JYU DISSERTATIONS 97

Olli Ohtonen

Biomechanics in Cross-country Skiing Skating Technique and Measurement Techniques of Force Production

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
HEALTH SCIENCES

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ABSTRACT

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Requirements of a successful skier have changed during last decades due to e.g. changes in race forms and developments of equipment. The purpose of this thesis was to clarify in four Articles (I-IV) what are the requests modern skate skiing sets for the athletes in a biomechanical point of view. Firstly, it was explained how skiers control speed from low to maximal speeds (I). Secondly, the effects of long simulated ski race were determined with traditional force measurement methods (III) as well as with novel propulsion methods (IV). During the work process a need for updated multi-dimensional leg force sensor appeared and it was materialized (II). During the thesis 16 national level athletes participated in the different experiments of the study. Measurements for controlling speed were carried out with 3D force sensor for legs and pole force sensor for arms. Conventional cycle, force and joint kinematic parameters were analysed (I). After, a need for reliable force sensor appeared especially for anterior-posterior forces. Two 2D force binding sensors (Skate binding: vertical and medio-lateral directions and Classic binding: vertical and anterior-posterior directions) were designed and built. Validation was done in different temperatures and mechanical stress situations as well as in diverse normal and sport specific jumping situations and skiing with both techniques (II). Effects of simulated ski skating race (20 km) on athletes' performance were analysed by direct force measurements from legs with updated force binding and from arms with pole force sensors. In addition, EMG and cycle definitions were conducted (III). Novel analysing method for propulsion was tested on the same data using additional 3D movement analysis (IV). Skiers control their speed during V2-skating with cycle length and cycle rate while length is dominant with lower speeds and rate governs with higher speeds. Force production of the arms and legs with increasing speeds is aided by vertical oscillation of COM (I). New force binding system was verified to be valid for skate skiing while some improvements were needed for classic binding (II). Effects of long simulated race were detected with slower skiing speed at the end of race caused by lower EMG activity and force production as indications of fatigue (III). Propulsion analyses gave new insights on athlete diagnostics by revealing the decrement of force production especially with legs which was overlooked with traditional analysing methods (IV).

Keywords: cross-country skiing, speed adaptation, force measurement, fatigue, propulsion

TIIVISTELMÄ (FINNISH ABSTRACT)

Ohtonen, Olli
Luisteluhiihdon biomekaniikka sekä suorituksen aikaisten voimien mittaamisen menetelmät
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Menestyksekkään hiihtäjän vaatimukset ovat muuttuneet viime aikoina merkittävästi esimerkiksi uusien kilpailumuotojen ja välinekehityksen myötä. Tämän tutkimuksen tarkoituksena oli selvittää neljässä artikkelissa (I-IV), mitä vaatimuksia nykyaikainen luisteluhiihto asettaa hiihtäjälle biomekaanisesta näkökulmasta. Ensiksi selvitettiin kuinka hiihtäjät kontrolloivat nopeutta hitaasta maksimaaliseen vauhtiin (I). Toiseksi tutkittiin pitkän simuloidun luisteluhiihtokilpailun vaikutuksia hiihtäjään perinteisillä voiman analysointimenetelmillä (III), sekä uudella propulsiovoimamenetelmällä (IV). Työprosessin aikana todettiin tarve uudelle voimanmittausmenetelmälle ja se toteutettiin (II). Tämän tutkielman aikana 16 kansallisen tason hiihtäjää osallistui tutkimuksen eri osiin. Nopeuskontrollitutkimuksessa käytettiin 3D voima-anturia jaloille ja sauvavoima-anturia käsille. Lisäksi mitattiin sykli- ja nivelkulmamuuttujia. Tämän työ-osion aikana todettiin tarve tarkemmalle jalkojen voimanmittausmenetelmälle, erityisesti pitkittäiseen suuntaan (I). Kaksi 2D voima-anturia (pysty- ja poikittaisvoima luisteluun sekä pysty- ja pitkittäisvoima perinteiseen) suunniteltiin, rakennettiin ja validoitiin. Validointi toteutettiin eri lämpötiloissa ja mekaanisissa kuormituksissa, sekä erilaisissa lajinomaisissa hypyissä. Lisäksi anturit testattiin referenssimenetelmiä vastaan lumella hiihdettäessä molemmilla tekniikoilla (II). Simuloidun luisteluhiihtokilpailun (20 km) vaikutuksia urheilijoiden voimantuottoihin tutkittiin uudella 2D voimanmittauslaitteistolla jaloista ja sauvavoima-anturilla käsistä. Lisäksi tutkittiin lihasaktiivisuutta ja syklimuuttujia (III). Uutta propulsiovoimamenetelmää testattiin samalla datalla 3D liikeanalyysin kanssa (IV). Hiihtäjät kontrolloivat nopeutta hiihtosyklillä ja –frekvenssillä, joista syklin mitan kasvattaminen on hallitsevampi matalammilla nopeuksilla, ja frekvenssin nostaminen kovilla nopeuksilla. Massakeskipisteen lisääntynyt pystysuuntainen liike edesauttaa voimantuottojen kasvua hiihtonopeuden kasvaessa (I). Uusi voimanmittausmenetelmä osoitettiin luotettavaksi luisteluhiihtoon, mutta perinteisen hiihdon anturiin tarvitaan parannuksia (II). Pitkä luisteluhiihtokilpailu aiheutti väsymystä, mikä nähtiin hidastuneena loppukirivauhtina. Tämä johtui heikentyneestä lihasaktiivisuudesta ja sitä kautta madaltuneista voimantuotoista (III). Propulsiovoima-analyysi paljasti suuremman voimien laskun jaloissa, mitä ei pystytty todentamaan perinteisillä voiman analysointimenetelmillä (IV).

Avainsanat: maastohiihto, nopeusmuutokset, voimanmittaukset, väsymys, propulsio

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Kajaani, 29.4.2019
Olli Ohtonen

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original Articles, which are referred to by their Roman numerals (I – IV). The thesis also includes unpublished data.

I	Ohtonen, O., Linnamo, V., & Lindinger, S.J. 2016 Speed control of the V2 skating technique in elite cross-country skiers. International Journal of Sports Science & Coaching 11 (2) 219–230
II	Ohtonen, O., Lindinger, S.J., Lemmettylä, T., Seppälä, S., & Linnamo, V. 2013 Validation of portable 2D force binding systems for cross-country skiing. Sports Engineering 16 (4) 281–296
III	Ohtonen, O., Lindinger, S.J., Göpfert, C., Rapp, W., & Linnamo, V. 2018 Changes in biomechanics of skiing at maximal velocity caused by simulated 20-km skiing race using V2 skating technique. Scandinavian Journal of Medicine & Science in Sports 28 (2) 479-486
IV	Ohtonen, O., Linnamo, V., Göpfert, C., & Lindinger, S.J. Effect of 20 km simulated race load on propulsive forces during ski skating. Submitted to International Journal of Performance Analysis in Sport 29.4.2019

These original articles (I-IV) have been written by the author by taking into account the comments from the co-authors. The author, in collaboration with the co-authors, has designed the study questions and done the preparations and the data collections of the experiments (I-III). The author has had the main responsibility of the data preparation and analysis as well as the statistical analyses of all the articles.

ABBREVIATIONS

XC	Cross-country
FIS	International Ski Federation
VO_{2max}	Maximal oxygen uptake
DPK	Double poling with kick
DP	Double poling
V1	Uphill terrain skating technique, also Gear 2 (G2)
V2	Flat to moderate uphill terrain skating technique, also Gear 3 (G3)
V2A	Flat terrain skating technique, also Gear 4 (G4)
COP	Center of pressure
PFA	Point of force application
COM	Center of mass
EMG	Electromyography
iEMG	Integrated electromyography
MVC	Maximal voluntary contraction
HD	Height difference of ski track
TC	Total climb of ski track
v_{max}	Maximal skiing speed
SJ	Squat jump
CMJ	Counter movement jump
DJ	Diagonal jump
SkJ	Skate jump
Ave 2-3	Averaged values for parameters from 2nd and 3rd lap
Ave 8-9	Averaged values for parameters from 8th and 9th lap
%BW	percentage of body weight
N	Newton
RFD	Rate of force development
RMS	Root mean square
R^2	Coefficient of determination
F_r	Resultant force
F_t	Translational part of resultant force
F_{ro}	Rotational part of resultant force
F_c	Propulsion calculated with novel method
ANOVA	Analysis of variance
SC	Similarity coefficient
n.s.	not significant
S1	Subject 1
S2	Subject 2
PSCD	Pole-ski contact difference
PoleProp%	Pole propulsion from pole resultant force
LegProp%	Leg propulsion from leg resultant force

CONTENTS

ORIGINAL PAPERS

1 INTRODUCTION

The history of cross-country skiing (XC-skiing) goes back 9000 to 7000 BP (before present) years in Russia with assumed ski like objects found from the lake Sindor region (Burov 1989). Later the modern XC-skiing developed and the first organized competitions were held in the 19th century. XC-skiing was part of the first Winter Olympics, Chamonix, France, in 1924 and the first World Championships, Janské Lázně, former Czechoslovakia, were held at 1925 (personal communications in Skiing Museum, Lahti, Finland). A new skating technique among classic skiing was introduced in the 80's where no kick waxes were used. The First world championships with divided races for classic and skating were held 1987 in Oberstdorf, Germany, and this division to separate techniques is still in use. Nowadays XC-skiing is a popular recreational and competitive sport in Nordic countries, Central Europe, Russia and North America while also increasing interest on XC-skiing is growing in China with upcoming Olympic Games in Beijing 2022.

The scientific research history of the biomechanics of XC-skiing goes back to early 80s with the analyses of force production using diagonal stride technique with small measurement units by Ekström (1981) and long force platform by Komi (1985). The scientific research interest in the late 80s and 90s focused largely in competition analyses (e.g. Smith et al. 1989; Smith & Heagy 1994; Street & Gregory 1994). During the present millennium the interest of the XC-research has increased due to the change in demands of what successful XC-skiing requires. Many studies have been focused on the sprint skiing (e.g. Losnegard, Myklebust & Hallen 2012; Losnegard & Hallen 2014; Losnegard et al. 2015; Sandbakk et al. 2011a; Stöggl, Lindinger & Muller 2007a; Stöggl, Lindinger & Muller 2007b; Zory et al. 2011; Vesterinen et al. 2009; Mikkola et al. 2010; Mikkola et al. 2013; Andersson et al. 2010; Sandbakk et al. 2010; Stöggl et al. 2010a; Sandbakk et al. 2011b) and therefore on the force and power capacities of the skiers. Nowadays an interesting field in the biomechanics of XC-skiing research is the analysis of the propulsive forces and propulsion a skier is producing (Göpfert et al. 2017; Hoset et al. 2014; Smith, Kvamme & Jakobsen 2006; Stöggl & Holmberg 2015). Movements during classic skiing occurs mainly in two dimensions, vertical and anterior-posterior, therefore, the calculation of the propulsive force, which is the force actually propelling skier forward, during classic skiing is rather straightforward. However, especially skate skiing contains movements in all three natural dimensions, which adds the medio-lateral direction supplementary to the above mentioned two other spatial directions. Consequently, analysing propulsion while using skating skiing requires movement analyses in addition to forces to resolve the propelling forces (Smith 2003). Propulsive forces during skating skiing have been calculated by Smith (2006) who reported that the arms are contributing more to V2-skating compared to legs. Propulsive forces of skating skiing have been of interest among the researchers lately (Stöggl & Holmberg 2015; Hoset et al. 2014; Göpfert et al. 2017) because it could be a useful tool for athlete technique and performance diagnostics. There are several skating techniques, but V2-technique is of special interest because it is a largely used skating technique in XC-skiing, biathlon and nordic combine races and the amount of usage of it has been positively correlated to race results in XC-sprint skiing (Andersson et al. 2010).

The purpose of this thesis was to investigate biomechanical requirements of V2-skating skiing. Specifically, the controlling mechanisms on how to increase speeds were studied as well as the effects of long simulated ski race to the athletes' performance with traditional force production and novel propulsion methods were analysed and compared. To enable these measurements multi-dimensional sensors for leg force measurements were designed, built and validated.

2 REVIEW OF THE LITERATURE

2.1 XC-skiing in general

2.1.1 Overview

XC-skiing is a locomotion where the movement are performed with skis attached to the legs by kicking and gliding and simultaneously with poles held by the hands and moved by the trunk and both arms. XC-skiing involves two main techniques, classic and skating which are divided into several sub-techniques under both main techniques to be used in different types of terrain and glide conditions (Smith 2003).

International competitive XC-skiing is organized by the International Ski Federation (FIS). At the moment in XC-skiing World Cup, World Championships and Olympic games the race program consists of race forms from sprint (~1 to 1.8 km and from 2 to 3 minutes) to 50 km (~2 hours) and several distances and race forms between these lower and upper limits. In addition to multiple race distances, XC-skiing contains interval starts, mass-starts, relays and handicap starts (FIS 2018a; FIS 2018b). Additionally, because XC-skiing races are performed outdoors and in different locations, conditions like temperature, snow and glide properties, altitude and track profile are always different. These above mentioned characteristics of XC-skiing set high demands for competitive and sometimes for recreational skiers as well. Studies suggested that the maximal aerobic capacity, VO_{2max}, is the most determinant factor for the success in XC-skiing (Ingjer 1991). However, during the last two decades the competitive XC-skiing has changed due to shorter sprint competitions and mass starts. It is noted that 15 km race can be done with ~90-95% of VO_{2max} (Rusko 2003). However, the VO_{2max} can be momentarily exceeded at some points of the race track with work levels equivalent to 140% and 120% of VO_{2max} level in sprint and in longer distance races, respectively (Norman & Komi 1987; Sandbakk et al. 2011a). This is possible due to the short duration of the uphill sectors and the following downhills. Also while VO_{2max} during double poling is ~90-95% of diagonal VO_{2max} (e.g. Bjorklund, Stöggl & Holmberg 2010; Bjorklund, Holmberg & Stöggl 2015; Fabre et al. 2010; Holmberg, Rosdahl & Svedenhag 2007) some studies show that nowadays skiers can achieve same the VO_{2max} using double poling compared to diagonal technique, highlighting the increased capacity of upper body work during the last decade (Stöggl et al. 2018). Also, race speeds have increased more in XC-skiing compared to any other Olympic sports (Sandbakk & Holmberg 2014) (Figure 1). This is partly due to development in equipment, waxes and track preparation, but also the increased capacity of the athletes to produce high speeds. All this has changed the requirements of successful XC-skiing. Nowadays, more force and power capacities, especially from the upper body as well as good technical and tactical skills are needed in addition to high VO_{2max} (Sandbakk & Holmberg 2014).

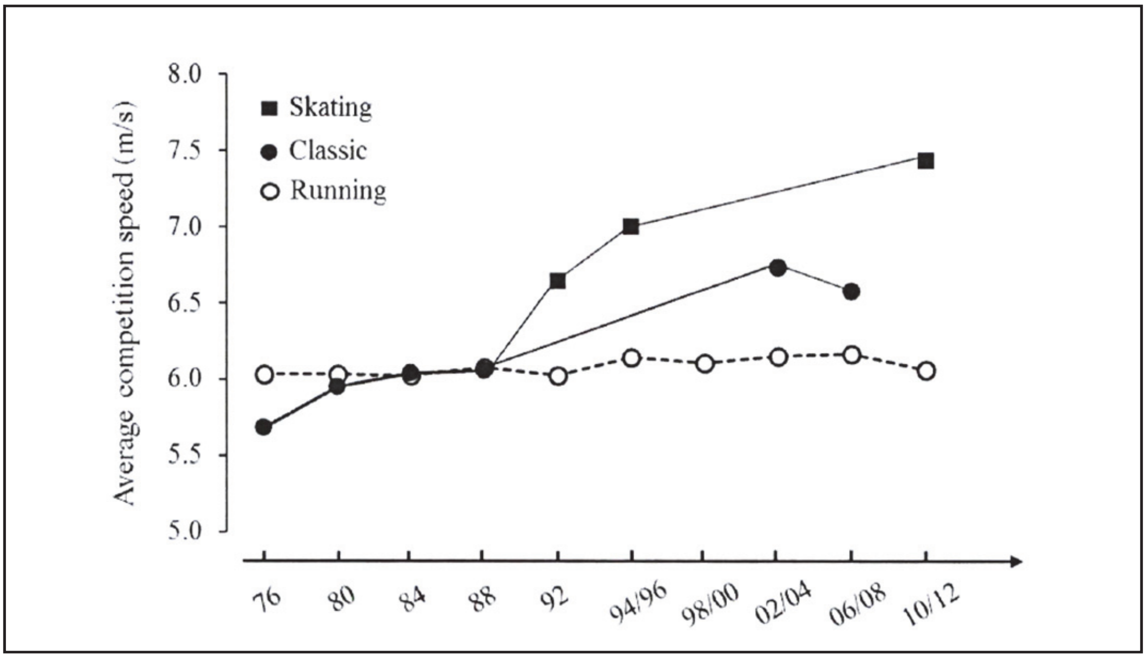

FIGURE 1 Speed development in XC-skiing and running races from 70s to nowadays (Sandbakk & Holmberg 2014), modified.

2.1.2 XC-skiing techniques

As mentioned there is several sub-techniques under classic and skating techniques (Smith 2003). Sub-techniques of classic skiing in order used from slowest to fastest and from steepest uphill to flat are herring bone, diagonal stride, double pole with kick (DPK) and double poling (DP). Sub-techniques of skating skiing in same order are diagonal skate (Gear 1), V1 (Gear 2), V2 (Gear 3), V2A (Gear 4) and free skate (without poles, Gear 5). Most relevant difference between classic and skating techniques is that the kick is done on a static ski when using classic techniques while skating kick is performed on a gliding ski (e.g. Smith 2003). This causes differences especially in push-off time which is approx. two to three times greater using skating techniques compared to classic (e.g.

Smith 2003; Vähäsöyrinki et al. 2008). In turn, poling action is more similar between the sub-techniques of the classic and skating skiing.

V2-technique is described here more specifically since it was the only technique used in this thesis. The relevance of V2-skating technique was highlighted by Andersson (2010) who showed that the sprint performance was related to the amount of usage of V2-technique during sprint race. Also the increasing amount of the usage of V2-during last decade have been noted among World Cup coaches (personal communications during World Cup races 2013-2019). V2-skating technique is used on flat to moderate and sometimes even steep uphill. Also this technique is used in places which require high speeds and accelerations like in final spurt, in start sections or in a short “wavelike” uphill. V2-technique is symmetrical where one double poling action is performed for each leg push-off phase separately and simultaneously. One V2-cycle (Figure 2) starts from the gliding phase of right ski continuing via unloading phase to the simultaneous leg and pole push-off phase. After push-off right ski releases snow to recovery phase and similar gliding – unloading – push-off action is done with left ski. One full cycle ends on the subsequent glide of the right ski. V2-technique contains also a special adaptation called Double-Push V2 which contains kick with outer edge of the ski followed by jump to inner edge during normal V2-glide. This technique adaptation enables faster skiing but is also physically and technically challenging (Stöggl, Muller & Lindinger 2008; Stöggl et al. 2010b).

As described earlier the best skiers have the highest aerobic capacity (Ingjer 1991), but last years have also shown that the best skiers can renew sport with some technical modifications. These have been seen with Norwegians Petter Northug using e.g. high frequency double poling and Johannes Høsflot Klæbo using running diagonal technique (coaches’ observations during world cup races (2013-2019). These new technique modifications introduced by top athletes change the technical requirements of good skiers and thereby have high impact on especially technique training.

FIGURE 2 One V2-cycle, kick and poling action on left (upper) and right side (lower) (Stöggl, Muller & Lindinger 2008), modified.

2.2 Biomechanics of XC-skiing

2.2.1 Force measuring and analysing methods

2.2.1.1 Force measurement methods

Force measurements in XC-skiing have been done for several decades. First attempts to measure force were done by Ekström (1981) in the early 80s. When scoping the force measurement methods used in XC-skiing two main methodical approaches can be found: 1) Force measurements with systems of which skier can ski on or over and 2) Smaller measurement systems that are installed on the skiing equipment. Both systems have their strengths and weaknesses that are reported and evaluated below. Many of these force measurement studies are carried out with custom made proto devices and often even though the calibration process has been described the reliability of these units has not been reported.

Force measurement systems that can be skied on or over

First attempts to use force measurement platforms buried under snow were done by Komi (1985) with a 6 m long system. This system has been later developed of consisting measurement area of 20 m (Vähäsöyrinki et al. 2008) (Figure 3A). These longer systems are restricted only to classic technique but in addition to vertical and anterior-posterior leg forces, also pole forces in these directions are possible to measure. Same measuring methodology have been also used for collecting forces from skating technique with short 2 meter long force platform (Leppävuori et al. 1994) (Figure 3B). Measurement beams were 10 cm wide and those measured forces from all three dimensions adding mediolateral direction compared to long (6 to 20 m) platforms. Advantages of these systems are the possibility to measure skiing in real conditions without any disturbing measuring devices on the subject. However, with under snow platforms the measurements are restricted to one place at a time and the changing of the measurement place requires a great effort of work and time. Also if measurements are done outdoors, snow fall is effecting the results and highlighting the need for proper calibration process (Leppävuori et al. 1994). Later large treadmills with force plates installed under the belt have come to markets (Aarts et al. 2018). With these treadmills the produced force and center of pressure (COP) is possible to calculate but the separation of the pole and leg forces is challenging.

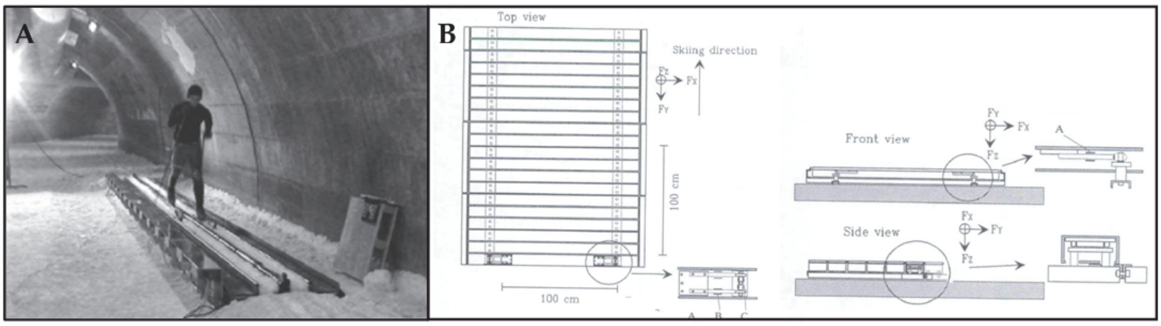

FIGURE 3 Force platforms of which athlete can ski over with (A) diagonal stride (Vähäsöyrinki et al. 2008), and (B) skating (Leppävuori et al. 1994), both modified.

