure of performance determinants for XC sit skiing (Original article III).

   It was hypothesized that performance of XC sit skiers while skiing on snow is different according to their sitting position (Rapp et al. 2014).

This result together with the agreement between skiing on snow and on the ergometer, allow to hypothesize that simulated action of poling on the ergometer can be a sport-specific measure of performance determinants and that analysing performance results with a cluster analysis would allow to group athletes with different impact of impairment according to their performance ability (article III).

3. To develop a new measure of trunk impairment for XC sit skiers (Original article II).

   Based on the existing literature to evaluate balance (Borghuis, Hof, & Lemmink 2008, Thigpen et al. 2009), it was hypothesized that trunk kinematics evaluated during unpredictable balance perturbations in forward-backward direction analysed with a cluster analysis would allow to group athletes according to their impact of impairment.

4. To develop a measure of impairment of strength and trunk control that can be used for the purpose of classification of XC sit skiers (original article IV).

   Since isometric contractions develop maximum level of force (Beckman et al. 2014, Beckman et al. 2017) and unpredictable balance perturbations define trunk control ability (Borghuis et al. 2008, Thigpen et al. 2009), it was hypothesized that a standard device, which allowed performing strength and trunk control tests, together with a cluster analysis would add scientific evidence useful to assess strength and trunk control according to Paralympic classification requests.

The following map summarizes what has been done for this Ph.D. project in order to reach these purposes.

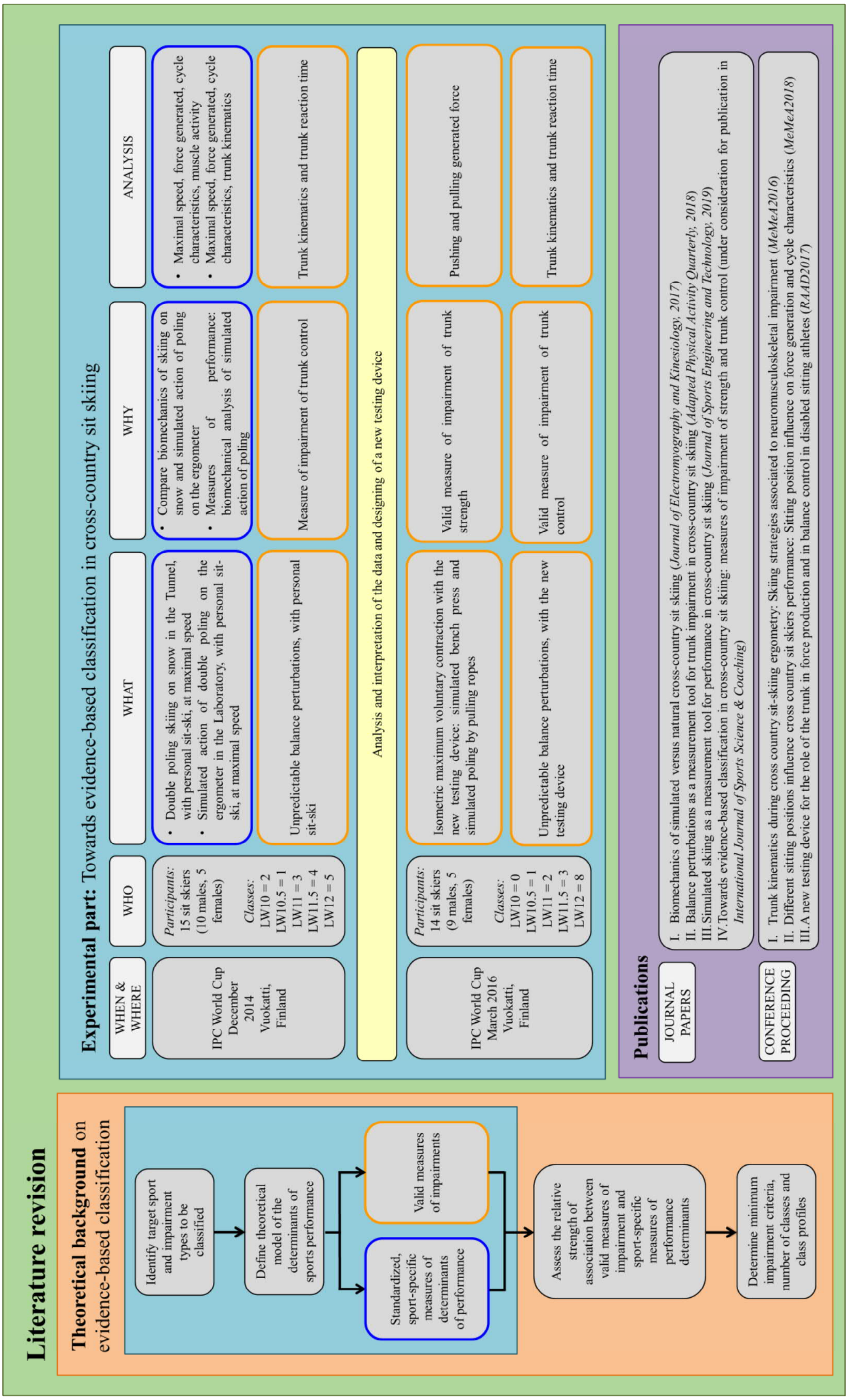


FIGURE 4 Thesis summary map

4 METHODS

Experimental investigations to develop measures of performance and measures of impairment took place in two separate periods of time. The first protocol was performed in December 2014 in which participants performed skiing test on snow, simulated action of poling on an adapted ergometer, and balance perturbation tests while seated on personal sit-ski. The first protocol was used to compare skiing on snow and simulated action of poling on the ergometer, to develop measures of performance, and to propose a measure for impairment of trunk control. After that, with the aim to develop measures of impairment that can be used for the purpose of classification, a new testing device that allowed for testing trunk strength and trunk control was designed. The second protocol took place in March 2016. In this protocol, participants performed isometric maximal voluntary contractions and unpredictable balance perturbations using the new testing device in order to develop measures of impairment of trunk strength and trunk control that can be used for classification purposes.

4.1 Participants

A total of 24 elite Paralympic XC sit skiers (16 males and 8 females) were recruited for the study. The study consisted of two separate investigations conducted respectively in December 2014 (Original articles I, II, III) and in March 2016 (Original articles IV). The fifteen participants (10 males and 5 females, 30±6 years, 168±19 cm, and 59±11 kg) recruited in December 2014 belonged to different classes as follows: LW10=2, LW10.5=1, LW11=3, LW11.5=4 and LW12=5. The fourteen participants (9 males and 5 females, 32±6 years, 160±18 cm, 55±13 kg) recruited in March 2016 belong to the five classes as follows: LW10=0, LW10.5=1, LW11=2, LW11.5=3, LW12=8 (Table 2). All the recruited participants have physical impairment, such as spinal cord injury, spina bifida, or amputation. Some participants were recruited in both investigations, whereas some were not included in the analysis because of missing values or outliers. Research methods and protocols were approved by the University of Jyväskylä ethics committee and procedures were performed in accordance with the declaration of Helsinki. All participants were informed about the tests and they signed informed consent before starting.

TABLE 2 Participants who volunteer in the thesis

	Investigations	
	December 2014	March 2016
Participants	15 athletes: 10 males, 5 females	14 athletes: 9 males, 5 females
Classes	LW10=2 LW10.5=1 LW11=3 LW11.5=4 LW12=5	LW10=0 LW10.5=1 LW11=2 LW11.5=3 LW12=8

4.2 Protocol

4.2.1 Protocol 1 (articles I, II, III)

Tests were conducted during the World Cup in December 2014 in Vuokatti (Finland). The protocol was separated in two parts: the first part took place in the Vuokatti Sports Technology Unit laboratory, whereas the second in the Vuokatti Ski Tunnel. In the laboratory both athletes' performance on the ergometer and athletes' trunk control were assessed; whereas in the tunnel only athletes' performance skiing on snow was evaluated.

In the Vuokatti laboratory, two separate tests were conducted. The first laboratory test consisted of simulated action of double poling on the ergometer at athletes' maximal speed (Ergo) to assess athletes' performance, whereas the second test was unpredictable balance perturbations (Pert) test to assess athletes' trunk control. For Ergo test, athletes' sit-ski were fixed in front of an adapted ergometer for cross-country sit skiing (Figure 4), at a distance that allowed skiers to have poling technique as similar as possible to the one used while skiing on snow. Two force transducers (University of Jyväskylä, 4 strain gauge connected with Wheatstone bridge, operating force range 0-1000N, supply voltage 5 V, sensitivity 5.10 mV/N) were mounted on the adapted ergometer between the ropes and the handles grip. Ergometer resistance was set at 7.5 out of 10 (arbitrary units) for all athletes in order to better simulate skiing conditions in the Vuokatti Ski Tunnel. This value was set based on pilot tests and on the feeling of the skiers. Two trials at the maximal speed were performed separated by 2 min of recovery and the fastest was used for the analysis. After the maximal speed was reached, 7 double poling cycles per trial were requested to the athletes.

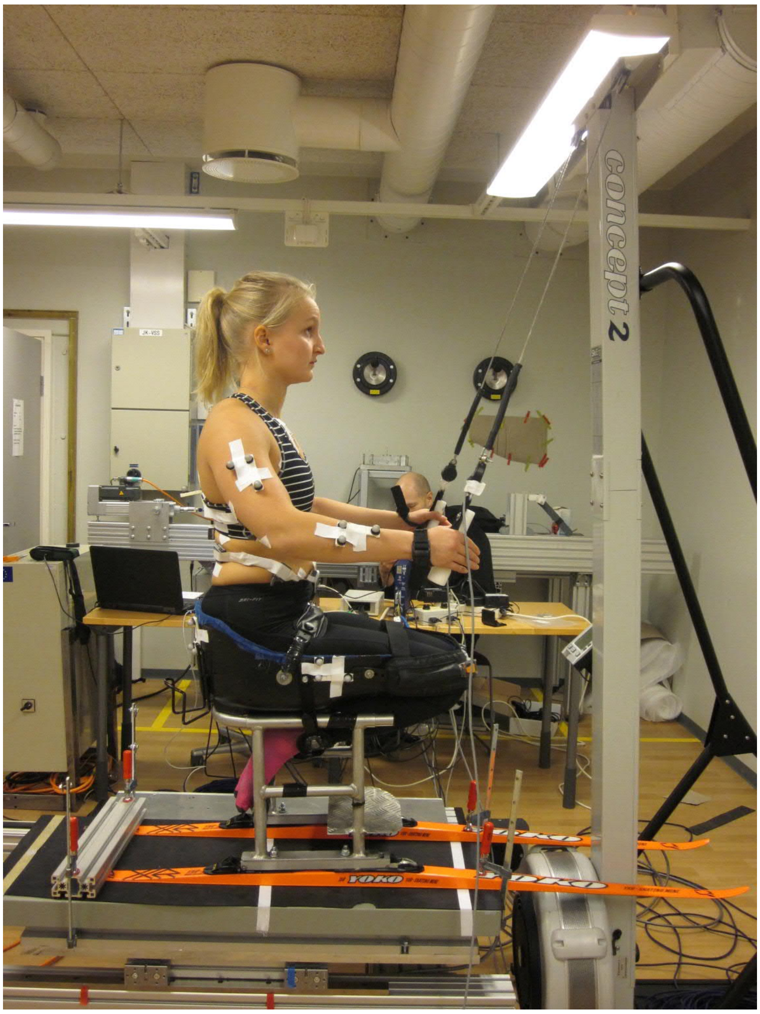


FIGURE 5 Laboratory tests setup for simulated action of double poling on the ergometer at athletes' maximal speed

For the Pert test, athletes' sit-ski were fixed on a motorized plate driven by an electromechanical servo actuator (IndraDyn S MSK; Bosh Rexroth, Lohr am Main, Germany) along a pair of parallel tracks (Figure 5). The plate could be moved anteriorly and posteriorly (maximum acceleration of ±2.5 m/s^2 and maximum velocity of ±0.5 m/s) by an operator using LabVIEW software (National Instruments). To test balance, perturbation stimuli were given to the athlete through the plate. A maximum of two stimuli in the same direction were allowed because of constructive design. A total of 12 perturbations stimuli (6 forward and 6 backward) were given to the athlete sitting on the sit-ski. Stimuli were given with a random order (anterior / posterior) and also inter-stimuli time was random to prevent anticipating movements that may alter perturbation response (Gilles, Wing, & Kirker 1999). Athletes' were instructed to keep upper limbs in a neutral position, avoiding any support function, and to keep the balance as much as possible during the test.

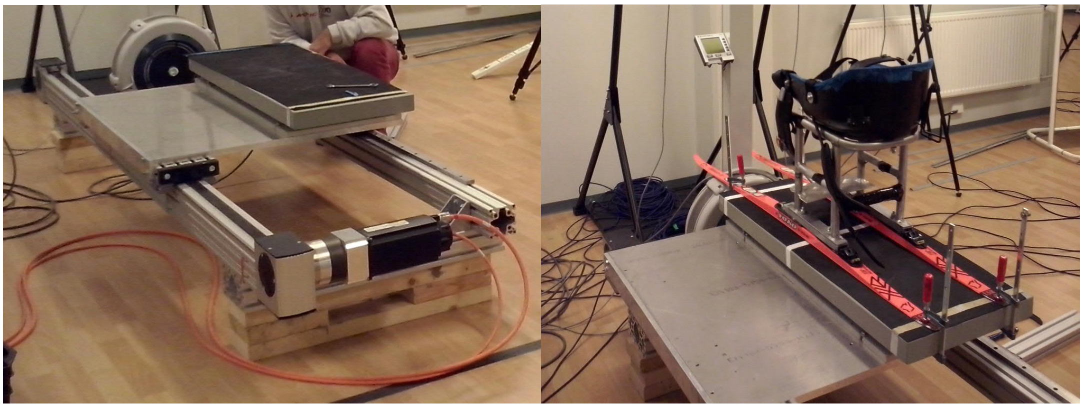


FIGURE 6 Laboratory tests setup for unpredictable balance perturbation

After laboratory tests, athletes were guided to the Vuokatti Ski Tunnel (constant temperature of −7 °C and humidity condition) for the second part of the protocol. In the tunnel tests, athletes' performance on snow was evaluated. Athletes' used their sit-ski and skis were prepared by athletes' ski service team before the beginning of the test. For propulsion athletes used a pair of poles with strain gauge force transducers mounted directly on the pole grip (University of Salzburg, Austria). In the tunnel, two separate tests were conducted. The first tunnel test consisted of skiing at the maximal speed using double poling technique along a track of 16 m at 2.5 deg of slope (uphill terrain, Figure 6). The second tunnel test consisted of double poling skiing at the maximal speed along a track of 14 m at 0 deg of slope (flat terrain). Each test was repeated two times with 2 min of recovery in between. Only the fastest repetitions in uphill and in flat terrain were considered for the analysis.

FIGURE 7 Tunnel uphill test

In the following table (Table 3) are summarized all the tests conducted during the Protocol 1:

TABLE 3 Protocol 1 sum up

Where	Tests	Description
Vuokatti Sports Technology Unit laboratory	Simulated action of double poling on the ergometer, with personal sit-ski, at athletes' maximal speed	7 double poling cycles at the maximal speed (2 trials, 2 min recovery in between)
	Unpredictable balance perturbations with personal sit-ski	6 forward and 6 backward perturbations in random order at 2.5 m / s^2 (1 trial)
Vuokatti Ski Tunnel	Double poling on snow, with personal sit-ski, at the maximal speed	Uphill: 16 m at 2.5 deg of slope of double poling at the maximal speed (2 trials, 2 min recovery in between) Flat: 14 m at 0 deg of slope of double poling at the maximal speed (2 trials, 2 min recovery in between)

4.2.2 A new testing device

In order to standardize measures of impairment a new testing device was designed (Figure 7). The testing device was designed with a metallic seat surrounded by a frame made by aluminum profile of 0.04 m. The frame size was: height 1.7 m, width 1 m, and depth 0.65 m; whereas the size of flat and rigid seat was 0.4x0.4 m. Two lateral bars were supposed to be used for protection from lateral falls. Because the lateral bars should be placed in correspondence of athletes' thorax, they were adjustable in height and depth. They were composed of an aluminum profile with a plate fixed longitudinally at one of the two extremities. To prevent athletes' movements or falls, the seat was covered with rubber material. Four elliptic slots were supposed to be made on the seat: two in front and two in back, close to four corners of the seat. The slots were designed in order to hold two belts, one anterior and one posterior, with the purpose of fixing respectively athletes shanks and pelvis.

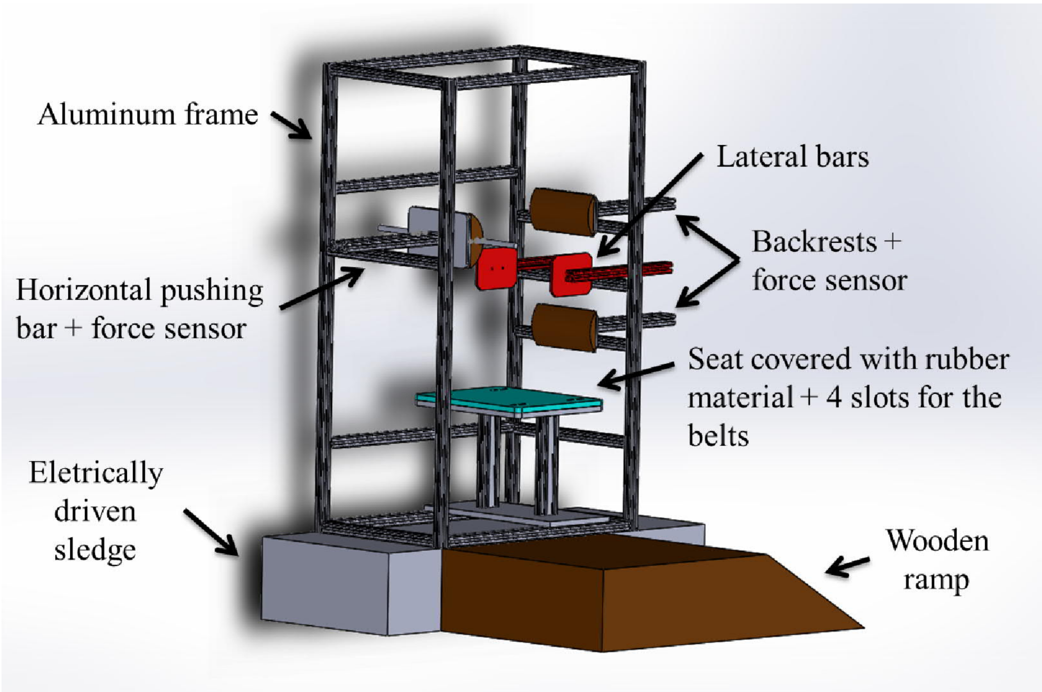


FIGURE 8 Project of the new testing device to standardize measures of impairment

It was thought to have a horizontal pushing bar in the anterior part and two backrests in the posterior part. The horizontal bar (Figure 8) and the two backrests (Figure 9) were designed to be adjustable in height and depth to fit all athletes' anthropometry. To be adjustable, they should be composed of an aluminum profile (0.5 m length) which can slide on a transverse profile (0.57 m length) embedded in the frame (Figures 8 and 9). At one extremity of both the anterior and the posterior aluminum profile, two metallic plates (0.2x0.3 m) were fixed orthogonally to the profile (Figures 8 and 9). Between the two metallic plates a force sensor should be fixed to collect force generated by athletes. A cover of wood was thought for the plates to avoid athletes' collision directly with the metallic surfaces (Figures 8 and 9). In addition, the anterior pushing bar was planned to have two lateral handles, which can be held by the athlete. Other than measuring forces, the new testing device would also be designed to perform perturbations. Therefore, the device would be fixed on an electrically-driven sledge (length 0.83 m and width 0.65 m) in order to allow movements in anterior and posterior directions. Finally, a wooden ramp was designed to facilitate the athletes' sitting procedure for those who have limited mobility, such as the one with spinal cord injury and moved on a wheelchair.

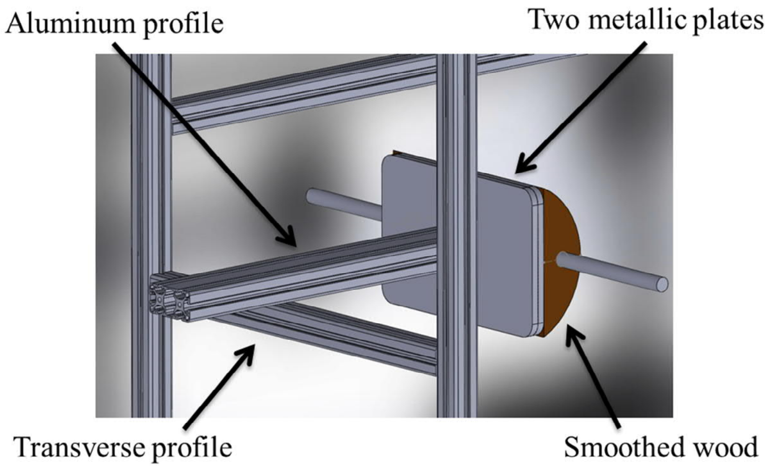


FIGURE 9 Details of the horizontal pushing bar of the new testing device

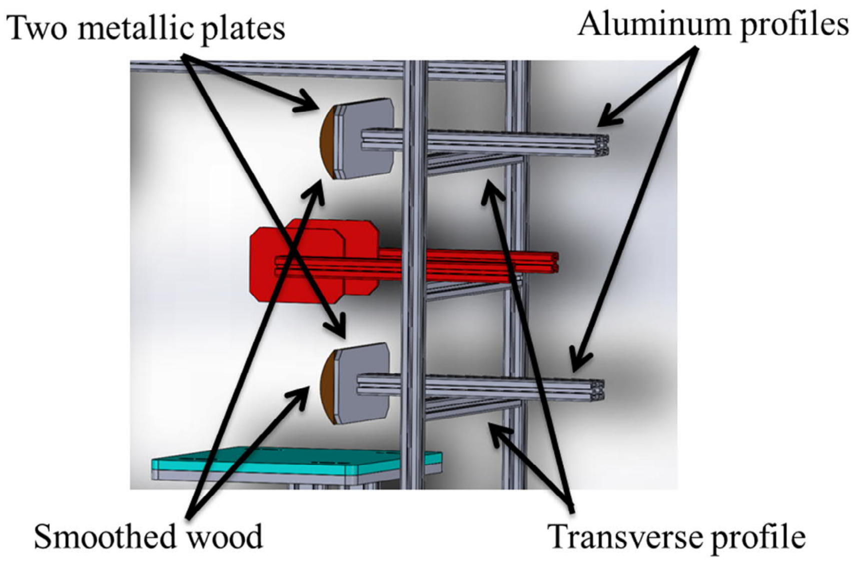


FIGURE 10 Details of the backrests of the new testing device

During the design phase, the use of the new testing device was simulated with a dummy of different sizes using Solidworks. In particular, assessments of two different anthropometrics were conducted, thus tests were assessed with similar anthropometrics to the tallest and shortest athletes tested in protocol 1: 1.75 m (Figure 10-A) and 1.30 m (Figure 10-B). It seemed that the dummy perfectly fit the new testing device in both cases by adapting the adjustable anterior pushing bar, posterior backrests, and lateral bars.

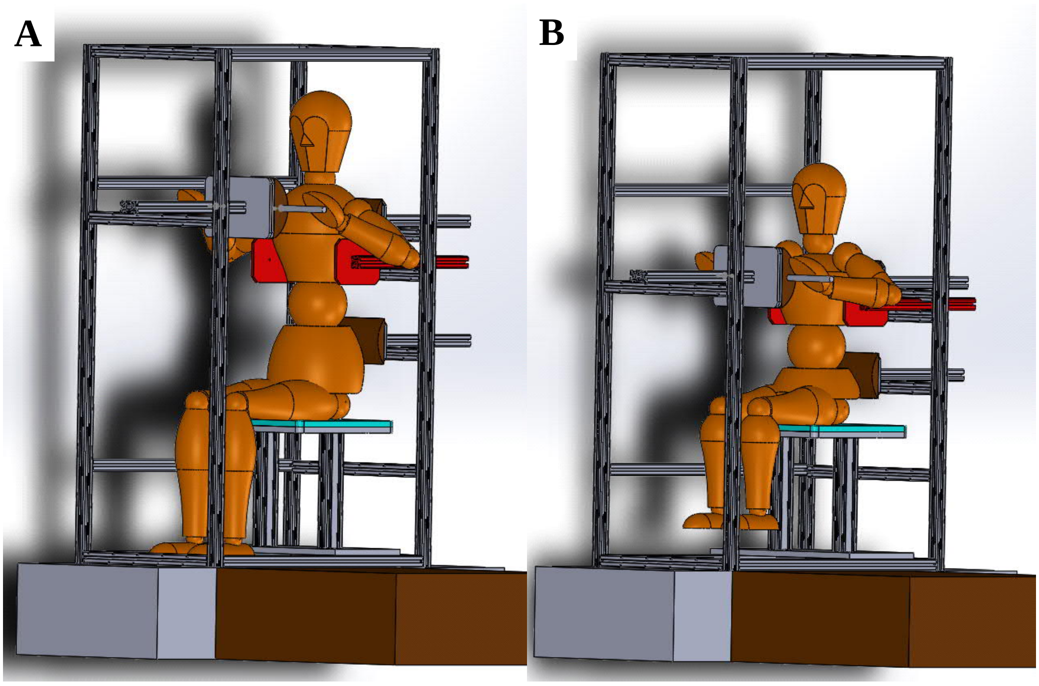


FIGURE 11 Simulation for the new testing device: (A) the highest dummy (1.75 m), (B) the shortest dummy (1.30 m)

After the design and the simulations, the new testing device was built with some changes due to practical improvements. The seat was made with wood instead of metal and it was fixed posteriorly to the frame by using an aluminum profile to increase its stability. In contrast, seat size remained 0.4x0.4 m and rubber material was used to cover the seat surface. According to the project, the frame was made by an aluminum profile of 0.04 m and its size was: height 1.7 m, width 1 m, and depth 0.65 m. The four elliptic slots were substituted with five metallic eyelets: three eyelets were positioned in top, front part of the seat, while two were fixed to bottom, back part (Figure 11). A belt was used to fix athletes' thighs to the seat by means of the three frontal eyelets and a second belt was used to fix athletes' pelvis to the seat using the two posterior eyelets (Figure 12). Athletes' shanks were suspended under the seat and supported by two padded belts (Figure 12).

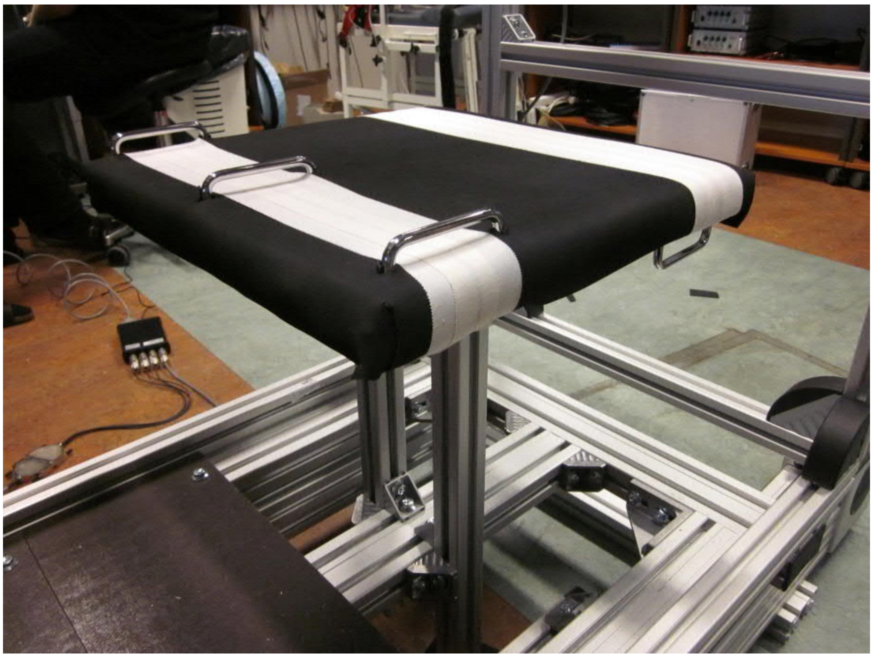


FIGURE 12 Metallic eyelets fixed to the seat: three in the top, front part of the seat and two in the bottom, back part of the seat

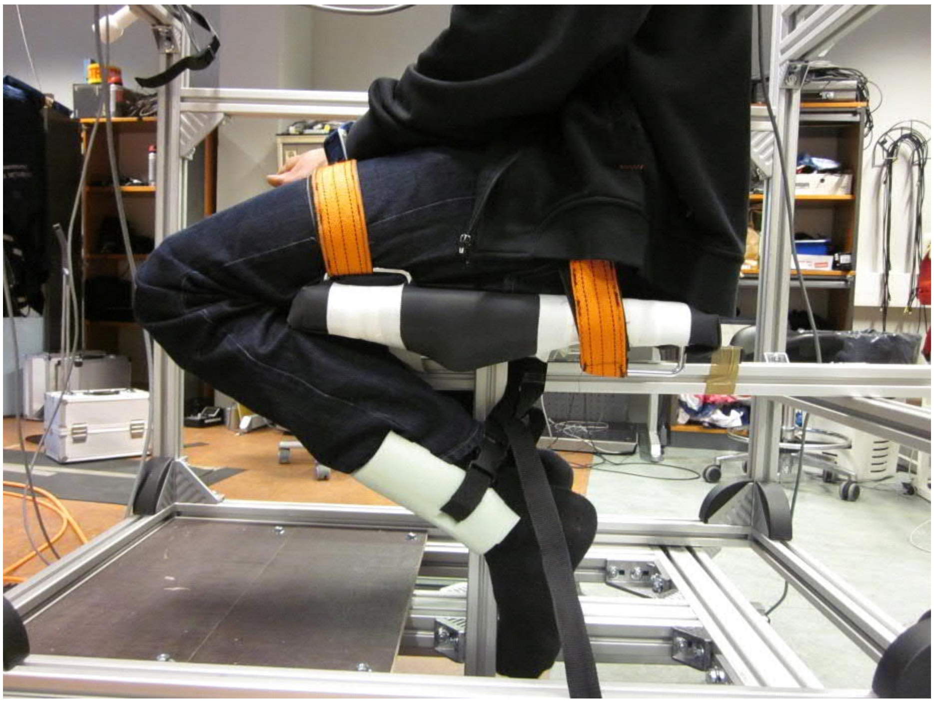


FIGURE 13 The three eyelets in front were used to fixed athletes' thighs, whereas the two in the back were used to tighten athletes' pelvis by means of two belts

To cover the lateral side of the new testing device, two lateral bars were embedded in the frame and were adjustable in height. According to the project, the horizontal pushing bar was fixed to the anterior part of the frame, but two transverse profiles instead of one were used to keep it in position and to increase its resistance while athletes generate force (Figure 13). Concerning the backrests, only one instead of two was used. Two transverse profiles instead of one were used to better fix the backrest to the frame.

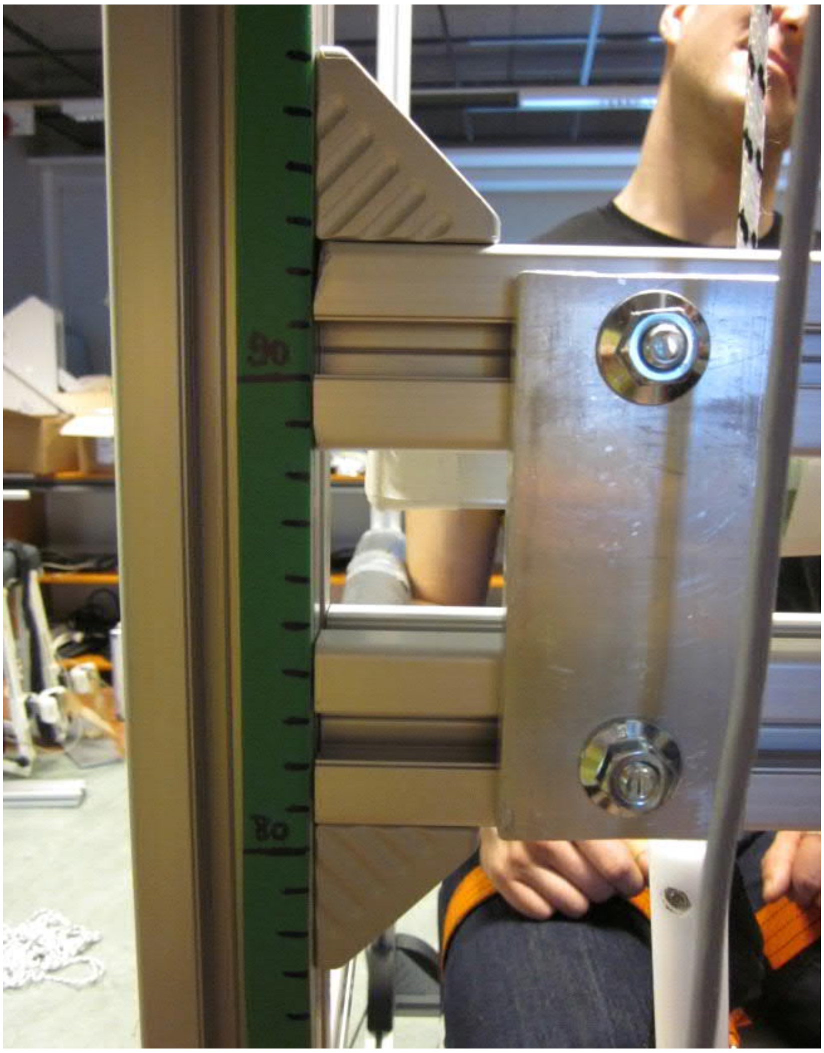


FIGURE 14 Fixation of the horizontal pushing bar to the frame

The anterior pushing bar and backrest were regulated in height using a laser so that their middle point was positioned in correspondence of the middle point of the athlete's sternum (Figure 14).

FIGURE 15 Horizontal bar and backrest regulation in height and depth according to athletes' anthropometry

For the anterior pushing bar, a tri-axial strain gauge force sensor (K3D120; Me-Meßsysteme GmbH, Germany, full range 2 kN) was used anteriorly; it was mounted between the aluminum profile and horizontal bar (Figure 15) without plates for support. For the backrest, a uniaxial strain gauge force sensor (TB5; Lahti Precision, Finland, full range 5 kN) was fixed posteriorly between the aluminum profile and backrest (Figure 16). Sponge material instead of wood was used to cover the horizontal bar, whereas wood and rubber material were still used for the backrest. In addition to the original project design, two ropes were elongated from the top of the frame (anterior part) to make simulated poling. The ropes could be regulated in length. The ropes ended with handles and a uniaxial strain gauge force sensor (University of Jyväskylä, Finland, full range 1 kN) was fixed between each rope and handle.

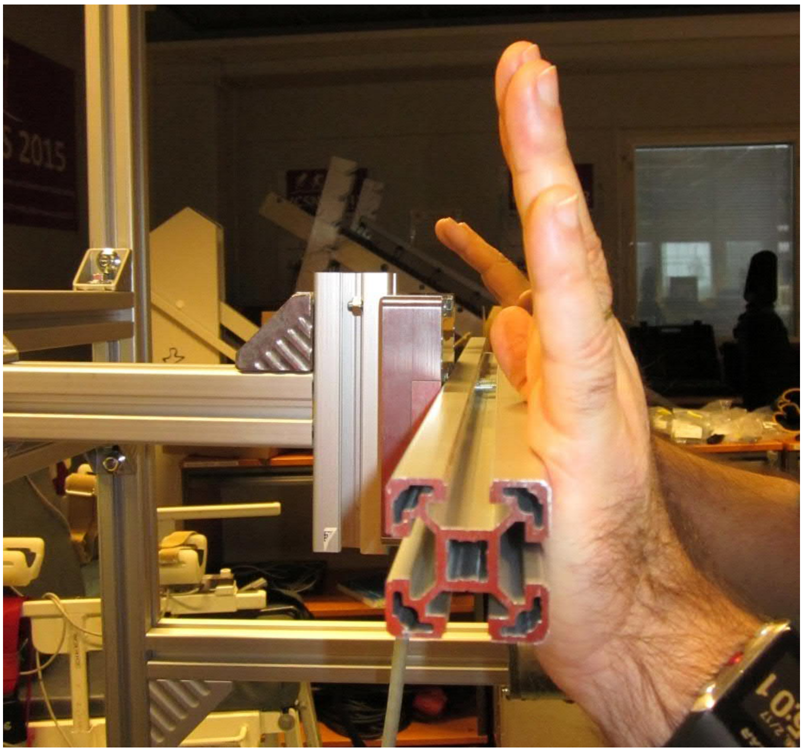


FIGURE 16 Tri-axial strain gauge force sensor between the aluminum frame and the horizontal pushing bar

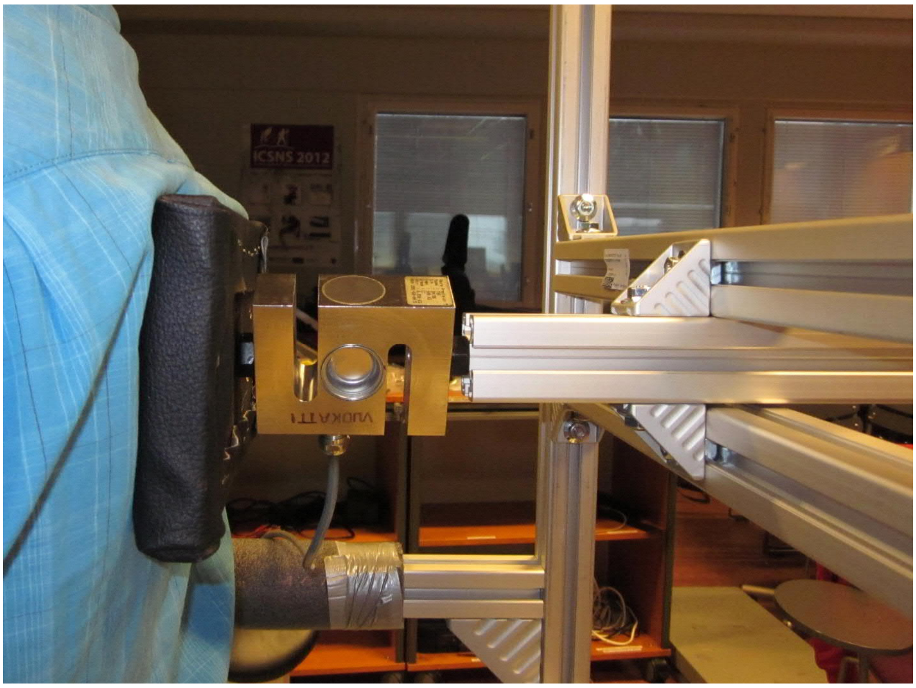


FIGURE 17 Uniaxial strain gauge force sensor between the aluminum frame and the backrest

According to the project, the new testing device was mounted on an electrically-driven sledge (University of Jyväskylä), which motions were guided by a linear rail (LF 12S; Bosch Rexroth) and actuated by a three-phase motor (MSK060C; Bosch Rexroth) and a servo drive (HCS01.1E; Bosch Rexroth). The sledge could be moved with a maximum acceleration of ±3 m/s^2, a maximum velocity of ±1 m/s, and a maximum stroke of 0.8 m by an operator using LabVIEW software (National Instruments).

In Figure 17 is reported the new testing device with the main elements highlighted:

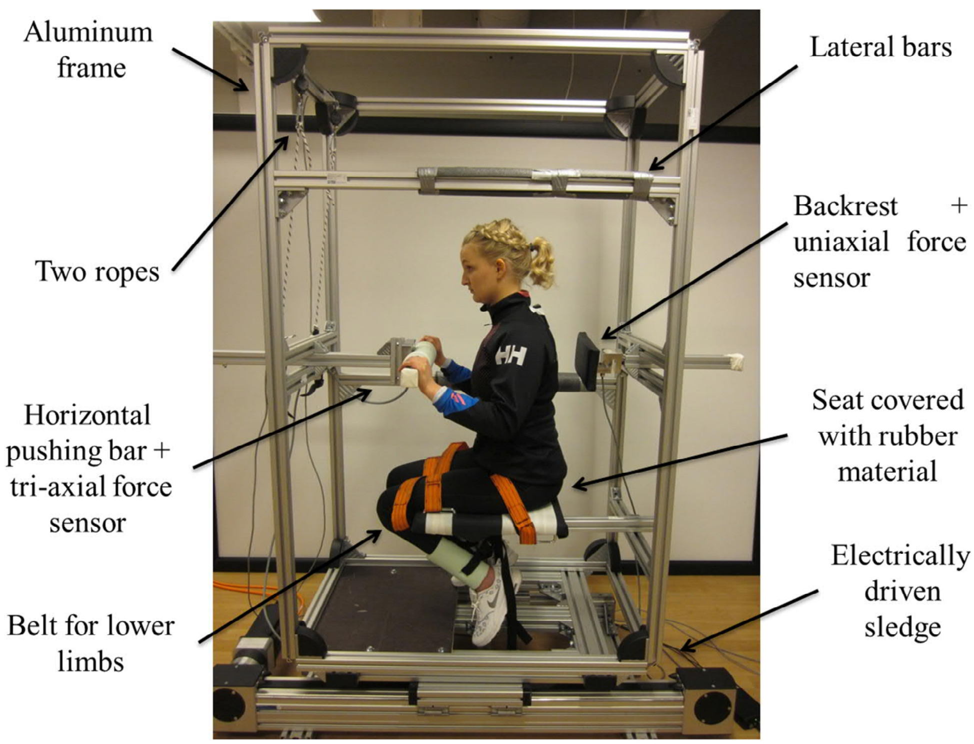


FIGURE 18 New testing device for maximal voluntary force tests and unpredictable balance perturbation test

4.2.3 Protocol 2 (article IV)

Tests were conducted during the World Cup in March 2016 in Vuokatti (Finland). Protocol took place in the Vuokatti laboratory and consisted of two parts: the first part was isometric maximum voluntary contraction (MVC) tests to assess athletes' strength impairment; whereas the second part was unpredictable balance perturbations (Pert) test to evaluate athletes' trunk range of motion impairment. For both MVC and Pert tests the new testing device was used and the tests were repeated two times with 24-36 hours in between. To assure standard and comparable measures between days, no physical effort was sustained by the athlete before the tests. MVC tests consisted of three tests: (A) simulated bench press without the back support (MVC_{wo}, Figure 18), (B) simulated bench press with back support (MVC_w, Figure 19), and (C) simulated poling by pulling ropes (MVC_p, Figure 20). In both simulated bench press tests, shoulder flexion angle with respect to the trunk was 30 deg and elbow flexion angle was 90 deg, elbow abduction angle was close to zero. In pulling test, upper arms were in a position similar to the one an athlete has at the beginning of the poling phase, so that an angle around 70 deg existed between the ropes and the horizontal. This angle was found in the literature as the angle between the pole and the terrain (in flat terrain) at the beginning of the poling phase (Bernardi et al. 2013). Three repetitions were performed for each MVC test with 30 seconds in between. Athletes were instructed to progressively increase the exerted force until the maximum was reached and then hold this maximum for a few seconds. The repetition in which the highest force generated was considered for the analysis.

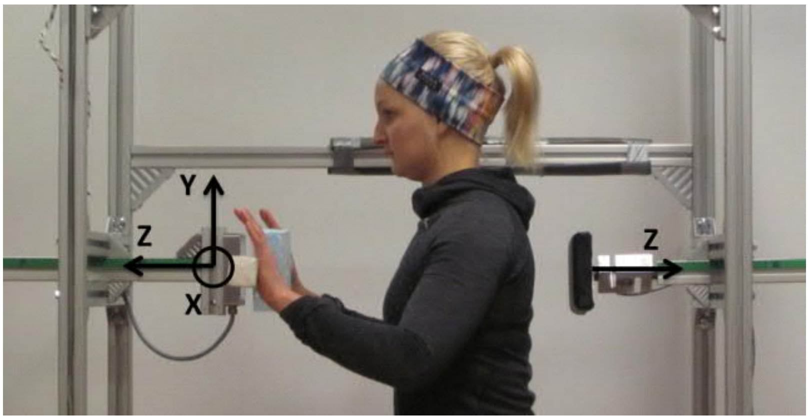


FIGURE 19 First maximal voluntary force tests: simulated bench press without back support

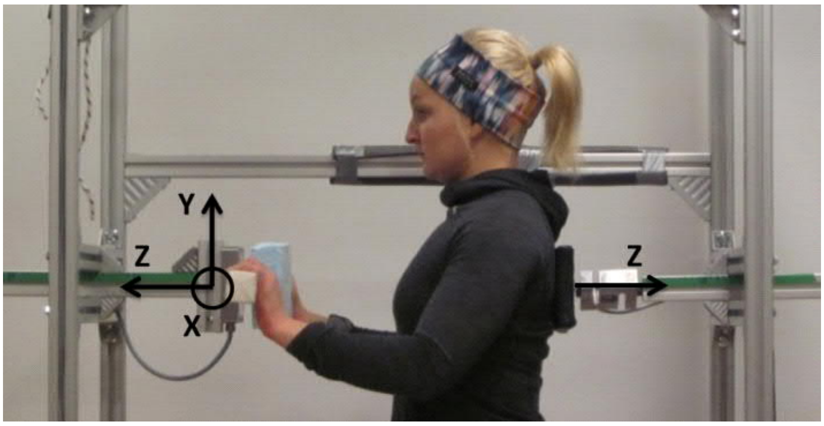


FIGURE 20 Second maximal voluntary force tests: simulated bench press with back support

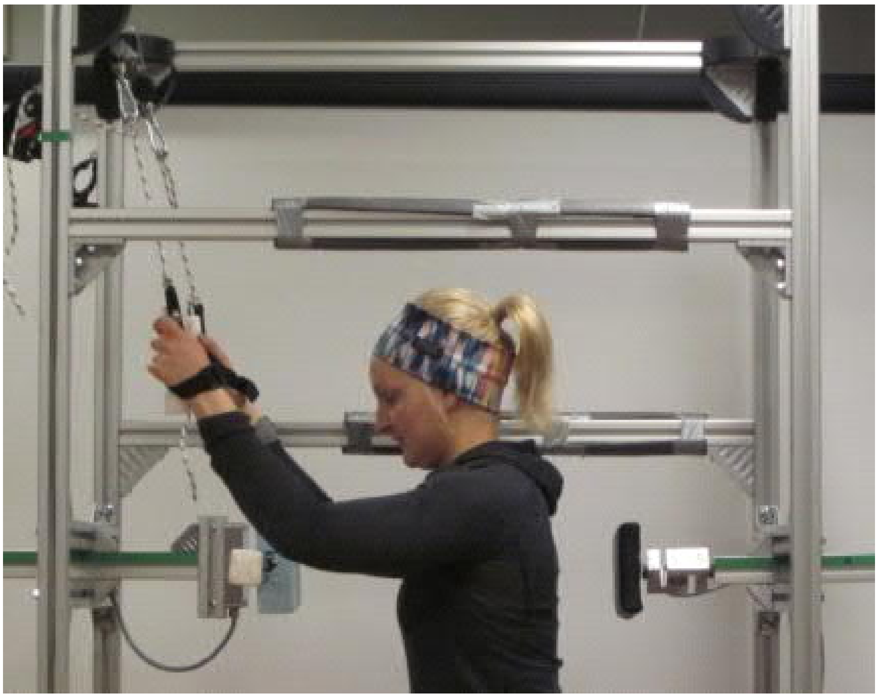


FIGURE 21 Third maximal voluntary force tests: simulated poling by pulling ropes

Pert test consisted of a total of 10 stimuli (5 forward and 5 backward) given to the athlete in antero-posterior direction (Figure 21), in random order and random inter-stimuli time. At the end of each stimulus, the sledge came back to the middle point of the track; therefore more consecutive stimuli can be given in the same direction. The Pert test was repeated at three accelerations: 0.5 m/s^2, 1 m/s^2, 2.5 m/s^2, with few minutes of rest in between. For all stimuli, the sledge stroke was 0.3 m. In this test, anterior horizontal bar and posterior backrest were set at a distance of 0.075 m from athletes' straight trunk to prevent extreme trunk movements or falls.

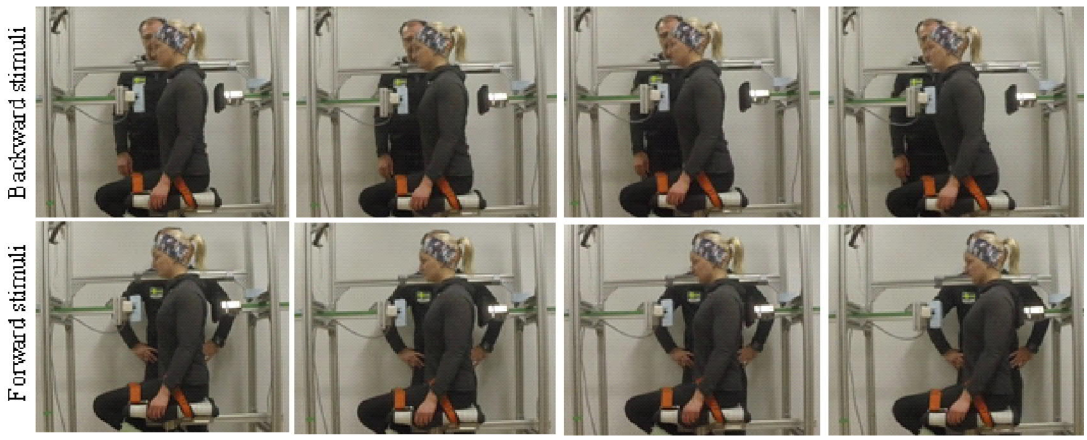


FIGURE 22 Unpredictable balance perturbation test with the new testing device

In the following table (Table 4) are summarized all the tests conducted during the Protocol 2 using the new testing device:

TABLE 4 Protocol 2 sum up

<table>
<tr><th colspan="2">Tests</th><th>Description</th></tr>
<tr><td rowspan="3">Maximal voluntary force tests</td><td>Simulated bench press without back support, with the new testing device</td><td rowspan="3">3 repetitions, 30 s recovery in between</td></tr>
<tr><td>Simulated bench press with back support, with the new testing device</td></tr>
<tr><td>Simulated poling by pulling ropes, with the new testing device</td></tr>
<tr><td colspan="2">Unpredictable balance perturbations with the new testing device</td><td>5 forward and 5 backward perturbations in random order, (3 trials at: 0.5 m/s^2, 1 m/s^2, 2.5 m/s^2 of acceleration)</td></tr>
</table>

4.3 Data collection and analysis

4.3.1 Maximal speed (articles I, III)

Maximal speed was collected in protocol 1. In the Vuokatti laboratory (articles I, III), in simulated action of poling on the ergometer maximal speed was calculated using the ergometer software. The ergometer gives the pace (in time) necessary to cover a distance of 500 m, if the speed the athlete has at that moment will be maintained. The maximal speed was calculated as the ratio between a theoretical distance of 500 m and the time given by the ergometer. In the Vuokatti Ski Tunnel (article I), maximal speed was measured with radar (Jenoptik LDM 300 C SPORT, Jena, Germany).