Small measurement units installed in equipment
Some disadvantages of the large force measurement platform units can be overcome with small sensors implemented in the equipment. Three different approaches for leg force measurements can be separated from this methodology. 1) Small force plates placed between ski and binding which measure forces from two (Ekström 1981; Komi 1987; Street & Frederick 1995; Pierce et al. 1987) or three (Ohtonen, Lindinger & Linnamo 2013; Linnamo et al. 2012; Babiel 2003) directions. (Figure 4A) 2) Instrumented roller skis which have been used for classic and skating skiing (Bellizzi et al. 1998; Hoset et al. 2014; Smith, Kvamme & Jakobsen 2009; Herzog, Killick & Boldt 2015) (Figure 4B), and 3) Pressure insoles, which have been widely used in XC-skiing research during last 15 years (e.g. Holmberg et al. 2005; Lindinger et al. 2009b; Stöggl et al. 2010b). All these systems have one major advantage when comparing them to big force platforms. Several consecutive cycles can be measured and the changing of the measurement place is rather straightforward compared to force platforms. However, with these systems a skier needs to inevitably carry on some data collecting equipment and small force plates also add some weight to the normal ski/roller ski. In addition, as a benefit when using pressure insoles, the COP can be obtained more accurately compared to small force plates. However, with the current methodology the measurement frequency is normally limited to 100 Hz with pressure insoles, which is much less than normally used with force plates (1000 Hz) and might be too little for some applications. In addition, pressure insoles measure only vertical force that might leave some important information out especially on skating push-off situations where the ski is extensively edged. It has been reported that propulsion analyses need all three force components to have reliable data and therefore, it seems that at the moment small force measurement units are the most suitable for this need (Göpfert et al. 2015; Hoset et al. 2014; Stöggl & Holmberg 2015)

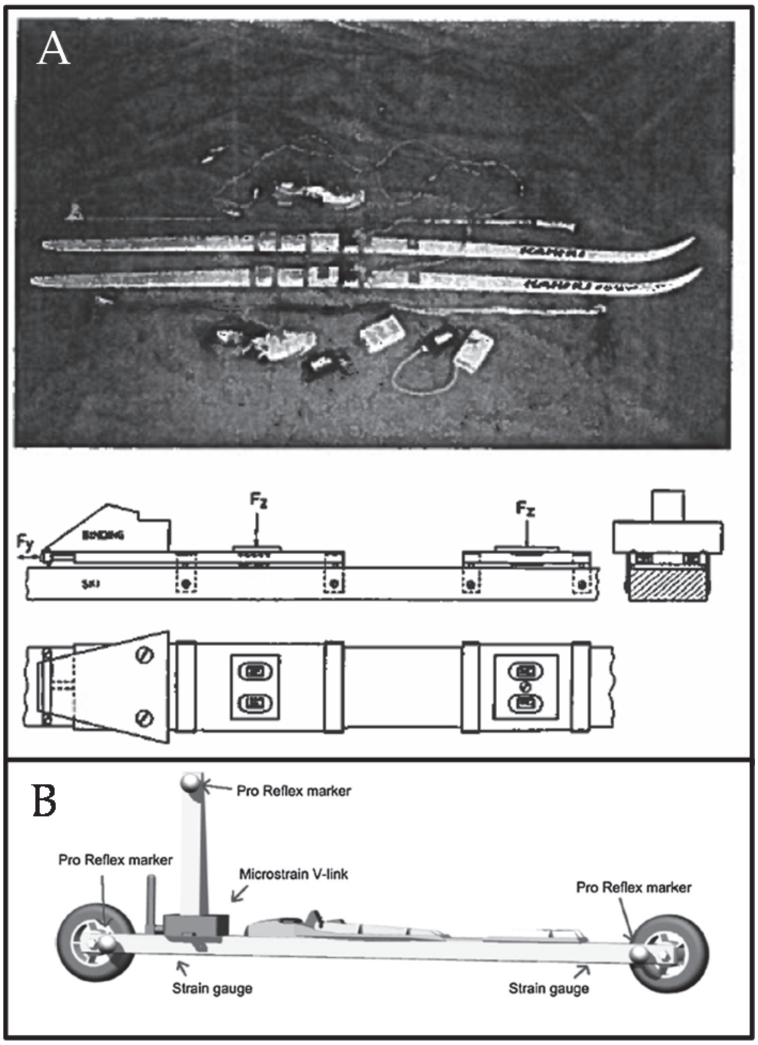

FIGURE 4 Example of (A) small force plates installed between ski and binding (Komi 1987) and (B) instrumented roller ski (Hoset et al. 2014), both modified.

Pole forces have widely been measured with small measurement sensors installed in pole grips (e.g. Holmberg et al. 2005; Lindinger et al. 2009b; Herzog, Killick & Boldt 2015; Göpfert et al. 2017; Smith, Kvamme & Jakobsen 2006; Stöggl & Holmberg 2015; Ohtonen, Lindinger & Linnamo 2013). These sensors unavoidably increase the weight of the pole but while it is placed in the pole grip or straight under it the effect of weight is described rather low.

2.2.1.2 Force and video analysing methods

The main different techniques (classic and skating) of XC-skiing require different measurement setups. Classic skiing is mainly performed in two-dimensional space (if we neglect slight rotations in legs, arms and trunk) with main relevance of vertical and anterior-posterior directions, and therefore those vertical and horizontal forces have to be measured. This is possible to be done with long force platform systems as presented above. From these systems, the propulsive force (anterior-posterior direction of force) locally under the ski and pole can be measured. It has been shown that the faster skiers produce greater propulsive force (Vähäsöyrinki et al. 2008) and it is also requiring better grip conditions (Vähäsöyrinki et al., unpublished). However, with skate skiing where the movements are occurring in all three natural directions (vertical, anterior-posterior and medio-lateral), one or two measurement dimensions are not enough if the propulsive force is needed to measure reliably (Göpfert et al. 2015; Hoset et al. 2014; Stöggl & Holmberg 2015). The medio-lateral force is of interest especially during the push-off phases where the ski is heavily edged. It has also been shown that the medio-lateral force is increasing when skiing on worse glide conditions (Ohtonen, Lindinger & Linnamo 2013) also highlighting the significance of this force component. Often force curves are used to calculate cycle parameters like cycle time and phase times for recovery, gliding and push-off phases for leg and pole movements. Traditionally force parameters are analyzed for peak, average and impulses of forces from the leg and pole force sensors (e.g. Stöggl et al. 2010b; Lindinger et al. 2009b).

However, when aiming to calculate the propulsive force during skating skiing a synchronized kinematic analysis is needed in addition to force measurements. From kinematic analyses the ski edging angle (α) and orientation angle (β) (Figure 5) as well pole angle are needed to calculate the propulsive force value (Smith 2003).

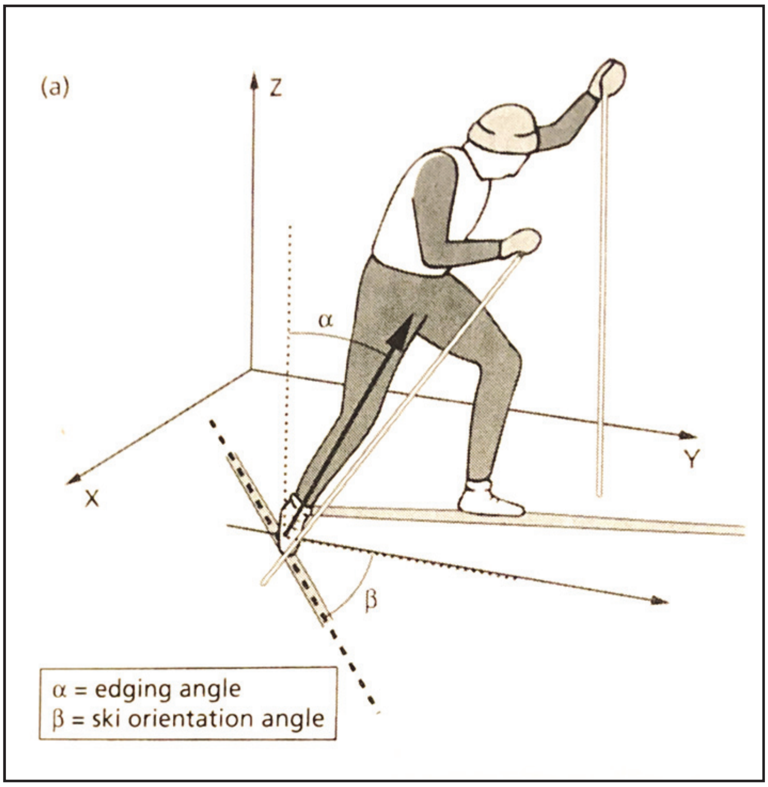

FIGURE 5 Angles needed for traditional propulsive force calculation (Smith 2003), p 46, modified.

In a recent study, Göpfert et al. (2017) presented an advanced method for propulsion calculation. While the traditional method calculates the propulsive force locally under the ski and pole the new method takes into account the point of force application (PFA) as a starting point of resultant force vector, a share of resultant force which is hitting the center of mass (COM) and calculates the forward pointing vector from that. This modified version observes how forces hitting the COM propels the skier forward (Figure 6) and provides possibilities for more specific athlete diagnostics e.g. comparing different levels of athletes and to evaluate the effect of technique changes and changes with different ski gliding properties and inclines. Traditionally propulsive force ($F_{propulsive}$, Figure 6) is calculated locally under ski of pole (Hoset et al. 2014; Stöggl & Holmberg 2015; Smith 2003; Smith, Kvamme & Jakobsen 2006). Traditional method assumes that the XC-skier is a rigid body. In rigid body case the propulsive force from skis and poles is the same compared to propulsion calculated through COM. However, XC-skier is not a rigid body, but the skiing posture is changing throughout the cycle and therefore the point of mass model presented by Göpfert et al. (2017) is used here. The method used by Göpfert et al. (2017) showed to be more accurate compared to traditional propulsive force method when comparing these force methods to force curve determined from COM motion data. Differences with method calculated through COM were -1.4% in mean value (4.8% in maximum value) while difference with traditional propulsive force method gave mean difference of 16.5% (25.0% in maximum value) suggesting more precise reproduction of COM acceleration with Göpfert et al. (2017) method.

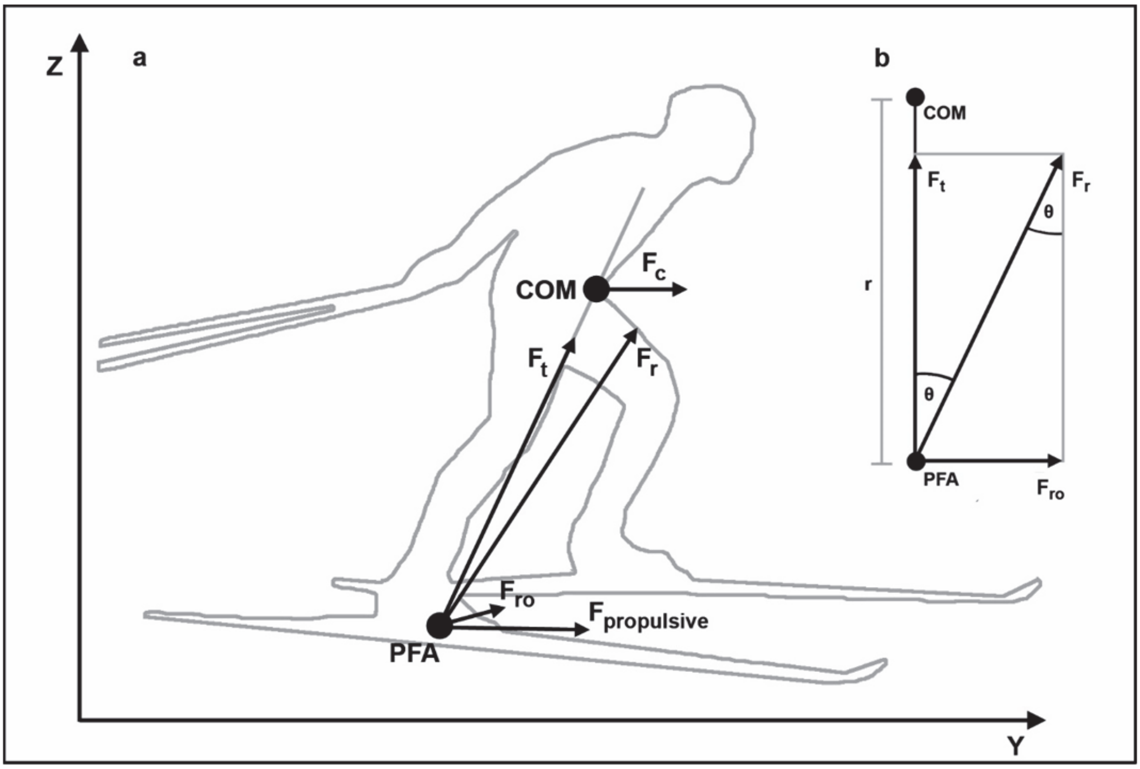

FIGURE 6 Novel calculation method for propulsion (F_c) (Göpfert et al. 2017), modified.

During the last years, combined biomechanical analyzing methods have become part of the everyday coaching process. One example of this is Coachtech – online feedback system (Ohtonen et al. 2016). With this system force measurements and essential parameters calculated straight from the data can be synchronized and combined with multi camera video feedback. Data with video and force curves and parameters is possible to present for athlete almost immediately online (approx. one minute delay) for technique training and performance optimization. Feedback systems to show biomechanical data for coaching purposes have also been done elsewhere (Gloersen et al. 2018).

2.2.2 Mechanisms of speed control of speed in XC-skiing

In all cyclic locomotion, the speed is the product of cycle rate and cycle length (Hay 2002). It seems that if modern athlete (coaches' observations of e.g. Petter Northug or Johannes Høsflot Klæbo) can vary between these two (cycle rate and length) differently in diverse track sections or even in same track sections a skier can distribute race load more equally to whole body and can also do great modifications to racing speeds in different track parts.

The usage of V2-skating technique, which is nowadays widely used in different sections of track from flat to even steep uphill, have showed to be essential for good race results. Andersson et al. (2010) reported that the amount of the V2-technique skiers used was positively correlated to the race result, which highlights the importance of this essential skating technique. In cyclic sports, which XC-skiing also is, it has been shown that the cycle length is the main governor of the speed increase with lower speeds while maximum speeds are reached with increasing cycle rate (Hay 2002). Earlier studies with skating technique (Smith 2003; Nilsson, Tveit & Eikrehagen 2004; Perrey et al. 2000) have suggested that the cycle rate is the only way to regulate speed while cycle length stays constant. However, other studies have noted that both, cycle length and cycle rate, contribute to speed increase with skating techniques (Millet et al. 1998; Hoffman, Clifford & Bender 1995; Smith 2003; Sandbakk et al. 2010; Sandbakk, Ettema & Holmberg 2012) as well as with classic techniques (Göpfert et al. 2013; Lindinger et al. 2009c; Vähäsöyrinki et al. 2008; Lindinger et al. 2009b). With modern sprint the increase in cycle rate has been found to be the only way to increase speed while cycle length started to even decrease at those highest speeds (Stöggl & Müller 2009). While speed effects have been widely studied in several locomotive sports (Hay 2002) including XC-skiing, the combined approach with force measurements in this topic has been rare. When skiing with increasing speeds using roller skiing on asphalt Millet et al. (1998) noted that even though peak pole forces slightly increased the average cycle pole forces remained unaltered suggesting that the speed increase of the V2 is more dependent on lower body actions. Smith (2006) reported increased both peak pole and leg forces with increasing speeds while skiing on a treadmill with V1 and V2-techniques. Greater COM oscillation movement linked to increased leg joint movement has been discussed to be essential and advantageous for increasing leg and pole forces and thereby increased performance while skiing with diverse techniques (Lindinger et al. 2009b; Lindinger et al. 2009c; Holmberg et al. 2005; Stöggl & Müller 2009; Myklebust, Losnegard & Hallen 2014). Also, it has been shown that while intensity is increasing with double poling legs are contributing more to this increment compared to arms which reach a plateau at rather low level when considering energy turn over (Bojsen-Møller et al. 2010). Even though the technique is different this same phenomenon might be the same during V2 due the same kind of pattern with COM described with down forward movement during poling (Myklebust, Losnegard & Hallen 2014). However, there is a lack of on skiing measurements under real snow conditions. In addition, as mentioned, skiing has changed a lot since the 90s due to e.g. sprint and specialized skiers and technique from these changes requires restudying the modern ways of how athletes control speed.

2.2.3 Effects of a longer distance race loads and fatigue on XC-skiing biomechanics

As described earlier, XC-skiing has changed a lot. In the World Cup calendar there was only 8 interval starts out of 37 races in the 2015-2016 season (FIS 2015). Also the World Championships and Olympic games calendar includes only one interval start (FIS 2018b). All other races contain group skiing, man-to-man fights in overtaking and final spurt situations. All this requires an extremely good capacity to ski fast several times during one race, recovery during race and most essentially a good ability to produce high speeds even at fatigued state. All this has guided athletes and coaches to focus much more on capability to achieve high speeds, concentrate on strength and power training and especially to improve their upper body (Sandbakk & Holmberg 2014).

Fatigue has been studied in XC-skiing with race analyses (e.g. Bilodeau et al. 1996; Rundell & McCarthy 1996; Viitasalo et al. 1997) which shows that cycle rate decreases at the end of the race while cycle length stays unaltered. The same phenomenon has been noticed in studies with competitive skiers in distance (Halonen et al. 2015) and sprint skiing (Vesterinen et al. 2009; Mikkola et al. 2010; Haugnes et al. 2018) research. So the decreased movement frequency is a typical effect of fatigue in XC-skiing regardless the distance. Muscle activity (electromyography, EMG) has been shown to shift in sprint skiing studies towards lower frequencies in the analysed values between first and last heat (Zory et al. 2011) as well as to decreased iEMG (integrated electromyography) values from upper and lower body when comparing pre speed test to end spurt of the sprint race (Vesterinen et al. 2009). After marathon skiing (40 km to 90 km) researchers have reported lower MVC (maximal voluntary contraction) and/or EMG amplitude values straight after the race when compared to the values before the race (Boccia et al. 2017; Millet et al. 2003; Viitasalo et al. 1982). Also an interesting approach on fatigue topic was done by Cignetti et al. (2009) who reported that fatigue is causing decreased performance due to compromised coordination observed with increased and more random variation during movements with legs and arms leading to decreased speed.

2.2.4 Propulsion in XC-skiing

Propulsive force analyses have been reported for skating skiing in few studies with V1, V2 and V2A techniques (Smith, Kvamme & Jakobsen 2006; Hoset et al. 2014; Stöggl & Holmberg 2015). Study by Smith (2006) demonstrates that while using V2-technique approx. 1/3 of the propulsive force is generated by legs and 2/3 by arms. When using V1-technique less than half of the propulsive force came from the poles. This was also the result of Stöggl (2015) who reported ~44% of the propulsive force from the poles using V1. These studies were performed using roller skis on a treadmill and by measuring only resultant leg forces with pressure insoles or instrumented roller skis. It was also reported by Stöggl (2015) and Hoset (2014) that lack of 3D force measurement might have some effect on the results. Also the propulsive force measurements were done locally on the pole and ski and as it has been shown (Göpfert et al. 2017) that all resultant ground reaction forces are possibly not pointed to COM and thereby not propelling the skier forward. Above mentioned problems were taken more deeply into account in the study by Göpfert et al. (2017) who validated the propulsion calculations for leg forces in an on snow situation using V2-alternative technique.

3 PURPOSE OF THE THESIS

The requirements of successful XC-skiing have changed a lot during the past decades due to development of the equipment and the track preparation as well as the changes in race formats and tracks. The main purpose of this thesis was to understand the biomechanical demands of modern skating skiing sets for the skier in different situations e.g. increasing speeds and fatigue. In addition to this, during the work process a force measurement system for leg forces was updated and validated

The specific aims and hypotheses for this study were:

1. To accomplish a more extensive biomechanical examination from whole body using kinetic and kinematic approach for studying speed control strategies during V2 performed under natural conditions on snow and over a wide range of speeds up to maximum skiing speed.

   It was hypothesized that the faster speeds are gained by increasing both cycle rate and cycle length, while with lower speeds cycle length is dominant. Secondly, the greater leg and arm joint movements with increasing ranges of motions and angular velocities would lead to higher force output with arms and legs.

2. To develop a novel force measurement system for the needs of XC-skiing research and coaching by designing, building and validating two separate two-dimensional (2D) force bindings, one for classic skiing and one for skate skiing analyses.

   The hypotheses was that the new force measurement system would be lighter and would show less cross-talk in skiing situations compared to the old system. The system was expected to be valid and practical.

3. To find out how the effects of a longer distance race load completed by XC-skiing on snow and possible fatigue affects the final spurt performance from a kinematic (cycle characteristics), kinetic (forces), and muscle activity point of view.

   It was hypothesized that the simulated race is causing fatigue and the performance is compromised and seen with decreased muscle activity and therefore lower force production from upper and lower body, which leads via decreased cycle rates to compromised maximal skiing speed.

4. To clarify how fatigue accumulated during the simulated race effects on the athletes' performance and propulsion force distribution between upper and lower body. Also of interest is whether new propulsion method is providing information which might be ignored with traditional methods.

   The hypothesis was that arms are more fatigued with propulsion analyses compared to legs. It was expected that the traditional force analysing methods might overlook some information especially with leg forces, which might be revealed with the new propulsion method.

4 METHODS

4.1 Subjects

Altogether 16 national level athletes from Finland and Austria participated in the study (Table 1). Several subjects participated in different experiments of the project. Every subject was informed about the nature of the measurements before and they gave their written permission about participating in the experiments. Methods and procedures used during the project were approved by the ethical committee of the University of Jyväskylä.

TABLE 1. Information of the subjects participated in the study separated by experiments.

Experiment no.	**Participants** (N)	**Age** (years)	**Height** (cm)	**Weight** (kg)	**FIS-points** (distance)	**Article**
Exp I	10	28 ± 6	176 ± 5	76 ± 8	110 ± 37	I
Exp II	1	44	187	85		II
Exp III	9	28 ± 6	177 ± 5	75 ± 6	136 ± 42	III
Exp III	5	27 ± 6	175 ± 5	74 ± 7	145 ± 29	IV

4.2 Experimental designs

4.2.1 General for all experiments

In all the experiments all or some of the measurements were done in indoor ski tunnel (Figure 7, Vuokatti, Finland). Ski tunnel is 1,25 km long with height difference (HD) of 18 meters and total climb (TC) 45 meters for one back and forth "loop". Ski tunnel offered equal conditions for subjects to perform with quite constant humidity (75-85%) and temperature (4-7 °C) in different experiments.

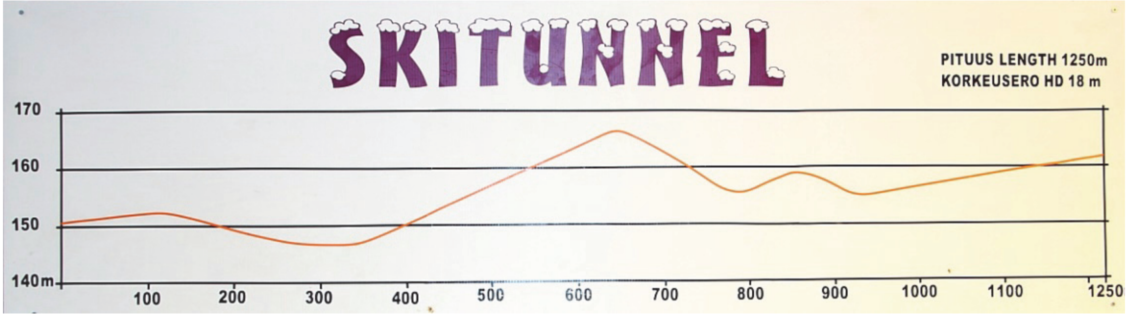

FIGURE 7 Track profile of the Vuokatti ski tunnel. HD = height difference (y-axis).

4.2.2 Experiment I

Experiment I was done to find out what strategies athletes use to control speed with the V2-skating technique. Results are reported in Article I. After performing 15 minutes of low intensity training speed for warming up subjects skied three randomized submaximal trials (slow, 4.0 m/s; medium, 4.8 m/s; fast, 5.6 m/s) paced with visual pace maker (Protom, Naakka Oy, Lappenranta, Finland) and after those maximal speed trial (v_{max}, 6.6 ± 0.4 m/s, mean ± SD). All speeds were performed twice and better trial, characterized by closer to target speed (submaximal) or faster speed (maximal) were selected for further analyses. All trials were done on 100 meter uphill with constant gradient of 4°. Recovery time between trials was three minutes to prevent fatigue accumulation during the measurements. In order to standardize the glide conditions all subjects used the same pair of skis (Peltonen Supra-x, Peltonen Ski Oy, Hartola, Finland) and waxing (rub-on high fluoride briquette Rex TK-72, Oy Redox Ab, Hartola, Finland) prepared by experienced serviceman.

4.2.3 Experiment II

Experiment II was carried out to build and validate a force measurement system (Figure 11, Force binding, NeuroMuscular Research Center, University of Jyväskylä, Finland) for XC-skiing used with classic and skating techniques. Results are reported in Article II. Developed force bindings consists of the front and rear part for classic and skating techniques. Force binding for classic skiing measures forces from vertical and anterior-posterior (longitudinal to ski) directions and force binding for skating skiing measures vertical and medio-lateral (transversal to ski) forces. Validation was done in three step process: (1) Accuracy of the force bindings in laboratory and field temperatures as well as after mechanical stress. (2) Comparing the force bindings against standard force plates in different kind of skiing imitation jumps in laboratory conditions. (3)

Testing the force bindings in natural skiing against currently used force measurement methods in XC-skiing.

Accuracy

The accuracy was tested by resolving the linearity and repeatability of the force binding against calibration sensor (Figure 12a, Raute precision TB5, Nastola, Finland) in three conditions (1) laboratory (22 °C), (2) ski tunnel (-5 °C) and (3) 1h of skiing in ski tunnel. In conditions 1 and 2, measurements were done twice with 2-h interval. In condition 3, measurements were done before and after 1 h skiing. Force bindings was tested separately for front and rear part (both directions) and for classic and skate bindings. Force bindings and calibration sensor were placed several hours before measurement in the target temperature systems to adapt in right temperature.