4.3.2 Cycle characteristics (articles I, III)

Cycle characteristics were measured in the Vuokatti laboratory during simulated action of poling on the ergometer (article I) and in Vuokatti Ski Tunnel in both uphill (articles I, III) and flat terrain. Among cycle characteristics there are: cycle time (CT), poling time (PT), and recovery time (RT) (Figure 22). CT is the total duration of an entire poling cycle (articles I, III). A poling cycle is composed of a poling phase, characterized by generation of force, and a recovery phase, in which force is negligible. The beginning and the end of the poling phase were calculated using a threshold of 10% of the maximum value of force. Poling phase duration is called PT and recovery phase duration is called RT (article I). Whereas, relative poling time (rPT) was calculated as the ratio between PT and CT (article III). Finally, time to impact (TtI) and time to peak (TtP) were calculated respectively as the time between the beginning of the poling phase and the time when the impact force and peak force occurred (article I).

4.3.3 Force generated (articles I, III, IV)

In protocol 1, force was measured in the Vuokatti laboratory when athletes simulated action of poling on the ergometer (articles I, III) and in Vuokatti Ski Tunnel in both uphill (article I) and flat terrain. In Vuokatti laboratory, the two force transducers mounted between the ropes and the handles grip were used to collect the generated force. Forces were collected at 3000 Hz by Vicon Nexus software (Vicon Motion Systems Ltd., Oxford, UK). In Vuokatti Ski Tunnel, force signals were collected by the two strain gauge force transducers mounted directly on the pole grip. Force signals were collected at 1000 Hz using a custom-made data collection system (Labview) explained in a previous study (Halonen et al. 2014).

Concerning the analysis of generated force (articles I, III), the following variables were evaluated: impact force (IF), peak force (PF), average force (aF), impulse of force (iF). IF corresponds to the first peak of the poling phase, whereas the PF was the second highest peak of the poling phase (Figure 22). aF was calculated as the average value of the force generated during the poling phase, whereas iF was calculated as the integral of the force exerted during poling phase.

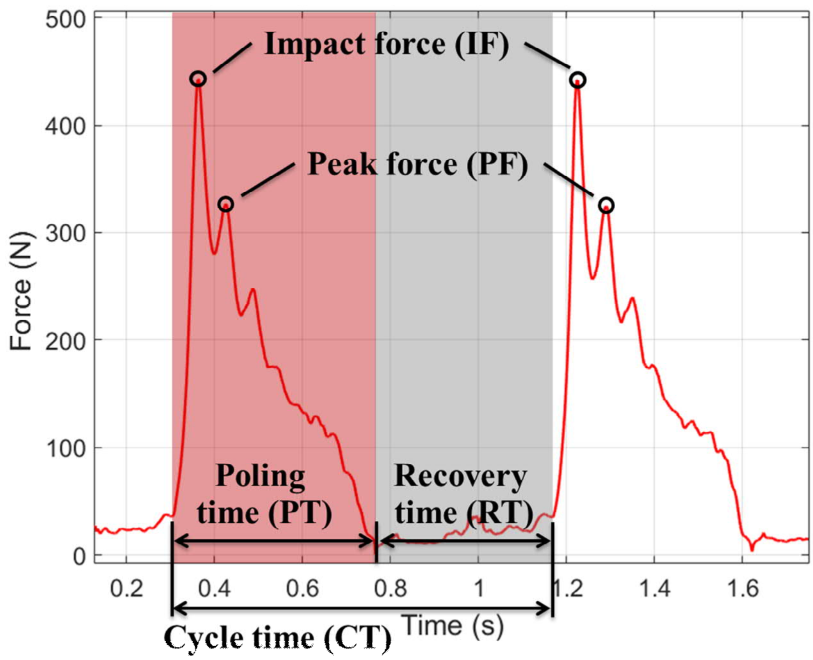


FIGURE 23 Variables of force (impact force and peak force) and cycle characteristics (cycle time, poling time, recovery time)

In protocol 2, force was measured in the three MVC tests using the new testing device (article IV). The anterior tri-axial strain gauge force sensor (fixed between the aluminum frame and the horizontal pushing bar, Figure 15) measured the pushing force exerted in simulated bench press with and without backrest. The posterior uniaxial strain gauge force sensor (placed between the aluminum frame and the backrest, Figure 16) registered the force generated during simulated bench press with back support. The uniaxial strain gauge sensors embedded in the two ropes handle collected force generated in simulated poling test. A custom-made data collection system (Labview) with a sampling frequency of 100 Hz was used to collect force signals. Because in protocol 1 both force and EMG were collected by Vicon Nexus software high sampling frequency was selected. In protocol 2, lower sampling frequency was chosen because only force signals were acquired. Concerning the analysis, the calculated variables were: peak of anterior force in simulated bench press without using back support (PFa_{wo}), peak of anterior (PFa_{w}) and posterior (PFp_{w}) forces in simulated bench press using back support, and average value between peak of left and right pulling force in simulated poling (PF_{p}). In addition, the ratio between peak of anterior force in simulated bench press without back support and peak of anterior force in simulated bench press with back support was calculated $\left(\frac{PFa_{wo}}{PFa_{w}}\right)$.

4.3.4 Muscle activity (articles I)

Muscles activation was evaluated in protocol 1 when athletes were skiing on the ergometer in the Vuokatti laboratory (article I) and when they skied on snow in the Vuokatti Ski Tunnel uphill (article I). Muscular activation was collected using surface bipolar electrodes (Ambu BlueSensor N, Ambu A/S, Denmark, Ag/AgCl surface electrodes, circle shape, area 28 mm^2, inter-electrode distance 15 mm) in a single differential configuration. After abrading and cleaning skin with alcohol, electrodes were positioned on muscles' belly according to SENIAM recommendation (Hermens, Freriks, Disselhorst-Klug, & Rau 2000). Muscles important in the action of poling were considered: Triceps (Tri), Pectoralis Major (Pec), Latissimus Dorsi (Lat), Rectus Abdominis (RecAb), Obliquus Abdominis (Obl), Erector Spinae (ES), Rectus Femoris and Biceps Femoris muscles. Since the movement can be considered symmetrical, only the right side of the body was considered for acquiring muscle activation. In addition, a reference electrode was placed on the right acromion. Electromyographical (EMG) data were transmitted to a personal computer wirelessly (TeleMyo DTS, Noraxon U.S.A. Inc, United States) and were acquired by Vicon Nexus software. The acquisition system applied a pass-band filter (20–400 Hz) and an analog to digital conversion (16-bit A/D converter). In the Vuokatti laboratory, to synchronize force and EMG data, muscle activation signals were collected at 3000 Hz by Vicon Nexus software. In the Vuokatti Ski Tunnel, EMG signals were acquired by Vicon Nexus software at a sampling frequency of 1500 Hz. In order to synchronize force and EMG data collected in the Tunnel, the activity of Triceps muscle was also acquired using the custom-made data collection system (Labview) used to collect force signals at a sampling frequency of 1000 Hz. For the analysis of muscle activation, average and peak muscle activity were assessed on five consecutive poling cycles. According to (Holmberg et al. 2005), collected signals were full-wave rectified to calculate the average muscle activity and low pass filtered at 10 Hz, creating a linear envelope, to calculate peak muscle activity. As it was done in (Pellegrini, Bortolan, Zory, Rouard, & Schena 2005), to compare muscle activation levels in different conditions, a ratio between EMG variables in Vuokatti Ski Tunnel and in Vuokatti laboratory was calculated $\left(\frac{Skiing\ on\ snow}{Skiing\ on\ the\ ergometer}\right)$. In addition, the electromechanical delay was calculated as a difference between two time instances. During each poling cycle both muscle activity and generated force increased from (onset) and then decreased to (offset) a baseline value. Onset muscle activity and onset force corresponded to those instants in which increasing signals reached 10% of the maximum. The difference between onset muscle activity and onset force was defined as onset delay. Offset delay was calculated in the same way when muscle activity and force signals decreased to a baseline value. Onset delay and offset delay were reported negative when muscle activity activate or deactivate earlier than force.

4.3.5 Trunk kinematics (articles II, III, IV)

In protocol 1, trunk kinematics was measured in the Vuokatti laboratory during the unpredictable balance perturbation test (article II) and when athletes were performing simulated action of poling on the ergometer (article III). Eight Vicon cameras were positioned to create the acquiring volume and Vicon Nexus software was used to register athletes' movement. A total of 6 passive reflective markers were used. One was placed on the posterior right corner of the plate (Figure 5); whereas five were fixed to the right side of the athlete on: shoulder (acromion), elbow (lateral epicondyle), wrist (ulnar styloid process), hip (great trochanter), and knee (lateral epicondyle). Since athletes used their own sit-ski, it was possible that the sit-ski seat did not allow fixing the marker directly on the hip (especially for those who used knee-high sitting position); therefore, in these cases, the marker was fixed on the sit-ski in correspondence to the great trochanter. Because trunk angle would be calculated with respect to a vertical plane (considered as 0 deg), only shoulder and hip markers were used for the analysis. In case also upper limbs kinematic were calculated, elbow and wrist makers would be used. The trunk was considered as a single, rigid segment articulated at the hip joint level. Trunk angle was reported positive when athletes moved the trunk anterior from the vertical position and negative when he/she moved the trunk posterior. Signals were collected at a sampling frequency of 200 Hz.

Concerning the analysis of unpredictable balance perturbations (article II), temporal and kinematic variables were calculated for each forward and backward stimulus. Temporal variables consisted of the delay between onset of the ski-ski acceleration and onset of the shoulder acceleration (DLY1) and the delay between onset of the shoulder acceleration and the time when the trunk inverted the motion (DLY2). Kinematic variables (Figure 23) consisted of: trunk angle at rest ($Trunk_{rest}$), trunk range of motion at 150 ms ($Trunk_{150}$), and trunk range of motion at the inversion ($Trunk_{rom\text{-}pert}$). $Trunk_{rest}$ was calculated before the first stimulus, $Trunk_{150}$ was calculated as the difference between trunk angle 150 ms after the onset of the shoulder acceleration and trunk angle at rest, and $Trunk_{rom\text{-}pert}$ was calculated between trunk angle when the trunk inverted the motion and trunk angle at rest. Trunk flexions are reported positive while trunk extensions are reported negative. Temporal and kinematic results of the six forward stimuli were averaged and the same was done for the six backward stimuli.

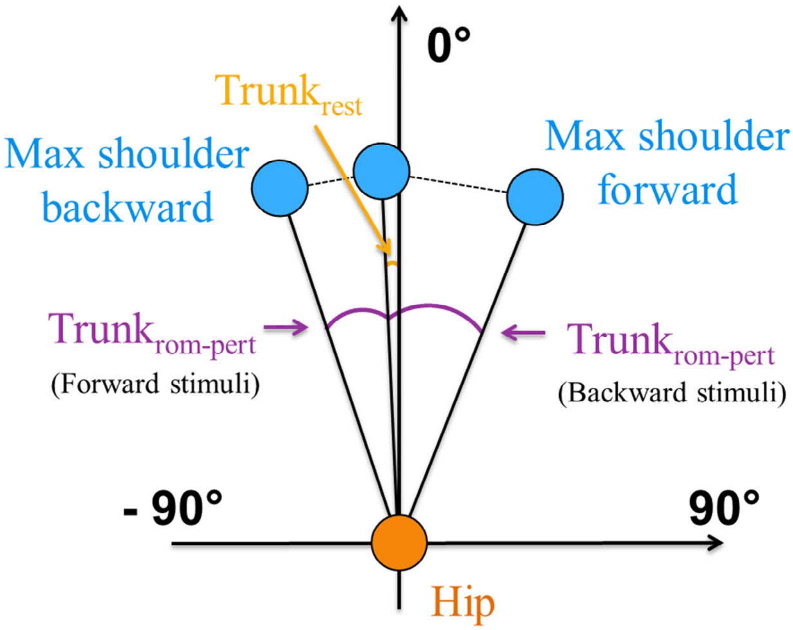


FIGURE 24 Trunk kinematic variables in unpredictable balance perturbations

Concerning the analysis of simulated action of poling (article III), kinematic and temporal variables were calculated for each poling cycle. Kinematic variables were: trunk maximal backward inclination in extension (TB), trunk maximal forward inclination in flexion (TF), and trunk range of motion of the poling phase ($Trunk_{rom-poling}$) calculated as the difference between trunk maximal forward and trunk maximal backward inclinations (Figure 24). Temporal variables were: beginning (BT) and end (ET) of trunk movement with respect to the beginning of the poling phase (considered as 0 s). These times were considered positive if trunk movement occurred after the beginning of the poling phase and negative in the other case. In addition, time to complete a trunk flexion during the poling phase (FET) was calculated as the difference in time between two following trunk maximal backward inclinations.

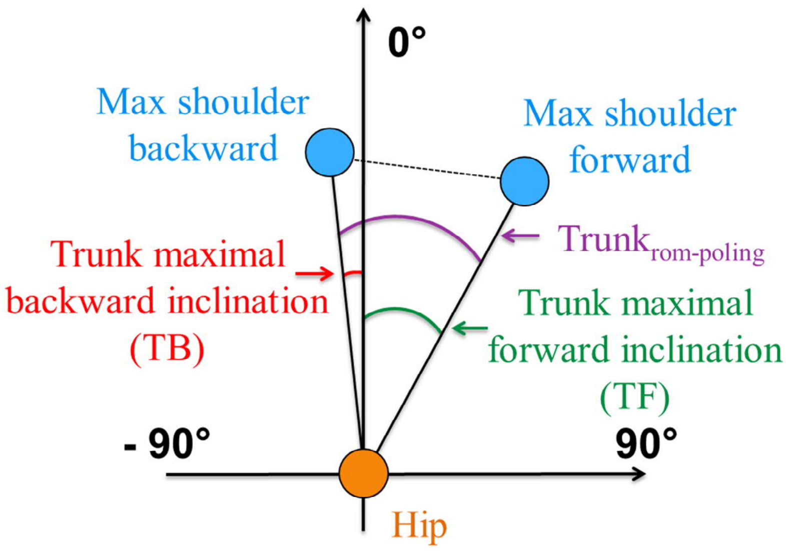


FIGURE 25 Trunk kinematic variables in simulated action of poling on the ergometer

In protocol 2, trunk kinematics was measured in unpredictable balance perturbations test using two inertial sensors (Physilog® 4, GaitUp, Switzerland) and the new testing device (article IV). One inertial sensor was placed on the 7th cervical vertebra and the second one was fixed at the bottom of the aluminum frame. Inertial sensors were composed of one tri-axial accelerometer (full range 16 g) and a tri-axial gyroscope (full range 2000 deg/s). Raw data were collected at a sampling frequency of 500 Hz. The inertial sensors were calibrated: to define the trunk longitudinal axis an assisted athlete upright posture was used and to define the trunk anterior-posterior axis controlled forward-backward sledge movements were used (Favre, Aissaoui, Jolles, de Guise, & Aminian 2009, Fasel, Spörri, Schütz, Lorenzetti, & Aminian 2017). The two inertial sensors were synchronized by an electronic trigger (Fasel et al. 2017). A pilot test was conducted to evaluate overall athlete's response to unpredictable balance perturbations performed with the new testing device. Then the tests were performed by a greater number of athletes (article IV) and the most significant variables of protocol 1 were also calculated in protocol 2. In particular, it was considered: trunk reaction time, calculated as the delay between onset of the shoulder acceleration and the time when the trunk inverted the motion (DLY2), trunk angle at rest before the first stimulus (Trunk$_{rest}$), and trunk range of motion calculated between trunk angle when the trunk inverted the motion and trunk angle at rest (Trunk$_{rom-pert}$) (Figure 23). Trunk angle was computed with the dot product between the trunk's longitudinal axis and the vertical axis in the fixed global frame (e.g. gravity). As for protocol 1, forward trunk angles were defined positive, whereas backward angles were considered negative.

4.4 Statistical analysis

Conventional statistical methods were used to obtain means, standard deviations, and Spearman correlation. Statistical significance was set at α = 0.05 for all analyses. All statistical analyses were processed using MatLab Software (MatLab and Release 2015, The MathWorks, Inc., Natick, Massachusetts, United States). Due to the small sample size, non parametric statistics were used:

(I) Article I: A Wilcoxon test was used to assess biomechanical differences between skiing on snow and simulated action of poling on the ergometer.

(II) Article II: A cluster analysis (k-means) was run using trunk kinematics results of unpredictable balance perturbations to cluster athletes according to their impact of impairment.

(III) Article III: A clusters analysis (k-means) was run using performance results during simulated action of poling on the ergometer to cluster athletes with different impact of impairment according to their performance.

(IV) Article IV: Wilcoxon test, intraclass correlation coefficient (ICC), and standard error of measurement (SEM) were used to assess test-retest reliability of the new standardized measure of strength and trunk control. Spearman correlation was evaluated between strength and trunk impairment measures. A cluster analysis (k-means) was run using strength and trunk control tests results to cluster athletes according to their impact of impairment.

In addition to what was shown in the original articles, Kruskal Wallis test was used to assess trunk kinematics of athletes with different impact of impairment while simulated skiing on the ergometer. Finally, a cluster analysis (k-means) was run using performance results on snow to cluster athletes with different sitting position.

4.4.1 Cluster analysis (articles II, III, IV)

Cluster analysis is a method used in order to group data maximizing similarity within elements of a cluster and maximizing differences between clusters. Cluster analysis, especially the k-means method, has been recently used in the field of Paralympic classification to identify measures of impairment (Connick et al. 2017, Altmann et al. 2018). Cluster analysis is composed of four steps:

1. Data pre-processing and variable selection: Data were checked for outliers, which have to be excluded from cluster analysis. Identification of outliers was done using the method of the mean and three standard deviations. For variable selection, the coefficient of variability was calculated for each variable as the ratio between standard deviation and mean value. Criteria

of coefficient of variability > 5% was used to select variables that could be considered for the cluster analysis.

2. k-means cluster analysis: Considering ability to control the trunk, athletes were grouped in clusters to maximize between clusters differences and to minimize differences within a cluster. Distances between clusters were evaluated using the squared Euclidean distance and the initial seeds were defined by the k-means++ algorithm. Since variables were measured in different scales, they were normalized using the z-score. k-means method requires a defined number of clusters (k) to be executed; the number k can be estimated from data (articles II, III) or can be defined a priori (article IV).

3. Cluster analysis validation: To validate cluster analysis both internal and external criteria were used. The internal validation criterion was used to choose the optimal number of clusters. In particular, the Silhouette was used to assess the strength of the class structure (articles II, III) (Rousseeuw 1987). In addition, the Principal Component Analysis was used to represent data in the space of the first two principal components in order to visualize formation of clusters (articles III, IV) (Everitt, Landau, Leese, & Stahl 2011). A priori the number of clusters was expected to be 3 to divide athletes according to their impact of impairment level in low, middle, and high (i.e. full, partial, or no trunk control). However, to keep analysis as general as possible and to avoid forced aggregation of elements, k-means was run with k in the range between 2 and 4, which is around the expected value, but lower than the current number of classes (which is 5). For each of the considered k model, the mean silhouette was calculated; coefficients ≤ 0.25 indicated no substantial structure, 0.26 - 0.5 weak structure, 0.51 - 0.7 reasonable structure, and ≥ 0.71 strong structure (Kaufman & Rousseeuw 2005). The k used for the analysis was identified as the highest mean silhouette (if the strength was identified from reasonable to strong) if the same number of groups were visible in Principal Component Analysis scatter plot. In the case that the highest mean silhouette would have been four, also higher values would have been tested.

   The external validation criterion was used to compare clustering results to a priori information and to assess how well the two matched (Xu & Wunsch 2008). The a priori information referred to the real athletes' classes and ability to control the trunk defined in the regulation (International Paralympic Committee 2018b). However, it should be remembered that the current classification is not evidence-based and thus it does not represent a gold standard. For this comparison, the number of clusters and classes had to be the same. If the number of clusters was lower than the number of classes, the five classes would be aggregated in k groups according to trunk control and balance ability defined in the regulation (International Paralympic Committee 2018b). The performance of the classifier was quantified calculating the accuracy, precision, and sensitivity

(Beleites, Salzer, & Sergo 2013). These indexes were respectively: the total number of participants classified coherently with the current classification system (accuracy), the percentage of athlete classified as belonging to a group among all the cases that the k means classify as belonging to that group (precision), and the percentage of athlete classified as belonging to a group among all the cases that truly belong to that group (sensitivity).

4. Variables relevance assessment: Mann-Whitney test (article II) and Kruskal Wallis test (Fisher's least significant difference post hoc) (articles III, IV) were applied to the variables to quantify how strongly they contribute in clusters discrimination and, thereby, to assess their relevance to the new model. To determine the meaningfulness of the variables, the effect size was calculated as correlation coefficient r (Tomczak & Tomczak 2014). To identify redundant variables Spearman correlation was used. In particular, the correlation was calculated in measures of performance (article III), between all the variables; in standardized measured of impairment between MVC variables of strength tests and between trunk control variables in Pert tests. The effect size and the Spearman correlation were interpreted using Cohen’s d: ≤ 0.40 small, 0.41 - 0.70 moderate, and ≥ 0.71 large (Cohen 1988). Statistics were performed using a custom made script in MatLab and statistical significance was set at an alpha of 0.05.

5 RESULTS

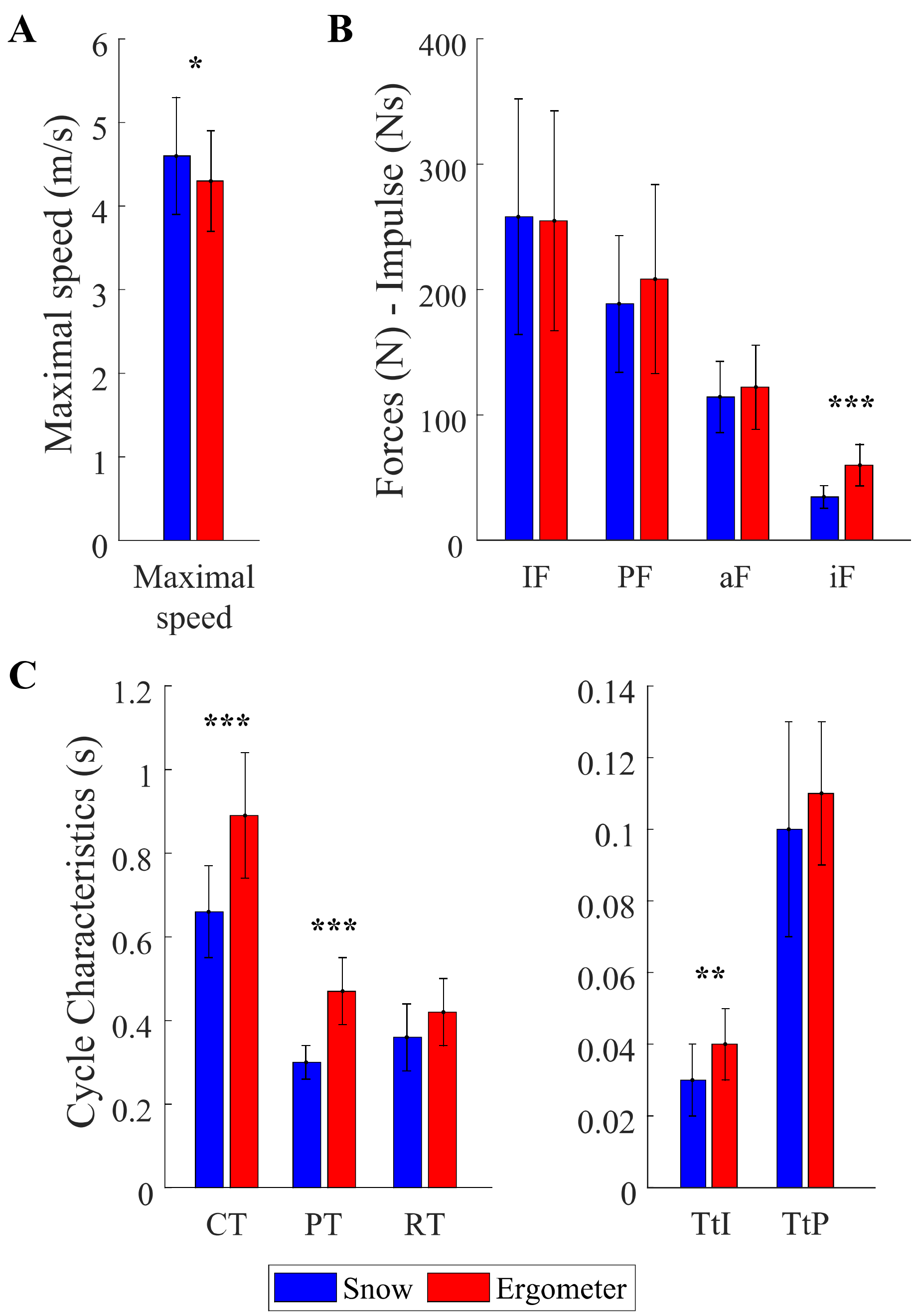
5.1 Biomechanical of XC sit skiers while skiing on snow and simulated action of poling on the ergometer (article I)

The biomechanics of XC sit skiers while skiing on snow and during simulated action of poling on an adapted ergometer was assessed and compared considering:

- maximal speed,
- force production,
- cycle characteristics,
- muscle activity.

Results for maximal speed, force production, and cycle characteristics in the two skiing conditions are reported as mean and standard deviation in Figure 25. Results for EMG peak and average for Tric, Pec, Lat, ES, RecAb are reported as a ratio between muscle activation skiing on snow and on the ergometer in Table 5; whereas onset and offset muscle activation are reported in Figure 26. Data from Obliquus Abdominis, Rectus Femoris, and Biceps Femoris muscles were not considered in the analysis because they were missing for most participants due to their physical conditions. Statistical differences between skiing on snow and skiing on the ergometer are reported as: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

While skiing on snow, athletes showed higher maximal speed ($p<0.05$), but lower iF ($p<0.001$), CT ($p<0.001$), PT ($p<0.001$), and TtI ($p<0.01$) compared to the simulated action of poling on the ergometer (Figure 25). A positive correlation between skiing on snow and simulated action poling on the ergometer was found in maximal speed ($r=0.79$, $p<0.001$), PF ($r=0.77$, $p<0.01$), aF ($r=0.78$, $p<0.01$), and TtI ($r=0.88$, $p<0.01$).