Imitation jumps

Force bindings were tested in applied situation with normal and skiing imitation jumps (Figure 8 A-D) on four situations: squat jumps (SJ, A), counter movement jumps (CMJ, B), diagonal jumps (DJ, C) and skate jumps (SkJ, D). SJ and CMJ situations were performed over standard force plates (NeuroMuscular Research Center, University of Jyväskylä, Finland) with both legs. DJs were done with one leg classic kick imitation jump over the same force plate. SkJs were performed sideways imitating skating push off form the same force plate. All situations were performed without extra weight and with 20 kg extra weight (two 10 kg barbell).

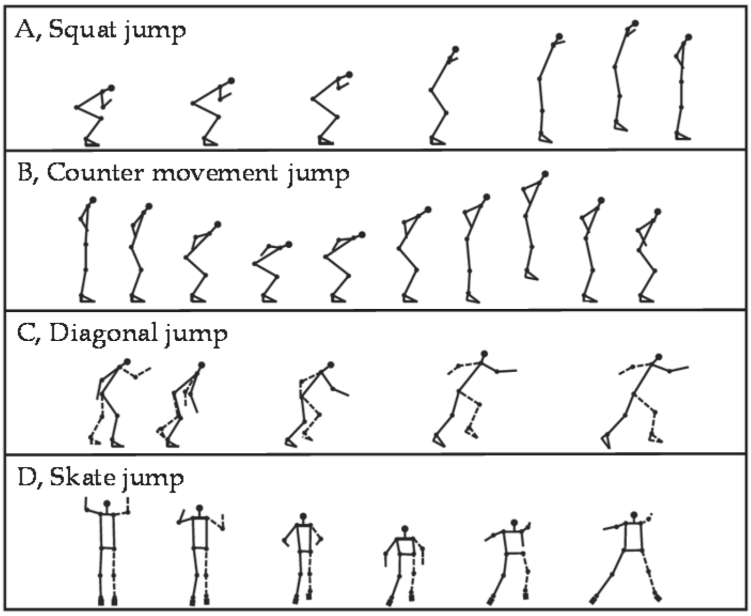

FIGURE 8 Stick figure illustration of normal and skiing imitation jumps performed over force plate during the validation process of force bindings.

Comparison against reference systems on snow
Last test in validation process was comparing the developed system against currently used force measurement systems in XC-skiing. Classic binding was tested against 20 m long force platform system (Vähäsöyrinki et al. 2008) and skating binding against Novel Pedar pressure insoles (e.g. Holmberg et al. 2005; Lindinger et al. 2009a; Stöggl et al. 2010b).

4.2.4 Experiment III

Experiment III was performed to clarify how possible fatigue caused by a longer distance race over 20 km is effecting on the athletes` performance during maximal V2-skate sprints and the results are reported in Articles III and IV. After 15 minutes of warming up with moderate training speed subjects skied a 20 km long simulated race. Race consisted of 10 laps of 2 km each in Vuokatti ski tunnel (Figure 7). Track consisted of 450 m of total climb. Subjects ran two full speed 100 m trials before (pre) the race and one during the final spurt (post) of the race on 4° uphill. Faster pre-trial was selected for analysis. Additionally in Article IV, the 3rd and 4th lap (Ave 2-3) as well as 8th and 9th lap (Ave 8-9) were averaged and used as submaximal race trials in analyses. The performed technique was individually selected by the subjects for all parts of the track. During the spurts and submaximal race trials, a V2-technique was used and also individually selected by all the athletes on the appropriate part of the track. All subjects used the same pair of skis (Peltonen Supra; Peltonen Ski Oy, Heinola, Finland) which were prepared with same manners by technician (Violet Rex Olympic; Oy Redox Ab, Hartola, Finland) to standardize the gliding conditions. Articles III and IV are written from experiment III with reduced subject amount in Article IV due to technical problems with movement analysis data (subjects in Table I).

4.3 Data recording and collecting methods

4.3.1 Kinematic measurements

For documentation purposes a video camera (NV-GS400, Panasonic, Japan, 25 Hz) was used in all experimental setups. A high-speed video camera (NXR-NX5E, Sony, Tokyo, Japan, 100 Hz) was used for 2D motion analyses in experiment II. Subject's actual speed throughout the measurement stations was detected with laser radar (Jenoptik, LDM 300 C SPORT, Jena, Germany, 100 Hz) in experiments I and III.

In experiment III motion data of the subjects and the equipment were collected with Vicon Nexus 1.7.1 -system (Figure 9A, Vicon, Oxford, UK) using 12 infra-red cameras (T-Series T40S) with 100 Hz measuring frequency. Cameras were mounted on a wooden frame on the walls and ceiling of the Vuokatti Ski tunnel covering all together measurement area of ~12 m enabling recording of one full cycle of V2-skating. Cameras were covered with Styrofoam boxes to keep them operating in cold temperature. In total 51 reflective markers (Figure 9B) were placed on subject (41) and the equipment (4 in poles and 6 in skis) based on modified XC-model developed in recent study (Göpfert et al. 2017).

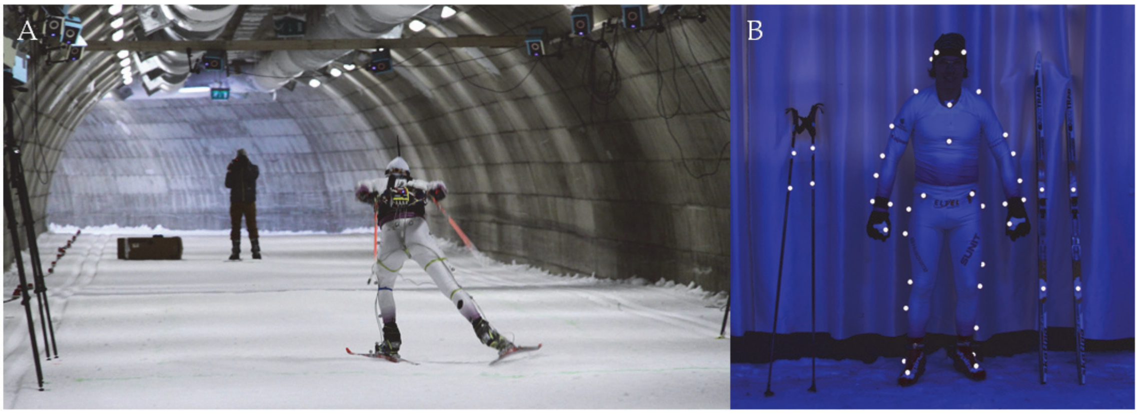

FIGURE 9 Vicon Nexus camera system mounted on Vuokatti ski tunnel and subject skiing with reflective markers as well as ski and pole force measurement systems installed (A). Subject and equipment showing the marker placement during the pilot measurements with one marker missing from both skis (B).

In experiment III muscle activity was measured with EMG-suit (Myontec Ltd., Kuopio, Finland) from following eight muscles and muscle groups: calf, quadriceps femoris, hamstrings, gluteus, triceps brachii, latissimus dorsi, pectoralis major and rectus abdominals. Analyses were done from the right side muscles of the body with 1000 Hz measurement frequency. The EMG-suit was used for the convenience during the long and active (simulated race) measurement setup. EMG was normalized to maximal isometric voluntary contraction done for every muscle group separately.

For detecting the joint angles in experiment I from the elbow, knee and hip joints (right side of body) goniometers (potentiometers: Megatron, Munich, Germany) were used with 1000 Hz measurement frequency. Goniometers were calibrated for every subject separately after attaching goniometer by recoding the voltage values for 180° (fully extent joint angle) and 90° (perpendicular angle between lower and upper arm for the elbow, shank and thigh for the knee, as well as thigh and trunk for the hip) and by calculating the conversion factor to degrees. 90° and 180° were controlled with mechanical angle meter.

4.3.2 Force measurements

4.3.2.1 Ski forces

In experiment I, leg forces were measured with earlier developed custom made 3D force measurement system (Figure 10, NeuroMuscular Research Center, University of Jyväskylä, Finland). System measures forces from all 3 natural directions: vertical, medio-lateral and anterior-posterior. 3D force measurement system weighed 1070 g for one ski adding altogether 2140 g to ski weight. Calibration of the force plate was done by pressing the force plate with five different loads for all the directions with ski stiffness measuring device (Nastolan Vaaka ja Kone Oy, Nastola, Finland), and by checking these values with standard force plate (NeuroMuscular Research Center, University of Jyväskylä, Finland). Checking of the calibration was done with standing and jumping situations. More detailed description of the system can be found from reports by Ohtonen et al. (2013) and Linnamo et al. (2012).

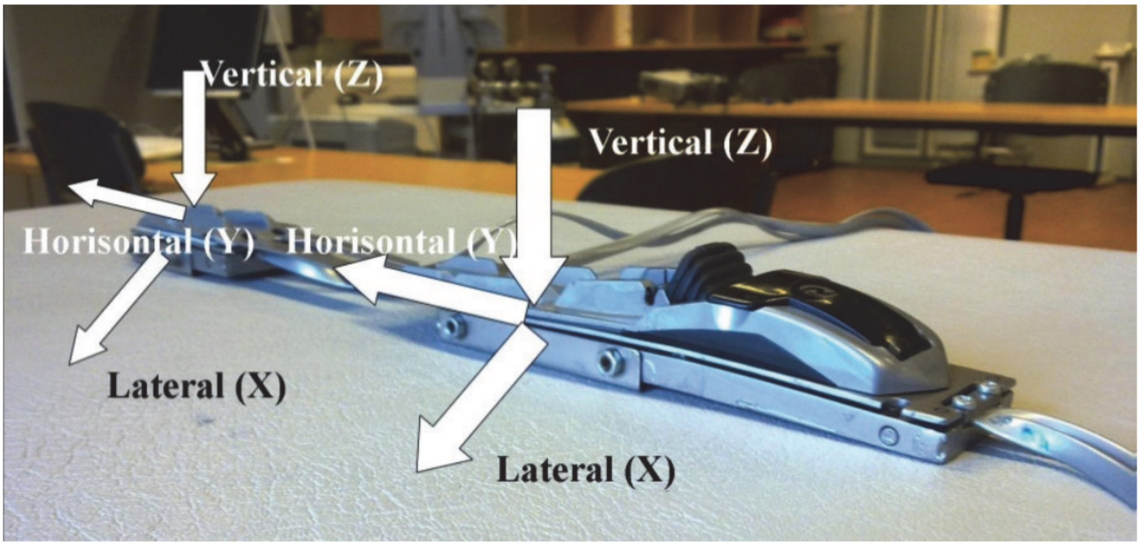

FIGURE 10 3D force measurement system used in Experiment I (Ohtonen, Lindinger & Linnamo 2013), modified.

Due to some problems with the 3D force binding (cross talk in anterior-posterior direction, weight of the system) there was a need to develop a new force measurement system. A new 2D force measurement system for both techniques of XC-skiing was developed (classic force binding and skating force binding) in experiment II (Figure 11, NeuroMuscular Research Center, University of Jyväskylä, Finland). A classic force binding was designed to measure vertical and anterior-posterior forces and a skate force binding for vertical and medio-lateral forces. Both force bindings consisted of the front and rear parts which measure forces from appropriate directions for classic and skating force bindings separately. The total weight of the binding pair was 980 g with 200 g for each rear part and 290 g for each front part. The measurement technology in the force binding was based on strain gauge technology where the resistance is changed when compression or stretch is directed to the gauge. Every direction was measured with 4-gauge full bridge circuit in order to have reliable results. Signals were pre-amplified in the force binding and transferred via wires to amplifier (8-channel ski force amplifier, NeuroMuscular Research Center, University of Jyväskylä, Finland) and collected with 1000 Hz. Attaching and removing of the force bindings were designed to be done with Rottefella (Rottefella as, Klokkarstua Norway) Nordic Integrated System (NIS). With this system it is possible to attach, remove and change the place of the force binding without screws.

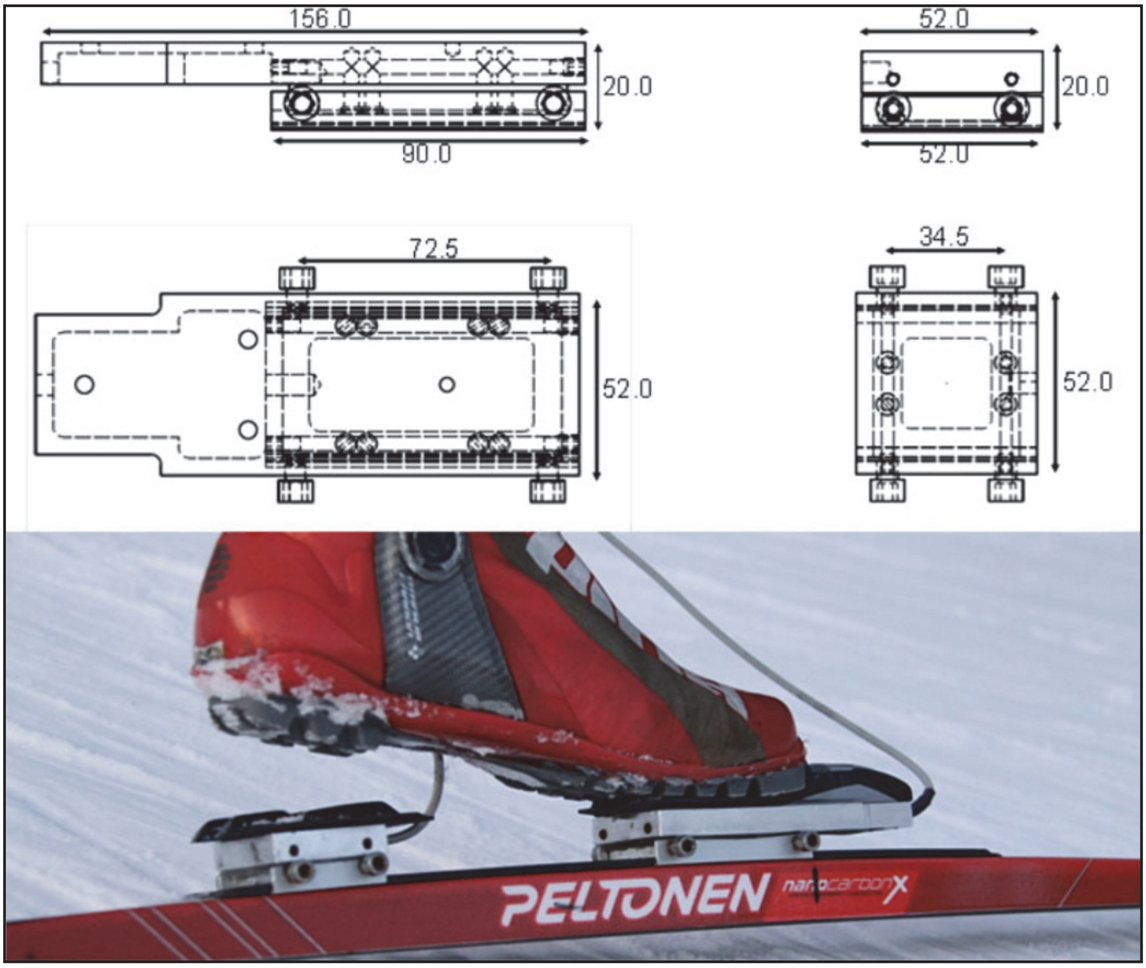

FIGURE 11 A new force binding developed in experiment II with schematic drawing including the dimensions in millimetres.

The calibration of the force binding was done with the special calibration device. The calibration device composed of calibration sensor (Raute precision TB5, Nastola, Finland) and the amplifier. Calibration sensor is attached to screw vice which is firmly connected to thick aluminium base plate. In the base plate an aluminium body, where force binding could be connected in three different positions for calibrating all directions, was also connected. With this setup a calibration with hand used screw vice system was able to implement for all the directions. Calibration system is presented in Figure 12 A-C. Calibration sensor was tested and calibrated by accredited laboratory for force measurements (MIKES: The Center for Metrology and Accreditation, Kajaani, Finland). The calibration report stated that the calibration sensor was reliable in the range of 0 to 1000 N with uncertainty range of 0.01 to 0.09%.

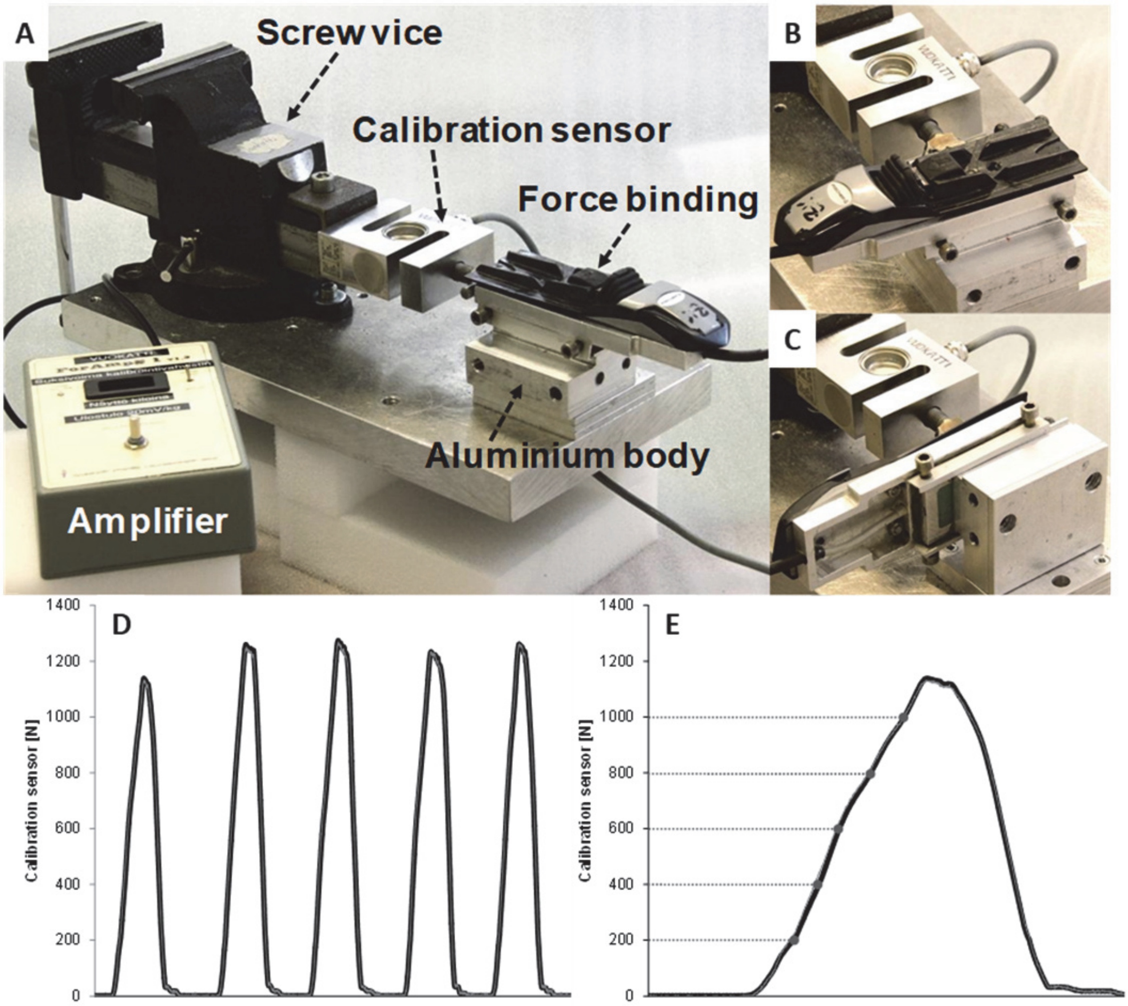

FIGURE 12 Calibration sensor (A) used with the calibration process of the developed force binding in all directions (A, B, C). Five force curves recorded during calibration of the vertical direction (D) and calibration points of the average calibration curve from the vertical direction (E).

For comparison purposes a pressure insole (Pedar Mobile System, Novel GmbH, Munich, Germany) was used in experiment II. Pressure insoles were placed in the ski boot and they measure vertical forces with 99 capacitive sensors in each sole with 100 Hz measurement frequency. Calibration of the system was done based on Pedar instructions with air pressure using the Pedar calibration device. In addition to insoles the system consists of cables, data logger and battery pack.

4.3.2.2 Pole Forces

Axial pole forces were measured in experiment I by using telescopically adjusted pole force measurement system (Figure 13A, University of Salzburg, Salzburg, Austria; sensor Hottinger–Baldwin Messtechnik GmbH, Darmstadt, Germany) placed on the pole grip with measurement frequency of 1000 Hz. One pole force sensor weighed 135 g totalling 270 g extra weight for one pair. Calibration of the pole force measurement system was conducted with free weights placed on the pole grip and sensor. The calibration process is described in detail by (Holmberg et al. 2005)

In experiment III axial pole forces were measured with pole force sensor (Figure 13B, Velomat Messelektronik GmbH, Kamenz, Germany, measurement frequency 1000 Hz) installed in pole grip. Pole lengths were adjusted for every athlete individually. Pole force sensor adds a 100 g extra weight for one pole thus 200 g together in total for one pair. The calibration of the system was done by loading and unloading the pole with sensor five times against standard force plate (NeuroMuscular Research Center, University of Jyväskylä). Forces used during calibration process were equal to forces measured during V2-skating (~250 N).

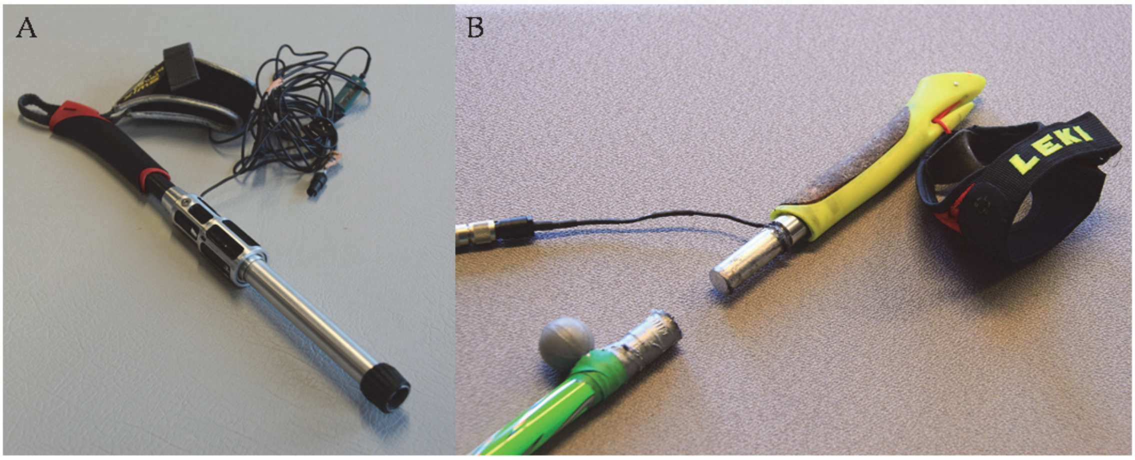

FIGURE 13 Pole force sensors used in Experiments I (A) and III (B).

4.3.2.3 Supporting force measurement systems

The force plates (10 m long force plate row, 8 plates of 1.25 m x 0.60 m with natural frequency 180 ± 10 Hz for the vertical force component and 130 ± 10 Hz for the anterior–posterior force component, linearity ≤ 1%, cross-talk ≤ 2%; University of Jyväslylä, NeuroMuscular Research Center, Jyväskylä, Finland; Sensors: Raute Precision, Finland) were used in the imitation jumps during the experiment II. The force plate used in pole force calibration during experiment III was built by NeuroMuscular Research Center, University of Jyväskylä. The measurement technology in both of these force plates were based on strain gauge technology.

A 20 m long force plate row (NeuroMuscular Research Center, University of Jyväskylä, Finland) designed for classic skiing was used in the comparison purposes in experiment II. 20 m long force plate row consists of four parallel sets of force plates where two of the middle were covered with snow for the skis and the two outermost were covered with tartan for the poles. The system consists of 20 one-meter-long force plates which were connected electrically series to each other's for forming a sum signal. Every force plate measure forces from vertical and anterior-posterior directions with 1000 Hz frequency. The system is described more carefully by Vähäsöyrinki et al. (2008) and is showed in Figure 3A.

The coefficient of friction of the used skis was needed in experiments I and III. A special ski tester (linear tribometer, Figure 14) was used to measure friction. With ski tester it is possible to run the ski with 6 m/s on the force plate row (6 x 1 m) which measures forces from vertical and anterior posterior directions. Ski tester was designed and build by NeuroMuscular Research Center, University of Jyväskylä, Finland and is described more carefully by Linnamo et al. (2008).

FIGURE 14 Ski tester used for collecting the data for friction calculations.

4.3.3 Data collecting methods

Forces, joint angles and EMG signals were collected with the same data collection system in all the experiments (I, II and III) and were thereby synchronized. Data collection system composed of analogue data acquisition board (NI 9205; National Instruments, Austin, TX, USA) connected to wireless transmitter (WLS-9163; National Instruments, Austin, TX, USA). Data collection equipment's were carried by the subject and weighed from 1050 g (experiment III) to 1160 g (experiment I). Data was transmitted online wirelessly to a computer with self-written data collection code (LabVIEW 2010, 2014; National Instruments, Austin, TX, USA). In experiment III, Vicon Nexus 1.7.1 (Vicon, Oxford, UK) software was used to collect the 3D motion data. Synchronizing the motion data with force data was done with three radio phones from which two were attached to Vicon and National Instruments systems and with third one a synchronizing signal was sent to both systems. With these signals the data could be synchronized. Data collection of the stationary force plates in experiments II and III was done with A/D converter (CED Power 1401, CED Ltd., Cambridge, UK) and Spike 5.14 software (CED Ltd., Cambridge, UK).

Overall for the analyses in Articles I and III nine consecutively cycles were recorded and averaged during the analyses for all the parameters and subjects. Experiment III propulsion part contains data only from one cycle due to limited 3D analysing space.

4.4 Data analyses

4.4.1 Cycle parameters

Skiing speed was analysed over the 100 m measurement station and expressed as meters per second in Articles I and III. V2-skating cycle definition was done based on following criteria's in Articles I and III (Figure 15 and 16). Cycle time was defined from right ski plant to next right ski plant and cycle rate was defined as cycle time^{-1}. Cycle length was calculated as a product of cycle time and average speed through the measurement station. Cycle time was divided into ground contact time and leg recovery time whereas ground contact time was further divide to glide time and kick time (Article III) or kick phase (Article I). Start of kick phase was defined as maximum knee angle (Article I) and start of kick time was defined from force minima prior the kick (Article III) to the ski release from snow. Poling cycle time was analysed from the right pole plant to consecutive right pole plant. Poling cycle time was divided into poling time (pole on ground contact) and poling recovery time (rest of the poling cycle). Overlap time of the legs was defined from left ski plant to right ski release in Article I. All cycle phase parameters are presented partly in relative values (relatively to cycle or poling cycle time) expressed as duty cycles (Article I) or relative values (Article III).

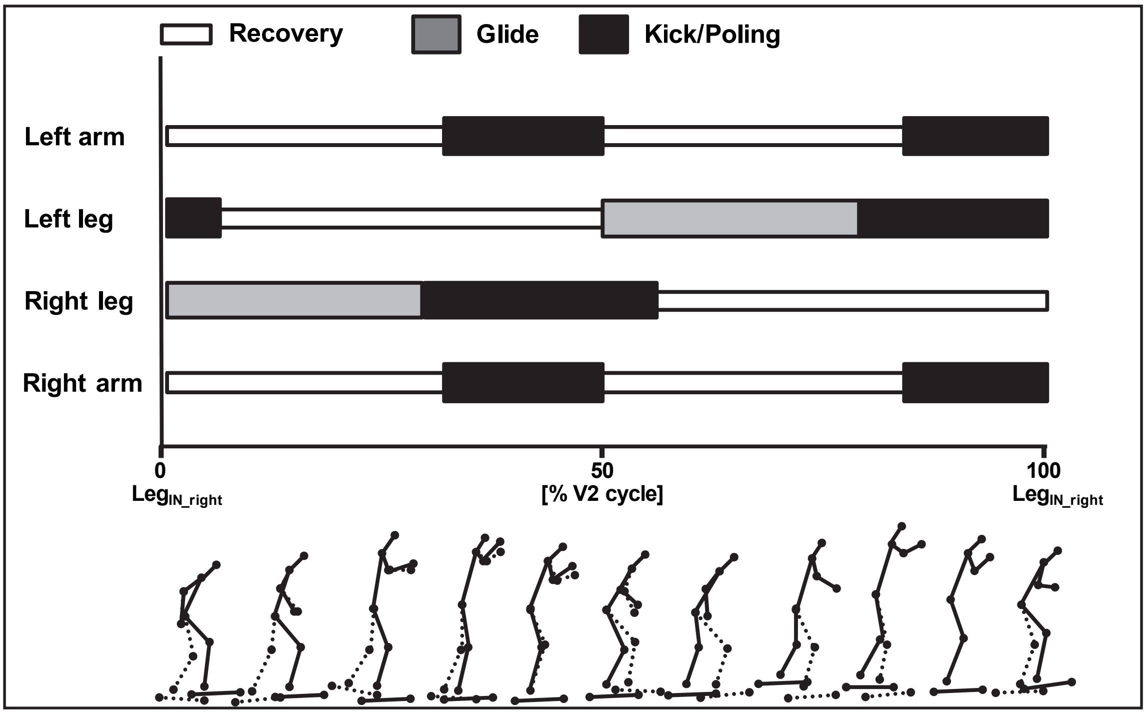

FIGURE 15 Phase definition of V2-skating cycle.

4.4.2 Force parameters

Forces were analysed with the following methods in Articles I and III (Figure 16). Peak pole force was defined as highest force after impact caused by initial pole contact to snow. Average poling cycle force and impulse were also analysed in Article III. Peak vertical leg (ski) force was defined as a highest force during kick phase/time. Delta leg force was the difference between force minima prior the kick to the peak leg force. Peak lateral (Article I) or transversal (Article III) leg force was defined as highest force during kick phase/time. Also average cycle force and impulse was analysed for vertical and transversal forces (Article III). All forces are presented relative to body weight (%BW) and partly in absolute (N) values.

Average rate of force development (RFD) was calculated by dividing the peak pole or delta leg force to time to peak pole or delta leg force. Average rate of force development is expressed as relative value (%BW/%CT) in Article I and as N/s in Article III. In Article III, a ratio between pole and vertical leg force was calculated for peak forces and RFDs and expressed as percentage value of pole from the leg. In addition, in this thesis, ratio between impulses of poles and vertical leg force was also calculated and expressed as percentage of pole force from leg force.

4.4.3 Angular parameters

In Article I, angular parameters were calculated for elbow, hip and knee joints. Elbow movement was analysed at three points (pole plant, minimum and pole release). Range of motion and angular velocity (degrees per second) was calculated for elbow flexion (1-2) and extension (2-3). Knee and hip angular data was analysed at four points during ground contact (minimum after ski plant, maximum during gliding, minimum during kick and at ski release. Hip and knee ROM was calculated for glide extension (1-2), kick flexion (2-3) and kick extension (3-4) and angular velocity (AV) only for kick flexion and extension. Respective points are shown in Figure 16.

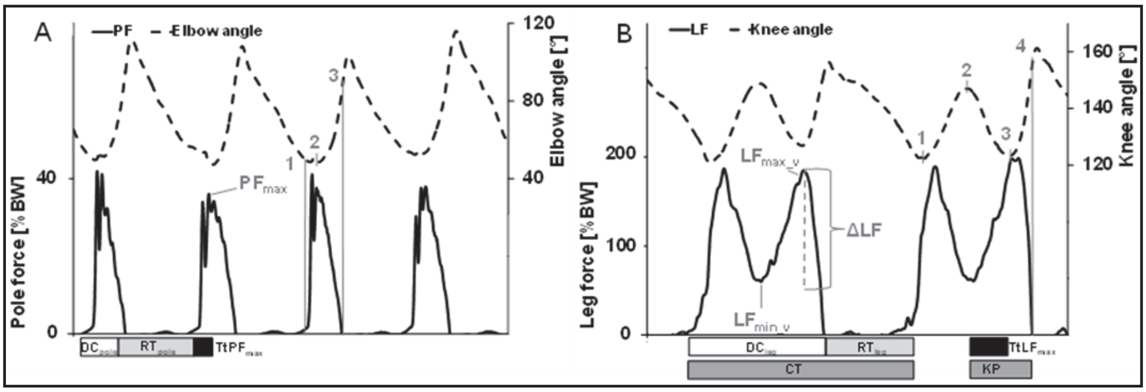

FIGURE 16 Analysed points from elbow, knee and hip joints. Force and cycle parameter definition illustrated.

4.4.4 Electromyography

In Article III, the EMG signals were processed with following manners. Raw signals were band passed (10-500 Hz) and rectified. For upper body muscles a root mean square signal (RMS) was calculated during the poling and correspondingly the RMS signal was calculated during the kicking for lower body muscles / muscle groups. A maximal isometric voluntary contraction was performed separately for all the recorded muscles and the skiing parameter was normalized to this value.

4.4.5 Force binding validation

Accuracy

In Article II, the accuracy of the developed force binding was tested for *linearity* and *repeatability*. Tests were conducted by loading force binding five times with calibration sensor up to 1000 N, 500 N and 250 N and by analysing points at 200 N, 100 N and 50 N interval for vertical, medio-lateral and anterior-posterior, respectively (Figure 12 D and E). Response from force binding was averaged at appropriate points. Linearity of the system was tested by representing averaged values at five points in XY-coordination with regression curve throughout points and R^2 values were calculated. A conversion factor to Newtons was calculated for all points separately with equation (1). From these values general conversion factor for all the directions separately was calculated by averaging the value from these points.

$$\frac{F_{Calib}}{F_{Binding}} = Conversion\ factor \tag{1}$$

Where F_{Calib} refers to absolute (N) value of the calibration sensor and $F_{Binding}$ refers to voltage value from the force binding.

Repeatability of the force bindings was calculated separately for all the directions by analysing relative difference of the conversion factor between pre and post-test for all the situations (laboratory, ski tunnel, 1 h skiing).

Imitation jumps

In SJ and CMJ the vertical signals from both bindings rear and front part were summed up and this signal was compared to results of the force plate. In addition, during CMJ also landings were analysed. With DJ and SkJ the jumps were performed with one leg imitating the push off action. Signals from vertical and anterior-posterior or medio-lateral direction were analysed and compared to force plate signal. During SkJ situation the force binding was edged and therefore the applied force needed to be calculated in the force plate coordination system with equations (2 and 3). Edging situation with calculations are shown in Figure 17.

$$F_{Z\_FP} = F_{Z\_FB} * \cos\alpha + F_{X\_FB} * \sin\alpha \tag{2}$$

$$F_{X\_FP} = F_{Z\_FB} * \sin\alpha + F_{X\_FB} * \cos\alpha \tag{3}$$

Where F_{Z_FP} and F_{X_FP} represents the vertical and medio-lateral force components of the force plate and F_{Z_FB} and F_{X_FB} the vertical and medio-lateral force components of the skate force binding.

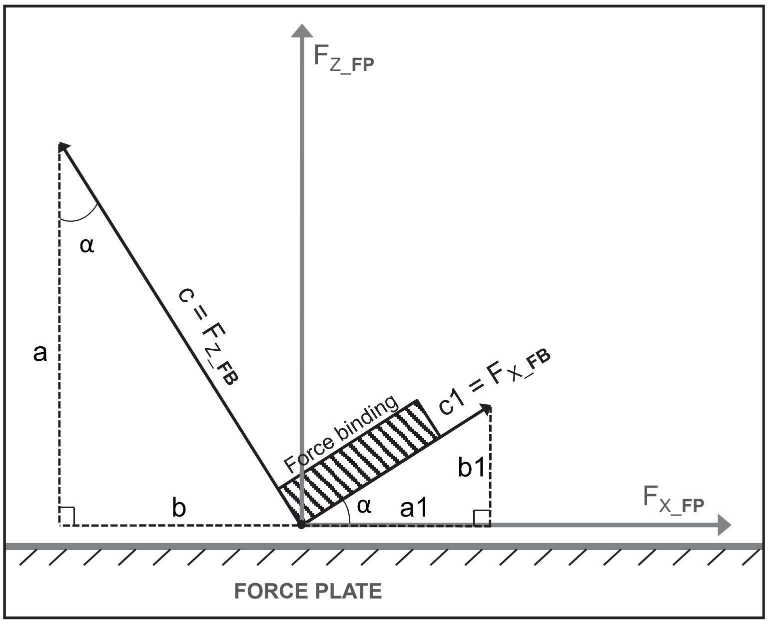

FIGURE 17 Mathematic calculation methods for resolving force binding force values to force plate coordination system.

Altogether 10 jumps in every situation were further analysed. For every situation peak forces and impulses with absolute and relative differences for force binding and reference system were analysed.

Comparison against reference systems on sow
In applied skiing tests with both techniques, the signals from front and rear part of force binding were summed up for vertical (skating and classic) and anterior-posterior (classic) directions and compared against reference systems by using similarity coefficients with Taylor polynomials. 10 consecutive cycles were recorded and analysed for skating and classic situation with skiing speeds ~4 m/s for classic and 5 m/s for skating.

4.4.6 Propulsion analyses

Calculation method and parameters
In Article IV, a novel calculation method for propulsion was used. Model is validated and presented by Göpfert et al. (2017). In this method a share of resultant force from poles and legs hitting to COM were calculated and the part which points to skiing direction was defined to be propulsion. and the main points are also presented here with following steps (refer to Figure 6).

a. *Force transformation between coordination systems*: 3D forces in local coordination system (force binding) were transformed to global coordination system (Vicon) by means of rotational matrices. Pole forces were straight in global coordination system and therefore didn't need transformation.
b. *Estimation of point of force application (PFA)*: estimated PFA for force binding was done by creating a virtual Ski Origin marker on the top of force binding. PFA location was calculated by force distribution between front and rear plates of the force binding. PFA location was transferred to motion capture system by moving ski origin based on PFA value. For poles PFA was estimated by creating virtual marker on pole tip based on pole length.
c. *Share of resultant leg force (F_r)*: because resultant force vector is not hitting the COM exactly, it needs to be shared into two vectors, translational force (F_t, acting direction from PFA to COM) and rotational force (F_{ro}, perpendicular share of F_r, Figure 6). With same manners the share of resultant pole force which hits the COM was determined.
d. *Calculation of propulsion*: finally, the propulsion of leg force (F_c) is described as the component of translational force pointing in the direction of skiing. With same way the component of translational pole force which points to skiing direction was defined as pole propulsion.

Resistive forces (air drag, friction and gravity) which are acting on skier during skiing were not subtracted from the propulsive forces in this study. This was done in order to understand the magnitude and the changes of the pole and leg propulsions separately and to be able to compare those. Impulse of propulsion force was calculated during one push-off for right leg and simultaneous right pole when the propulsion force curve exceeds zero level. Values are presented relatively to body weight. In addition, an effectiveness index was calculated by expressing propulsion (impulse) as a percentage from resultant (impulse) for both, poles (PoleProp%) and legs (LegProp%), separately. For comparisons a ratio between pole and leg propulsion impulses were calculated and presented as percentage of pole from leg.

Only one cycle was analysed in every situation for Article IV. During one leg push off both poles are producing force and the propulsion of the right pole force was duplicated because left pole forces could not be measured due to technical problems.

4.4.7 Friction calculation

In Articles I and IV a coefficient of friction (μ) was calculated from the results of the ski tester with equation 4.

$$\mu = \frac{F_{ant-post}}{F_{vert}} \tag{4}$$

Where the coefficient of friction (μ), was calculated by using anterior-posterior force ($F_{\text{ant-post}}$) and vertical force (F_{vert}) from the ski tester. Five glides were analysed and averaged for the calculation.

4.5 Data processing

In all Articles (I, II, III, IV) raw data was processed and merged with IKE-master v. 1.34 software (IKE Software Solutions, Salzburg, Austria). Further data was analysed for mean values with Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA, USA). 2D video analyses were done with Dartfish software (Dartfish, Fribourg, Switzerland) in Article II. In Article IV 3D motion analyses were processed with Vicon Nexus 1.7.1 software (Vicon, Oxford, UK). Calibration, labelling, gap-filling and filtering were done based on standard software operations. Also a self-made XC-skier model were used which included the skis and poles to the body model for acquiring the COM. Statistical analyses were done using IBM SPSS Statistics 20 (IBM Corporation, New York, USA) or the previous versions of it.

4.6 Statistical methods

In Articles I, III and IV conventional statistical methods were used in order to check the normality of the data and to obtain means and standard deviations. In

Articles I, III and IV repeated measures ANOVA -test was used with using a Bonferroni alpha correction to investigate the difference between situations. Statistical significance level was set to $P < 0.05$. In Article I calculation for the effect size using partial eta square ($p\eta^2$) and the statistical power were done for further evaluation of the parameters. In Article II the determination of the correlation between time series were done by using similarity coefficients (SC) which are mathematically based on Taylor polynomial. With similarity coefficients results are classified as follows -1\similarity\1, where -1 means contrary time histories, 0 means no similarity, and 1 means high similarity. This statistical method has been used earlier with rather similar validation paper determining reliability of 3D-dynamometer for alpine ski and snowboarding (Stricker et al. 2010).

5 RESULTS

Main results of the thesis are presented here, the complete results can be found from the original Articles I – IV. Roman numbers in titles are referring to Articles.

5.1 Speed adaptations of V2-skating (I)

In Article I a maximum speed of 6.6 ± 0.4 m/s was reached and a correlation to cycle length was found ($r = 0.90$, $r^2 = 0.81$; $P < 0.01$). Cycle length increased from lowest speed to other speeds and cycle rate increased between every submaximal and maximal speed (all, $P < 0.01$, Figure 18A). The percentage change between speeds decreased with cycle length from 11.1 ± 4.3% over 4.7 ± 4.9% to -0.1 ± 7.3% while percentage change in cycle rate increased from 8.2 ± 4.3% over 11.7 ± 4.3% to 18.4 ± 8.8% over speeds (Figure 18B).

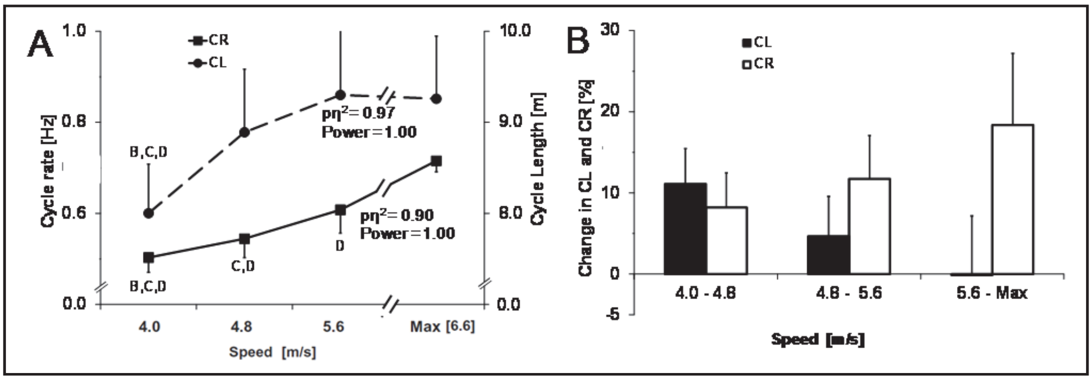

FIGURE 18 Cycle rate (A, left axis) and cycle length (A, right axis), change between speeds in percentage (B). a, A; b, B; c, C; d, D, different to 4.0 m/s, 4.8 m/s, 5.6 m/s and v_{max}, respectively. Capital letters = $P < 0.01$.

Peak pole force increased by 44% from slowest to fastest speed ($P < 0.01$). Delta leg force increased by 106% ($P < 0.01$) while peak leg force increased only by 19% ($P < 0.05$) over speeds. Average rate of force development increased with legs and poles by 215% and 47%, over speeds, respectively (both, $P<0.01$) (Figure 19 A–C).

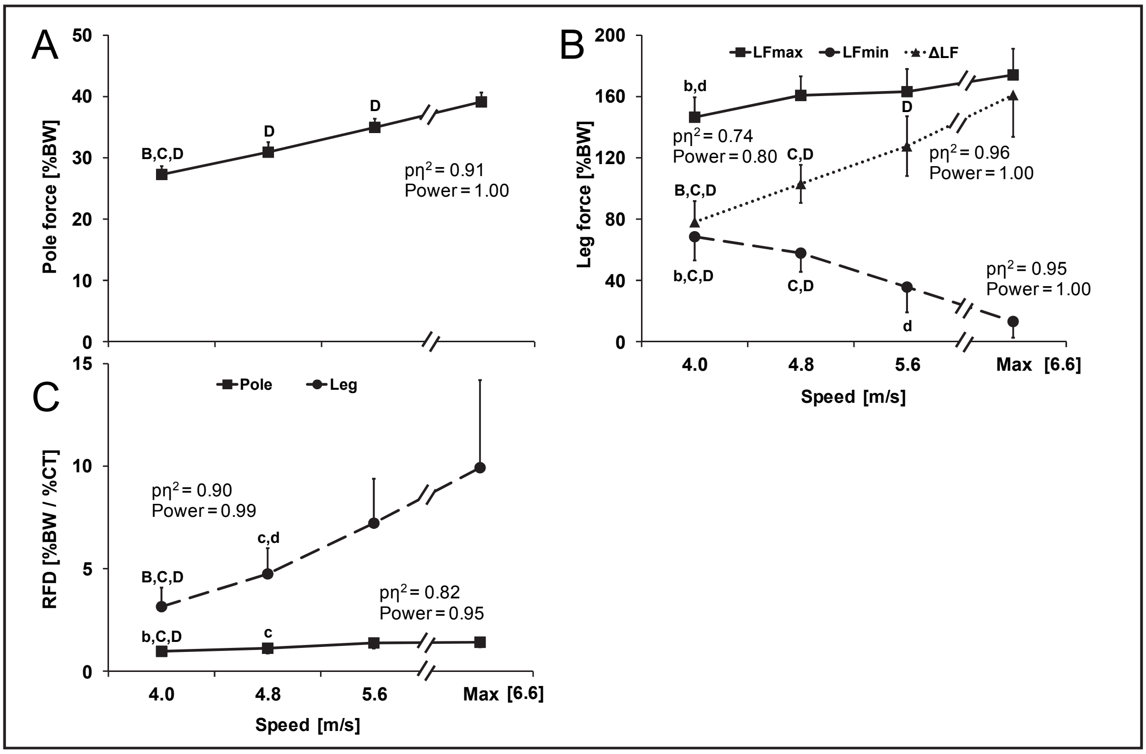

FIGURE 19 Pole force maximum (A), maximum, minimum and delta vertical leg force (B), average rate of leg and pole force development (C) with four speeds up to v_{max}. a, A; b, B; c, C; d, D, different to 4.0 m/s, 4.8 m/s, 5.6 m/s and v_{max}, respectively. Small letters = $P < 0.05$; capital letters = $P < 0.01$.

In joint kinematics, generally, knee and hip joint showed changes over three submaximal speeds while changes were smaller up to maximum speed. Over speeds knee joint showed 3% ($P < 0.05$) larger angle maximum prior the kick while both, knee and hip showed 9% smaller angle minima during the kick (both, $P < 0.01$). These changes lead to 38% and 35% increased flexion and extension ROMs during kick with knee while 56% and 25% larger (both, $P < 0.01$) flexion and extension ROMs where detected with hip joint. Elbow joint showed 17% decrease ($P < 0.05$) with minimum during poling. Behaviour of the joint kinematics can be seen in Figure 20 (A–C).