Variables legend: IF = impact force; PF = peak force; aF = average force; iF = impulse of force; CT = cycle time; PT = poling time; RT = recovery time; TtI = time to impact; TtP = time to peak

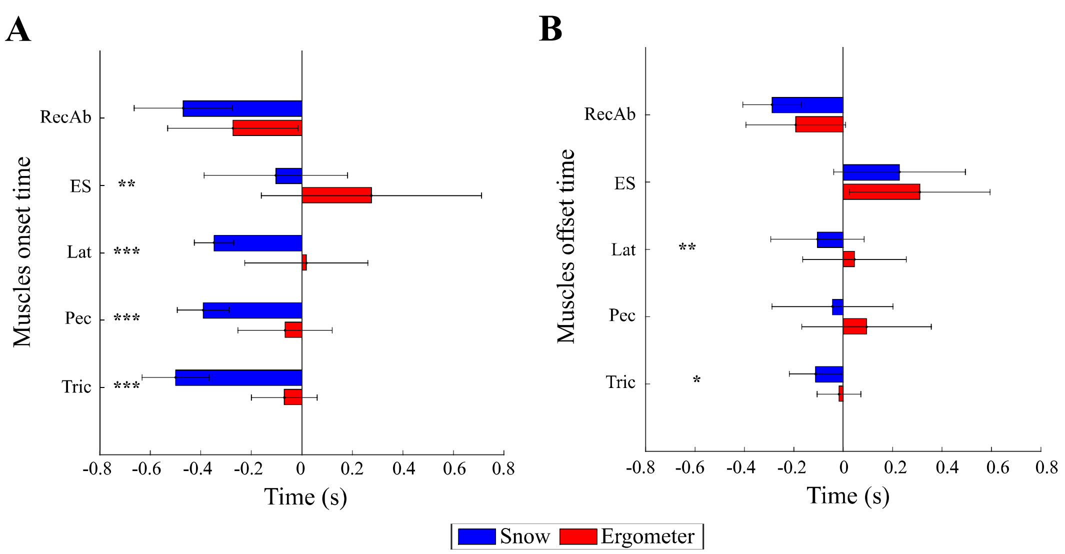
FIGURE 26 Results for biomechanical comparison between skiing on snow and simulated action of poling on the ergometer: (A) maximal speed, (B) generated force, (C) cycle characteristics

Overall, no statistical differences were found in both peak and average muscle activation between the two skiing conditions. The only exception was found for the lower activation for Lat ($p<0.05$) and RecAb ($p<0.05$) with athletes skiing on snow compared to the simulated action of poling on the ergometer (Table 5). A significant correlation between skiing on snow and simulated action poling on the ergometer was found for all muscles in EMG peak ($0.77<r<0.94$, $p<0.01$-0.05) and in EMG average ($0.65<r<0.80$, $p<0.01$-0.05).

TABLE 5 EMG ratio between muscle activation skiing on snow and on the ergometer

Muscles	ratio of EMG peak	ratio of EMG average
Tric	1.07±0.48	0.94±0.39
Pec	1.11±0.50	0.96±0.46
Lat	0.85±0.19*	0.80±0.22*
ES	1.12±0.26	1.40±0.53
RecAb	0.95±0.34	0.73±0.35*

When skiing on snow, athletes activated Tric ($p<0.001$), Pec ($p<0.001$), Lat ($p<0.001$), and ES ($p<0.01$) earlier than during simulated action of poling on the ergometer (Figure 26-A). On average, when athletes skiing on snow Tric ($p<0.05$) and Lat ($p<0.01$) were deactivated earlier than in simulated action of



Variables legend: Tric = Triceps; Pec = Pectoralis Major; Lat = Latissimus Dorsi; ES = Erector Spinae; RecAb = Rectus Abdominis

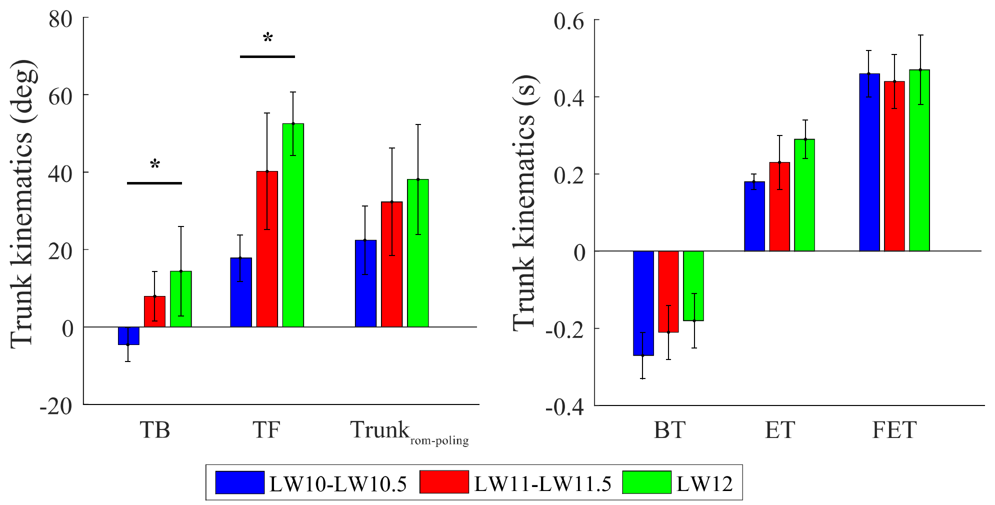
FIGURE 27 Results for skiing on snow and on the ergometer comparison: (A) onset delay and (B) offset delay

poling on the ergometer (Figure 26-B).

5.2 Trunk kinematics of athletes with different impairment in simulated action of poling on the ergometer

In addition to the results in the original articles, the trunk kinematics of XC sit skiers with different impact of impairment was assessed during simulated action of poling on an adapted ergometer. For the analysis, athletes were aggregated in three groups, which gather intermediate classes with the lower one: LW10-LW10.5 (N = 3), LW11-LW11.5 (N = 7), and LW12 (N = 6). Results for the trunk kinematic are reported in Figure 27. Statistical differences between groups are reported as: * $p<0.05$.

Results for TB showed that athletes with high impact of impairment (LW10-LW10.5) had the trunk close to vertical, whereas athletes with low impact of impairment (LW12) kept the trunk flexed ($p<0.05$, effect size = 0.63). Athletes with low impact of impairment reached greater TF compared to those with a high impact of impairment ($p<0.05$, effect size = 0.67).



Variables legend: TB = trunk maximal backward inclination; TF = trunk maximal forward inclination; Trunk $_{rom\text{-}poling}$ = trunk range of motion during the poling phase; BT = beginning of trunk movement; ET = end of trunk movement; FET = time to complete trunk flexion during the poling phase

FIGURE 28 Results for trunk kinematics of athletes with different impact of impairment

5.3 A new measure of performance (article III)

In addition to the results in the original articles, XC sit skiing performance of athletes skiing on snow in flat terrain using two different sitting positions (knee high and kneeling) was assessed with a cluster analysis applied on performance variables (in terms of maximal speed, generated force, cycle characteristics, and trunk kinematics) results. Using the most relevant variables identified in the previous analysis together with trunk kinematics variables, a cluster analysis was run to cluster athletes with different impact of impairment according to their performance during simulated action of poling on the ergometer (article III).

Results for the cluster analysis applied to performance variables while athletes are skiing on snow in flat terrain using two sitting positions are reported below:

(I) No outliers were found in the dataset using the method of mean plus or minus three standard deviations. Coefficient of variability for maximal speed was equal to 5%; whereas for all the other variables it was clearly higher than the threshold: IF = 26.0%, PF = 22.0%, aF = 22.0%, iF = 14%, CT = 17.0%, PT = 14.0%, RT = 26.0%, TtI = 43.0%, TtP = 27.0%.Therefore, all the variables were included in the cluster analysis.

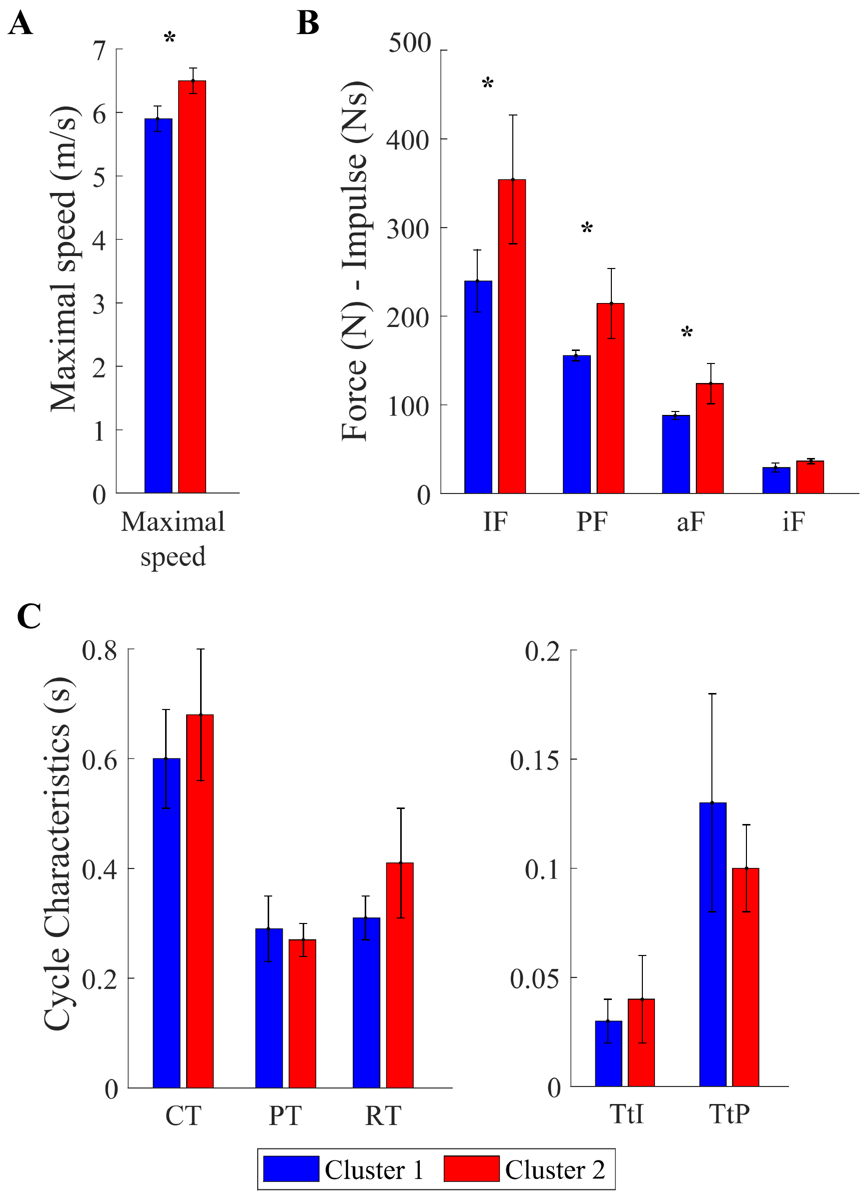
(II) and (III) Cluster analysis was run with a number of clusters between 2 and 4. Results of internal validation showed a peak for the mean silhouette in correspondence of 2 clusters: mean silhouette = 0.54, which correspond to a reasonable overall class structure. This result is corroborated by the principal component analysis results, which showed two clear and separate aggregations of data when data are reported in the space of the two principal components. Internal validation results divided athletes in knee high and kneeling sitting position. The external validation was assessed through the evaluation of the precision and sensitivity of the comparison between cluster analysis results with a priori information (real athletes' sitting positions). Results for external validation are reported in Table 6, showing very high sensitivity and precision for the two groups and clusters:

TABLE 6 A new measure of skiing performance on snow, cluster analysis external validation results

	Group_1 (knee high)	Group_2 (kneeling)	Precision
Cluster_1 (knee high)	3	0	100%
Cluster_2 (kneeling)	0	7	100%
Sensitivity	100%	100%	

(IV) Results for maximal speed, force production, and cycle characteristics variables for the two clusters are reported as mean and standard deviation values in Figure 28. Statistical differences between cluster_1 (knee high) and cluster_2 (kneeling) are reported as: * $p<0.05$.

Variable relevance showed that when skiing on snow, the most relevant variables in discriminating the two clusters were maximal speed ($p<0.05$, effect size = 0.65), IF ($p<0.05$, effect size = 0.72), PF ($p<0.05$, effect size = 0.72), and aF ($p<0.05$, effect size = 0.72). In contrast, cycle characteristic variables seem not to be relevant in clustering athletes.



Variables legend: IF = impact force; PF = peak force; aF = average force; iF = impulse of force; CT = cycle time; PT = poling time; RT = recovery time; TtI = time ti impact; TtP = time to peak

FIGURE 29 Results for variable relevance of a new measure of skiing performance in flat terrain on snow: (A) maximal speed, (B) generated force, (C) cycle characteristics

This section reports the results for the cluster analysis applied to performance variables calculated while athletes with different impact of impairment performed simulated action of poling on the ergometer (article III):

(I) No outliers were found in the dataset. Coefficient of variability for all variables was higher than 5%: Maximal speed = 14.7%, IF = 34.6%, PF = 35.6%, aF =27.5%, iF =28.4%, CT =16.4%, rPT = 6.6%, TB = 144.2%, TF = 39.4%,

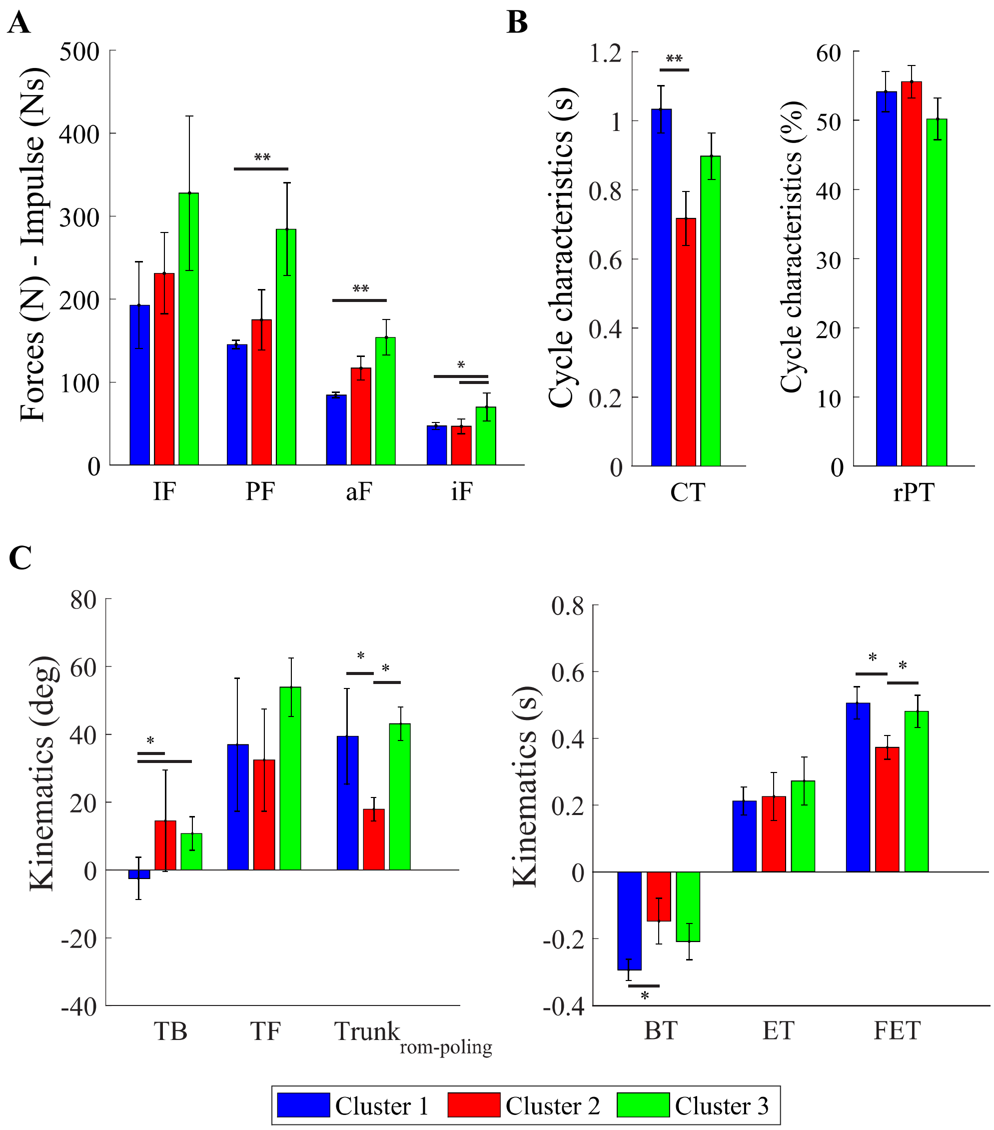
$Trunk_{rom\text{-}poling}$ = 40.4%, BT = 36.0%, ET =27.1%, FET = 15.6%; therefore all force and kinematic variables were included in the cluster analysis.

(II) and (III) Cluster analysis was run with a number of clusters in the range 2-4 and internal validation was assessed for each model. The internal validation showed that among the models the highest value for mean silhouette was found when 3 clusters were used: mean silhouette = 0.51, identifying a reasonable overall class structure. In addition, principal component analysis results clearly showed three aggregations of data when data are represented in the space of the first two components. Internal validation results divided athletes in high, middle, and low impact of impairment. Then the external validation was assessed evaluating precision and sensitivity of the comparison between cluster analysis results with a priori information (real athletes' ability to control the trunk). Results for external validation are reported in Table 7, showing an overall accuracy of 69% and high to very high sensitivity and precision for the three groups and clusters:

TABLE 7 A new measure of skiing performance on the ergometer, cluster analysis external validation results

	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%	

(IV) Results for generated force, cycle characteristics, and kinematics for the three clusters are reported as mean and standard deviation values in Figure 29. Statistical differences between cluster_1 (high impairment), cluster_2 (middle impairment), and cluster_3 (low impairment) are reported as: * $p<0.05$.



Variables legend: IF = impact force; PF = peak force; aF = average force; iF = impulse of force; CT = cycle time; rPT = relative poling time; TB = trunk maximal backward inclination; TF = trunk maximal forward inclination; $\text{Trunk}_{\text{rom-poling}}$ = trunk range of motion during the poling phase; BT = beginning of trunk movement; ET = end of trunk movement; FET = time to complete trunk flexion during the poling phase

FIGURE 30 Results for variable relevance of a new measure of skiing performance on the ergometer: (A) generated force, (B) cycle characteristics, (C) trunk kinematics

Variables relevance showed that when athletes simulated the poling action on the ergometer, the maximal speed contributed in discriminating between cluster_1 and cluster_3 (p<0.01, effect size = 0.86). Concerning generated force, PF (p<0.01, effect size = 0.91), aF (p<0.01, effect size = 0.88), and iF (p<0.01, effect size = 0.81) discriminated between cluster_1 and cluster_3; iF discriminated also between cluster_2 and cluster_3. Concerning the cycle characteristics, CT distinguish between cluster_1 and cluster_2 ($p<0.01$, effect size = 0.88). Concerning kinematic variables, TB discriminated between cluster_1 and the other two clusters ($p<0.05$, effect size = 0.69) and $Trunk_{rom\text{-}poling}$ discriminated between cluster_2 than the other two clusters ($p<0.05$, effect size = 0.77). FET contributed to distinguish between cluster_2 and the other two clusters ($p<0.02$, effect size = 0.78); whereas BT discriminated between cluster_1 and cluster_2 only ($p<0.05$, effect size = 0.76).

Concerning the Spearman correlation, a significant correlation was found between maximal speed and force variables ($0.64<r<0.96$, $p<0.05$) and between the four force variables ($0.64<r<0.91$, $p<0.05$). Significant correlations were also found between cycle characteristics and trunk kinematics variables. In particular, CT correlated with TB ($r = -0.67$, $p<0.01$), BT ($r = -0.86$, $p<0.001$), and FET ($r = 0.81$, $p<0.001$); whereas rPT correlated with TF ($r = -0.62$, $p<0.05$) and $Trunk_{rom\text{-}poling}$ ($r = -0.64$, $p<0.05$). BT and ET correlated respectively with TB ($r = 0.71$, $p<0.01$) and TF ($r = 0.64$, $p<0.05$); whereas FET correlated with $Trunk_{rom\text{-}poling}$ ($r = 0.73$, $p<0.01$) and BT ($r = -0.63$, $p<0.05$).

5.4 A new measure of impairment of trunk control (article II)

The new measure of trunk impairment consisted of the evaluation of temporal and kinematic variables during unpredictable balance perturbations in forward and backward directions. The results of these variables were used to run a cluster analysis to group athletes according to their impact of impairment. Cluster analysis was composed of four steps which results are reported below:

(I) No outliers were found in the data set. Coefficient of variability for all variables was: DLY1 (forward) = 1.4%, DLY1 (backward) = 2.4%, DLY2 (forward) = 34.7%, DLY2 (backward) = 23.7%, $Trunk_{rest}$ = 142.7%, $Trunk_{150}$ (forward) = 23.4%, $Trunk_{150}$ (backward) = 47.1%, $Trunk_{rom\text{-}pert}$ (forward) = 28.7%, $Trunk_{rom\text{-}pert}$ (backward) = 11.6%. Since coefficient of variability for DLY1 in both forward and backward directions was lower than the threshold value (5%), this variable was discarded from the cluster analysis.

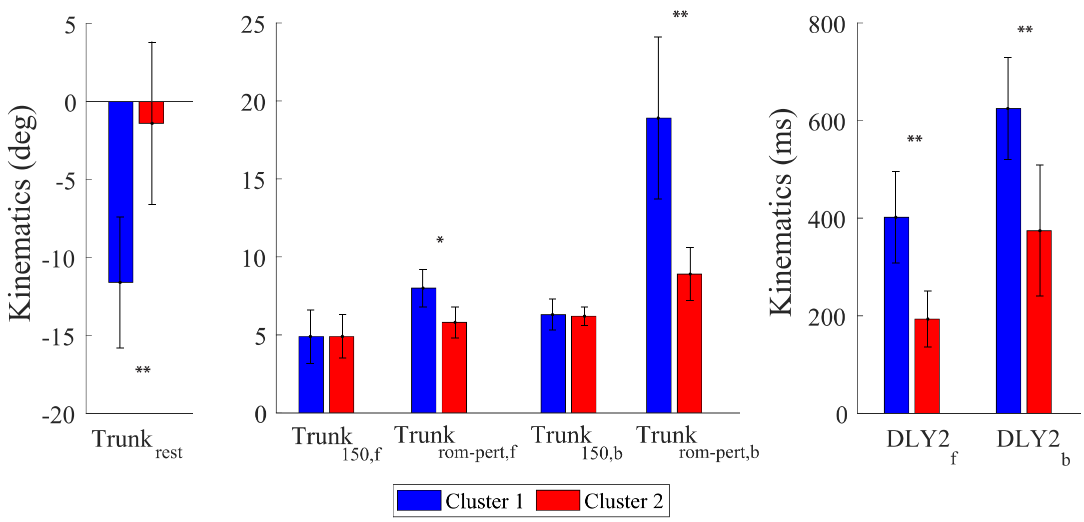
(II) and (III) Cluster analysis was run with a number of clusters in the range 2-4 and for each model the internal validation was assessed using the mean silhouette. The highest value for the mean silhouette was reached for a number of clusters equal to two (silhouette = 0.52, reasonable overall class structure) dividing athletes in high and low impact of impairment. Results for the external validation are reported in Table 8, showing accuracy of 80% and high sensitivity and precision for the two groups and the two clusters:

TABLE 8 A new measure of trunk impairment, cluster analysis external validation results

	Group 1 (LW10-LW11)	Group 2 (LW11.5-LW12)	Precision
Cluster 1 (high impact of impairment)	4	1	80%
Cluster 2 (low impact of impairment)	2	8	80%
Sensitivity	67%	89%	

(IV) Results for trunk kinematic for the two clusters are reported as mean and standard deviation values in Figure 30. Statistical differences between cluster_1 (high impact of impairment) and cluster_2 (low impact of impairment) are reported as: * $p<0.05$, ** $p<0.01$.

Variables relevance showed that the most relevant variables in discriminating between the two clusters were: $Trunk_{rest}$ ($p<0.01$, effect size = 0.71), $Trunk_{rom\text{-}pert}$ in forward ($p<0.05$, effect size = 0.59) and in backward ($p<0.01$, effects size = 0.74) stimuli, and DLY2 in forward ($p<0.01$, effect size = 0.77) and backward ($p<0.01$, effects size = 0.64). In contrast, $Trunk_{150}$ seemed not to be relevant in discriminating between clusters.



Variables legend: $Trunk_{rest}$ = trunk angle at rest; $Trunk_{150}$ = trunk range of motion 150 ms after the stimulus; $Trunk_{rom\text{-}pert}$ = trunk range of motion at the inversion; DLY2 = delay between the should acceleration onset and the time when the trunk inverted the motion; f = forward; b = backward

FIGURE 31 Results for trunk kinematic variables relevance of a new measure of impairment of trunk

5.5 Measure of impairment of strength and trunk control for purpose of classification (article IV)

A new testing device was proposed to assess impairment of strength and impairment of trunk control through three MVC tests and one Pert test respectively. The MVC protocol consisted of two simulated bench press tests and one simulated poling test; Pert test consisted of one balance control test at three different accelerations. To test for the adequacy of the protocol a pilot study was done involving one athlete LW10.5, which is one of the most severe impairment. Then, the protocol was extended to a greater number of XC sit athletes. Firstly, it was assessed if the proposed tests can be used for the purpose of classification, then generated force and trunk kinematics results were used to run a cluster analysis to group athletes according to their impact of impairment (article IV).

Results for the pilot study conducted on the athlete LW10.5 showed that the proposed protocol is also suitable for athletes with high impact of impairment without any particular drawbacks, especially feeling pain at the buttock related to the absence of padding on the seat. In addition, no particular risks were highlighted for the athletes; indeed no appreciable slips were observed during perturbations of the balance test, even at higher accelerations.

Results for the test protocol extended to 14 XC sit skiers with different impact of impairment are reported here. To assess if measures of impairment can be used for purpose of classification, test-retest reliability was calculated. None of the variables showed a statistical difference between day 1 and day 2. MVC variables showed high to very high ICC and small SEM: PFa_{wo} (ICC = 0.93, p<0.001; SEM = 49.8 N), PFa_{w} (ICC = 0.98, p<0.001; SEM = 44.6 N), PFp_{w} (ICC = 0.95, p<0.001; SEM = 80.7 N), PF_{p} (ICC = 0.94, p<0.001; SEM = 33.0 N), $\left(\frac{MVC_{wo}}{MVC_{w}}\right)$ (ICC = 0.71, p<0.05; SEM = 0.1). For Pert variables, very high ICC was found for $Trunk_{rom\text{-}pert}$ in the three accelerations and both stimuli directions (0.94<ICC<0.96, p<0.001) and for DLY2 at 1 m/s^2 and 2.5 m/s^2 in both stimuli directions (0.83<ICC<0.99, p<0.001-0.01); whereas $Trunk_{rest}$ did not show significant ICC. SEM was low for all variables in the three Pert accelerations. Spearman correlation results showed negative moderate correlations between PFa_{wo} and $Trunk_{rom\text{-}pert}$ for all accelerations and stimuli directions (-0.54<r<-0.76, 0.01<p<0.05). In the case of acceleration equal to 1 m/s^2, a correlation was also found between $Trunk_{rom\text{-}pert}$ and PFa_{w} (-0.55<r<-0.58, p<0.05) and between $Trunk_{rom\text{-}pert}$ and $\frac{PFa_{wo}}{PFa_{w}}$ (-0.56<r<-0.57, p<0.05).

Results of MVC and Pert tests day 1 were used to run a cluster analysis to group athletes according to their impact of impairment. Results of the four steps of the cluster analysis are reported below:

(I) No outliers were found in the data using the mean plus or minus three standard deviations. Coefficient of variability was higher than 5%, set as threshold, for all the MVC and Pert variables; therefore all of them were included in the cluster analysis.

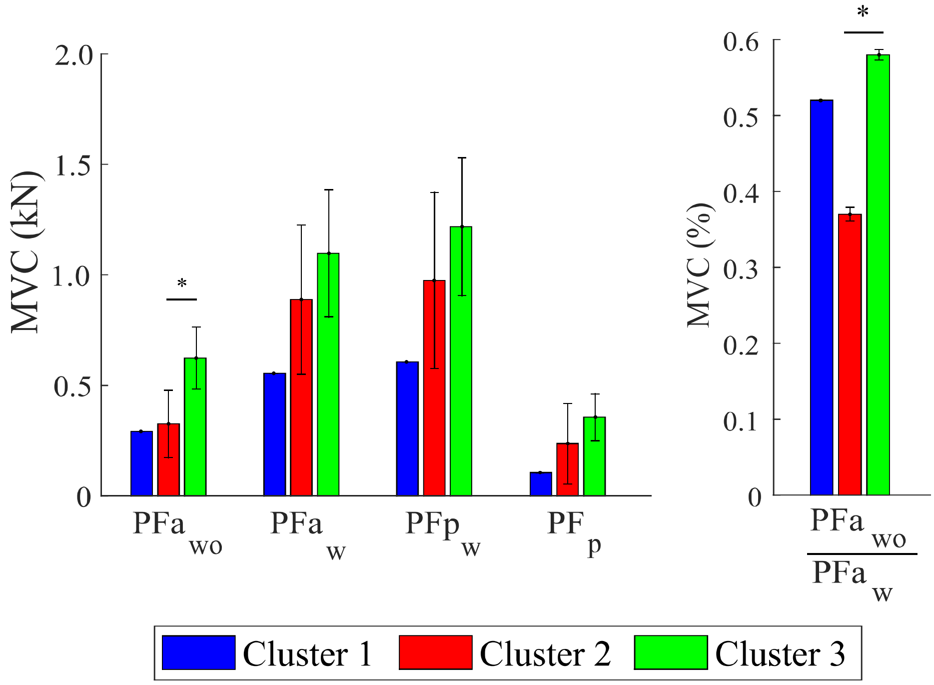
(II) and (III) Cluster analysis was run with three clusters. Internal validation, using the principal component analysis, showed three clear aggregations of data when data are reposted in the space of the first two components. Internal validation results divided athletes in high, middle, and low impact of impairment. For the external validation, results about precision and sensitivity of the comparison between cluster analysis output with a priori information on real athletes' classes are reported in Table 9, showing accuracy equal to 86% and high to very high sensitivity and precision for the three groups and clusters.

TABLE 9 Standardization of the new measures of impairment, cluster analysis external validation results

	Group_1 (LW10-LW10.5)	Group_2 (LW11)	Group_3 (LW11.5-LW12)	Precision
Cluster_1 (high impact of impairment)	1	0	0	100%
Cluster_2 (middle impact of impairment)	0	2	2	50%
Cluster_3 (low impact of impairment)	0	0	9	100%
Sensitivity	100%	100%	81.8%	

(IV) Results for trunk strength for the three clusters are reported as mean and standard deviation in Figure 31. Results for trunk kinematics for the three clusters are reported as mean and standard deviation in: Figure 32 for perturbations 0.5 m/s^2, Figure 33 for perturbations 1 m/s^2, and Figure 34 for perturbations 2.5 m/s^2. Statistical differences between cluster_1 (high impact of impairment), cluster_2 (middle impact of impairment), and cluster_3 (low impact of impairment) are reported in all the figures as: * p<0.05, ** p<0.01.

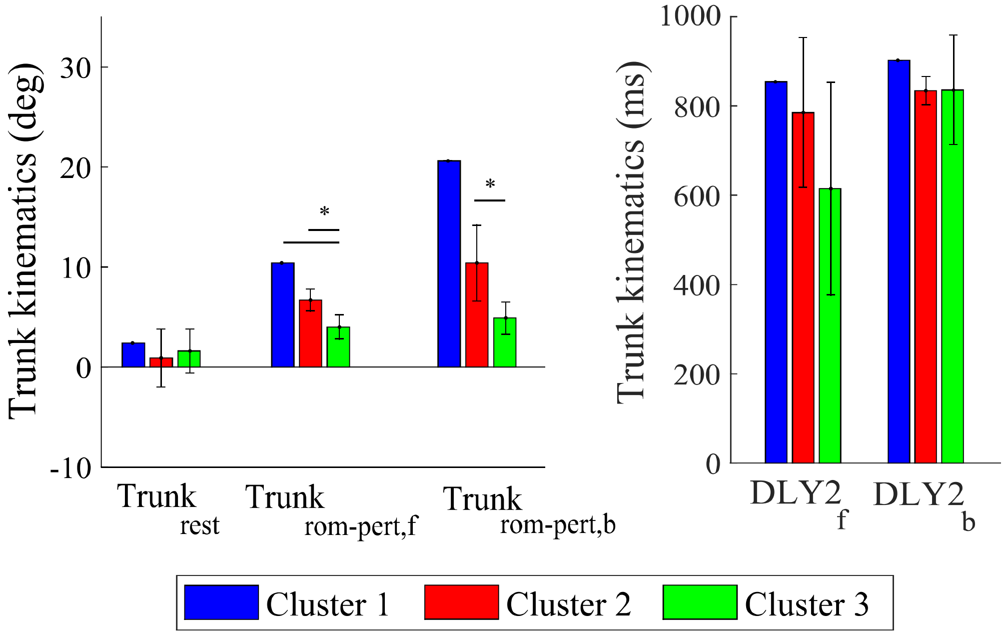
For MVC, variables relevance showed that PFa_{wo} ($p<0.02$, effect size = 0.77) and $\frac{PFa_{wo}}{PFa_{w}}$ ($p<0.03$, effect size = 0.72) discriminated between cluster_2 and cluster_3.



Variables legend:
PFa_{wo} = anterior force in simulated bench press without backrest; PFa_{w} = anterior force in simulated bench press with backrest; PFp_{w} = posterior force in simulated bench press with backrest; PF_{p} = average pulling force in simulated poling;

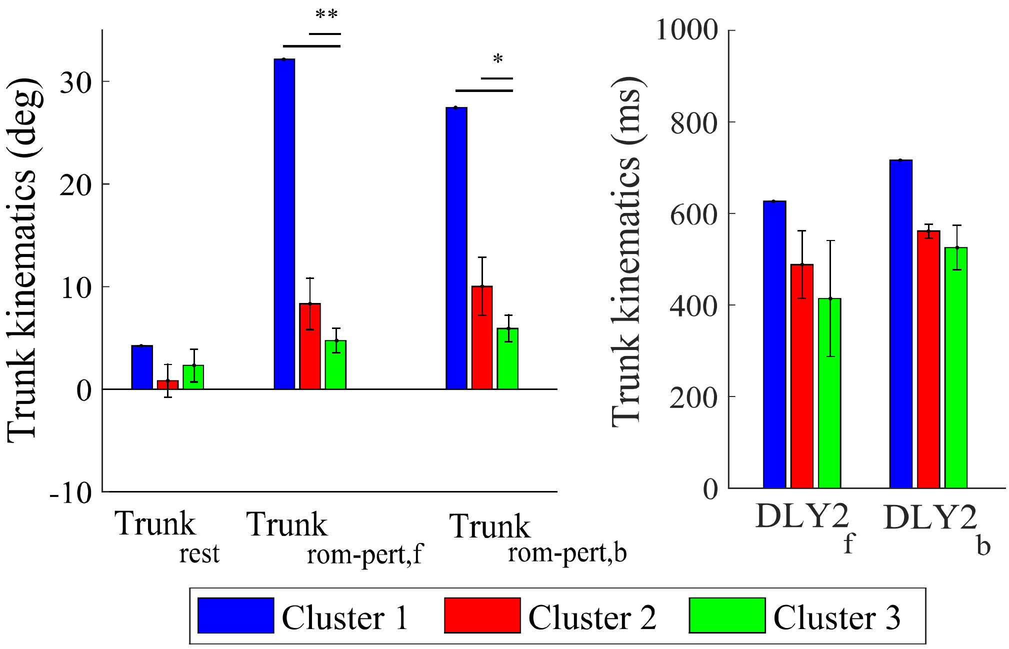
FIGURE 32 Results for variables relevance of the new standardized measure of impairment of trunk for trunk strength tests

Concerning Pert test, the variable $Trunk_{rom\text{-}pert}$ was the most relevant variable because overall it was able to discriminate between cluster_1 and cluster_3 and between cluster_2 and cluster_3. At 0.5 m/s^2 (Figure 32), $Trunk_{rom\text{-}pert}$ discriminated between cluster_3 and the other two clusters in forward stimuli ($p<0.02$, effect size = 0.75) and between cluster_2 and cluster_3 in backward stimuli ($p<0.04$, effect size = 0.69). At 1 m/s^2 (Figure 33), $Trunk_{rom\text{-}pert}$ discriminated between cluster_3 and the other two clusters in forward stimuli ($p<0.01$, effect size = 0.81) and backward stimuli ($p<0.02$, effect size = 0.75). At 2.5 m/s^2 (Figure 34), $Trunk_{rom\text{-}pert}$ discriminated between cluster_3 and the other two clusters in backward stimuli ($p<0.01$, effect size = 0.81) and DLY2 discriminated between cluster_2 and cluster_3 in backward stimuli ($p<0.02$, effect size = 0.77).



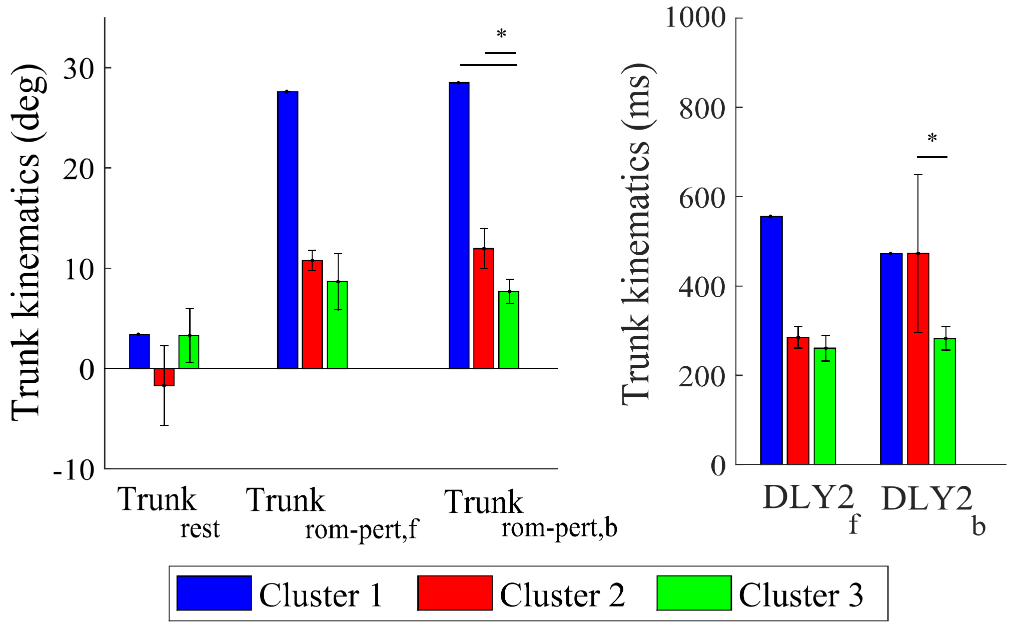
Variables legend: $Trunk_{rest}$ = trunk angle at rest; $Trunk_{rom\text{-}pert}$ = trunk range of motion at the inversion;
f = forward; b = backward

FIGURE 33 Results for variables relevance of the new standardized measure of impairment of trunk control tests for perturbations 0.5 m / s²



Variables legend: $Trunk_{rest}$ = trunk angle at rest; $Trunk_{rom\text{-}pert}$ = trunk range of motion at the inversion;
f = forward; b = backward

FIGURE 34 Results for variables relevance of the new standardized measure of impairment of trunk control tests for perturbations 1 m / s²



Variables legend: $Trunk_{rest}$ = trunk angle at rest; $Trunk_{rom\text{-}pert}$ = trunk range of motion at the inversion; f = forward; b = backward

FIGURE 35 Results for variables relevance of the new standardized measure of impairment of trunk control tests for perturbation 2.5 m / s^2

6 DISCUSSION

The purpose of this thesis was to evaluate the biomechanics of cross-country sit skiers with different impact of impairment in order to propose a measure of performance and a measure of impairment that can be used for the purpose of classification in order to develop an evidence-based classification system for XC sit skiing. The main findings of these studies were:

(I) Comparing skiing on snow and simulated action of poling on the ergometer, athletes showed no differences in generated force and in upper body muscle activity. In addition, a good correlation was found between the two skiing conditions in maximal speed, generated force, and muscular activity (article I). With a special focus on trunk kinematics during simulated action of poling on the ergometer, athletes with low impact of impairment kept trunk with a more forward inclination during the entire poling cycle compared to athletes with high impact of impairment.

(II) The use of a cluster analysis applied on performance determinants results showed good outcomes for grouping athletes according to their performance when athletes skied on snow and during simulated action of poling on the ergometer (article III). When skiing on snow, two clusters of athletes were found, which reflected the two most used sitting positions: kneeling and knee high. Overall, athletes skiing in kneeling position had higher maximal speed and generated greater force than athletes seated in knee high position. In simulated action of poling on the ergometer, three clusters of athletes were found: high, middle, and low impact of impairment (article III). Athletes with low impact of impairment showed higher maximal speed and generated greater force than athletes with high impact of impairment. Compared to the others, athletes with high impact of impairment needed more time to execute poling cycles and to complete a trunk flexion-extension cycle. Athletes with low and middle impact of impairment kept trunk flexed during the poling phase, whereas athletes with high impact of impairment start the poling phase with trunk slightly extended. The smallest trunk range of motion was showed by athletes with middle impact of impairment.

(III) The use of a cluster analysis applied to impairment results showed different results for grouping athletes according to their impact of impairment in case of athletes' personal sit-ski or a standardized seat was adopted. When their personal sit-ski was used, only impairment of trunk control was assessed (article II). In this case, two clusters of athletes were found: high and low impact of impairment. At rest, athletes with low impact of impairment have a trunk position close to vertical, whereas athletes with high impact of impairment have an extended trunk position. During unpredictable forward and backward perturbations, athletes with low impact of impairment needed less time to stop and invert trunk motion, showing smaller trunk range of motion than athletes with high impact of impairment. When a standard seat was used, both impairment of strength and trunk control were assessed (article IV). In this case, three clusters of athletes were found: high, middle, and low impact of impairment. During maximal voluntary contraction tests, athletes with low impact of impairment showed higher level of generated force than athletes with middle impact of impairment. During unpredictable forward and backward perturbations at different accelerations, athletes with low impact of impairment showed the smallest trunk range of motion, whereas athletes with high impact of impairment showed the greatest. Overall, very high reliability was found for measure of strength and measure of trunk control.

6.1 Biomechanics of XC sit skiers while skiing on snow and in simulated action of poling on the ergometer (article I)

Compared to able bodied athletes, skiing technique and biomechanics of XC sit skiers is less extensively investigated and the few existing studies are focused on the kinematic evaluation of athletes while skiing on snow using markerless video analysis (Bernardi et al. 2013, Gastaldi et al. 2012, Gastaldi et al. 2013, Gastaldi et al. 2016). However, these studies highlight the difficulties in conducting tests on snow obtaining accurate, precise, and comparable results due to the high variability of natural environmental conditions. For this reason, standardized and less technologically demanding procedures for testing and training XC sit athletes were developed. Laboratory tests, simulating the action of poling on the ergometer, were performed by able bodied athletes showing very good reliability for ergometer power output and for validity in relation to skiing on snow (Holmberg & Nilsson 2008). Biomechanics of able bodied athletes on the ergometer showed a strong correlation in force production, muscle activation, and impact of fatigue when compared to skiing on snow (Halonen et al. 2014). For athletes with physical impairment, simulated action of poling on the ergometer showed similar peak oxygen consumption, but higher peak heart rate, respiratory exchange ratio, and blood lactate due to the constant resistance of the ergometer compared to the varying speeds and slopes that athletes encountered on snow (Forbes et al. 2010). In alternative to the ergometer a large treadmill has already been used to evaluate biomechanics of XC skiers (Holmberg et al. 2005), but an ergometer is usually used more in indoor training and it can be easily moved for classification purposes. Indeed, most of the sit athletes who volunteer in this study usually train with an adapted ergometer. Because of the importance of ergometer in training and due to the lack of biomechanical analysis of XC sit skiers, a comparison of the biomechanics of skiing on snow and simulated action of poling was conducted.

6.1.1 Maximal speed

To compare the biomechanics of XC sit skiers, maximal speed test was adopted. This strategy is named “all out” and was chosen because of its importance in race: athletes start with a high speed and try to keep velocity as high as possible during the race (Bernardi et al. 2013). Although lower maximal speed was obtained on the ergometer than on snow, the positive correlation between the two skiing conditions means that athletes with better performance on snow also had a greater performance on the ergometer making the two skiing conditions comparable. Also able bodied athletes showed lower maximal speed on the ergometer than on snow probably because of the air resistance system of the ergometer (Halonen et al. 2014).

6.1.2 Generated force

In force generated during the poling phase, standing able bodied athletes showed a first peak at the ground impact followed by a sharp rate of force development to a higher peak force (Holmberg et al. 2005). Differently, sitting athletes with physical impairment showed higher value of force generated at the impact and then smaller peak force. This very high impact force is coherent with the pre-activation of Pectoralis, Rectus Abdominis, and Latissimus muscles, which are activated earlier than the generation of force. Indeed, this activation would increase core stiffness, preparing upper body for the impact and stabilizing upper limbs joints to increase the propulsion at the beginning of the subsequent pushing phase (Holmberg et al. 2005). The higher force at the impact of the poles with the ground or snow may be also due to kinematics of sitting position that may influence the position of poles tip with respect to the sit-ski and poles bending during the ground contact and, subsequently, force transmitted to the ground during the poling phase. However, to verify this assumption, force direction and upper body kinematics should be evaluated. Athletes’ kinematics during simulated action of poling was collected; however, kinematics while skiing on snow was not acquired because of difficulties related in obtaining accurate video analysis data in extreme environment conditions due to temperature, humidity, and track profiles. Overall, the lack of differences and the high correlation between skiing on snow and on the ergometer in impact force and peak force is coherent to what was previously found when able bodied athletes were skiing in these two conditions (Halonen et al. 2014).

6.1.3 Cycle characteristics and muscle activity

The longer cycle time and poling time found on the ergometer compared to skiing on snow and the similar duration of the recovery phase are in agreement with previous studies on able bodied athletes (Pellegrini et al. 2005, Halonen et al. 2014). The longer duration of pushing cycle may be due to the air resistance system of the ergometer, which is coherent with the lower maximal speed (Halonen et al. 2014). A second reason could be related to the elastic return of the flywheel on the ergometer and, thereby, to different kinematics between ergometer and skiing on snow. Because of the elastic return, upper limbs might reach a more extended elbow angle and higher wrist position at the end of the recovery phase on the ergometer compared to snow, which is coherent with the later deactivation of Triceps and Latissimus muscle on the ergometer. Then, in the following poling phase, the first part of elbow flexion might be similar to a pull-up movement (Stöggl, Lindinger, & Müller 2006). This explanation would justify the higher Latissimus activation during the poling phase on the ergometer compared to skiing on snow, in which the Latissimus works as extensor muscle at the very beginning of the poling phase (Holmberg et al. 2005). Other than influence cycle time, the elastic return of the ergometer would explain also the later activation of Triceps, Pectoralis, Latissimus, and Erector Spinae on the ergometer compared to snow. Despite the difference in onset time, muscles activation pattern is similar between ergometer and snow: before Triceps and Pectoralis and later Latissimus and Erector Spinae. In addition, high correlation was found in muscle activity between ergometer and snow.

6.2 Trunk kinematics in simulated action of poling on the ergometer

All sitting athletes have impairment at the lower part of the body, but different ability to control the trunk; therefore athletes are divided in the five classes (International Paralympic Committee 2018b). Since trunk flexion and extension movements contribute significantly in propulsive force enhancement and reducing muscular fatigue onset (Vanlandewijck, Theisen, & Daly 2001), trunk kinematics has been extensively evaluated in athletes' classification using tests such as test-table-test (Pernot et al. 2011). During this test, athletes are strapped to a board by three belts at the level of pelvis, knees, and ankles and are supported by cushions under knees and feet. The test consisted of four tasks: trunk flexion of 45 deg, trunk extension of 45 deg, to lift a ball above the head, and maximum trunk rotation. These kinds of tests are used in the current classification system to evaluate general athletes' balance ability, but no tests evaluate trunk kinematics in specific sport gestures. Previous studies assessed athletes' kinematic while skiing on snow comparing different classes (Gastaldi et al. 2012, Karczewska-Lindinger et al. 2016) and athletes' experience (Bernardi et al. 2013). However, because of the technological difficulties in conducting accurate measures on snow (Gastaldi et al. 2012) and because of the good biomechanical agreement between skiing on snow and on the ergometer (article I), simulated action of poling on the ergometer could be used to assess trunk kinematics of athletes with different impact of impairment in more controlled environment conditions. In addition to what was shown in the original articles, trunk kinematics was evaluated gathering intermediate classes together with the lower one: athletes with no or limited trunk control and no balance ability (LW10-LW10.5), athletes with fair of near to normal trunk control and balance ability (LW11-LW11.5), and athletes with complete trunk control because of lower limbs amputation (LW12).

Results of this evaluation showed that amputee athletes had trunk forward inclination during the entire poling cycle, whereas athletes with no or limited trunk control started the poling phase with the trunk close to vertical and reached smaller trunk flexion at the end of the poling phase. These results are in line with previous findings for sitting athletes skiing on snow: trunk with a forward inclination during the poling phase for athletes with complete trunk control (Gastaldi et al. 2012, Karczewska-Lindinger et al. 2016) and trunk close to vertical for athletes with no or limited trunk control (Gastaldi et al. 2012). The ability of athletes with high trunk control to keep trunk in a forward inclination during the poling phase, allow their shoulders and elbows to work in a less extreme position, increase control on pole inclination, and reduce air drag; therefore allows to generate greater force limiting fatigue (Gastaldi et al. 2012). In contrast, athletes with no or limited trunk control use straps to keep the trunk in a more vertical position compensating for lack of core muscles in the stabilization and balance on the sit-ski (Gastaldi et al. 2012). Because of this constraint, those athletes take advantage from the gravity force to flex the trunk, whereas to recovery the initial trunk position they use compensation mechanisms that exploit head, arms and upper trunk inertia (Gastaldi et al. 2012, Gastaldi et al. 2016).

Somewhat unexpected results occurred with trunk range of motion. Despite trunk range of motion increased while increasing classes, no significant statistical differences were found among the three groups. A difference between groups was expected because in previous studies greater trunk range of motion was found for athletes LW12 than LW10 (Gastaldi et al. 2012, Karczewska-Lindinger et al. 2016). The absence of statistical difference in trunk range of motion could be due to three aspects. The first aspect could be how athletes of different classes were gathered in the three groups. For the analysis athletes were grouped according to the description of trunk control and balance ability, keeping athletes with lower limbs amputation (LW12) as a separate class because of their complete ability to control the trunk. LW10 and LW10.5 were brought together because of no or limited trunk control and absent ability to keep balance; whereas LW11 and LW11.5 were combined because of fair or near to normal trunk control and ability to keep balance. However, it might be that athletes of intermediate classes were not grouped appropriately. In particular, athletes LW11.5, because of their near to normal trunk control, may have been gathered with athletes LW12 instead of athletes LW11, which have only fair trunk control. The lack of difference may also be influenced by the model used to calculate trunk range of motion: the trunk was approximated to a single, rigid segment with a joint at the hip level. This choice was taken because it is a common practice to calculate trunk motion as the angle between the vertical line and a line between the acromion and the great trochanter (Vanlandewijck et al. 2001). However, this approximation did not consider spinal flexion due to relative vertebrae movements, shoulder protraction and retraction, and straps that fixed trunk at the lumbar or thorax level limiting movements of trunk lower part. Considering a model composed of more than one single, rigid segment placing for example markers at the thorax level or using different acquisition system, such as inertial sensors, may improve trunk movement accuracy and can have effects on trunk range of motion when different classes are compared. Finally, the last reason for the lack of difference could be related to the large standard deviation and low number of athletes for each group that may allow identifying only the greatest differences between groups, missing others such as trunk range of motion.