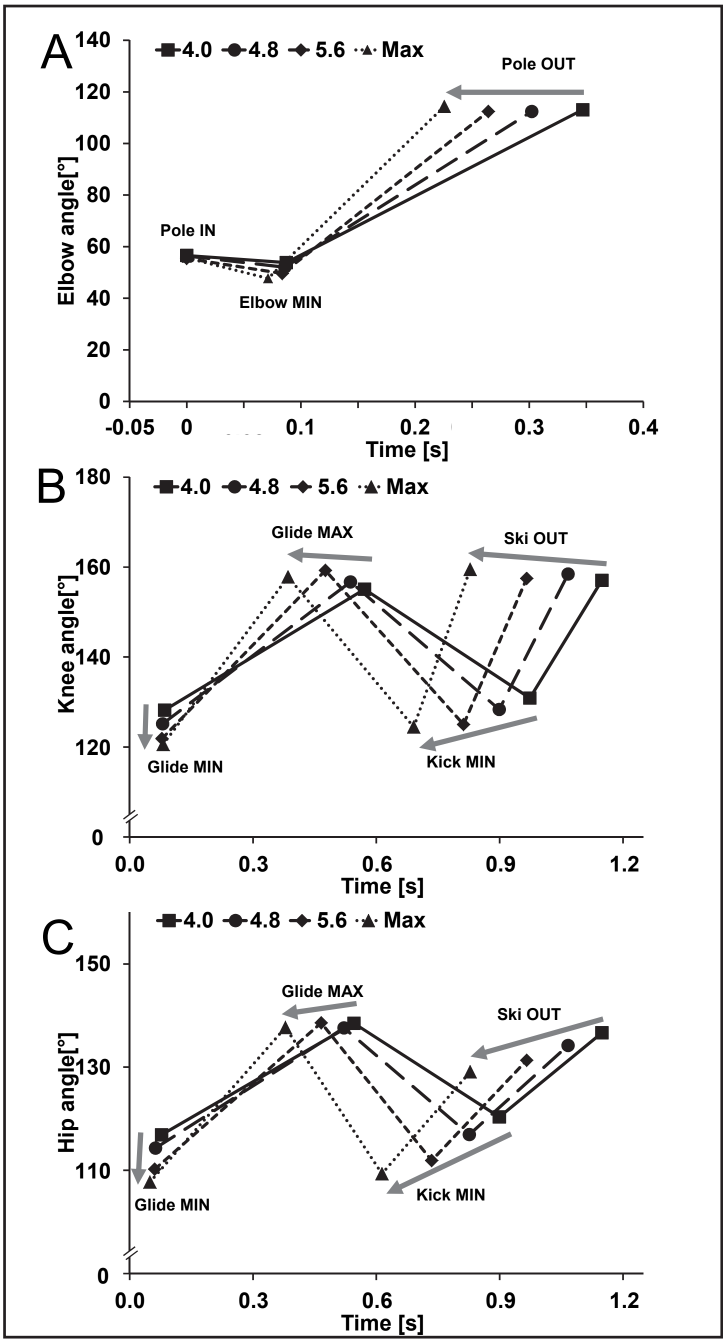

FIGURE 20 Behaviour of elbow (A), knee and (B) hip (C) angle change at four speeds up to v_{max}.

5.2 Force binding validation (II)

Accuracy

High linearity was found in the accuracy tests with all situations (pre- and post-tests in lab, tunnel, 1 h of skiing) with R^2 values ranging from 0.998 to 1.000. Lowest values were reported after 1 h of skiing with the rear part of classic binding. Results from the repeatability (between pre and post in lab, tunnel and 1 h skiing) tests are shown in Article II, table 1. In the lab, results varied between -2.4% to 3.9% (highest difference with skate binding, rear part, mediolateral direction). Results in ski tunnel showed range of -4.2% to 2.9% (greatest difference with skate binding: rear part, medio-lateral force component). Mechanical stress (1 h skiing) caused differences from -2.0% to 9.7% with greatest differences in classic binding (rear part, vertical force component).

Imitation jumps

During the SJ and CMJ (Figure 21) the greatest relative differences at force levels were observed with CMJ (~6%) while SJ showed differences around ± 1.5%. The mean absolute difference was 74 N for SJ and 77 N for CMJ. Landing situation with CMJ caused 8% lower peak values recorded with force binding compared to force plate.

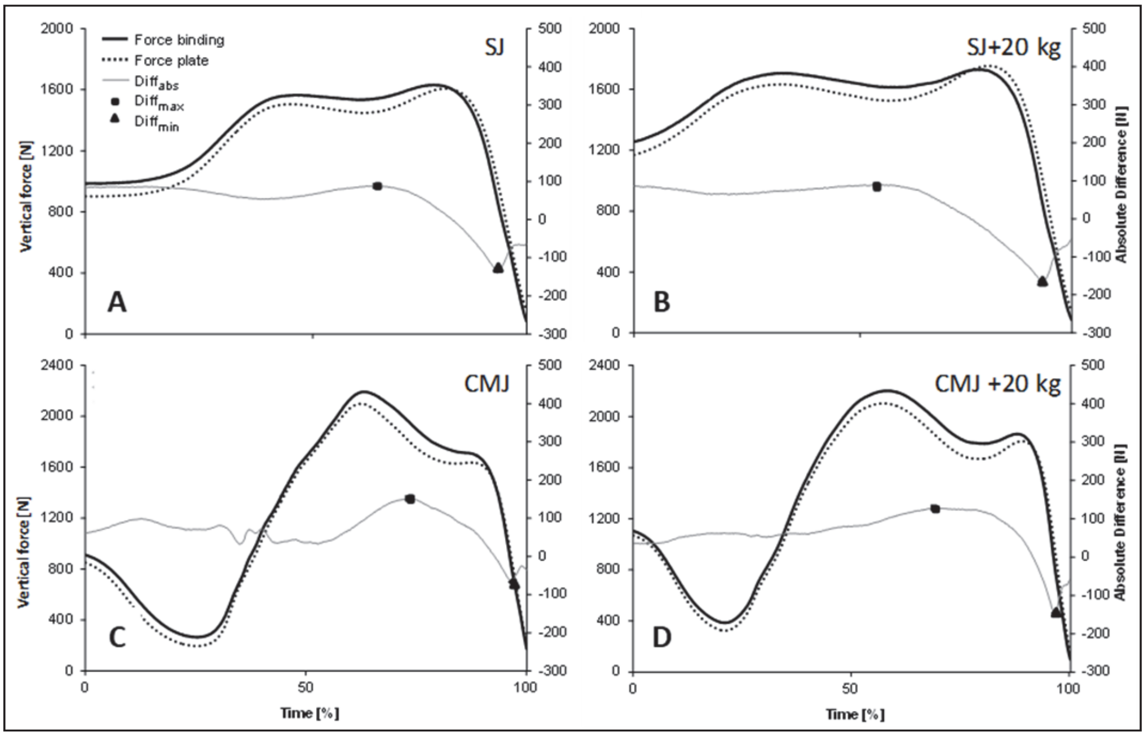

FIGURE 21 Comparison of vertical force curves with force bindings (bold line) against force plate (dotted line) during SJ (A, B) and CMJ (C, D). Jumps without and with 20 kg extra weight were performed. Absolute differences between systems are presented (grey line, right axis).

During DJ and SkJ the greatest differences were found with diagonal jumps (peak vertical forces ~10-15% and 18% for anterior-posterior direction). With skate jumps differences in vertical direction were 5.5% and in medio-lateral direction -3.9%. Results from imitation jumps are presented in Figures 22 (DJ) and 23 (SkJ)

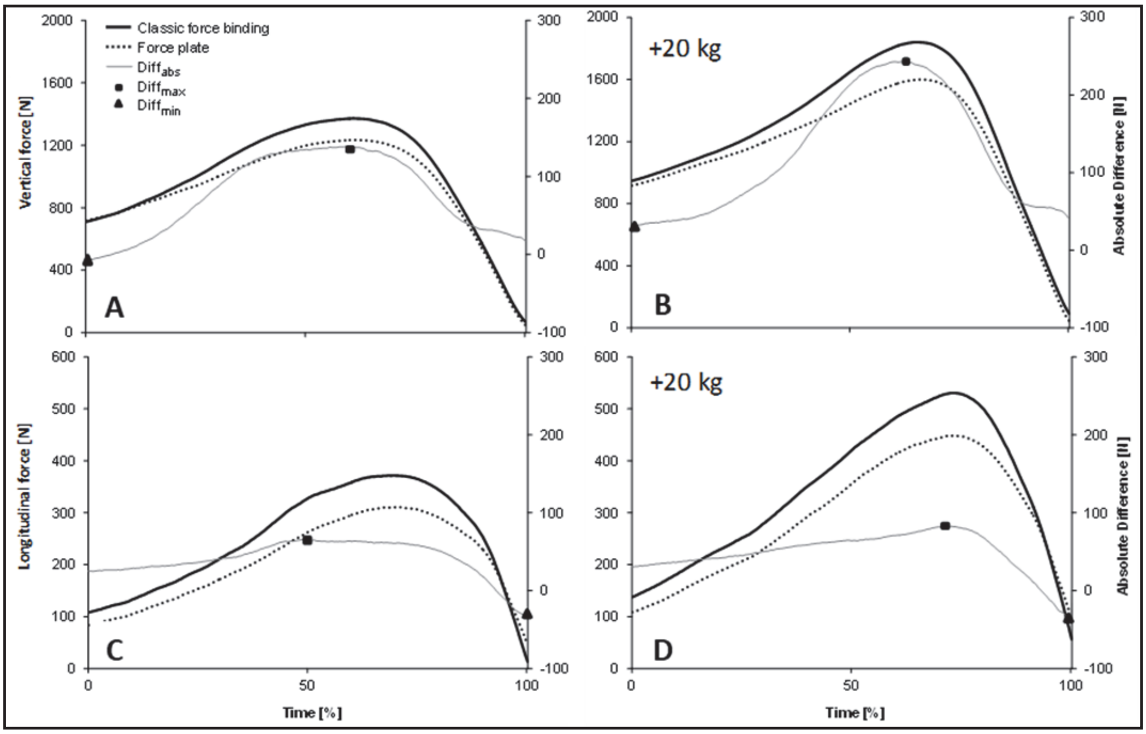

FIGURE 22 Vertical (A, B) and anterior–posterior (C, D) force curves with classic force binding (bold line) against force plate (dotted line). Jumps without and with 20 kg extra weight were performed. Absolute differences between systems are presented (grey line, right axis).

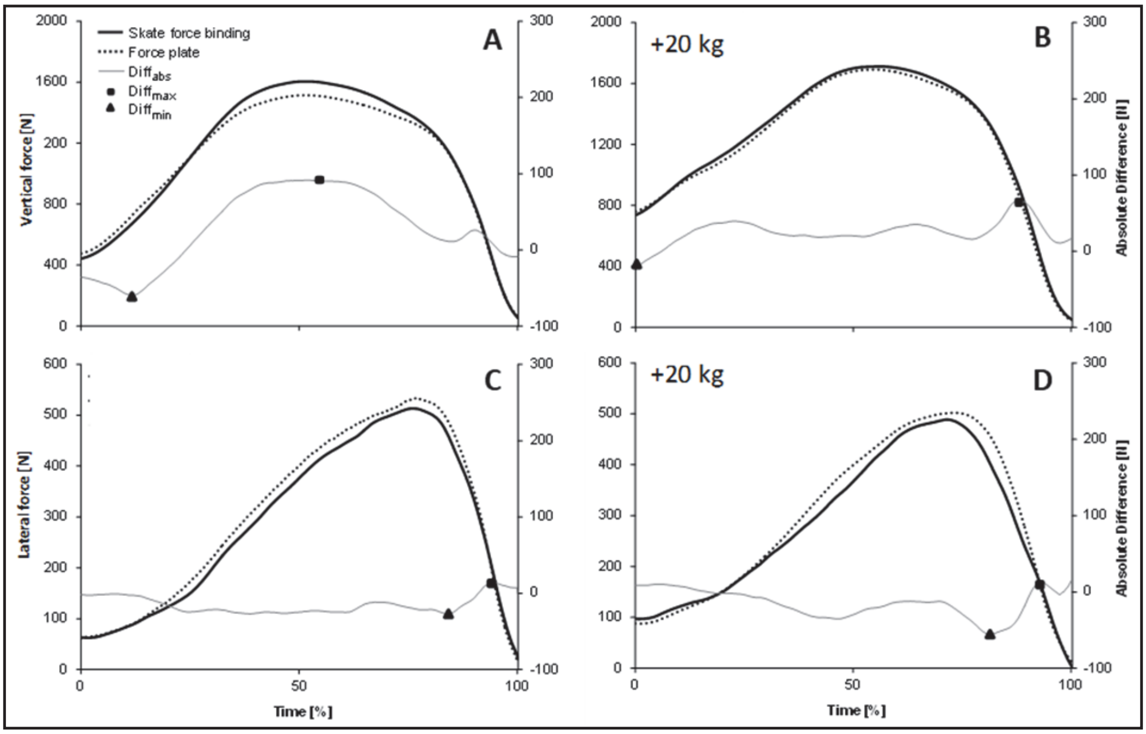

FIGURE 23 Vertical (A, B) and medio-lateral (C, D) force curves with skate force binding (bold line) against force plate (dotted line) at SkJ. Jumps without and with 20 kg extra weight were performed. Absolute differences between systems are presented (grey line, right axis).

Applied on snow test against existing measurement systems

When comparing force binding to existing force measurement systems (against long force plates with classic and pressure insoles with skating) it was observed that with classic skiing during whole ground contact the mean difference was 58 N corresponding ~7% for the vertical direction whereas the difference was 17 N and ~12% for anterior-posterior direction. In both cases, force binding measures higher forces. During skate skiing vertical direction force binding recorded 93 N and 13% higher values. Similarity coefficients varied from 0.979 (skating) to 0.993 (classic, vertical). The results from the comparisons are presented in Article II, Table 4.

5.3 Influence of physical race loads and individual fatigue on V2-skate biomechanics and maximal skating speed (III, IV)

Results presented in Articles III and IV are from the same experiment (III) with a smaller subject group in Article IV (N=5) compared to Article III (N=9) due to technical challenges with motion data. Maximum skiing speed decreased after simulated race (Article III, average time: 1:00:33) by 11.6% from 6.13 ± 0.34 m/s to 5.42 ± 0.43 m/s indirectly quantifying a certain fatigue status.

5.3.1 Cycle characteristics

After race cycle time increased by 8.9% and cycle rate decreased by 8.0%, (both, $P < 0.01$) while a tendency was observed in decrease of cycle length ($P < 0.07$). Relative cycle values (temporal patterns) showed increase in kick time of approx. 10.9% ($P<0.01$) while tendency to decrease (3.4%) was observed with poling time ($P<0.07$). Behaviour of the temporal patterns with leg and pole forces is shown in Figure 24.

5.3.2 Forces and muscle activity

Peak and delta ski force decreased by 8.1 and 13.4%, respectively (both $P < 0.01$). Medio-lateral ski forces (peak, average and impulse) showed an average non-significant decrease of 7.2%. Peak pole force decreased by 24.9% after simulated race ($P < 0.05$). Ratio between pole force and leg force change was -18.5% for peak forces ($P < 0.10$) and -22.3% for impulses ($P < 0.05$), indicating that pole forces decreased more. The average rate of force development showed quite similar changes with poles and legs with 31.2% and 31.4% decrease, respectively (both, $P < 0.01$).

RMS EMG activity with lower body muscles and muscle groups (calf, quadriceps, hamstrings, gluteus, and total average) decreased by 25.8%, 32.5%, 35.5%, 25.4%, and 30.7%, correspondingly (all $P < 0.01$). With upper body (triceps, latissimus dorsi and total average) RMS EMG activity decreased by 32.0%, 56.2%, and 39.2%, respectively (all $P < 0.01$).

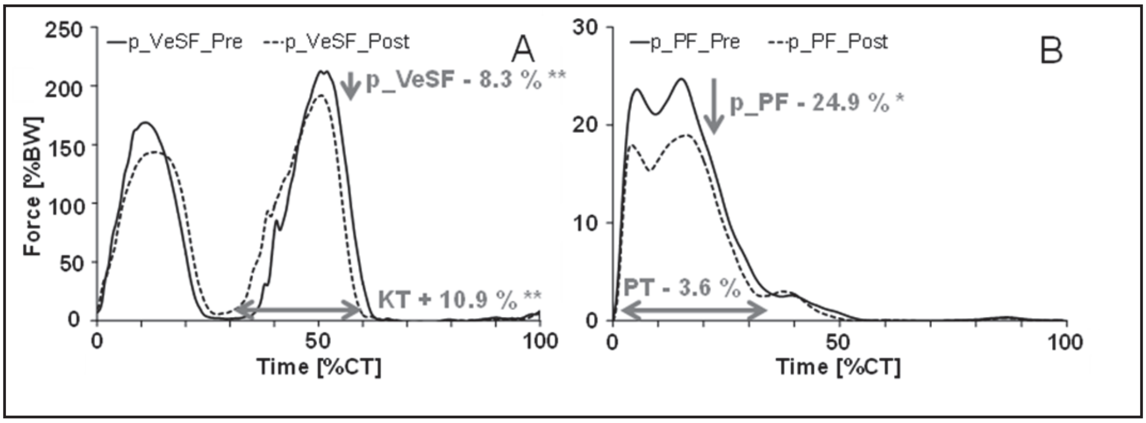

FIGURE 24 Leg and pole force curves (A and B, respectively) from one representative subject averaged over nine cycles. Mean changes from all subjects are shown with percentage values for selected parameters (KT, kick time; p_VeSF, peak vertical ski force; PT, poling time; p_PF, peak pole force). *, $P < 0.05$; **, $P < 0.01$.

5.3.3 Skating propulsion

Due to small amount of subjects (N=5) no statistical differences were observed in data. However, due the novelty of this research we wanted to highlight some interesting points on the results.

Propulsion force impulse from poles stayed on maintained level (~3.4%BW) from pre-test to race tests (submaximal) and then decreased (~22%, non-significant, n.s.) to post-test. Leg propulsion decreased from pre-test (3.9%BW) to submaximal race speeds and post-test with ~33% (n.s.). The propulsion distribution between upper vs. lower body changed from dominant leg (54% vs. 46%) in the pre situation to opposite in submaximal race speeds (~44% vs. 57%) with dominant pole propulsion. At the post-test upper and lower body showed quite equal production of propulsion (Figure 25). The ratio between pole and leg propulsion impulse change was 14.5% (n.s.), indicating that leg forces decreased more.

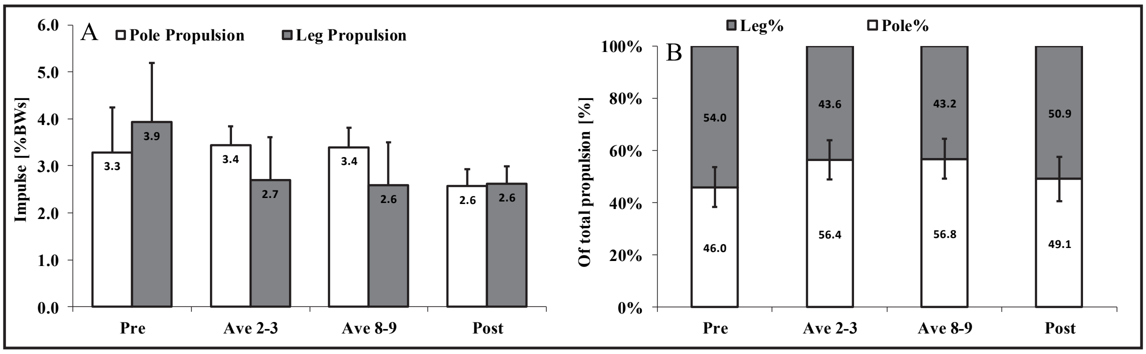

FIGURE 25 Pole and ski propulsion (A) as well as percentage share (B) of ski (Ski%) and pole (Pole%) propulsion at pre and post-tests and submaximal race tests (Aver2-3 and Ave 8-9).

Effectiveness index decreased (n.s.) with legs and increased with pole from pre-test to other situations (Figure 26, n.s.).

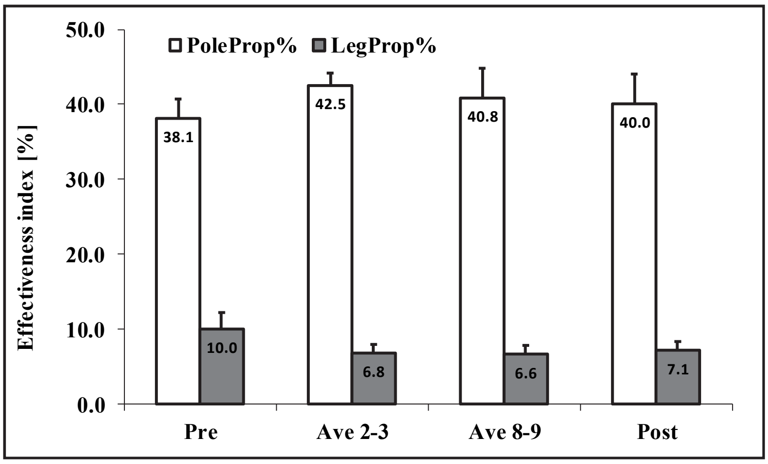

FIGURE 26 Behaviour of the effectiveness index (PoleProp%, LegProp%) from pre and post-tests and submaximal race tests (Ave 2-3 and Ave 8-9).

Individual propulsion curves for all subjects are shown in Figure 27. Two cases which show extraordinary fatigue adaptations with over 50% decrease pole force propulsion and leg force propulsion are highlighted.

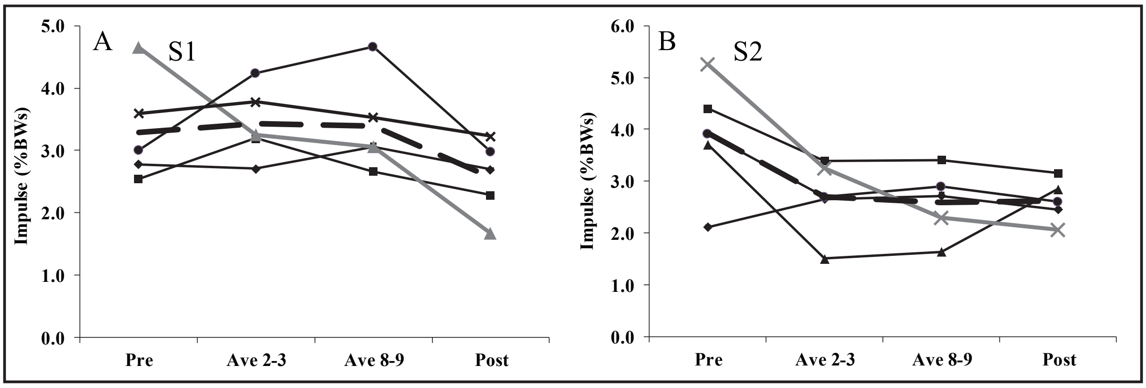

FIGURE 27 Individual propulsion curves for pole (A) and leg (B) propulsion forces. Two extreme cases with different fatigue adaptations highlighted. Subject 1 (S1, A) bold grey line with triangles, Subject 2 (S2, B) bold grey line with crosses. Average of all subjects showed with black dashed bold line.

6 DISCUSSION

The main purpose of this thesis was to understand the biomechanical demands of V2-skating skiing in different situations. In addition to this during the work process a need to develop a more sophisticated force measurement system appeared.

The main results of this thesis were that the athletes are controlling speed with V2-skating technique by cycle length with lower speeds while cycle rate is more dominant factor on controlling speed when working towards maximal speed. With increasing speeds, legs are contributing more to the total force production than arms. In addition, vertical movement of the COM, indicated by greater ROM with knee and hip joint, is to an increasing extent aiding force production of the arms and legs as the speed increases. A new system with two 2D force bindings for skating and classic skiing separately were developed. Skating skiing binding were successfully validated while there remained some points to still improve with classic skiing system. With the new skate binding system effects of long simulated skating skiing race were investigated. The main findings on this topic were that the impaired muscle functionality was seen with lower muscle activity and force production levels especially on the arms. The second important finding was that by analysing the results with conventional methods the fatigue effects of the legs might be underestimated compared to propulsion methods that would be useful tools in athlete diagnostics in the future.

6.1 Speed control mechanisms (I)

6.1.1 Maximum speed

A maximum speed of 6.6 ± 0.4 m/s which was reached in current study, is well in line with studies on quite similar conditions and terrain (5.7 to 7.2 m/s) using elite skiers (Stöggl, Muller & Lindinger 2008; Stöggl et al. 2010b). In addition, the found maximum speed is comparable (6.13 m/s) to our fatigue study (experiment III) in the same measurement place with a different subject setup. Maximum speed was positively correlated to cycle length (r = 0.90; P < 0.01) which highlights the importance of long cycle lengths for skiing fast which was also shown earlier (Stöggl & Müller 2009). On the other hand, no correlations were found between cycle length and any anthropometric parameters such as body mass or height. This has also been the case with different skiing techniques in other studies (Lindinger et al. 2009a; Stöggl et al. 2010a) and was also found in running (Hunter, Marshall & McNair 2004).

6.1.2 Cycle characteristics

With cycle length vs. cycle rate progression over speeds to maximum, we found similar strategies as with other modes of human locomotion (Hay 2002). The speed (cycle rate * cycle length) was contributed by both parameters, cycle length and cycle rate, but with different extents. In our study cycle length showed concave-down and cycle rate concave-up behaviour (Figure 18A) while maximum cycle length was reached at 85% of maximum speed. In other words, cycle length contributed more to the V2-skate speed increase in the slower and medium ranges of speed and cycle rate more in the medium to maximum ones while in the last speeds cycle length even decreased or plateaued. In numbers, V2-skate cycle length decreased ~11 to 0% while cycle rate increased ~8 to 18% over the performed speeds (Figure 18B). Similar cycle rate – cycle length relationship have been reported in several earlier studies with skating (Millet et al. 1998; Smith, Kvamme & Jakobsen 2006; Hoffman, Clifford & Bender 1995; Sandbakk, Ettema & Holmberg 2012; Sandbakk et al. 2010; Haugnes et al. 2018) and classic skiing (Göpfert et al. 2013; Lindinger et al. 2009b; Lindinger et al. 2009c). Both cycle rate and cycle length have also been reported to increase up to absolute maximum (Sandbakk et al. 2010). Race load and fatigue induced speed decreases by ~12% during V2-skating in one of the current studies (III) and was clearly created by cycle rate decreases while cycle lengths were on average uninfluenced. This indicates that the changes in high-end speeds are regulated by cycle rate changes regardless the reason, which in itself is a relevant finding for XC-skiing with consequences for training conceptions.

Duty cycles of the poles decreased from the slowest speed and found their "optimal" length after that with constant relative values regardless the speed increase. This behaviour was rather similar to Millet (1998) and Sandbakk (2012) but in our present study duty cycle values were slightly smaller probably due to development of the sport (Millet et al. 1998) and different conditions (Sandbakk, Ettema & Holmberg 2012). It seems, in general, that decreasing duty cycle seems to be a strategy for skiers with increasing cycle length during any skiing technique where poles are involved. Athletes need to produce higher forces at relatively shorter times with increasing speeds up to their individual maximum. This pattern clearly reflects modern, explosive XC-skiing in classic as well as skating techniques performed by athletes with altered full body strength capacities towards high level maximum and explosive strength abilities similar to track and field athletes. In contrast, Nilsson (2004) reported constant duty cycles across speeds which could possibly be explained by the level of the skiers in that study. In this present study, leg duty cycles slightly increased between 4.8 m/s to maximum. This was unexpected because V2-skating is performed using similar movement patterns with arms and legs on both sides of the body and therefore there should not be differences. This phenomenon was explained by increasing overlap time, which means that the subjects positioned a contralateral leg on ground relatively earlier, which might take the pressure off too early from the push off leg and transfer the COM to a contralateral leg. So v_{max} was negatively correlated to overlap time possibly indicating that faster skiers may control balance better and therefore secure the push off and thereby showing smaller overlap times. This is an interesting phenomenon from a coaching perspective. Results from overlap time lead to thinking whether this parameter could be a useful tool for athlete diagnostics. Based on this, overlap parameter was further developed in a coaching perspective and parameter pole-ski contact difference (PSCD), which tells the difference between pole lift off and ski plant, was presented. This parameter was used later on treadmill training for showing athletes explicit with number when they should transfer weight to other leg and thereby finish push offs properly.

6.1.3 Forces and joint kinematics

Peak pole forces showed distinct increases from low to maximum speeds with rises of 44%. However, peak vertical leg forces increased significantly less. Though, when considering the delta leg forces which take also the unweighting phase during a V2-skate cycle into account we found an increase of 106% which is more than double compared to pole forces. (Figure 19B). This unweighting phase which is a preparatory requirement for producing force efficiently especially with higher speeds has been shown to elicit stretch shortening cycle patterns in different sports like jumping (Avela, Finni & Komi 2006) and running (Kyröläinen, Avela & Komi 2005). Also in skiing with V2-technique, Myklebust et al. (2014) showed that unweighting is essential for generating high forces. This movement pattern has also been shown to be an efficient way of producing force at maximal speeds showed with increasing rates of force development (Stöggl, Muller & Lindinger 2008; Stöggl et al. 2010b; Lindinger 2005). In the current study, the rate of leg force development increased to three fold from slowest to fastest speed compared to rate of pole force development, which increased only by ~50% from slowest to fastest speed. This is due to more pronounced unweighting combined with relatively shorter kick times. As shown above leg force production is much more complex than pole force production and by analysing only maximum force levels important information gets uncovered. This is because a skier carries body weight with their legs and the unloading is strongly effecting the push-off while poling starts naturally in an unloaded situation.

With increasing speeds leg joint kinematics (angle values and ROMs of knee and hip) in general showed an increase during submaximal speeds while maintaining values from last submaximal to maximal speed. With poles, only elbow angle minimum showed changes with decreasing values during submaximal speeds. This means that arms are showing rather a "rigid" behaviour. This is different to double poling, where the push off is started with straighter arms continued with greater flexion-extension ranges of motion during push off (Lindinger et al. 2009b). During V2-skating the elbow joint is in a more fixed position throughout the whole push off. However, this might also be the case with double poling when skiing uphill with greater gradient. All in all, with this rigid arm movement in the current study arms might transfer energy from vertical movement of the body (showed with increasing knee and hip movement) more economically this way, rather than produce it actively, which was also confirmed by Myklebust (2014). As a summary it can be stated that with increasing speeds leg joint movement is increasing and lifting the body to a higher and possibly more forward position prior the kick and poling. From this higher position greater potential energy is transferred via the "rigid" upper body to increasing poling forces and via greater unweighting (higher position) to greater delta leg forces.

During this study, it was noticed that the used 3D force sensor was unreliable for anterior-posterior forces. Also based on subjects review the weight of the sensor was too high. This caused a need to develop a new sensor for further studies.

6.2 Force binding validation (II)

New force binding was notably lighter compared to older version (Linnamo et al. 2012; Ohtonen, Lindinger & Linnamo 2013) with weight of 980 g (current version) against 2140 g (old version). This enabled skiing with less interference on the performance. However, the height of the system had to be increased to 20 mm from ~10 mm from the old version due to accuracy requirements, but this was not experienced as a problem based on subjective feedback.

6.2.1 Accuracy of the force binding sensors

In the accuracy measurements, the linearity and repeatability tests gave congruent results about the reliability of the force binding measurements. Results suggested that in laboratory and ski tunnel tests (static and 1 h of skiing) with a 2 h interval the accuracy was high in all situations while it was lowest (0.998) on the rear part of the classic binding. In addition to this, also changes in conversion factor levels were greater in this part (classic rear force, up to 10%) after 1 h of skiing compared to other tests (laboratory and tunnel tests without skiing). However, conversion factor levels were quite constant in all other channels (less than 5%) in all situations. The reason for this phenomenon is unclear. We speculate that skiing might have had some mechanical effects on the classic binding's rear part. However, skate binding showed no negative effects after skiing. Skate and classic bindings were constructed slightly different in terms of placing the strain gauges and this might have led to a different level of sensitivity to mechanical loading between the bindings.

6.2.2 Comparison of systems during imitation jumps

With SJ and CMJ the mean absolute differences (74 N and 77 N) were quite constant during the push off phases indicating that the error was not caused by the movement itself rather than some mechanical reason, probably in the classic binding which showed unstable results also in accuracy tests.

Landing was also analysed for CMJ, this situation caused extremely high peak forces (over 5000 N). These forces are much higher compared to normal skiing where force can vary in maximum situation ~1500 N. Nevertheless, the peak force between force plate and force binding showed differences of -8% in this situation. These results can be described as low with such extreme forces which suggests that the rather robust construction of the force binding can handle also high forces.

During the DJs overvalued results could be detected in vertical forces during the highest forces while anterior-posterior channel seems to overvalue the results during whole push off (Figure 22 a-d). With this natural skiing imitation movement where the point of force application is moving along the binding is causing constant error on the anterior-posterior direction. We speculate that this might be due to cross talk effect. These errors (high forces on vertical and constant on anterior-posterior) also caused differences in impulses with ~10% and 20% overvalued results on vertical and anterior-posterior directions, respectively.

Skate binding seemed to work more reliably compared to classic binding which can be seen during SkJ situations. In vertical direction differences to force plate were 5.5% or less and on medio-lateral direction less than 4% compared to force plate. These are less than half compared to DJ with classic binding. Skate binding results can consider promising especially because the forces from the binding are needed to subject a calculation process to orientate the force measurement systems in the same coordination.

The difference between results of the classic and skating bindings might be caused by the different mechanical construction and the different loading movements to the bindings. During SkJ push off phase the force is distributed a longer time for both parts (rear and front) of the binding and the force is targeted perpendicular to force binding while during DJ the heel is lifted in early phase of the push off and the point of force application is moving along the binding. This effect probably causes moment effect on the classic binding and causes greater error.

Mean absolute difference during jumps were smallest for SkJ (27 N to 50 N) and highest with DJ (77 N to 125 N). With SJ and CMJ absolute differences were around 75 N. These results also support the suggestion that classic binding measure too high forces and the error is smaller in two leg situation with both bindings. Above mentioned results pinpoint the difference in behaviour of the differently constructed (in terms of strain gauge placement) force bindings.

When concerning similarity coefficients all situations showed high values ranging from 0.982 to 0.999. This suggests a high force curve reproduction which is essential with larger subject groups and larger inter-individual differences e.g. in technique diagnostics.

Above mentioned similarity coefficients have also been used earlier when comparing force measurement systems. Stricker et al. (2010) compared custom made 3D dynamometer for alpine skiing against Pedar insoles and reported similarity coefficients ranging from 0.974 to 0.977.

6.2.3 Comparison against reference systems on snow

The classic binding showed quite similar differences to reference systems in field compared to DJ in laboratory. Differences were over 50 N in absolute values for vertical and less than 20 N for anterior-posterior direction. There might be different reasons in addition to those discussed above with jump situations. In field measurements, a ski might be slightly edged where the coordination systems differ and this might cause error to results. Therefore, these results are only indicative.

During skate skiing we reported greater differences to reference systems (pressure insole) with values of 93 N and 13.0% higher with force binding. However, this has also been the case in earlier studies (Lindinger et al. 2009a; Lindinger 2005; Holmberg et al. 2005) with greatest differences up to 14%. It seems that pressure insoles, regardless of the situation measures lower forces. Also in alpine skiing similar results have been reported with lower values while using pressure insoles (Stricker et al. 2010; Nakazato, Scheiber & Muller 2011).

However, again with on field skiing similarity coefficients can be describe rather high (classic: vertical 0.993, anterior-posterior 0.979; skating: vertical 0.988) suggesting the system to be reliable in field conditions.

6.3 Influence of physical race loads and individual fatigue on V2-skate biomechanics and maximal skating speed (III, IV)

Fatigue, by one determination is the reduction in power or force of the muscle caused by exercise (e.g. Gandevia 2001; Enoka & Stuart 1992). Based on this, subjects were in fatigued state due to 12% lower speed in post maximum test after 20 km simulated race. Fatigue caused decreased muscle activity seen with lower EMG values leading to decreased force production and thereby lower movement frequency. Several skiing studies using roller skis (Vesterinen et al. 2009; Mikkola et al. 2013) or skis on snow (Halonen et al. 2015) reported similar decreases in post sprint speeds with ranges from 9% to 16% in both techniques.

6.3.1 Muscle activity (III)

As mentioned, fatigue is causing impaired capability of muscles, which can be seen with lower levels in measured surface EMG values. However, with the methods used here, the share of how much fatigue was based on central and peripheral origin was not possible to deduce. EMG measurements during race or race simulations are rare, however muscle activity has been measured in isometric situations before and after marathon skiing races. Results are comparable to ours with ~20% to 30% decreases in EMG activity (Boccia et al. 2017; Millet et al. 2003; Viitasalo et al. 1982) using leg muscles while 10% decreases have been noted with arms (Boccia et al. 2017). When observing dynamic skiing situations, the latissimus dorsi muscle shows interesting behaviour with 150% EMG activity during pre-test compared to isometric MVC situation. Same kind of result was observed with double poling (Halonen et al. 2015). Latissimus dorsi and pectoralis major showed greatest decreases (~50% and 36%, tendency) between pre- and post-test, these muscles have also been highlighted by Holmberg (2005) and Lindinger (2009) as important muscles for double poling where the poling model is quite similar to V2-skating.

Earlier studies (Myklebust, Losnegard & Hallen 2014, Article I) have shown that the COM should be in high position before poling action where the mass of the body can be “dropped” onto the poles and therefore transferred to force propelling the skier forward. To perform this action successfully the above mentioned (latissimus dorsi and pectoralis) upper body muscles are important. If the stability of these muscles is compromised and the upper body is not forming a rigid “frame” the force is not optimally transferred to poles due the “softness” in upper body. This highlights the importance of these muscles where the decreases in EMG activity were greatest. The greater decrease (39%) in upper body activity compared to lower body (31%) could be linked to greater force level decrease in pole force versus vertical ski forces, although there was no statistical difference between the decrease in upper and lower body muscle activity. Despite the importance of latissimus dorsi in this study (Vesterinen et al. 2009) didn’t report decreases in this muscle after sprint race, although they noticed decrease (18%) in general upper body muscles (iEMG from triceps brachii and vastus lateralis).

6.3.2 Cycle characteristics (III)

Decreasing speed was caused by greater decrease in cycle rate and minor decrease in cycle length (tendency). With speed adaptations it is noted that the higher speeds are achieved by cycle rate (Hay 2002, Article I). While these high speeds cannot be reached due to fatigue and impaired movement frequency is the reason for this. In skiing studies this was also reported by Vesterinen et al. (2009). However, what happens in temporal patterns while cycle time increases is interesting. While poling time and poling recovery time slightly (tendency) decreased and increased, respectively, greater and more interesting changes were seen in leg work. Leg cycle, which is divided into ground contact time and recovery time, showed no changes in relative values with above mentioned parameters. But, when observing ground contact time only, which is again divided to relative glide and kick time we saw changes with minor decreasing (~5%, tendency) glide time and clearly increasing (~11%) kick time. This means that fatigue is causing different changes in the patterns of the upper and lower body force production mechanisms. Increasing of the kick time is causing 70% of the increase in cycle time due to fatigue and even the length of the phase is only ~25% of the cycle time. Impaired unloading phase at fatigued state is partly explaining this. Impaired unloading changes the initial point of the kick, starting earlier. The same kind of behaviour can be seen in speed adaptations in Article I showing that the relative kick time is increasing while speed increases up to maximum. This indicates that the ability to produce fast push off and well timed even in fast speeds as well as fatigued state could be a discriminating factor for successful athletes.

6.3.3 Force and propulsion adaptations due to race load (III, IV)

When analysing accumulated fatigue during long distance skiing with conventional methods (III) some results or reasons might not be recognized. An interesting addition to conventional methods can be propulsion approach (IV) which gave essential information especially from leg force production.

In general, Article III showed rather similar force levels in a non-fatigued state (1478 N) compared to previous studies from V2-skating. Peak vertical forces have varied from ~1300 N to 1400 (Stöggl et al. 2010b; Stöggl, Muller & Lindinger 2008, Article I) while axial pole forces were at comparable level also with ~250 N in this study compared to 270 to 300 N in previous studies (Smith, Kvamme & Jakobsen 2009; Stöggl et al. 2010b, Article I). When observing results from propulsion perspective (IV) the same thing was noticed. The total (arms and legs together) propulsion impulses varied from ~57 Ns (non-fatigued state) to ~40 Ns (submaximal race speed and maximum in fatigued state). Göpfert et al. (2017) reported values of ~53 Ns while using V2A-technique. Propulsion was divided in their study with ~65% on arms and 35% on legs. In our study propulsion varied from ~55% to 43% from legs from pre-test (non-fatigue) to submaximal race speed. Results are different which might be due to different technique (V2 vs. V2A) and terrain (4° vs 1°). With V2A-technique poling phase is longer (arms pass body into fully extended position) comparing to poling with V2-technique (arms are "hooked" and push ends to bodyline) especially on slight uphill (Smith 2003). However, these results are at a congruent level with this new proposed analysing method.

Literature did not show fatigue studies with simulated race situations (sprint or distance) which analysed leg forces, highlighting the importance of these results. With conventional (III) methods, vertical ski force decreased by 8% while delta leg force decreased by 13%. This demonstrates that the unloading phase is compromised prior to the kick due to fatigue. This also leads to increasing kick time by changing the initial point of the kick phase earlier. It has been also reported earlier (Myklebust, Losnegard & Hallen 2014, Article I) that the unloading is important for generating high forces during leg push off. Due to decreased movement frequency and increased kick time the impulse of force increased by 6% while average vertical cycle force decreased by 12%. This takes into account also frequency changes and seems therefore to be a more useful tool in force interpretations with conventional methods. However, at this point propulsion approach (IV) reveals interesting differences to conventional methods. With propulsion analyses, leg impulse was decreasing with ~30% while conventional methods gave an above-mentioned increase of 6%. This pinpoints one of the benefits of propulsion analyses; it only counts the propelling force. When using conventional methods a subject can go slower while they still have a lot of impulse recorded due to body weight. It would be worth considering whether impulse should be analysed like delta leg force, from the force minima instead of zero level. In this case, propulsion analyses gave information, which has been hidden with traditional methods. This highlights the complexity of the skating technique and the importance of the right alignment of the push off which only propulsion analyse reveals.

With conventional methods pole forces decreased from 20 to 26% in peak, average and impulse of force, which is more than double compared to conventionally analysed leg forces (~10%). With these results, a conclusion was drawn in Article III that the fatigue is effecting differently in upper and lower body interpreted with rather different decreases in force levels. Decreases in pole force levels were well in accordance with previous studies from sprint simulation using DP (Mikkola et al. 2013) with 20 to 24% decrease. While a longer 6 km DP simulation (Halonen et al. 2015) showed decreases of 14%. Also the importance of poling have been highlighted by Sandbakk (2013) when comparing poling vs. no-poling situation with different speeds on cyclic and physiological parameters. In propulsion perspective (IV) decreases were rather equal in level compared to conventional methods. Traditional methods show changes of ~20% while propulsion methods gave ~22% decrease in impulse. This is probably due to the more simplified movement of poling where the pole tip is at fixed position during the push off compared to skating push-off with a moving and edging ski.

When trying to highlight the differences in upper and lower body with traditional methods the ratios of peak forces (III) decreased by 19% from pre- to post-test. This means that pole forces decreased more compared to ski forces and it was discussed as confirmation for the different response to fatigue with upper and lower body. In addition, when analysing the ratio from impulses behaviour was the same with 21.4% decrease more with poles. However, in this case propulsion analyses gave contrary results with change in impulse ratios by an increase of 14.5% indicating that the propulsion of the legs decreased more.

6.3.4 Propulsion methods and individual athlete diagnostics

6.3.4.1 Upper versus lower body distribution

While analysing propulsion with methods presented by Göpfert et al. (2017) the present study find somewhat different results compared to earlier V2 studies as discussed before (Smith, Kvamme & Jakobsen 2006). With upper body vs. lower body distribution we found higher propulsive forces with legs compared to poles during maximal skiing at a non-fatigued status (legs 54% vs. poles 46%, Figure 25B) while at fatigued state propulsion was created equally with legs and poles (~51% vs. 49%). With submaximal speeds the relation is vice versa and poles are generating more propulsion (~44% vs 56%). This result is a contradiction to previous V2 propulsive force results by Smith et al. (2006). They reported approx. one third of propulsive force from legs and two thirds from poles with submaximal speeds, which is also closer to our results with submaximal speeds. It seems that legs might take greater responsibility of propulsion generation while skiing full speed especially at non-fatigue state. In addition, earlier study (Smith, Kvamme & Jakobsen 2006) measured only vertical forces and it has been reported that also medio-lateral forces play an important role (Göpfert et al. 2015). Also, this earlier study (Smith, Kvamme & Jakobsen 2006) measured propulsive forces locally from the skis and poles, not propulsion via COM. Methodology used here takes into account all three dimensions of forces and PFA to COM vector and these differences might be one reason for higher leg propulsions. In addition, incline angle was different in these studies which also might have impact on the different results. Also, the present study was performed under natural conditions on snow where a ski reacts somewhat differently compared to roller skis e.g. by penetrating in the snow. Shift from higher leg propulsions to higher pole propulsion from maximal to submaximal speeds is very interesting and might also be linked to total unloading of the ski at maximal speeds vs. incomplete unloading at submaximal speeds.

6.3.4.2 Effectiveness index

Effectiveness index is described as a percentage of propulsion impulse from resultant impulse and discussed to be a good indicator for the overall economy on force production of the athletes (Stöggl & Holmberg 2015; Smith, Kvamme & Jakobsen 2009; Göpfert et al. 2017). Effectiveness index showed interesting behaviour from maximal to submaximal speeds. Highest values were recorded at maximal speed with legs (same as with propulsion) while highest values with poles were seen with submaximal speeds. This indicates that the leg push off is more optimally aligned (resultant force is hitting more closely to COM from PFA) at maximal speed compared to submaximal speed, while with poles the result is opposite. We speculate that the cause for this during maximal speed trials is as follows: the body is inclined to be more forward at maximal speeds compared to submaximal speeds, which enforces the poles to be placed further at initial poling phase in relation to COM. This more forward starting position with maximal speeds is causing more horizontal displacement between leg PFA to COM and vice versa less horizontal displacement (or even negative, pole PFA in front of COM) from pole PFA to COM. This could explain the changes in effectiveness index from maximal to submaximal speeds. Even though, this phenomenon needs further studies, effectiveness index could be a powerful tool on athlete diagnostics in the future. Stöggl et al. (2015) reported values of effectiveness index ~60% from poles and 11% from legs (with small increase over speed) while using V1-technique. However, here the propulsive force is also calculated locally at ski and pole PFA that effects especially on pole effectiveness index when pole force vector is not pointing to COM rather in a more forward direction, which probably causes the difference (40% vs 60%) between the results of present study to Stöggl et al. (2015).

6.3.4.3 Comparing two extreme cases – single case data

As already discussed here and by several authors (Göpfert et al. 2017; Stöggl & Holmberg 2015) propulsion might be a good tool for athlete's performance and technique diagnostics and it might tell something traditional force measurement methods do not reveal. In order to clarify this using the current data set we selected two subjects (S1 and S2, Figure 27) with increasing lap times (showing quite extensive fatigue during race). S1 (placed 5th in final time rank) showed highest pole propulsions at beginning (pre-test) which decreased to be lowest at the end (post-test) with over 50% decrease. This result could be detected also with traditional measurement methods using axial pole forces. However, when scoping S2 (placed 4th in final rank) the same kind of decreases (over 50%) between pre- and post-test were noted with leg propulsion. However, this cannot be seen as clearly with traditional methods, which shows only 20% decreases in peak leg forces and no changes in impulses. This result shows that calculation of propulsion is highly relevant. If only forces with traditional analysing methods are used, interpretations might not be correct for example on detecting the source of fatigue and how it was divided to upper and lower body.

6.3.4.4 Advantages of presented propulsion methods

Propulsion method presented by Göpfert et al. (2017) and used here gives important information especially from legs compared to traditional methods. When analysing only peak vertical leg forces the changes were rather low (Articles I and III) but when delta leg force (change from force minima to maximum) is analysed the results are a bit closer to propulsion results, but still strongly underestimated. Also impulses analysed with traditional methods often don't change or even increase (with fatigue and lower movement frequency). Therefore, it would be worth considering whether also impulses should be analysed from force minima instead of the zero level.

Older propulsive force models (Smith, Kvamme & Jakobsen 2006; Hoset et al. 2014; Stöggl & Holmberg 2015) calculate the propulsive force locally from the ski or pole PFA and don't take into account 3D forces or the force vector from the PFA to COM. If the skier would be rigid body the results of the propulsive forces calculated at PFA would be the same as calculated via COM. However, XC-skier is not rigid body and therefore point of mass model where forces acting to COM and propulsion calculated from there presented by Göpfert et al. (2017) seems to be more appropriate. The lack of the abovementioned calculation with 3D forces and PFA to COM part of forces is also discussed as a small limitation in these earlier studies (Stöggl & Holmberg 2015; Hoset et al. 2014). However, when using pressure insoles (Stöggl & Holmberg 2015) or instrumented roller skis (Hoset et al. 2014) the disturbance caused by the measurement devices is smaller compared to the force binding, which necessarily adds weight to skis.

Our hypotheses about greater decreases in pole propulsion forces were denied, but as it was estimated propulsion results gave new insight compared to traditional force measurements especially with leg forces.

6.4 Limitations

In this study, like all studies, there are always some limitations. In general, in this study the group of subjects was a small sub elite group. On absolute top level, athletes are always individual and their winning capacities are based on their own characteristics. In addition, top level skiing is always changing as seen during last year with e.g. the Norwegian Johannes Høsflot Klæbo who basically came to world cup with a new winning technique development for diagonal skiing using running with skis on the uphill. Therefore, generalizing the results is often challenging. Secondly, in all experiments subjects needed to carry extra weight caused by sensors and measurement equipment which may have effected the subjects' performance.