6.3 A new measure of performance (article III)

It has been stated that the development of sport-specific test to measure performance is guided by three requirements:

- outcome of the test should be highly predictive of overall performance in the sport,
- outcome measure should be sensitive to different impairment,
- factors that are not classified should have minimal influence on measure (Tweedy et al., 2016).

Since skiing on snow in kneeling sitting position allows athletes to have great performance compared to skiing in knee high position (Gastaldi et al. 2012, Karczewska-Lindinger et al. 2016, Schillinger et al. 2016), the most relevant variables that allow to discriminate athletes according to their performance while skiing on snow in flat terrain using different sitting positions were investigated using k-means cluster analysis. In a second step, this set of variables together with trunk kinematics were used to group athletes with different impact of impairment according to their performance during simulated action of poling on the ergometer.

6.3.1 Performance of skiing on snow

Cluster analysis divided athletes according to their performance in two clusters, which reflected real athletes' sitting position (knee high and kneeling) with very high precision and sensitivity assuring the validity of cluster analysis results. Cluster analysis identified maximal speed and generated force (impact force, peak force, and average force) as the most relevant variables; whereas cycle characteristics seemed not to be relevant in discriminating athletes according to their performance on snow in flat terrain. Maximal speed and generated force results were expected, whereas cycle characteristics output was unforeseen. When skiing on snow, a positive correlation between maximal speed and classes was found, showing higher speed for athletes LW12 compared to athletes LW10 (Karczewska-Lindinger et al. 2016). Since usually athletes in class LW12 sit in kneeling position and athletes LW10 sit in knee high position, results on maximal speed and generated force of the present study are in line with the literature (Karczewska-Lindinger et al. 2016). Also able bodied athletes who simulated action of poling on the ergometer sitting in kneeling position reached higher speed (Lappi 2014, Rapp et al. 2014, Rapp et al. 2016) and higher generated force compared to knee high sitting position (Lajunen 2014). In contrast, two studies (Hofmann et al. 2016, Lund Ohlsson & Laaksonen 2017) did not find differences in generated force between knee high and kneeling sitting position; however their results cannot be compared to the present findings since in these studies athletes seated kneeling position had the trunk leaning forward on a support. Overall, the higher speed and generated force found when athletes were seated in kneeling position might be due to the higher trunk control of these athletes, which allow them to better stabilize their trunk on the sit-ski and to increase their trunk movements. Indeed, athletes with near to normal and normal trunk control (LW11.5-LW12) lean the trunk more forward reducing shoulder extension (Gastaldi et al. 2012, Karczewska-Lindinger et al. 2016), keep poles closer to the ground increasing the horizontal component of the propulsive force (Schillinger et al. 2016), and reduce poling frequency preventing fatigue (Karczewska-Lindinger et al. 2016). In contrast, the low contribution of cycle characteristics in discriminating between cluster_1 and cluster_2 was somewhat unexpected, because it was previously found longer relative recovery time for athletes of class LW12 compared to the class LW10 while skiing on snow (Schillinger et al. 2016). In addition, able bodied athletes skiing on the ergometer while seating in knee high position increase cycle rate reducing recovery time in order to reach higher skiing speed (Lajunen 2014). This lack of relevance for cycle characteristics may be due to the small sample size, which increase the variability.

6.3.2 Performance of simulated action of poling on the ergometer

The set of variables identified as most relevant to discriminate athletes according to their skiing performance on snow was used also on the ergometer. In addition to maximal speed and generated force variables, also cycle characteristics were used. This choice was due to the fact that the low relevance of cycle characteristic variables in discriminating clusters based on skiing performance on snow was not expected and may be due to small sample size instead of real absence of difference between clusters. In addition to maximal speed, generated force, and cycle characteristics, trunk kinematics was included in the analysis because of its important role in increasing performance (Gastaldi et al. 2012).

Cluster analysis divided athletes in three clusters (low, middle, and high impact of impairment), which correspond to real athletes' impairment with high accuracy, precision, and sensitivity. Cluster analysis identified: maximal speed, peak force, average force, impulse of force, cycle time, trunk maximal backward inclination, trunk range of motion, and trunk flexion time as the most relevant variables to group athletes with different impact of impairments according to their performance. The higher maximal speed and generated force together with the lower cycle time of athletes with low impairment compared to athletes with middle and high impairment is in line with the literature that identified higher generated force and lower cycle time as methods to increase the maximal speed (Lindinger, Stoggl, Müller, & Holmberg 2009). Force results are in line with the previous findings on athletes skiing on snow using kneeling and knee high sitting positions (paragraph 6.2.1), because usually kneeling position is used by athletes with low impact of impairment and knee high position is adopted by athletes with high impact of impairment. Also able bodied athletes in simulated action of poling on the ergometer when sitting in kneeling position generated higher impulse of force compared to knee high position (Lajunen 2014). Other studies compare generated force during simulated action of poling on the ergometer while sitting in knee high and kneeling position (Hofmann et al. 2016, Lund Ohlsson & Laaksonen 2017); however, due to different protocol and equipment, present findings are not comparable with their results. Concerning the cycle time, the longest cycle time for athletes with high impairment can be due to the straps used to support the trunk overcoming the lack in core muscles control, which might make their trunk movement slower, as it is also suggested by the longer time to complete trunk flexion during the poling phase. Although not significant, athletes with low impact of impairment have slightly longer cycle time than athletes with middle impact of impairment probably because they can lean their trunk more forward, covering a longer distance with trunk and poles and lengthening total cycle time (Stöggl & Holmberg 2011).

Concerning the kinematics, athletes with high impact of impairment reached, at the end of the poling cycle, trunk position close to vertical, since they can take advantage of this backward trunk inclination to increase the trunk range of motion (Gastaldi et al. 2012) and, thereby, to raise the trunk momentum, transferring more force on the poles. Because of this backward trunk inclination at the beginning of the following poling phase, athletes with high impact of impairment started their trunk movement earlier with respect to the generation of force compared to other athletes. Concerning trunk range of motion, it discriminated between athletes with middle and low impact of impairment;

however, the lowest value was shown for athletes with middle impact of impairment, whereas athletes with high and low impact of impairment had similar trunk range of motion. It was previously shown great trunk range of motion for lower impact of impairment and vice versa (Gastaldi et al. 2012). When trunk kinematics was compared between athletes of different classes (paragraph 6.2), three aspects were identified as possibly responsible for unexpected results: inappropriate classes' aggregation, trunk model, and small sample size. Therefore, for the current cluster analysis validation, one of these aspects was changed, gathering athletes in different groups. As it was previously discussed, athletes of intermediate class LW11.5 were now gathered with LW12 instead of with LW11. This change may explain the ability of cluster analysis in discriminating between athletes with low and middle impact of impairment. In contrast, the higher trunk range of motion for athletes with high impact of impairment compared to athletes with middle impact of impairment could be due to the athletes' model used, which considered trunk as a single, rigid segment neglecting spinal flexion and shoulder protraction and retraction. Indeed, athletes with high impairment, because of the lack in core muscles, use straps at pelvis and often under the chest to fix trunk in the most vertical position possible, preventing lower trunk movement, but keeping the upper part of the trunk free to move. The model of single, rigid segment to approximate the trunk probably best fits athletes with low and middle impact of impairment that usually flex trunk forward and straight during the poling phase, but it seems not to be suitable for athletes with high impairment. Instead, to detect more accurate trunk movement, a model with a minimum of two segments should be considered. However, to confirm this assumption additional analysis has to be conducted.

Analysis on variable relevance showed higher effect size for maximal speed, generated force, and cycle characteristics variables compared to kinematic variables, suggesting their greater contribution in discriminating athletes with different impact of impairment according to their performance. However, among the variables that showed greater relevance, a correlation was found, which means that some of these variables were redundant in the clustering analysis. In particular, because of the positive correlation between maximal speed and force variables (impact force, peak force, average force, and impulse of force) selecting one of these variables would be enough for the cluster analysis. Among the other variables, cycle time, trunk maximal backward inclination, and trunk range of motion are the three variables that showed the lowest correlations among each other, making them more suitable for clustering compared to beginning time and time to complete trunk flexion.

6.4 New measures of impairments (articles II-IV)

6.4.1 A new measure of impairment of trunk control (article II)

Trunk stability, being the ability of equilibrium recovery after a perturbation (Zazulak et al. 2007), plays an important role in controlling the balance on a sit-ski. Although all the XC sit skiers have physical impairment at the lower limbs, they have different ability to control the trunk, thereby, trunk stability. Trunk control ability is usually evaluated using perturbations of the support surface. Inertial forces in perturbations move body centre of mass away from the equilibrium position, which is then recovered by the induced reactive responses (Borghuis et al. 2008). During unpredictable perturbation, trunk control can be quantified measuring automatic postural responses of core muscles by electromyography (Enoka 2008) or by giving perturbations to the centre of pressure and measuring reactions magnitude and timing (Hendershot & Nussbaum 2013); since the first technique is demanding in everyday use (Borghuis et al. 2008) and it may be difficult to measure muscle activation of people with physical impairment, the second one was adopted here and discussed as possible measure of impairment of trunk.

Cluster analysis divided athletes in two clusters (low and high impairment) that corresponded to real athletes' impairment (International Paralympic Committee 2018b) with high accuracy, precision, and sensitivity making cluster analysis results valid. The most relevant variables identified by the cluster analysis were trunk reaction time, trunk angle at rest, and trunk range of motion at inversion; whereas shoulder acceleration time and trunk range of motion after 150 ms seem not to be relevant in discriminating athletes. Although result on shoulder acceleration time was expected since it was related to stimuli parameters, the less importance of trunk range of motion after 150 ms was somewhat unexpected. Muscles activation at 150 ms was related to reflexes, which contribute to 42% in stabilizing trunk in dynamic conditions (Moorhouse & Granata 2007). In people with spinal cord injury, reflex act under the lesion level is intact; however, connections to the brain are disrupted, evoking a hypertonic response (Mukherjee & Chakravarty 2010). This might explain why there was no difference in trunk range of motion after 150 ms between athletes with high and low impairment.

Concerning the variables that were identified as most relevant in clustering athletes, it was expected to find extended trunk angle at rest for athletes with high impact of impairment because of the advantage these athletes can take from trunk inclination in increasing trunk range of motion (Gastaldi et al. 2012) and in transferring more force on the poles, as it was explained in the previous paragraph. In contrast, athletes with low impact of impairment usually adopt a kneeling position, in which trunk is kept close to vertical in rest condition. Those athletes, having a normal or near to normal ability to control the trunk core muscles, are able to voluntary perform a wide range of trunk flexion and extension because of the stronger neuromuscular activation. Indeed, using a co-contraction of core muscles, they are able to increase trunk stiffness and, thereby, trunk stability. In particular, anterior core muscles, such as transversus abdominis and oblique, increase intraabdominal pressure (Akuthota & Nadler 2004), while posterior core muscles, such as erector spinae, balance external load (Bergmark 1989). This higher neuromuscular activation may explain the lower trunk reaction time and the smaller trunk range of motion found for the athletes with low impact of impairment compared to those with high impact of impairment.

Both groups of athletes, independently from the impact of impairment, had longer trunk reaction time and greater trunk range of motion at inversion during backward stimuli, suggesting that this direction has governed more difficulty. Indeed, it was shown that voluntary, forward trunk lean is predictive on trunk stability limits (Gauthier et al. 2012). In addition, during forward perturbations the trunk first has a backward movement; therefore trunk range of motion may be influenced by the presence of a backrest commonly adopted in knee high sitting position.

6.4.2 Measures of impairments of strength and trunk control for purpose of classification (article IV)

The development of measures of impairment that can be used for the purpose of classification, each measure has to be: specific for the impairment of interest, reliable, parsimonious, ratio-scaled, and quantitative (Tweedy & Vanlandewijck 2011, Tweedy et al. 2016, Tweedy, Connick, & Beckman 2018). Satisfying these requirements allows to identify the measure of impairment that quantifies the extent of an activities limitation caused by a particular impairment, limiting confounding influence of other impairments (Tweedy 2002). Therefore, two different measures are proposed here, the first one was to assess impairment of strength and the second one was to assess impairment of trunk control. Measure of strength has been largely discussed in Paralympic sport classification literature since impairment of strength is a fundamental component of 16 out of 27 Paralympic sports (Beckman et al. 2017). Beckman et al. (Beckman et al. 2017) revised literature on methods for assessing strength in Paralympic classification and identify isometric, multi-joint contractions as the most suitable methods to assess strength because they generate maximal voluntary force and are training resistant. For measure of trunk control, unpredictable balance perturbations, as described in the previous paragraph, were used and kinematic variables calculated. Differently from the previous protocol, in which athletes were sitting on their sit-ski and utilized personalized constraints (such as backrest and straps), in the present measurements the seat was standard (flat and rigid) for all athletes and two straps (at pelvis and thigh level) were used.

If the new device to measure impairment can be used for purpose of classification was assessed verifying the requirements stated in the Position Stand and following documents: specific for the impairment of interest, reliable, parsimonious, ratio-scaled, and quantitative (Tweedy & Vanlandewijck 2011, Tweedy et al. 2016, Tweedy et al. 2018). The new device was designed to measure two impairments separately: impairment of strength that was measured with maximal voluntary contraction tests (simulated bench press and simulated poling) and impairment of trunk control using unpredictable balance perturbations test. Moreover, when able bodied athletes performed these tests and were included in the cluster analysis, they were clustered together with athletes with low impact of impairment (Rosso et al. 2019), suggesting that this measure is specific for impairment of trunk and limits the contribution of lower limbs. The second requirement was the reliability, which was very good for both measure of strength ($0.71<ICC<0.98$) and measure of trunk control ($0.83<ICC<0.99$). The third requirement was to be parsimonious. Among all the variables calculated in both measures of impairment, anterior maximal voluntary force in strength test and trunk range of motion in perturbation tests at 1 m/s^2 showed a very high correlation; thereby these two variables are those which better represent athletes' variability. Because these two variables, which cover the greatest possible athletes' variance, can be obtained using only one device and two tests they allow making the proposed measures parsimonious. Finally, since the variables were expressed using numeric and not ordinal scale, requirements to be ratio-scaled and quantitative are satisfied, making the proposed measure of impairment overall suitable for purpose of classification.

Cluster analysis divided athletes in three clusters (low, middle, and high impact of impairment), showing good validity (high precision and sensitivity) when its outcome was compared to athletes' real impairment. Although one of the three clusters (cluster_1) was composed by one athlete only, the statistical analysis was able to differentiate this athlete from the others. Since the athlete in cluster_1 (high impact of impairment) was classified as LW10.5, cluster analysis results seem to be in line with the current classification system. Among all the athletes, only two out of fourteen were misclassified. These two athletes were classified in cluster_2 (middle impact of impairment); however according to the current classification system they are classified as LW11.5 and LW12, therefore should be included in cluster_3 (low impact of impairment). One of these two athletes, having a spinal cord injury, has partial trunk control ability, which is more coherent with the description of trunk control of cluster_2, making current result acceptable. Cluster analysis identified anterior force in strength test without the back support and the ratio between anterior forces in strength test without and with back support as the two most relevant variables for impairment of strength. Generated force in strength test was identified as relevant variable also in discriminating wheelchair athletes (Connick et al. 2017). However, both current results and results on wheelchair athletes (Connick et al. 2017), showed generated force of trunk and upper limbs as variables able to discriminate between athletes with middle to low impact of impairment, but not between athletes with high impact of impairment. The greater force generated during test without back support by athletes with low impact of impairment compared to athletes with middle and high impact of impairment reflects their control on core muscles, which may be used to increase trunk stiffness during maximal voluntary contractions in condition of absence of back support. Cluster analysis identified trunk range of motion in balance tests as the most relevant variables in perturbation test at all the three accelerations and in both forward and backward stimuli directions. In case of standard seat only trunk range of motion contributes to discriminate athletes, while in the case of athletes sitting on their sit-ski, both trunk reaction time and trunk range of motion were relevant. This result suggests that sitting position and personalized constraints, such as backrest and straps, may affect the time needed to invert trunk movement, but not its displacement.

Analysis of variable relevance for strength test showed high effect size for two variables: anterior force in the test without back support and ratio between anterior forces in the conditions without and with back support. Because the moderate correlation found between these two variables, selecting one of the two would be enough to cluster athletes according to their impairment of strength. Analysis of variable relevance for trunk control test identified trunk range of motion as the most relevant variable to cluster athletes according to their impairment of trunk control. However, trunk range of motion showed significant correlations between forward and backward stimuli within the acceleration and between stimuli of different accelerations, highlighting a redundancy of information. Therefore, to cluster athletes according to their impairment of trunk control, a single perturbation test using forward and backward stimuli would be enough. Because the trunk range of motion showed higher effect size for 1 m/s^2 in both forward and backward stimuli, this acceleration would be suggested for future tests.

7 MAIN FINDINGS AND CONCLUSIONS

The purposes of this thesis were to develop a sport-specific measure of performance determinants and to develop a measure of impairment that can be used for the purpose of classification for cross-country sit skiing. The main findings of the present thesis are the following:

1. Good biomechanical agreement between skiing on snow and simulated action of poling on the ergometer in terms of maximal speed, generated force, cycle characteristics, and muscle activation. In simulated action of poling on the ergometer, athletes' impact of impairment affected trunk kinematics.
2. Performance while skiing on snow at the maximal speed was influenced by athletes' sitting position. Performance during simulated action of poling on the ergometer was related to athletes' impact of impairment and can be quantified by maximal speed or generated force together with cycle time or trunk kinematics.
3. Trunk kinematics during unpredictable balance perturbations, while athletes were seated on their own sit-ski or on a standard seat, was related to athletes' impact of impairment of trunk control. Athletes' impact of impairment of strength influenced force generated during strength test.

In summary, this thesis contributed to address the request of the International Paralympic Committee of developing an evidence-based classification system for cross-country sit skiing. In particular, the novel finding of this thesis allowed developing a measure of performance and a measure of impairment that can be used for the purpose of classification. Once it was found that athletes skiing on snow and simulated action of poling on the ergometer had similar biomechanics, tests performed in a more controlled environment, such as a laboratory, were used to develop measure of performance. Measuring maximal speed or generated force together with trunk maximal backward inclination or trunk range of motion during poling phase, would allow discriminating athletes' with different impact of impairment according to their performance. Because in cross-country sit skiing propulsion is obtained by pushing a pair of poles and is enhanced by trunk flexion and extension movement; impairment of strength and trunk control limits skiing performance. Once it was found that athletes' trunk control can be assessed by evaluating trunk reaction time and trunk range of motion measured during unpredictable balance perturbations while they were seated on their own sit-ski, a new testing device was designed to develop measure of impairment. This device, composed of a standard seat, was designed to give unpredictable perturbations in forward and backward direction to the athletes in order to measure impairment of trunk control. In addition, the device was equipped with force sensors in order to measure impairment of strength. Trunk range of motion measured during trunk control test together with force generated during strength test would allow discriminating athletes according to their impairment. Identifying the minimum set of variables and the tests protocol that quantify performance and impairment, the current thesis allowed moving towards an evidence-based classification system for cross-country sit skiing.

Three possible sources of weakness can be identified for the current thesis. First, it would be important to have a representative number of athletes for the five classes and with different impairment. The small sample size, especially for participants with high impact of impairment, may contribute to generate unexpected results, such as the one on cycle characteristics and trunk kinematics. Because the number of elite cross-country sit skiers is small worldwide, it may be worth to recruit and properly train novice athletes or to include athletes from other, but similar sitting sports (wheelchair racing, wheelchair basketball).
The second possible source of weakness of the thesis is that both male and female participants were merged during the data analysis. Considering together both genders should not considerably affect kinematics, but may have effects for generated force, especially for measures of performance. In future studies, normalized performance outcomes with respect to the body weight or maximal voluntary contractions would help to reduce the gender influence. In contrast, it is expected that gender did not affect current measure of impairment of trunk strength because the ratio between peak anterior force in the condition without and with the backrest is considered in the analysis.

The third possible source of weakness is the necessity to establish the relationship between the measure of performance determinants and the measure of impairment. In this thesis, the relationship was not quantified because it would require additional tests. Indeed, in order to quantify the strength of this relationship athletes have to perform both measure of performance and measure of impairment. The assessment of this relationship would allow determining the minimum impairment criteria, the number of classes, and classes profile for cross-country sit skiing. Therefore, evaluation of this relationship becomes mandatory as a future perspective of this study in order to completely develop an evidence-based classification for this sport. Another future perspective of this work could be to evaluate the possibility of extending current finding and current methodologies including athletes with different impairment and/or including other sitting sports. Indeed, trunk plays a key role in XC sit skiing, but also other sports, such as wheelchair racing and wheelchair rugby. In this sense, it could be possible to evaluate if the inhere proposed measure of impairment with the new testing device may be suitable for impairment different than the ones of cross-country sit skiing and/or other sitting disciplines in which trunk movements have such great importance. Eventually, it would also be interesting to improve the ergonomics of the new testing device to make it more comfortable for athletes and easier to use for operators. Moreover, when a great database of impairment measure is collected, a more complete statistical analysis, such as hierarchical cluster analysis, could be carried out in order to generalize results.

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ORIGINAL PAPERS

I

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Biomechanics of simulated versus natural cross-country sit skiing

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ABSTRACT

The purpose of this study was to investigate the biomechanics of cross-country sit-skiing in simulated and natural skiing. Thirteen international level athletes participated in a ski ergometer test (simulated conditions) and a test on snow in a ski-tunnel (natural conditions) using their personal sit-ski. Tests in both conditions were performed at individual maximal speed. When comparing the two conditions the main results were: (1) maximal speed in simulated conditions was lower ($p < 0.05$) but correlated well with the natural condition ($r = 0.79$, $p < 0.001$); (2) no differences in pole force variables were found; peak force ($r = 0.77$, $p < 0.01$) and average force ($r = 0.78$, $p < 0.01$) correlated well; (3) recovery time and time to peak did not differ and time to impact correlated with each other ($r = 0.88$, $p < 0.01$); (4) no differences were found in peak electromyography (EMG) and average EMG for Triceps, Pectoralis, and Erector Spinae; Rectus Abdominis did not differ in peak. EMG peak and average EMG of all muscles were correlated between the two conditions ($r = 0.65$–0.94; $p < 0.05$–0.01). Although some differences were observed, this study demonstrated that technical skill proficiency in natural and simulated cross-country skiing is comparable from a force production and muscle activation perspective.

1. Introduction

Since the first Paralympic cross-country (XC) skiing event, the number of athletes who practice this discipline has grown markedly while live television broadcasting and print media attention have also increased (Rombach and Rapp, 2014). Paralympic athletes with neuromusculoskeletal impairments are divided in two categories: standing and sitting. To ensure equal and fair competitions and to minimize the effects of impairment on performance within each category, athletes are divided into classes according to the impact of neuromusculoskeletal impairment on XC-skiing performance (Vanlandewijck, 2006; Tweedy and Vanlandewijck, 2011; International Paralympic Committee, 2015). All sit-skiers have impairment in the lower limbs, but a different level of ability to control the trunk. Therefore, sit-skiers are grouped in five different classes LW (locomotor winter), from LW12 (athletes can perfectly control their trunk muscles) to LW10 (athletes with no voluntary abdominal and trunk extensor control), with three intermediate categories: LW11.5, LW11 and LW10.5 (International Paralympic Committee, 2015). Independent of the impairment level, all sit-skiers adopt the double poling (DP) technique for propulsion. DP is a technique in which athletes sitting on a sledge mounted on a couple of cross-country skis, sit-ski, generate propulsion by using shoulder and arm muscles to push on two poles synchronously; the propulsion is increased by a flexion-extension movement in the trunk.

Although many studies have been conducted on the physiology (Hoffmann et al., 1991; Pellegrini et al., 2013), biomechanics (Millet et al., 1998a, 1998b; Holmberg et al., 2005, 2006; Stöggl and Holmberg, 2011; Zoppirolli et al., 2015), and neuromuscular activity (Holmberg et al., 2005) of able-bodied skiers in DP, very few studies have assessed this technique in sit-skiing. Bernardi

Abbreviations: CT, cycle time; EMG, electromyography; aEMG, average muscle activity; EMG_{peak}, muscle activity peak; ES, Erector Spinae muscle; DP, double poling; $force_{avg}$, average force during poling phase; $force_{impact}$, force at the impact; $force_{peak}$, peak of force in the poling phase; $force_{int}$, integral of force during poling phase; IPC, International Paralympic Committee; IQR, interquartile range; Lat, Latissimus Dorsi muscle; LW, locomotor winter; Pec, Pectoralis Major muscle; PP, poling phase; PT, poling time; RP, recovery phase; RT, recovery time; SD, standard deviation; $Speed_{max}$, maximal speed; TtP, time to peak; TtI, time to impact; Tric, Triceps Brachii muscle; RecAb, Rectus Abdominis muscle; VO_2, oxygen consumption; XC, cross-country.

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et al. (2013) evaluated changes in speed and kinematic parameters during flat and uphill tracks, finding an average cycle duration of 0.98 s and 0.84 s respectively, while Gastaldi et al. (2012, 2014, 2016), investigated DP kinematics in sit-skiing athletes belonging to different classes using a markerless kinematic analysis. In the comparison of DP technique of different classes (LW10 and LW11) it was demonstrated that athletes kneeling on the sit-ski (kneeing position) and athletes sitting on the sit-ski with the knees in a higher position relative to the hip joints (knee-high position) had significantly different trunk movement (Gastaldi et al., 2012). Finally, the trunk movement was assessed in simulated skiing among athletes with different impairments, demonstrating that athletes with a lower impairment level had a greater range of motion (ROM) and a more flexed trunk position during the DP cycle than athletes with a higher impairment level (Rosso et al., 2016).

Studies on DP sit-skiing (Gastaldi et al., 2012; Bernardi et al., 2013) showed that conducting tests skiing on snow (natural conditions) can be challenging in providing precise and comparable results due to the environmental constrictions; therefore it is necessary to introduce standardized test procedures for valid assessment and training. Such test procedures can be conducted in a laboratory, which guarantees standardization, easy access to the athlete, and less technological challenges. In able-bodied athletes laboratory tests on an ergometer (simulated conditions) have been conducted to evaluate if testing and training simulating DP technique gives accurate and valid results and comparable movements in terms of muscle recruitment and forces (Holmberg and Nilsson, 2008; Halonen et al., 2014). Although Halonen et al. (2014) found a difference in abdominal muscle activation time between simulated and natural conditions, a strong correlation was found in power generation during a six-minute test (Holmberg and Nilsson, 2008), in force production and muscle activities, and in impact of fatigue (Halonen et al., 2014). Comparison between simulated and natural conditions has also been done in XC sit-skiing. Forbes et al. (2010) compared aerobic response measuring cardiorespiratory variables, such as peak oxygen consumption ($VO_{2\text{-}peak}$), peak heart rate, peak respiratory exchange ratio, and anaerobic response measuring blood lactate. Forbes et al. (2010) reported no differences in VO_2, but higher values in all other variables in simulated compared to natural conditions. Other studies have used simulated conditions to describe sit-skiers' physical fitness and consequently give advice on training and performance (Bernardi et al., 2010, 2012; Bernardi and Schena, 2011). An arm cranking ergometer was used to assess both aerobic and anaerobic responses showing high values for VO_{2peak}, heart rate, and blood lactate (Bernardi et al., 2010; Bernardi and Schena, 2011), while upper body muscular strength was identified as a key factor for both aerobic and anaerobic capacity (Bernardi et al., 2012). $VO_{2\text{-}peak}$-values as a result of incremental maximal cardiopulmonary arm-cranking, present a close relationship with VO_2 measured during a 5 km simulated race (Bernardi et al., 2010).

The aim of this paper is to compare force generation and muscle activity patterns in sit-ski athletes using an XC-ergometer versus natural conditions on snow. It would permit to consider if XC-ergometer is a valid alternative for specific training, to improve XC sit-skiing performance in natural conditions.

2. Methods

2.1. Participants

Thirteen healthy elite Paralympic XC sit-skiers (8 male, members of seven different National teams; representing different classes LW10 n = 1, LW10.5 n = 1, LW11 n = 3, LW11.5 n = 4, LW12 n = 4; age 27 ± 3 years (20–33), height 167 ± 20 cm (110–192), weight 58 ± 12 kg (30–79)) volunteered as participants. Participants were informed in full detail about the aim and the nature of the study and they signed an informed consent. The research methods and the protocols were standard and have been approved by the Ethics Committee of the University of Jyväskylä and the measurements were performed in accordance with the Declaration of Helsinki.

2.2. Overall design and experimental setup

All the tests were conducted during the International Paralympic Committee (IPC) World Cup in December 2014 in Vuokatti, Finland. The protocol consisted of two parts: the first part took place in a laboratory, while the second part was conducted in the Vuokatti Ski Tunnel.

The athlete was prepared for testing and practiced with the XC-ergometer (Concept2 Inc, Morrisville, Vermont, USA) for 5–10 min to warm up and to become familiar with the equipment. All the athletes used the same ergometer but with their own sit-ski. For each athlete, the sit-ski was fixed with respect to the ergometer at the distance that allowed the skier to have technique as similar as possible to the one usually used in natural condition. The XC-ergometer (Fig. 1) was fixed to the wall in a vertical position; this setup allowed the athletes to activate the flywheel by pulling the ropes using two handles. The ergometer resistance was set at 7.5 out of 10 (arbitrary units) for all participants; this level was chosen

Fig. 1. Laboratory setup used for simulated skiing. A XC-ergometer allowed athletes to simulate the skiing gesture by means of a mechanical system of ropes and pulleys. A force transducer is inserted between each rope-handle grip coupling to collect force data and to evaluate cycle characteristics. Athletes performed the simulated skiing using their personal sit-ski and skies. The sit-ski was fixed with respect to the XC-ergometer at an adequate distance to allow the athletes to better simulate the gesture they demonstrated during natural skiing.

based on pilot tests to best simulate natural skiing conditions in the Vuokatti Ski Tunnel. Two maximal speed ($speed_{max}$) trials were performed and separated by 2 min of recovery. The athletes were requested to execute at least 7 cycles after $speed_{max}$ was reached. As a consequence, each trial lasted no longer that 15 s. The best trial at $speed_{max}$ (characterized as the fastest) was selected and analyzed. The $speed_{max}$ condition was chosen because of its importance in race strategies. It has been demonstrated (Bernardi et al., 2012) that in races sit-skiers adopt the "all out" strategy in which athletes start with a high speed and that this subsequently decreases during the race.

For the second part of the experiment, the athlete was transferred to the Vuokatti Ski Tunnel (constant temperature of −7° and humidity condition). The sit-ski was the same used in the laboratory test (personal sit-ski) and poles equipped with force transducers were provided to skiers (lengths from 100 to 130 cm at 2.5 cm increments). The skis were prepared by the athletes' own ski service team before the measurements started. The track profile was chosen to be 16 m long at 2.5° of slope and was also selected based on pilot tests. Two $speed_{max}$ tests with a recovery of 2 min in between were performed; the fastest was selected for further analysis.

2.3. Maximal speed

In simulated conditions the maximal speed was calculated by using data recorded by the ergometer software. The ergometer gave a value, which is the time required to cover a distance of 500 m if the speed the athlete has in that moment will be maintained. The maximal speed was the ratio between the theoretical distance of 500 m and the time given by the ergometer. In natural conditions the speed was measured with radar (Jenoptik LDM 300 C SPORT, Jena, Germany).

2.4. Force and cycle characteristics measurements

In simulated conditions, the ergometer was equipped with force transducers (University of Jyväskylä, Finland) mounted between the pulling rope and handle grip. Pulling forces were collected at 3000 Hz by Vicon Nexus software (Vicon Motion Systems Ltd. UK). In natural conditions poles were equipped with a strain gauge force transducer mounted directly in the pole grip (University of Salzburg, Austria). Force data were collected at 1000 Hz using a custom-made data collection system explained in a previous study (Halonen et al., 2014).

In Fig. 2 cycle characteristics and poling forces are presented for both simulated and natural conditions. Cycle time (CT), poling time (PT), and recovery time (RT) were the duration of the DP cycle, poling phase (PP), and recovery phase (RP) respectively. The impact force ($force_{impact}$) occurred at the impact of the pole to the ground and was characterized as the first force peak occurring during the PP; the peak force ($force_{peak}$) is related to propulsion and was determined as the highest active peak force after the impact during the PP (Fig. 2). The other force variables calculated were average force ($force_{avg}$) and integral force ($force_{int}$), while the cycle characteristics variables were time to impact (TtI) and time to peak (TtP). TtI and TtP were defined as the time between the beginning of the PP and the time when the $force_{impact}$ and $force_{peak}$ occurred, respectively. All biomechanical variables were calculated for each of seven consecutive propulsion cycles in the same manner in both simulated and natural conditions.

2.5. Muscle activity measurements

Muscle activity was acquired by a surface electromyographical system that transmitted the data wirelessly (TeleMyo DTS, Noraxon U.S.A. Inc, United States) to a personal computer and was stored by Vicon Nexus software. The TeleMyo DTS system is composed of sensors system, which include a small amplifier, and a belt transmitter, to transmit data from the sensors to a synchronization station and then to a personal computer by a USB connection. The system applied a pass-band filter (20–400 Hz) and converted analog signals to digital data by a 16-bit A/D converter. In simulated conditions signals were sampled at 3000 Hz and synchronized with force data. In natural conditions a sample frequency of 1500 Hz was used. Moreover, the Triceps (Tric) activity was registered at 1000 Hz by the custom-made system used to collect pole forces. This double acquisition was used to manually synchronize forces and muscle activity signals from the two acquisition systems.

Muscle activity signals were recorded in a single differential configuration using pre-gelled Ag/AgCl bipolar surface electrodes (circle shape, sensor area 28 mm^2) with an inter-electrode distance of 15 mm (Ambu BlueSensor N, Ambu A/S, Denmark). The electrodes were positioned according to SENIAM recommendation (Hermens et al., 2000) on the most prominent muscle belly in the line of the muscle fiber direction, and were placed over 8 muscles: Tric, Pectoralis Major (Pec), Latissimus Dorsi (Lat), Rectus Abdominis (RecAb), Obliquus Abdominis, Erector Spinae (ES), Rectus Femoris and Biceps Femoris muscles of the right side of the body. A reference electrode was placed on the right acromion. Before electrode positioning, the skin was abraded and cleaned with alcohol. Since for the majority of the participants the activity of Obliquus Abdominis, Rectus Femoris and Biceps Femoris was low, these muscles were not taken into account in final analysis. The low activation was justified by the individuals' impairment and their lack in trunk and lower limb muscle control.

Raw muscle activity signals were full-wave rectified and 10 Hz low pass filtered to create a linear envelope. For each cycle the average muscle activity (aEMG) and the muscle activity peak (EMG_{peak}) were calculated on the rectified signals and on the linear envelope respectively (Holmberg et al., 2005). Since the minimum number of good cycles available for all the athletes was lower than seven, neuromuscular variables were calculated from five out of seven consecutive propulsion cycles. To analyze coordination patterns, an electromechanical delay was evaluated as a difference between two time instances. During each PP both muscle activity and force signals increased from and then decreased to a baseline value. The muscle activity and force onset corresponded to the time instant when increasing signals reached 10% of their maximum. The difference between muscle activity onset and force onset is generally defined as onset delay. The offset delay was calculated in the same way when the muscle activity and force signals decreased. The onset and offset delay was reported negative when the muscle activation occurred before the force, both in terms of activation and deactivation. A ratio between natural and simulated conditions for muscle activity variables has been calculated to compare muscle activation levels in different conditions (Pellegrini et al., 2005).

The force, cycle characteristics, and neuromuscular data were processed using custom-made code prepared in MatLab (MatLab and Release 2015, The MathWorks, Inc., Natick, Massachusetts, United States).

2.6. Statistics

Since the data did not show a normal distribution (Kolmogorov-Smirnov test; $p < 0.01$) non-parametric statistics was applied. Data was presented as mean and standard deviation and median ± interquartile range (IQR) in the tables. To check for statistical differences between the two conditions, a Wilcoxon test was applied and a pairwise comparison using Spearman correlation

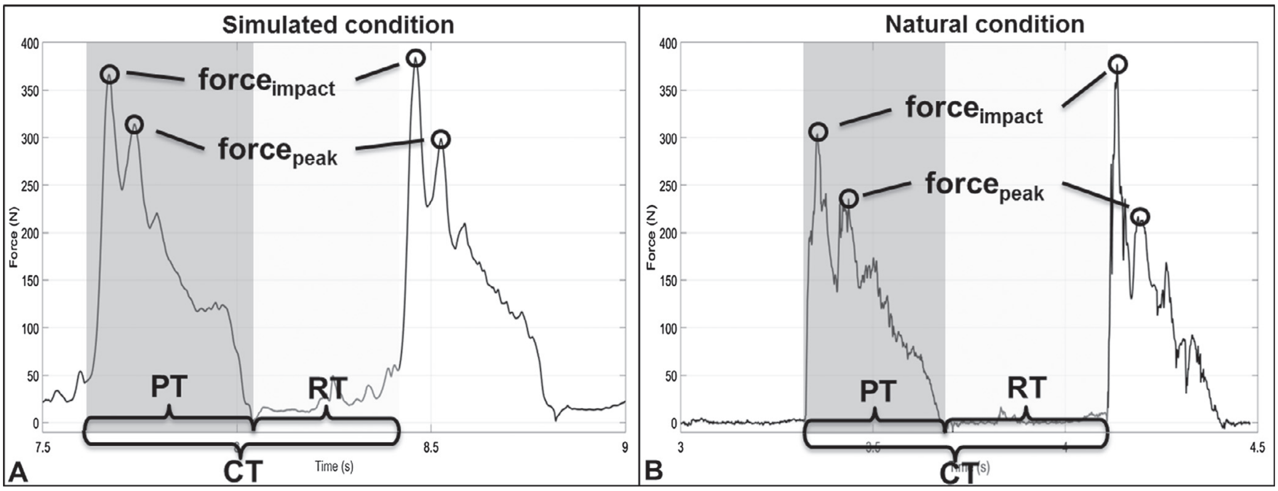

Fig. 2. Force and cycle characteristics in the two conditions. A. This figure shows two of the force variables, impact force ($force_{impact}$) and peak force ($force_{peak}$), and three cycle characteristics variables, cycle time (CT), poling time (PT), and recovery time (RT), for simulated conditions. The $force_{impact}$ was characterized as the first force peak which occurred during the poling phase, while the $force_{peak}$ was determined as the highest active peak force after the impact during the poling phase. The CT measured the double poling duration in seconds; the PT was the period of time which began when the force started to grow sharply with respect to the baseline value and ended when the force came down to the initial value; the RT was the mathematical difference between the CT and PT. B. The same force and cycle characteristics are shown in natural conditions.

coefficient (r) was calculated for each variable. Statistical significance was set at $p < 0.05$ for all analyses. All statistical analyses were processed using MatLab.

3. Results

$Speed_{max}$ values, forces and cycle characteristics in natural and simulated conditions were reported as mean ± SD and median ± IQR in Table 1. $Speed_{max}$ in natural conditions was higher ($p < 0.05$) than in simulated conditions. A positive significant correlation was found between simulated and natural skiing ($r = 0.79$, $p < 0.001$).

No differences were found between simulated and natural conditions in the $force_{impact}$, $force_{peak}$, $force_{avg}$, RT, and TtP. In contrast, in simulated conditions the $force_{int}$ ($p < 0.001$), the CT ($p < 0.001$), the PT ($p < 0.001$), and the TtI ($p < 0.01$) were higher compared to the natural conditions. A positive significant correlation was found between simulated and natural conditions in $force_{peak}$ ($r = 0.77$, $p < 0.01$), $force_{avg}$ ($r = 0.78$, $p < 0.01$), and TtI ($r = 0.88$, $p < 0.01$).

Muscle activation values were reported as mean ± SD and median ± IQR of the ratio natural/simulated in the Table 2, while muscle activation onset and offset delay in the two conditions were reported as mean ± SD in Fig. 3.

Concerning the muscle activation, no differences were found between simulated and natural conditions in the EMG_{peak} and aEMG for Tric, Pec, ES, and in EMG_{peak} for RecAb. In contrast, higher activation was found in simulated compared to natural conditions in EMG_{peak} for Lat ($p < 0.05$), in aEMG for Lat ($p < 0.05$) and RecAb

Table 2
Muscular activation values in the two conditions (simulated and natural) were reported as a mean ± SD and median ± IQR. These values were obtained averaging the same five cycles per each subject used for the force and cycle characteristics estimation. The statistical differences between the two conditions were reported, $* = p < 0.05$. EMG_{peak} (ratio), ratio between natural and simulated values of the muscle activity peak; aEMG (ratio), ratio between natural and simulated values of the average muscle activity; Tric, Triceps Brachii muscle; Pec, Pectoralis Major muscle; Lat, Latissimus Dorsi muscle; ES, Erector Spinae muscle; RecAb, Rectus Abdominis muscle.

Variable	Muscle	Natural/simulated conditions mean ± SD	Natural/simulated conditions median ± IQR
EMG_{peak} (ratio)	Tric	1.07 ± 0.48	0.95 ± 0.38
	Pec	1.11 ± 0.50	0.97 ± 0.50
	Lat	0.85 ± 0.19*	0.88 ± 0.33*
	ES	1.12 ± 0.26	1.11 ± 0.25
	RecAb	0.95 ± 0.34	0.93 ± 0.44
aEMG (ratio)	Tric	0.94 ± 0.39	0.92 ± 0.39
	Pec	0.96 ± 0.46	0.86 ± 0.60
	Lat	0.80 ± 0.22*	0.81 ± 0.44*
	ES	1.40 ± 0.53	1.27 ± 0.99
	RecAb	0.73 ± 0.35*	0.73 ± 0.39*

Table 1
Maximal speed, force, and cycle characteristic values in the two conditions (simulated and natural) were reported as a mean ± SD and median ± IQR. These values were obtained averaging five cycles per each subject. The statistical differences between the two conditions were reported, $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$. $Speed_{max}$ (m/s), maximal speed; $force_{impact}$ (N), force at the impact; $force_{peak}$ (N), peak force in the poling phase; aforce (N), average force during poling phase; iforce (N), integral force during poling phase; CT (s), cycle time; PT (s), poling time; RT (s), recovery time; TtP (s), time to peak; TtI (s), time to impact.

Variable	Simulated conditions mean ± SD	Natural conditions mean ± SD	Simulated conditions median ± IQR	Natural conditions median ± IQR
$speed_{max}$ (m/s)	4.28 ± 0.63*	4.61 ± 0.67*	4.42 ± 0.94*	4.68 ± 1.16*
$force_{impact}$ (N)	254.73 ± 87.65	257.95 ± 94.02	225.89 ± 125.33	256.23 ± 86.28
$force_{peak}$ (N)	208.37 ± 75.33	188.55 ± 54.58	166.85 ± 104.05	169.18 ± 62.53
$force_{avg}$ (N)	122.17 ± 33.48	114.28 ± 28.36	116.98 ± 53.90	123.68 ± 33.89
$force_{int}$ (Ns)	59.91 ± 16.60***	34.61 ± 9.12***	54.74 ± 17.25***	33.14 ± 15.05***
CT (s)	0.89 ± 0.15***	0.66 ± 0.11***	0.93 ± 0.20***	0.62 ± 0.19***
PT (s)	0.47 ± 0.08***	0.30 ± 0.04***	0.46 ± 0.14***	0.30 ± 0.07***
RT (s)	0.42 ± 0.08	0.36 ± 0.08	0.43 ± 0.12	0.32 ± 0.15
TtP (s)	0.11 ± 0.02	0.10 ± 0.03	0.10 ± 0.03	0.09 ± 0.05
TtI (s)	0.04 ± 0.01**	0.03 ± 0.01**	0.04 ± 0.01**	0.03 ± 0.03**

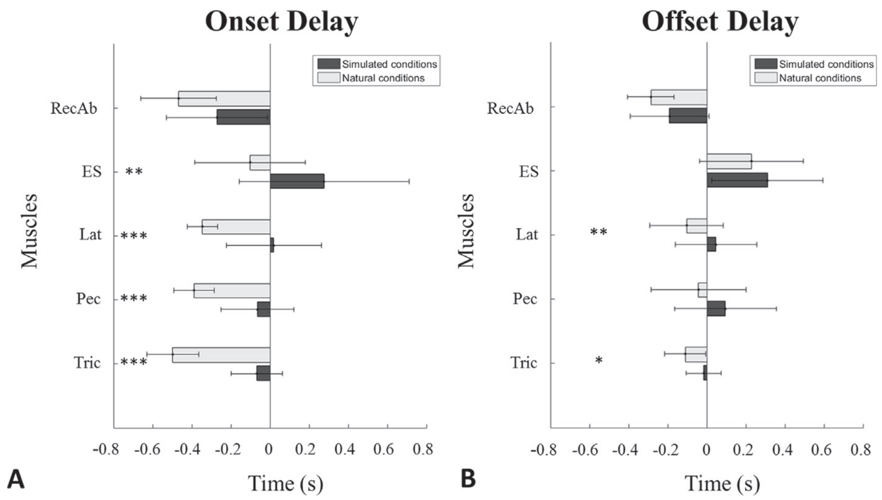

Fig. 3. Onset and offset delay. The figure reported onset delay (A) and offset delay (B) for the five muscles (Tric, Pec, Lat, ES, RecAb) as mean ± SD. This delay is calculated considering a threshold of 10% of the muscular activity and force peak. Statistical difference between the two conditions are reported, ∗ = $p < 0.05$, ∗∗ = $p < 0.01$, ∗∗∗ = $p < 0.001$.

($p < 0.05$). Concerning the onset delay (Fig. 3A), Tric ($p < 0.001$), Pec ($p < 0.001$), Lat ($p < 0.001$), and ES ($p < 0.05$) were activated later in simulated than in natural conditions. Regarding the offset time (Fig. 3B), Tric ($p < 0.05$) and Lat ($p < 0.01$) were deactivated later in simulated than in natural conditions.

A positive significant correlation was found between simulated and natural conditions for all muscles in EMG_{peak} Tric ($r = 0.69$, $p < 0.01$), Pec ($r = 0.88$, $p < 0.01$), Lat ($r = 0.94$, $p < 0.01$), ES ($r = 0.77$, $p < 0.05$), RecAb ($r = 0.78$, $p < 0.01$) and aEMG Tric ($r = 0.69$, $p < 0.05$), Pec ($r = 0.77$, $p < 0.01$), Lat ($r = 0.80$, $p < 0.01$), ES ($r = 0.65$, $p < 0.05$), RecAb ($r = 0.75$, $p < 0.01$).

4. Discussion

The present study aimed to compare force generation, cycle characteristics, and muscular activity of XC sit-skiers during simulated and natural conditions and showed that activity patterns of the major trunk and arm muscles during simulated XC-skiing on an ergometer mirrored natural XC-skiing well.

Comparing the two conditions, maximal speed was significantly lower using the ski ergometer than in the tunnel. Nevertheless, the positive correlation found between the two conditions means that athletes skiing faster on the snow were able to obtain better performances also in simulated conditions. Mean speed values obtained in the current study in natural conditions are higher compared to the speed measured during the first lap of a race in a previous study (Bernardi et al., 2013); a lower slope (2.5° vs 8.3°) and a shorter time of effort in the present study might explain these differences.

Force is generated differently in simulated conditions (traction force) and natural conditions (pushing force), thus comparing the muscle activity pattern and the biomechanical responses in both conditions may be influenced. A large treadmill would probably be closer to natural skiing than a simulation on the ski ergometer, but a ski ergometer is more accessible for many athletes to be used in training. One fundamental question of the present study was to compare generated forces in these two conditions and, despite the obvious differences, the forces measured were quite similar. If the main aim was to compare joint kinematics, a treadmill would have been preferred.

Forces generated showed two peaks per each DP cycle (Fig. 2). The first peak occurred at the impact, while the second is related to propulsion. Compared to able-bodied athletes who showed lower impact force with respect to peak force (Holmberg et al., 2005), XC sit-skiers impact force was higher in both conditions. This higher impact force may be due to the sitting position and the ability of the athlete to take advantage of the force of gravity when poling, which influences the inclination of the pole at ground contact and subsequently the force transmitted to the ground at the impact through each pole. However, to verify this assumption, the direction of the force application should be measured. The impact force induced a pre-activation of Pectoralis and Rectus Abdominis (Fig. 3A) to increase the muscle stiffness in order to prepare the body for the pole impact, and stabilizes the involved joints to generate more propulsion at the beginning of the poling phase similar to able-bodied skiers (Holmberg et al., 2005).

At maximal speed, the cycle time and the poling time were longer for athletes skiing in simulated conditions compared to natural conditions, while the recovery time was similar between the two conditions, which is in agreement with previous studies in able-bodied skiers (Pellegrini et al., 2005; Halonen et al., 2014). Moreover, the longer poling time leading to higher integral force during the poling phase is in line with a previous study conducted in able-bodied skiers as well (Halonen et al., 2014). The difference in the cycle time and poling time might be due to the higher resistance in simulated conditions indicated by lower speed and/or to different kinematics of the upper arms (traction force), which might lead to a greater elbow and shoulder range of motion during the poling phase. More specifically, it could be that in the simulated conditions at the end of the recovery phase athletes' wrists are in a more elevated position and the elbow joint angles are more extended than in natural conditions because of the elastic return force generated by the elastic mechanism inside the flywheel bringing the arms forward during the recovery phase. As a result, the first part of elbow flexion in the propulsion phase might be similar to a pull-up movement (Stöggl et al., 2006). This greater range of motion in the upper limbs could also explain the higher peak and average muscle activity for Latissimus during the poling phases in simulated compared to the natural conditions because of its extensor function in the first part of the poling phase (Holmberg et al., 2005). Moreover, a greater trunk flexion in simulated conditions during the poling phase could explain the higher Rectus Abdominis activation, which indicates better stability.

Concerning the onset and offset delay the high variability shown especially in abdominal muscles (Rectus Abdominis and

Erector Spinae) can be due to the different classes of athletes included in this study. The decision to consider all the classes in the current sit-ski classification in the present study was because of the possibility to extend results to all sit-skiers and the low number of athletes per each class. Statistical analysis on onset delay revealed later activation for Triceps, Pectoralis, Latissimus, and Erector Spinae in simulated compared to natural conditions. This could be due to the advantage in raising the upper limbs that athletes get from the elastic return force generated by the ergometer's flywheel during the recovery phase, while in natural conditions skiers must raise their upper limbs voluntarily. In contrast, the lack in difference for Rectus Abdominis onset delay is in contrast with the behavior showed by able-bodied athletes activating the Rectus Abdominis 0.1 s earlier using the ergometer compared to skiing on snow (Halonen et al., 2014). Despite this difference in activation time, the upper limb extensor muscle activation order is similar between simulated and natural conditions. This similarity suggests that in both conditions the gesture involves first a push (Triceps and Pectoralis) and then a pull (Latissimus and Erector Spinae) action, even though skiing on the ergometer athletes pull a rope while skiing on snow they push a couple of poles (Fig. 3A). The offset delay showed a later deactivation of Triceps and Latissimus in simulated compared to natural conditions, which could be explained by the supposed greater upper limbs range of motion during the poling phase.