More explicitly in different Articles published during this work, following limitations were reported:

In Article I there were problems with the weight of the system as well as with anterior posterior direction of force. This was detected to be due to mechanical construction of the old force binding. However, these limitations directed this study to develop a new force binding enabling the further studies.

In Article II the developed system was unable to validate properly against current technology in field measurements due to lack of the present systems.

In Article III only above mentioned general limitations occurred as well as some data loss due to broken sensors during measurements. Also, EMG was measured with suit-based solution which might have some effect on the accuracy results especially with upper body muscles.

In Article IV, which was a highly applied study, a main limitation was the low amount of subjects which could be used during the analyses due to problems with motion data. Because of this, no statistical differences could be reported. Second limitation is that only one kick could be analysed for one situation due to short 3D measurement area and the nature of the study (simulated race). Thirdly, the left pole force values were duplicated from the right side due to sensor problems. Fourthly, the 3rd dimension of force (anterior-posterior, friction force) needed for propulsion calculations were estimated based on earlier studies but on similar conditions.

7 PRIMARY FINDINGS AND CONCLUSIONS

The motivation for this PhD work was to determine and clarify the biomechanics of skating skiing in various situations on snow with novel force measurements methods. *First study* was conducted to clarify how skiers control their speed during V2-skating technique. However, during the process some problems were noticed with 3D force measurement system, and it was not fully reliable in all directions. Secondly, the system needed to be lighter in order to measure trustworthy skating skiing. This led us to the topic of our *second study*. We wanted to build a custom made force measurement system with proper validation in order to measure forces during XC-skiing. With this new force measurement system our *third study* was performed to clarify how fatigue is effecting on the final spurting performance in biomechanical perspective. As a continuation to fatigue topic our *fourth study* implemented to resolve how propulsion, calculated with recently presented novel methods, is distributed between upper and lower body and changed during long distance skating skiing.

The main findings of this thesis were

1. The speed is controlled during the V2-skating by cycle length with lower speeds up to 85% of maximum. After this cycle rate is the main governor on speed increase. Leg forces expressed with delta leg force, increased more towards higher speeds and up to maximum compared to pole forces. Higher forces with especially legs are elicited via greater vertical movement of COM which might evoke SSC for greater force output.

2. It is possible to measure forces reliably, with error less than 6%, during skate imitation jumps on vertical and medio-lateral directions with custom-made force measurement system (skate force binding). Some improvements are recommended for classic force binding due to error up to 20% during classic imitation jumps.

3. 20 km long simulated skating race is causing fatigue which is seen with impaired functionality of the muscles. This can be detected with lower

EMG activity both in upper and lower body causing lower force production and movement frequency. Traditional force measurement methods suggest that the fatigue is seen with greater decrease in force levels with arms compared to legs and therefore the hypotheses of third aim were accepted using these methods.

4. Related to previous, when analysing the data with novel methods using propulsion analyses fatigue effects of the legs can be revealed more specifically and the difference in arms is smaller. Based on this the propulsion method seems to have potential to be a proper analysing tool with new information for coaches and athletes on technique diagnostics in different situations e.g. fatigue, speed or acceleration.

Summary, practical implications and future perspectives

First part, the speed study, of this thesis confirmed several findings done with roller skis about cycle rate – cycle length relation with increasing speeds to be valid also on snow situation. Results guide athletes and coaches to concentrate on force and technique trainings to achieve longer cycle lengths on submaximal race speeds while aiming to high frequencies on speed trainings. First Article also gave strong objective to orient this thesis highly on coaching direction. Based on the results of the speed study, especially parameter overlap time, gave ideas for technique coaching in treadmill training. A new parameter, PSCD, pole-ski contact change, for more precise push-off and poling timing, was presented for coaches and athletes. Parameter was able to be calculated with Coachtech online feedback system described by Ohtonen et al. (2016) and gave instant information about the timing with single numerical value.

During the second part of the thesis, force binding validation, it turned out that the forces were possible to measure reliable during XC-skating skiing in two main directions (vertical and medio-lateral). Later it has been showed that the measurement of medio-lateral forces is essential for recording reliable propulsion results. However, at the moment anterior-posterior forces can only be measured from contralateral force binding, which is not the best solution. Further studies are needed to resolve how to acquire accurate anterior-posterior (friction) force from the same measurement unit during XC-skiing trials.

Third and last part, the fatigue study, was the first larger measurement setup with the novel propulsion method related to fatigue on snow. Despite the many limitations propulsion study encountered it gave valuable information about the importance of measuring of the propulsion by this novel way. It turned out that a lot of important information might be overlooked if only traditional force parameters are measured. Further goals for this new propulsion method is to analyse it online during treadmill skiing with instant numerical feedback e.g. about propulsion force or effectiveness index, as the PSCD parameter already does. By combining this with visual video feedback it could be powerful tool for athlete technique and performance diagnostics. At the moment coaches and athletes have opinions how to ski but with this method it could be showed to the athlete by numerical feedback which could lead to better learning and changing the technique. Possibilities for how to use this diagnostics systems could be for example to analyse skilful top level athletes and to use this information as a data base for athletes who have challenges with technique. Secondly, the usage of this system to detect the problems which are occurring during situations where athletes' performance is compromised like fatigued state or at high speeds which needs optimising in the force production and movement patterns.

YHTEENVETO (FINNISH SUMMARY)

Luisteluhiihdon biomekaniikka sekä suorituksen aikaisten voimien mittaamisen menetelmät

Maastohiihto on muuttunut merkittävästi viimeisten vuosikymmenten aikana. Suurin muutos tekniikoissa tapahtui 80-luvulla, jolloin hiihtäjät alkoivat käyttää luistelupotkuja hiihdon aikana. Kansainvälinen hiihtoliitto FIS eriyttikin luistelu- ja perinteisen hiihdon omiksi kilpailumuodoikseen ja ensimmäiset arvokilpailut, joissa oli matkoja kummallakin tekniikalla, pidettiin vuonna 1987 Oberstdorfissa Saksassa. Myös tämän jälkeen muutoksia on tullut merkittävästi. Välineet ovat kehittyneet kevyemmiksi ja jäykemmiksi mahdollistaen paremman voimanvälityksen. Voiteet ovat kehittyneet ja erityisesti fluorivoiteiden käyttöönotto 90-luvulla vaikutti merkittävästi hiihtämiseen. Tämän lisäksi 2000-luvun taitteessa esiteltiin uusia kilpailumuotoja ja -tapoja. Erityisesti sprinttihiihto ja yhteislähtöjen lisääntyminen, sekä hiihtoratojen muuttuminen siten, että käytössä ovat lyhyemmät lenkit jyrkempine nousuineen ja laskuineen, ovat muovanneet nykypäivän hiihtoa. Kaikki edellä mainitut muutokset ovat vaikuttaneet erityisesti hiihtonopeuteen. Nopeus hiihtokilpailuissa on kasvanut eniten verrattuna muihin olympialajeihin 70-luvulta tähän päivään. Kaikki nämä yhdessä ovat merkittävästi muuttaneet vaatimuksia, mitä menestyksekkäältä hiihtäjältä vaaditaan nykypäivänä. Hiihtoa on myös tutkittu aktiivisesti pitkän aikaa. Ensimmäiset voimamittaukset hiihtosuorituksen aikana on tehty 80-luvulla ja 90-luvulla tehtiin useita kilpailuanalyysejä biomekaanisesta näkökulmasta. Lisäksi hiihdon fysiologisia vaatimuksia on selvitetty ja osoitettu, että maksimaalinen hapenottokyky on merkittävin hiihtosuorituksen tulosta määrittävä tekijä. 2000-luvulla maastohiihdon tutkimus on laajentunut ja erityisesti edellä mainittuja vaatimuksia nopeuden ja suorituskyvyn suhteen, on selvitetty useiden tutkimusryhmien toimesta. Tämän tutkielman tarkoituksena oli selvittää luisteluhiihtotekniikka V2:n (suomessa käytetään nimeä ″wassu″ tai ″wasberg″ tekniikka) biomekaanisia vaatimuksia erilaisissa tilanteissa. Tarkemmin tutkittiin, kuinka hiihtäjät kontrolloivat nopeuttaan biomekaanisesta näkökulmasta hitaasta maksimaaliseen vauhtiin. Toiseksi selvitettiin 20 km pitkän simuloidun hiihtokilpailun vaikutuksia biomekaanisesta näkökulmasta niin perinteisillä voiman analysointimenetelmillä, kuin uudella propulsiovoimamenetelmällä. Lisäksi tutkimusten aikana kävi ilmi, että olemassa oleva voimanmittausanturi ei ollut riittävän tarkka. Tämän vuoksi uusi menetelmä, voimien mittaamiseen jaloista hiihtosuorituksen aikana, kehitettiin toisessa osatutkimuksessa.

Tutkielman eri vaiheisiin osallistui 16 kansallisen tason hiihtäjää. Tutkimuksen ensimmäisessä osassa (I) selvitettiin, kuinka urheilijat kontrolloivat V2 tekniikan hiihtonopeutta 100 metrin matkalla 4° nousukulmaan kolmella submaksimaalisella, ja maksimaalisella nopeudella. Hiihtovoimien mittaamiseen käytettiin 3D voima-anturia jaloille ja sauva-anturia käsille. Tämän osatutkimuksen perusteella todettiin, että 3D voima-anturi ei ollut riittävän tarkka ja tämän vuoksi toisessa osatutkimuksessa (II) suunniteltiin, rakennettiin ja validoitiin uusi 2D voima-anturi niin luistelu- (pysty- ja poikittaisvoima) kuin perinteisen (pysty- ja pitkittäisvoima) tekniikan analysointiin. Anturin validointi toteutettiin erilaisissa lämpötiloissa ja mekaanisen kuormituksen tiloissa. Lisäksi tehtiin erityyppisiä lajinomaisia luistelu– ja perinteisen hiihdon potkua mallintavia hyppyjä referenssivoimalevyiltä. Viimeisenä vaiheena voima-anturit testattiin olemassa olevia mittauslaitteita vastaan oikealla lumella hiihdettäessä molemmilla tekniikoilla. Kolmas osatutkimus toteutettiin simuloidun luisteluhiihtokilpailun biomekaanisten vaikutusten selvittämiseksi uudella voimanmittausanturilla. Hiihtäjät hiihtivät 10 * 2 km matkan Vuokatin hiihtoputkessa ja heidän hiihtosuoritusta analysoitiin 100 metrin matkalta 4° nousukulmaan ennen kilpailua, sekä kilpailun lopussa (loppukiri). Tutkimuksen ensimmäisessä osassa tutkittiin perinteisiä hiihtosuorituksen voimamuuttujia sekä syklimuuttujia ja lihasaktiivisuutta (III). Tutkimuksen toisessa osassa käytettiin uutta propulsiovoimamentelmää samalla datalla. Propulsiovoimamenetelmässä lasketaan liikeanalyysiä hyväksikäyttäen käsien ja jalkojen voimien resultanttien massakeskipisteeseen osuva osa, ja siitä hiihtosuuntaan vievä voiman komponentti (IV).

Tutkielman päätulokset osoittivat, että hiihtäjät kontrolloivat hiihtonopeutta V2 tekniikalla muokkaamalla syklin mittaa ja hiihtofrekvenssiä. Syklin mitan kasvattaminen on määräävässä roolissa hitaammilla nopeuksilla (noin 85% hiihtonopeudesta), kun taas hiihtofrekvenssin kasvattaminen määrittää nopeusmuutoksia kovemmilla nopeuksilla. Vauhdin kasvaessa jalat vaikuttavat kokonaisvoimantuottoihin enemmän kuin kädet. Massakeskipisteen suurempi pystysuuntainen liike, joka voidaan todeta suurentuneina liikelaajuuksina polvi- ja lantiokulmissa, auttaa käsien ja jalkojen voimantuotoissa hiihtonopeuden kasvaessa (I). Uusi voima-anturi validoitiin useissa erityyppisissä staattisissa ja lajinomaisissa tilanteissa, ja todettiin luotettavaksi luisteluhiihtoanturin osalta, maksimivirheen ollessa alle 6%. Perinteisen hiihdon anturi ei ollut riittävän luotettava erityisesti pitkittäisvoiman osalta (maksimivirhe noin 20%). Perinteisen hiihdon anturiin suositeltiin tehtäväksi muutoksia ennen sen käyttämistä myöhemmissä tutkimuksissa (II). Uudella luisteluhiihtoanturilla tutkittiin pitkän simuloidun luistelukilpailun vaikutuksia hiihtäjään. Päätuloksina oli, että heikentynyt lihasaktiivisuus sekä ala- että ylävartalossa, vaikutti voimantuottoihin laskevasti. Perinteiset voimananalysointimentelmät osoittivat, että voimantuottojen lasku pitkän hiihtokilpailun seurauksena, olisi suurempaa erityisesti ylävartalossa kuin alavartaloon (III). Edelliseen liittyen, kun dataa tarkasteltiin uudella propulsiomentelmällä, huomattiin että voimantuoton muutokset voidaan todeta tarkemmin, erityisesti alavartalon osalta. Uusi menetelmä osoitti, että muutosten suuruus oli samankokoinen käsien osalta, mutta jalkojen osalta nähtiin selvästi suurempi muutos, verrattuna perinteisiin analyysimenetelmiin. Tähän perustuen propulsiomenetelmä näyttäisi olevan tarkempi, erityisesti monimutkaisemman luistelupotkun analysoinnissa. Menetelmä voisi täten olla hyvä työkalu hiihtäjän tekniikan analysointiin erilaisissa tilanteissa, joihin liittyy esimerkiksi kovavauhtista hiihtämistä ja väsymystä.

Tutkimuksen tulokset vahvistivat edellisten tutkimusten tuloksia, mitä oli tehty rullasuksilla, ja antoivat uutta tietoa luisteluhiihdon biomekaniikasta eri tilanteissa. Tutkimustulokset ohjaavat urheilijoita ja valmentajia keskittymään voima- ja tekniikkaharjoituksiin, jotka tähtäävät pitempiin syklin mittoihin kilpailujen matkavauhdeissa ja kovempiin frekvensseihin kirivaiheissa. Lisäksi ensimmäisen osatutkimuksen tuloksena löydettiin muuttuja, joka kertoo hiihtäjän potkun ja työnnön ajoituksesta. Tätä muuttujaa voidaan käyttää suorana numeerisena palautteena luistelutekniikasta urheilijalla, kun hän hiihtää rullasuksilla juoksumatolla. Tutkielman viimeinen osio, joka käsitteli propulsiovoima-analyysiä, osoitti että kyseinen menetelmä paljastaa urheilijan tekniikan muutokset ja niiden vaikutukset hänen voimantuottoihin paremmin kuin perinteiset voimananalysointimenetelmät. Kun kyseinen propulsiovoimamuuttuja voidaan esittää urheilijalle reaaliaikaisena, esimerkiksi rullahiihdon aikana juoksumatolla, päästään tarkempaan tekniikan ja suorituskyvyn optimointiin.

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ORIGINAL PAPERS

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SPEED CONTROL OF THE V2 SKATING TECHNIQUE IN ELITE CROSS-COUNTRY SKIERS

by

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Speed control of the V2 skating technique in elite cross-country skiers

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Abstract

The aim was to examine how skiers control skiing speed using V2-skating. Subjects skied with three submaximal and maximal speeds on 100 m 4° uphill. Cycle variables and force parameters form the arms and legs were analysed. Cycle rate increased up to the maximum speed. Cycle length increased from the slowest speed to the all other speeds. Pole force and delta leg force increased up to the maximum speed. Ranges of motions and angular velocities of kick flexion and extension with knee and hip joints increased till highest submaximal speed. Speed was regulated with cycle length and rate while the latter was dominant after ~5.0 m/s. Higher speed was reached with higher forces from arms and legs while legs were emphasized with faster speeds. Higher forces were partly generated with greater vertical movement of the body, which might have elicited stretch-shortening cycle type of movement leading to greater force output.

Keywords

Cross-country skiing, cycle characteristics, joint kinematics, leg forces, pole forces, speed adaptations

Introduction

Since the ski skating technique was established in cross-country skiing, nordic combined and biathlon racing in the 1980s, it has been further developed and speeds have increased considerably.[1,2] V2 skating (also called as gear 3, G3), with a symmetrical and synchronous double pole thrust at each leg push-off,[3] has become one of the most commonly used skating techniques, which nowadays is applied in a wide range of terrains. V2 skating can be used on flat surfaces, moderate and even steep uphill sections, as well as in final sprints and in parts of the race that require fast changes in speed. It has been shown that sprint race results were positively related to the amount of use of V2 skating during races,[4] which highlights the importance of V2 skating among all skating techniques as specific cyclic locomotion on skis.

In other cyclic sports the cycle length has been shown to be the primary factor for speed increases at lower speed ranges, while cycle rate dominated speed control at higher speeds up to the individual maxima.[5] Some earlier studies in speed skating[6] or ski skating[3,7,8] termed cycle rate the only governor of speed regulation with cycle length remaining unchanged or even decreasing from low speeds, while others found both cycle length and rate contributing to speed increases within submaximal speeds using V1, V2 or V2a[9–14] skating technique or other diverse classic techniques.[15–18] In modern sprint skiing, cycle rate increase was found to be the only possible strategy at the very last speed range up to V_{max} to further push the individual speed limit.[19]. Cycle length started to decrease at the very highest speeds and showed a kind of optimum value for sprint skiers.[19] There are several articles on speed control using V2 technique from physiological and/or biomechanical point of view.[9,11–13,20] However, to the best of our knowledge, only two earlier studies have explicitly examined mechanisms of speed control by simultaneously measuring forces during skating and these are done using roller skis on asphalt[9] or treadmill.[11] Millet et al.[9] found slightly increased peak pole forces but unchanged average cycle forces, suggesting that V2 depends more on lower body actions for generation of

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the additional propulsion to increase speed. Smith et al.[11] demonstrated that in national level skiers, peak pole and leg forces during V1 and V2 roller ski skating increased with speed but without any changes in the average resultant forces, which contradicts Millet's findings.[9] Greater leg joint ranges of motion (ROM) during cross-country skiing techniques have been discussed in connection with greater vertical oscillations of the center of mass (COM) during gliding and push-off phases, most likely optimizing leg and pole force production, energy transfer and performance using diverse skiing techniques.[17,21–24] However, the essential question about how elite skiers gain speed when using modern V2, one of the most important skating techniques, under real conditions on snow is still unanswered.

Kinetic and kinematic analyses with pole and leg force as well as joint angle measurements are needed in order to more deeply understand the mechanisms of how speed regulation is accomplished and the role of lower as well as upper body actions. In addition, since the maximal skiing speeds have increased during the last decade, there is a need to re-examine whether cycle characteristics have changed as well. Therefore, the aim of the current study was to accomplish a more extensive biomechanical examination of speed control strategies during V2 performed *under natural conditions on snow* and over a wide range of speeds up to V_{max}. We hypothesized that skiers gain higher skating speeds by 1) increasing both cycle length and rate, while cycle length increase will dominate within the lower range of speeds, 2) and by intensifying the leg and arm joint movements with greater ROM and angular velocities (AVs) leading to greater force output from legs and arms.

Method

Some results of the present study have been partly presented in recent article from our group discussing the effects of different gliding frictions on V2 skating.[25]

Subjects

Ten Finnish national and international level male distance cross-country skiers (age 28.1 ± 5.8 years; height 175.6 ± 5.0 cm. body mass 76.1 ± 8.4 kg; distance FIS points 109.5 ± 36.7; means ± SD) volunteered to participate in this study.

All subjects gave their written consent for participation after they were familiarized with the measurement protocol. All methods used in this study were approved by the ethics committee of the University of Jyväskylä, Finland.

Overall design and protocol

Tests were performed using real snow conditions in the indoor Vuokatti ski tunnel where temperature (−7°C), humidity (80%) and snow conditions were constant over the measurement period. All trials were performed on a 100 m section of the track with a constant uphill gradient of 4° using V2 skating technique. 4° uphill inclination was chosen because it is typically skied with V2 technique by elite skiers regardless the used speed. In addition, it has been reported that ~5° is the crossover point where after V1 is advantageous to V2 from physiological point of view.[11,20] On the other hand, Losnegard et al.[6] did not find out any differences in O_2 cost between these two techniques in 4, 5 and 6°. V2 skating is symmetric on both sides of the body and consists of an arm push for each leg kick. Phase detection of the V2 cycle is presented in Figure 1. To standardize the glide conditions for athletes, they all used the same pair of skating skis (Peltonen Supra-x, Peltonen Ski Oy, Hartola, Finland), which were prepared by the same skilled service man and waxed (rub-on high fluoride briquette Rex TK-72, Oy Redox Ab, Hartola, Finland) in the same way for every athlete. The measurement protocol consisted of a 15-min low intensity warm-up followed by test trials with three different submaximal (slow, 4.0 m/s; medium, 4.8 m/s; fast, 5.6 m/s) speeds and maximum speed (V_{max}, 6.6 ± 0.4 m/s; mean ± SD). The orders of the submaximal speed trials were randomized, and the maximum speed trial was always performed last in order to ensure that the athletes were fully warmed-up and to standardize the fatigue state of the athletes for the maximum speed trial. All speeds were performed twice and the better trial, characterized by more stable speed over the measurement area for submaximal trials and higher speed for maximum trials, was selected for further analyses. Recovery time between trials was set at three minutes to minimize the effect of the fatigue between trials.

Instruments and materials

Axial pole forces were measured with a special force measurement system based on a strain gauge force transducer placed below the pole grip (Hottinger – Baldwin Messtechnik GmbH, Darmstadt, Germany). The force measurement system and calibration procedures are described in detail by Holmberg et al.[21] The force measurement system was used with carbon-fibre poles and was possible to adapt telescopically for the individual length of every athlete. Leg forces were measured with a custom-made force measurement system (Neuromuscular Research Center, University of Jyväskylä, Finland) placed between the ski and the binding. All three natural directions of forces (Z, vertical; X, medio-lateral and Y, anterior-posterior) were

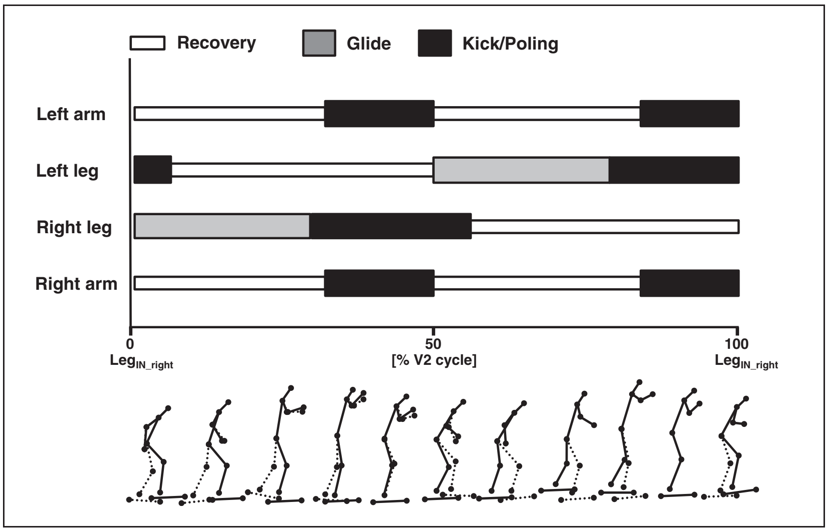

Figure 1. Definition of the gliding and the kicking phases of the leg as well as the poling and the recover phases over one V2 cycle starting from the right ski plant till the next right ski plant.

measured. Anterior-posterior forces, however, were not fully reliable and were therefore discarded from the results. Calibration of the leg force measurement system was conducted using five different loads with a ski stiffness measuring device (Nastolan Vaaka ja Kone Oy, Nastola, Finland) and checked using a standard force plate (Neuromuscular Research Center, University of Jyväskylä, Finland) with standing and jumping situations. The force measurement system and calibration procedures are described in detail by Linnamo et al.[26] and Ohtonen et al.[25] Joint angles of the elbow, knee and hip were measured with goniometers (potentiometers: Megatron, Munich, Germany) from the right side of the body. A 180° angle implied a fully extended joint and a 90° angle corresponded to perpendicular angles between fore- and upper arm for the elbow, shank and thigh for the knee, as well as thigh and trunk for the hip.