Despite these differences in Latissimus and Rectus Abdominis activity and the longer cycle and poling time, high correlations were found in the peak and average values of muscle activity for all muscles, in time to impact, peak force, and average force. These high correlations suggest that on the XC ergometer athletes who had higher absolute muscle activity and generated force in simulated conditions reacted the similarly in natural conditions.

To sum up, similar muscular activity in Triceps, Latissimus, and Erector Spinae muscles, activation pattern for Triceps, Pectoralis, Latissimus, Erector Spinae, and Rectus Abdominis muscles, and level of force generated were observed between natural and simulated conditions, while simulated condition had longer poling and cycle time and higher integral force. This comparable muscular activity, together with the similar pattern of activation and generated force in natural and simulated conditions suggest that the XC-ergometer is a good device for training specific upper body maximal strength and testing aerobic and anaerobic capacity in sport-specific reliable and repeatable conditions. In contrast it might be that endurance training has negative effect on the technique due to the different upper limbs and trunk kinematics (Stöggl et al., 2006), but additional study focusing on motion analysis should be done.

4.1. Limitations

In the present study there are three main limitations. The first limitation is the small sample size. It would be important to get a representative number of athletes from each class, but this is difficult due to the low number of elite athletes competing in XC-sit skiing. The second is the lack of a kinematic analysis to evaluate trunk and upper limb angles and ROM, which allow only speculation regarding the possible explanations for the statistical differences found in time variables and muscle activation. The third is the lack of analysis in force directions that compared to sit-ski kinematics could give a reasonable explanation for the differences between standing able-bodied and sit-skiers in the impact force and peak force values and for the opposite order of activation in shoulder extensors. Indeed, athletes with strong trunk impairment try to compensate by changing their DP technique.

Conflict of interest

The authors declare that there are no conflicts of interest.

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II

BALANCE PERTURBATIONS AS A MEASUREMENT TOOL FOR TRUNK IMPAIRMENT IN CROSS-COUNTRY SIT SKIING

by

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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

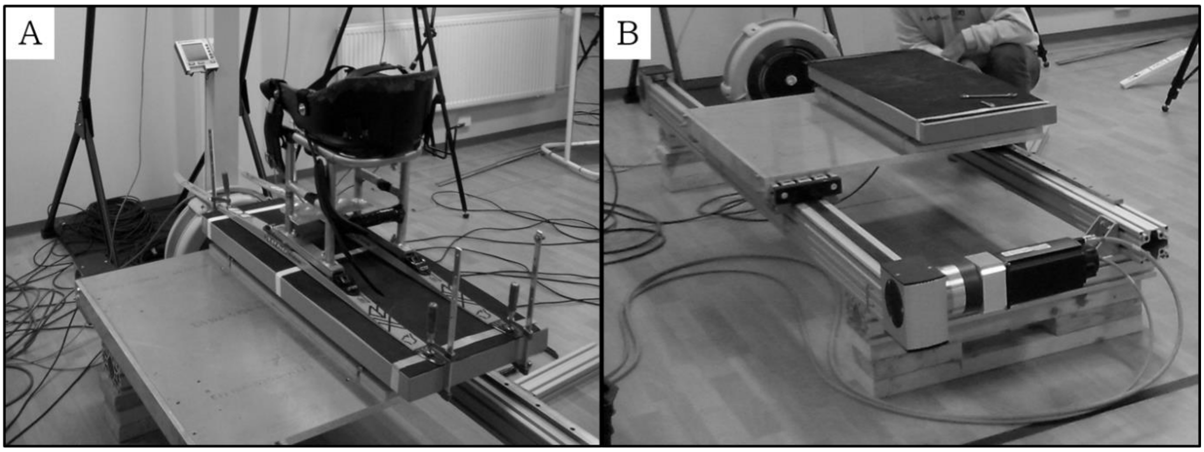

Figure 1. Setup used for unpredictable stimuli. (A) Athlete’s sit-ski was fixed on a movable plate by four clamps. Athlete was sitting on his/her personal sit-ski strapped as for a competitive event. (B) The movable plate (0.94 m long and 0.84 m wide) can be moved along a couple of parallel tracks 1.4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

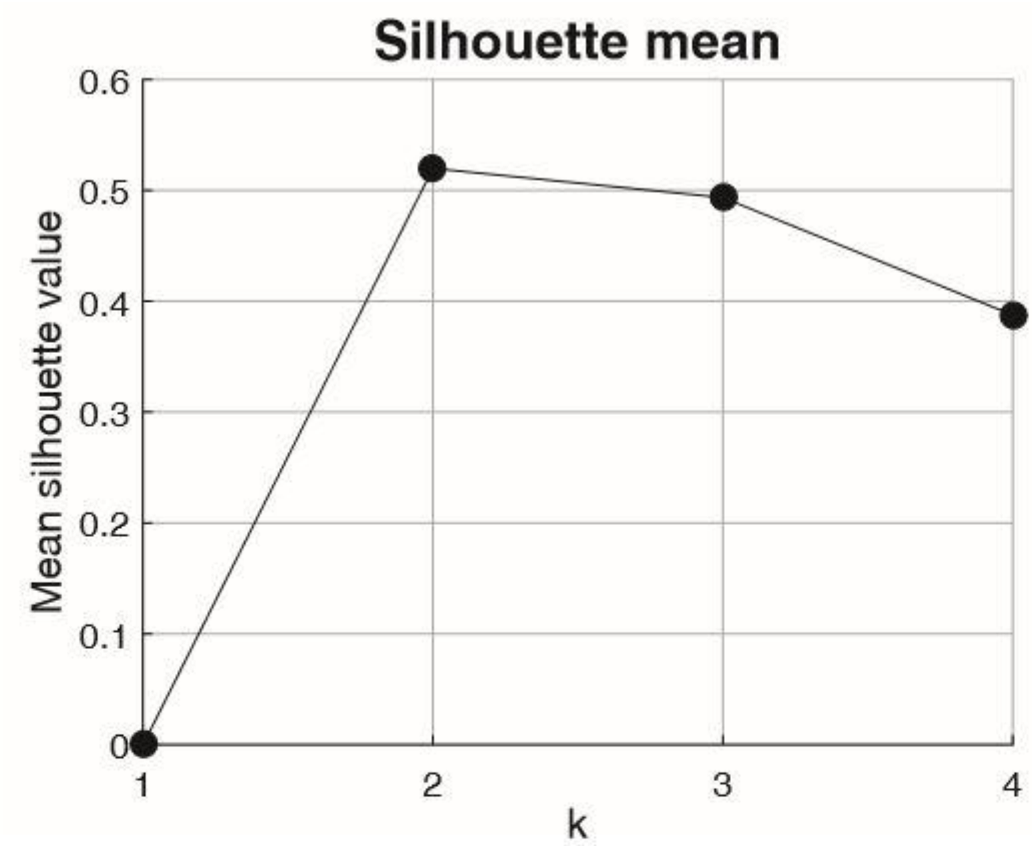

Figure 2. Mean silhouette graph. To define the number of clusters (k) for the analysis, the k-means was run with three different k (from 2 to 4) and the mean silhouette for each k was calculated. The k = 2 was chosen for the analysis because of it showed the highest mean silhouette value (0.52).

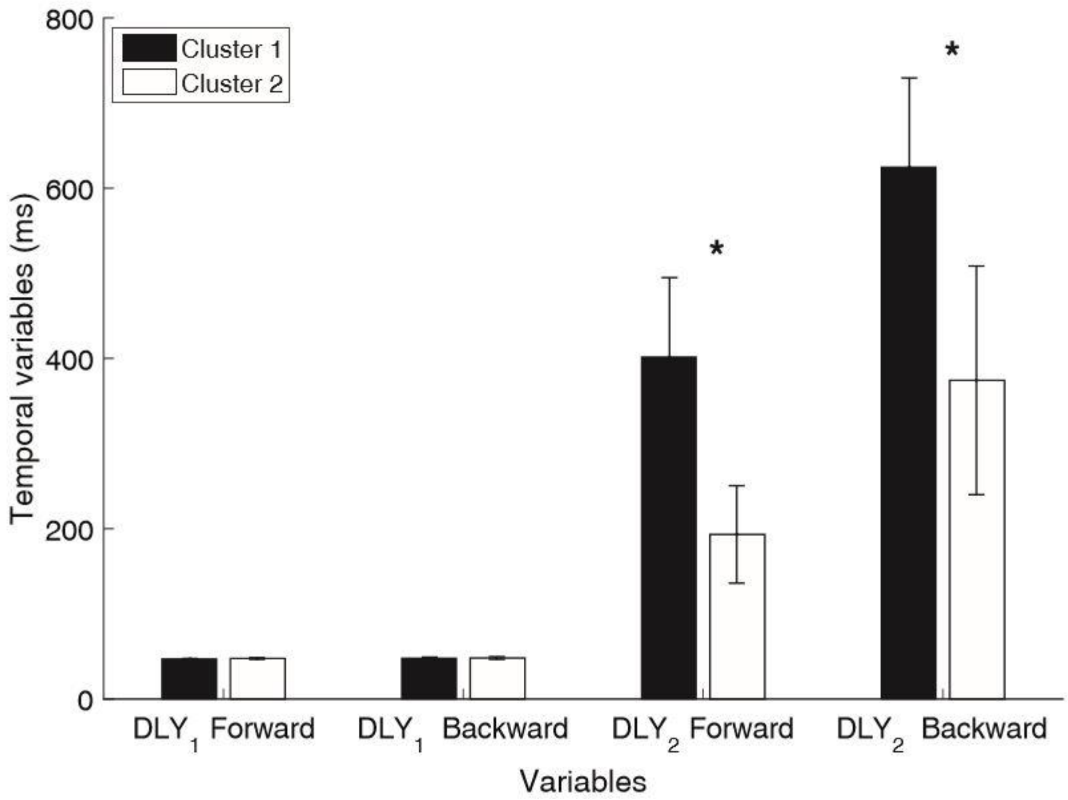

Figure 3. Temporal variable. The delay between the onset of the sledge acceleration and the onset of the shoulder acceleration (DLY_1) and the delay between the onset of the shoulder acceleration and the time when the trunk inverted the motion (DLY_2) in both forward and backward perturbations were represented 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.

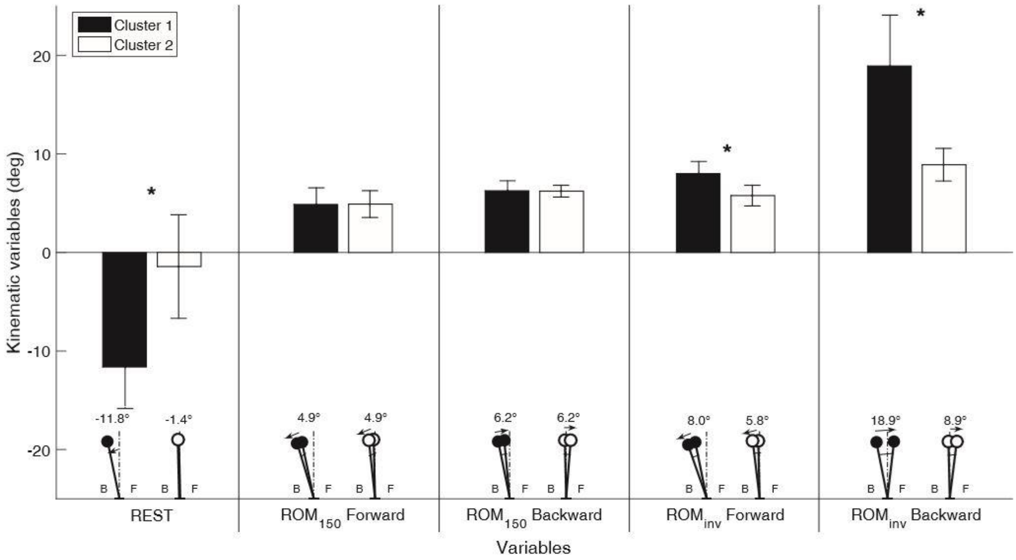

Figure 4. Kinematic variables. The trunk angle with respect to the vertical at rest (REST), the trunk range of motion 150 ms after the shoulder acceleration (ROM_{150}) and trunk range of motion when the trunk inverted the motion (ROM_{inv}) in forward and backward perturbations were reported in upper 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.

III

SIMULATED SKIING AS A MEASUREMENT TOOL FOR PERFORMANCE IN CROSS-COUNTRY SIT SKIING

by

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Simulated skiing as a measurement tool for performance in cross-country sit-skiing

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Abstract
The International Paralympic Committee 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 kinematics, 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

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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.[5–7]

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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 (ROM) 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, and 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.[15,16] 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 (1) if athletes with different impairments perform differently on a ski ergometer while ski sitting on their own sit-ski and (2) if there is an agreement on performance between cluster analysis outcome and current athletes' classification system.

Method

Participants

A total of 13 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, and lower limb amputation: n = 4) and belonged to the five classes as follows: LW10 = 1, LW10.5 = 1, LW11 = 3, LW11.5 = 4, and 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 (Figure 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,

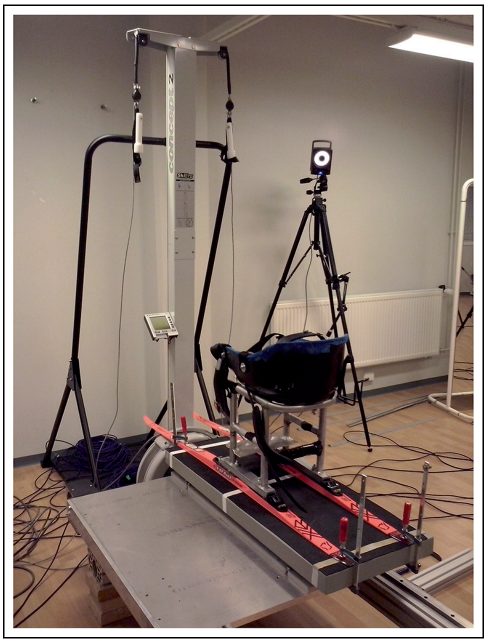

Figure 1. Maximal speed test setup.
An adapted ergometer was fixed to the wall in a vertical position with two ropes elongated from the top; each rope ended with a handle that the participant held while pulling; participant's sit-ski was fixed in front of the ergometer at a distance that allows the participant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

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.

The protocol consisted of 5–10 min 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 or she, using double-poling technique, had to reach his or 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 2 min 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 (Figure 2a). 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 CT, 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 (Figure 2a). The aF and the iF were calculated as the average value and the integral of the force curve during the poling phase, respectively.

The shoulder and hip markers were used to calculate trunk flexion–extension angle with respect to a vertical plane (considered as 0°), 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°) and negative when they moved posterior (Figure 2b). Trunk ROM of the poling phase was calculated for each poling cycle as the difference between TF and TB (Figure 2b). 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 (Figure 2a). Time to complete a trunk flexion during the poling phase (FET) was calculated as the difference in time between ET and BT (Figure 2a).

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 this study, to identify a measure of performance, cluster analysis was composed of four steps:[20]

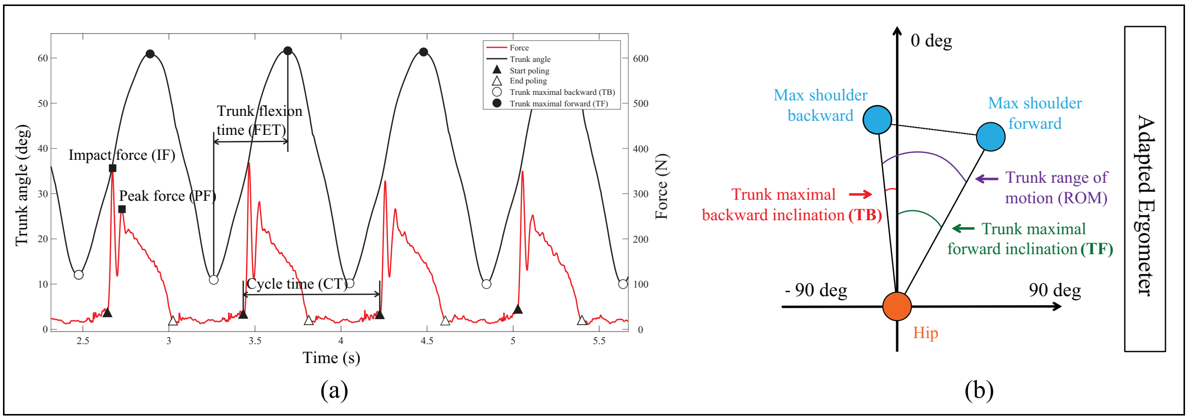

Figure 2. Cycle characteristic and kinematic variables: (a) on generated force, the start and end of the poling phase were identified to calculate cycle phases. On trunk angle, maximal backward and forward inclinations were used to calculate trunk range of motion and (b) trunk maximal backward (TB) and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

1. 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 $> 5\%$).
2. 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, and 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.
3. 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 $\leqslant 0.25$ indicated no substantial structure, 0.26–0.5 weak structure, 0.51–0.7 reasonable structure, and $\geqslant 0.71$ 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.
4. 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 χ^2 is the chi-square and N is the total number of participants in the study.[30] The effect size was interpreted using Cohen's d: $\leqslant 0.40$ small, 0.41–0.70 moderate, and $\geqslant 0.71$ large.[31] Once the most relevant variables were selected, the Spearman's correlation was used in order to identify redundant variables. Spearman's correlations were interpreted using Cohen.[31]

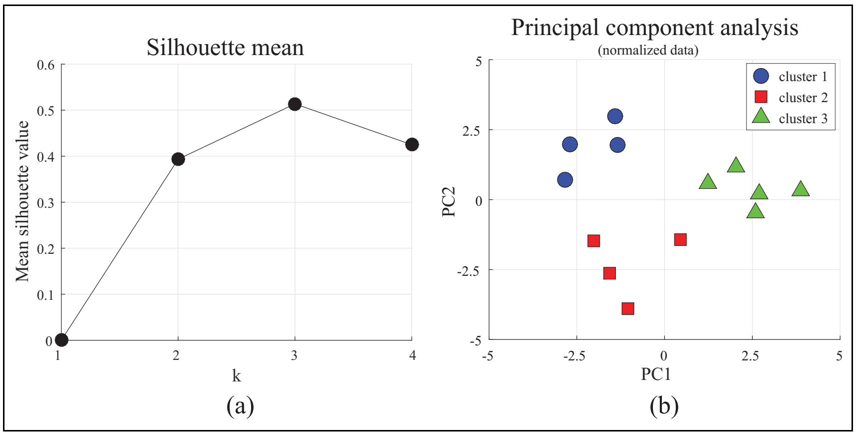

Figure 3. Mean silhouette and principal component analysis: (a) number of clusters (k) was defined running k-means with different k = 2, 3, and 4 and calculating the mean silhouette for each k and (b) representation of normalized data in the space of the first two principal components (PC1 and PC2): the three clusters were visible.

The analyses and statistics were performed using custom-made scripts in MATLAB Software (MATLAB and Release 2015, MathWorks, Inc., Natick, Massachusetts, USA). 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.

Cluster analysis

1. 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.

2. and 3. Internal validation showed a peak in mean silhouette for $k = 3$ (Figure 3a), 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 (Figure 3b). Therefore, three clusters were identified: Cluster 1 (high impact of impairment), Cluster 2 (middle impact of impairment), and Cluster 3 (low impact of impairment).
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%.

4. 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 Figures 4 and 5.

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 (Figure 4a). 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 (Figure 4b).

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 (Figure 5a). 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 (Figure 5b). Finally, Cluster 1 showed longer BT ($p < 0.05$, $r = 0.76$) than Cluster 2 (Figure 5b).

Table 1. Maximal speed, force, cycle characteristics, and kinematic results.

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

(continued)

Table 1. Continued

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

For each participant and variable, the mean (standard deviation) and median (interquartile range) among the seven poling cycles are reported. The coefficient of variability of each variable is reported in the last column. Speed: maximal speed (m/s); force and cycle characteristics: IF (N): impact force; PF (N): peak force; aF (N): average force; iF (N s): 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.

	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%	

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.

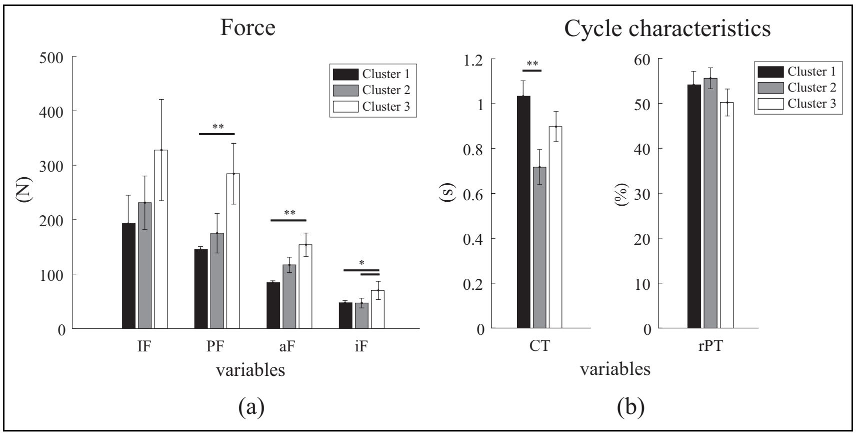

Figure 4. Force and cycle characteristic variables: (a) impact force (IF), peak force (PF), average force (aF), and impulse of force (iF) were represented as mean ± standard deviation for the three clusters. Cluster 3 showed higher PF, aF, and iF than Cluster 1 and (b) cycle time (CT) and relative poling 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, $^{*}p < 0.05$; $^{**}p < 0.01$.

Results for Spearman's 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).

Discussion

Considering the determinant role of propulsion generation in XC 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 PF, 45% lower aF, and 32% lower iF compared to participants with low impact of impairment (Cluster 3; Figure 4a). 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

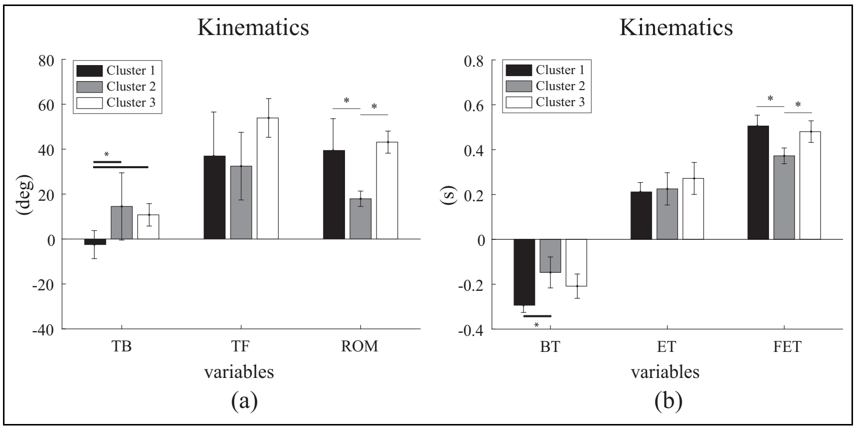

Figure 5. Kinematic variables: (a) trunk maximal backward inclination (TB), trunk maximal forward inclination (TF), and trunk range of motion (ROM) were reported as mean ± standard deviation for the three clusters. Cluster 1 showed negative TB compared to Cluster 2 and Cluster 3. Cluster 2 showed lower ROM compared to Cluster 1 and Cluster 3 and (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 3. Variables relevance.

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 (N s)	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

Speed: maximal speed (m/s); force and cycle characteristics: IF (N): impact force; PF (N): peak force; aF (N): average force; iF (N s): 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.
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.

Cluster 1 participants), generate lower iF compared to the kneeling posture (similar to the position of Cluster 3 participants).[34]

Current results on CT are in line with literature that identify higher poling frequency (lower CT) as primary method for increasing skiing speed in non-disabled athletes.[14,35,36] The longer CT 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 CT between Cluster 3 and Cluster 2 (Figure 4b), which may be due to the small sample size. Although not statistically significant, on average, slightly longer CT was found for Cluster 3 compared to Cluster 2, which is 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 (Figure 5a). These results are in line with literature on XC sit-skiing[8,38] and wheelchair racing:[39] athletes with high impact of impairment, using a deeper sitting

Table 4. Variables redundance.

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

Speed: maximal speed (m/s); force and cycle characteristics: IF (N): impact force; PF (N): peak force; aF (N): average force; iF (N s): 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.
Spearman's correlation coefficient for all the variables included in the cluster analysis.
[a]Significant correlation at 0.05.
[b]Significant correlation at 0.01.

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 ROM found for Cluster 3 (LW11.5–LW12) than Cluster 2 (LW11) was expected since it was in line with a previous study on XC sit-skiing on snow.[38] In contrast, comparable trunk ROM for Cluster 1 and Cluster 3 was not expected because the literature reports reduced trunk ROM 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 ROM 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 other variables. Among the variables that showed relevance in clustering, the high positive correlation found between maximal speed and force variables (IF, PF, aF, and iF) suggest that selecting one of these variables could be enough for the cluster analysis. Concerning cycle characteristics and trunk kinematic variables, CT, trunk maximal backward inclination, and trunk ROM 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 this 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 CT 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 may be responsible for unexpected results on trunk ROM. 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 XC 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 XC sit-skiers perform differently based on their impairment. Results of this study showed good sensitivity and an overall acceptable precision and accuracy in clustering XC sit-skiers in three clusters according to performance determinants using variables such as maximal speed or generated force, CT, 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 this 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 XC sit-skiing for an evidence-based classification based on measured performance, accounting for impairment severity that impacts performance.

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IV

TOWARDS EVIDENCE-BASED CLASSIFICATION IN CROSS-COUNTRY SIT SKIING: MEASURES OF IMPAIRMENT OF STRENGTH AND TRUNK CONTROL

by

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