Data from pole and leg force measurement equipment in addition to goniometers were collected with the same system and thereby synchronized. The system consisted of an A/D converter (sampling rate 1 kHz, NI 9205, National Instruments, Austin ,TX, USA) connected to a wireless transmitter (WLS-9163, National Instruments, Austin, TX, USA). Data was transmitted via WiFi and collected with laptop equipped with special data collecting software (LabVIEW 8.5; National Instruments, Austin, TX, USA). Extra weight added by the measurement equipment was 3570 g, as follows: leg force measurement system 1070 g for one ski, pole force measurement system 135 g for one pole, and data collecting equipment 1160 g. Data collecting equipment were placed on subjects' waist in a waist pack to minimize the disturbance to skiing.

The speed of the athlete was controlled with a visual pacing system (Protom, Naakka Oy, Lappeenranta, Finland). In addition, trials were recorded with radar (Jenoptik LDM 300 C SPORT, Jena, Germany) to monitor the athletes' actual speed and in order to select trials for later analyses. Trials were also videotaped (Panasonic NV-GS400, 25 Hz) for documentation.

The coefficient of friction of the skis used was analysed once during measurements by special ski tester[27] where the vertical and horizontal components of force during gliding could be measured. Based on these forces, the coefficient of friction was calculated using the equation (1).

$$\mu = \frac{F_y}{F_z} \tag{1}$$

where μ stands for the coefficient of friction, F_y and F_z are the horizontal and vertical forces from the ski tester. Five glides were averaged and analysed for the calculation. The coefficient of friction was 0.028 for the test ski.

V2 cycle and variable definitions

Due to the similar movement pattern in both sides of the body during V2 skating, all variables were analysed only from the right side of the body. For every trial, nine consecutive cycles were analysed and averaged. Cycle time (CT, Figure 2(a)) was determined as time in seconds between two consecutive right ski plants and cycle rate as cycles per second (Hz). Average cycle length was calculated as the product of average speed

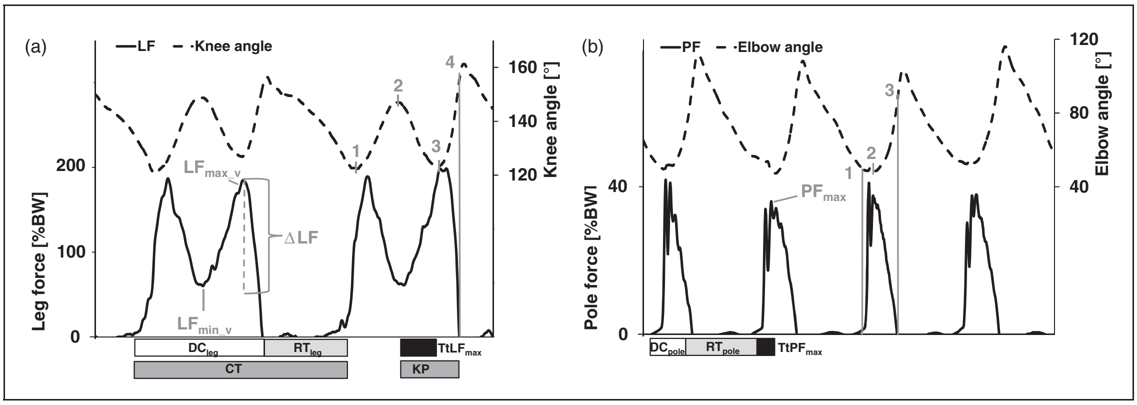

Figure 2. Vertical leg force (A, LF, left axis) and knee angle (A, Knee angle, right axis) curve from right leg as well as pole force (B, PF, left axis) and elbow angle curve (B, Elbow angle, right axis) from right arm with selected cycle, force and angle variable definitions. A and B are showing same time period.

of the trial and CT. Percentage change between the speeds (4.0 to 4.8 m/s, 4.8 to 5.6 m/s and 5.6 m/s to V_{max}) was calculated for cycle length and cycle rate. Duty cycles of the leg (DC_{leg}) and pole (DC_{pole}) are defined as ground contact time of the leg and poling time as percentage of the CT (Figure 2(a) and (b)). In addition, overlap time of the legs was defined from left ski plant to right ski release as percentage of the CT.

All force variables are presented relative to body weight (%BW). Maximum pole force (PF_{max}, Figure 2(b)) was defined as the highest active maximum force after impact. Maximum vertical and lateral leg forces were the highest forces recorded during the kick phase for both directions (vertical, LF_{max_v}, Figure 2(a) and lateral). Average rate of force development for the pole was calculated as maximum pole force divided by time to maximum pole force ($TtPF_{max}$, Figure 2(b)) as a percentage of the poling CT (%CT). Average rate of force development for the legs was calculated by dividing the delta leg force (ΔLF, Figure 2(a)), which is described as the difference between minimum leg force (LF_{min_v}, Figure 2(a)) prior to the kick phase and maximum leg force during the kick phase, by the time between these two points ($TtLF_{max}$, Figure 2(a)) as %CT. These specifications are equal to the unit for average rate of force development: %BW/%CT.

From elbow angular data, the following points were detected during poling: elbow angle at pole plant, elbow angle minimum during poling, and elbow angle at pole release (Figure 2(b), events 1, 2 and 3, respectively). Additionally, ranges of motions (ROMs) as well as AVs were calculated for flexion (Figure 2(b), 1–2) and extension (Figure 2(b), 2–3). From knee and hip angular data, the following points were analysed during ground contact of the ski: minimum after ski plant, maximum during gliding phase, minimum during kick phase and point at ski release (Knee, Figure 2(a), points 1, 2, 3 and 4, respectively). Maximum knee angle was used to divide ground contact into gliding and kicking phases (KP, Figure 2(a)). Hip and knee ROMs were calculated for glide extension (Figure 2(a), 1–2), kick flexion (Figure 2(a), 2–3) and kick extension (Figure 2(a), 3–4). In addition, AVs were calculated for the two latter phases.

Data analysis and statistics

Data was processed using IKE-master v. 1.34 software (IKE Software Solutions, Salzburg, Austria) and Microsoft Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA). All data were checked for normality, calculated with conventional procedures and presented as mean values and standard deviations (±SD). A one-way repeated measure ANOVA was conducted using a Bonferroni alpha correction to show the difference between four different speeds. Further evaluations for the variables were done by calculating the effect size using partial eta square ($p\eta^2$) and the statistical power. Correlations were examined by using a Pearson's product-moment correlation coefficient test. The statistical level of significance was set at $P < 0.05$. All statistical tests were processed using the SPSS 17.0 Software (SPSS Inc, Chicago, IL, USA).

Results

The maximum speed (V_{max}) measured in the current study was of 6.6 ± 0.4 m/s and it was correlated with cycle length ($r = 0.90$, $r^2 = 0.81$; $p < 0.01$). Cycle length and V_{max} were not related to anthropometric measures.

Cycle characteristics

All cycle characteristics are shown in Figure 3(a) to (d). With increasing speeds cycle rate and cycle length increased by 42% and 16%, respectively, up to V_{max}

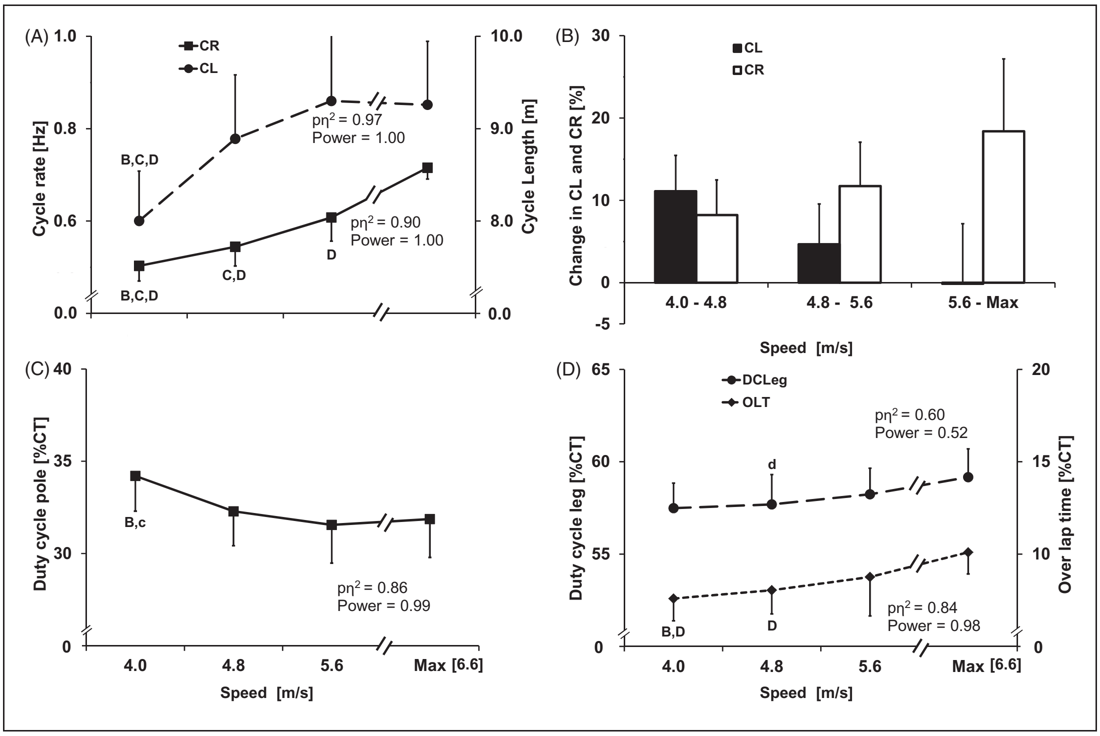

Figure 3. Cycle rate (A, left axis) and cycle length (A, right axis), percentage change of the cycle length and cycle rate from speed to speed (B), duty cycle of the pole (C), duty cycle of the leg (D, left axis) and overlap time of the leg (D, right axis) at three increasing submaximal speeds and v_{max}.

Note: The data are presented as mean ± SD. Partial eta square effect size (p?2) and power are presented for One-way repeated-measures ANOVA. a, A; b, B; c, C; d, D, different to 4.0 m/s, 4.8 m/s, 5.6 m/s and v_{max}, respectively. a, b, c, d = $P > 0.05$; A, B, C, D = $P < 0.01$.

(both, $p < 0.01$). As speeds increased, the percentage change in cycle length decreased from 11.1 ± 4.3% over 4.7 ± 4.9% to −0.1 ± 7.3% while change in cycle rate increased from 8.2 ± 4.3% over 11.7 ± 4.3% to 18.4 ± 8.8%. Overlap time of the legs increased by 33% ($p < 0.01$) from slowest to fastest speed.

Pole and leg forces

Pole and leg forces are presented in detail in Figure 4(a) to (c). While speed was increased from slowest to fastest peak pole and delta leg forces increased by 44% and 106%, respectively (both, $p < 0.01$). No speed related changes in relative time to maximum pole force were observed. Relative time to maximum leg force decreased by 31% from slowest to V_{max} ($p < 0.01$). Average rate of pole and leg force development increased by 47% and 215%, respectively, (both, $p < 0.01$) while speed increased to V_{max}. No changes were observed on lateral leg forces.

Joint kinematics

Only the most relevant changes in knee and hip as well as elbow joint movements are shown here. For exact values at certain speeds and significant differences refer to Table 1 and the behaviour of the elbow, hip and knee joint refers to Figure 5(a) to (c).

With increasing speeds leg joint kinematics showed distinct changes within the first three submaximal speeds with minor changes from the last submaximal speed up to V_{max}. The eccentric and concentric phases during leg kick showed changes up to the highest speeds (5.6 m/s and V_{max}) where knee joint showed up to 3% larger angle maxima before kick-off ($p < 0.05$) and knee together with hip joint up to 9% smaller angle minima during kick-off (both, $p < 0.01$), leading to 38% and 56% larger knee and hip flexion (knee $p < 0.05$, hip $p < 0.01$) and 35% and 25% larger knee and hip extension ROM during leg kick (knee $p < 0.01$, hip $p < 0.05$). The temporally shortened flexion and extension times in knee and hip joints lead to 80% and 152% higher knee and hip flexion (both, $p < 0.01$) as well as 76% and 59% higher knee and hip extension AVs (knee $p < 0.01$, hip $p < 0.05$) during leg kick.

Changes in elbow joint kinematics during poling in angle positions showed only change of 17% decrease in elbow angle minimum during poling ($p < 0.05$). No changes in elbow ROMs were observed. Flexion and extension AVs showed 440% and 90% increases,

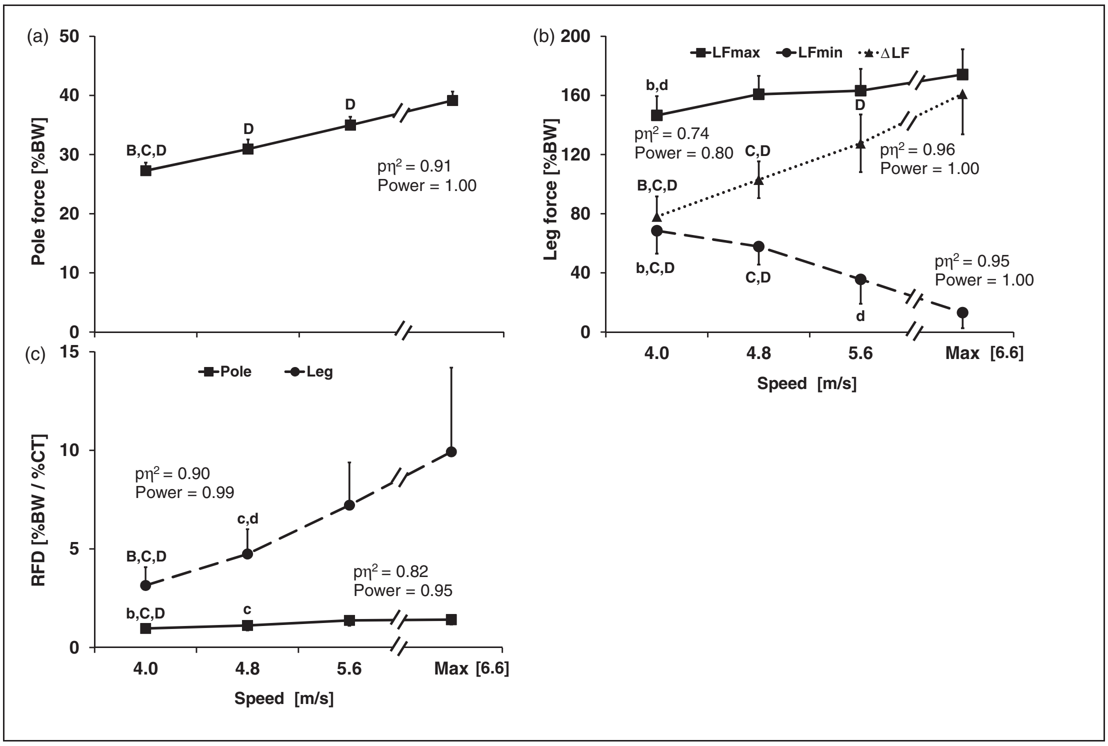

Figure 4. Maximum pole force (a), maximum, minimum and delta vertical leg force (b, LF_{max}, LF_{min} and ΔLF), average rate of pole and leg force development (RFD) (c) at three increasing submaximal speeds and V_{max}. The data are presented as mean ± SD. Partial eta square effect size ($p\eta^2$) and power are presented for one-way repeated-measure ANOVA. a, A; b, B; c, C; d, D, different to 4.0 m/s, 4.8 m/s, 5.6 m/s and V_{max}, respectively. a, b, c, d $= P < 0.05$; A, B, C, D $= P < 0.01$.

respectively (flexion $p < 0.05$, extension $p < 0.01$), up to the V_{max}.

Discussion

The main findings in the current study were:

1. During V2 skating, as previously reported by Millet et al.[9] in roller skiing, cycle length governs speed increase more during lower speeds whereas cycle rate governs speed increases more during higher speeds up to V_{max}.
2. Leg joint kinematics followed cycle length development at all speeds, showing distinct increases in ROM and AVs within all submaximal speeds. This increasing vertical movement of the COM is an essential strategy on speed increase.
3. Comparing the leg versus pole force changes over speeds, the relative increase in leg force production was greater.

Maximum speed

A V_{max} of 6.6 ± 0.4 m/s was reached in the current study, which is well in line with recent ski skating studies on snow at similar terrains (5.7 to 7.2 m/s) using elite skiers.[28,29] The level of individual maximum speed can be considered an essential performance factor in cross-country skiing, especially in sprint skiing. The distinct positive correlation of V_{max} to cycle length ($r = 0.90$) and high coefficient of determination ($r^2 = 0.81$) observed confirms results from a recent sprint skiing study performed on a treadmill using elite skiers.[19] Consequently, 81% of the V_{max} variability among participants could be explained by cycle length if a linear model is assumed. This suggests that the ability to generate long cycle lengths during V2 skating was predominantly responsible for creating high skiing speeds and sprint performance. Interestingly, the independence of cycle length from anthropometric variables such as body height or leg length has been shown for diverse skiing techniques[22,30] as well as running[31] and can be confirmed for V2 skating at V_{max} in the present study.

Cycle characteristics

In this study, multiple trials of V2 skating technique were performed on snow at a range of speeds and without any restrictions on cycle rate or cycle length. We found similar strategies of cycle rate/speed and cycle

Table 1. Knee, hip and elbow joint kinematics at four increasing skiing speeds using V2 skating technique ($N = 10$).

Variables	4.0 m/s	4.8 m/s	5.6 m/s	V_{max} [6.6]	$p\eta^2$	Power
$KA_{GlideMIN}$ (°)	$128 \pm 10^{B,C,D}$	$125 \pm 10^{c,d}$	122 ± 11	121 ± 12	0.852	0.984
$KA_{GlideMAX}$ (°)	155 ± 8^{c}	157 ± 9^{c}	159 ± 9	158 ± 10	0.678	0.679
$KA_{KickMIN}$ (°)	$131 \pm 10^{B,C,D}$	128 ± 10	125 ± 10	125 ± 10	0.867	0.992
KA_{OUT} (°)	157 ± 7	159 ± 8	158 ± 9	160 ± 7	0.636	0.592
$ROM_{K\_ext\_G}$ (°)	$27 \pm 5^{B,C,D}$	32 ± 6^{C}	37 ± 9	37 ± 10	0.841	0.976
ROM_{K_flex} (°)	$24 \pm 5^{b,C,d}$	28 ± 5^{C}	34 ± 8	33 ± 9	0.809	0.939
$ROM_{K\_ext\_K}$ (°)	$26 \pm 4^{B,C,D}$	$30 \pm 3^{c,D}$	33 ± 4	35 ± 4	0.927	1.000
AV_{K_flex} (°·s^{-1})	$60 \pm 13^{B,C,D}$	$78 \pm 14^{C,D}$	102 ± 22	108 ± 24	0.883	0.997
$AV_{K\_ext\_K}$ (°·s^{-1})	$151 \pm 26^{B,C,D}$	$183 \pm 32^{C,D}$	217 ± 42^{D}	265 ± 68	0.898	0.999
$HA_{GlideMIN}$ (°)	$117 \pm 14^{b,C,D}$	$114 \pm 14^{C,D}$	110 ± 14	108 ± 15	0.873	0.995
$HA_{GlideMAX}$ (°)	139 ± 17	138 ± 17	139 ± 17	138 ± 17	0.327	0.195
$HA_{KickMIN}$ (°)	$120 \pm 16^{C,D}$	$117 \pm 17^{C,D}$	112 ± 16	109 ± 16	0.981	1.000
HA_{OUT} (°)	$137 \pm 20^{C,D}$	134 ± 19^{D}	131 ± 19	129 ± 19	0.856	0.987
$ROM_{H\_ext\_G}$ (°)	$22 \pm 6^{C,D}$	$23 \pm 7^{c,d}$	28 ± 8	30 ± 6	0.778	0.888
ROM_{H_flex} (°)	$18 \pm 6^{C,D}$	$21 \pm 6^{C,D}$	27 ± 7	28 ± 5	0.870	0.993
$ROM_{H\_ext\_K}$ (°)	16 ± 9^{c}	17 ± 8^{c}	19 ± 9	20 ± 7	0.732	0.796
AV_{H_flex} (°·s^{-1})	$50 \pm 18^{B,C,D}$	$70 \pm 21^{C,D}$	101 ± 26	126 ± 35	0.952	1.000
$AV_{H\_ext\_K}$ (°·s^{-1})	$58 \pm 38^{c,d}$	74 ± 37	85 ± 38	92 ± 35	0.805	0.933
EA_{IN} (°)	57 ± 12	56 ± 12	55 ± 13	56 ± 13	0.128	0.089
EA_{MIN} (°)	54 ± 14^{d}	52 ± 14^{D}	50 ± 14	48 ± 13	0.722	0.773
EA_{OUT} (°)	113 ± 15	112 ± 16	112 ± 19	114 ± 15	0.094	0.077
ROM_{E_flex} (°)	3 ± 4	4 ± 4	6 ± 3	8 ± 4	0.484	0.347
ROM_{E_ext} (°)	59 ± 12	60 ± 14	63 ± 15	67 ± 12	0.460	0.318
AV_{E_flex} (°·s^{-1})	$20 \pm 47^{c,D}$	36 ± 56^{D}	68 ± 41^{d}	108 ± 51	0.755	0.843
AV_{E_ext} (°·s^{-1})	$229 \pm 40^{B,C,D}$	$279 \pm 53^{C,D}$	348 ± 71^{D}	433 ± 61	0.935	1.000

$KA_{GlideMIN}$: knee angle minimum after ski plant; $KA_{GlideMAX}$: knee angle maximum during glide phase; $KA_{KickMIN}$: knee angle minimum during kick phase; KA_{OUT}: knee angle at ski release; $ROM_{K\_ext\_G}$: knee extension range of motion during glide phase; ROM_{K_flex}: knee range of motion during flexion phase; $ROM_{K\_ext\_K}$: knee extension range of motion during kick phase; AV_{K_flex}: average knee angular velocity during flexion phase; $AV_{K\_ext\_K}$: average knee extension angular velocity during kick phase; $HA_{GlideMIN}$: hip angle minimum after ski plant; $HA_{GlideMAX}$: hip angle maximum during glide phase; $HA_{KickMIN}$: hip angle minimum during kick phase; HA_{OUT}: knee angle at ski release; $ROM_{H\_ext\_G}$: hip extension range of motion during glide phase; ROM_{H_flex}: hip range of motion during flexion phase; $ROM_{H\_ext\_K}$: hip extension range of motion during kick phase; AV_{H_flex}: average hip angular velocity during flexion phase; $AV_{H\_ext\_K}$: average hip extension angular velocity during kick phase; EA_{IN}: elbow angle at pole plant; EA_{MIN}: elbow angle minimum during poling; EA_{OUT}: elbow angle at pole release; ROM_{E_flex}: elbow range of motion during flexion phase; ROM_{E_ext}: elbow range of motion during extension phase; AV_{E_flex}: average elbow angular velocity during extension phase; AV_{E_ext}: average elbow angular velocity during extension phase. Data are presented as the mean ± SD. Partial eta square effect size ($p\eta^2$) and power are presented for one-way repeated-measure ANOVA. a, A; b, B; c, C; d, D, different to 4.0 m/s, 4.8 m/s, 5.6 m/s and V_{max} (6.6 m/s) respectively. a, b, c, d = $P < 0.05$; A, B, C, D = $P < 0.01$.

length/speed relationships as for other modes of cyclic human terrestrial or aquatic locomotion.[5] Considering the shapes of the curves, a curvilinear relationship between cycle rate versus speed (concave-up shape) and cycle length versus speed (concave-down shape) was observed for elite skiers while the maximum cycle length was reached at a high submaximal speed of ~85% of V_{max} (Figure 3(a)). This is comparable to modern double poling showing the highest cycle lengths at ~92% of the specific speed maximum.[17] Thus, the mechanisms used in the control of speed during V2 skating were characterized by the following pattern: both variables contributed to speed increase up to V_{max} (speed = cycle rate × cycle length) but to different extents depending on speed. Cycle length was the main factor in the lower speeds and cycle rate at the higher speeds. This can be supported by the relative (%) cycle length and cycle rate modifications between the single speed increases ranging from ~11 to 0% versus ~8 to 18%, respectively (Figure 3(b)). Some previous speed effect studies on skating[9–13] as well as classic skiing[15–17] with roller skis, confirm the observed cycle length and cycle rate development as a function of speed. While skiing with V2 technique on treadmill Sandbakk et al.[12,13] reported that both cycle rate and cycle length increase with submaximal speeds[12] as well as up to maximum speed.[13] Cycle length development up to V_{max} was controversial to our results. Friction

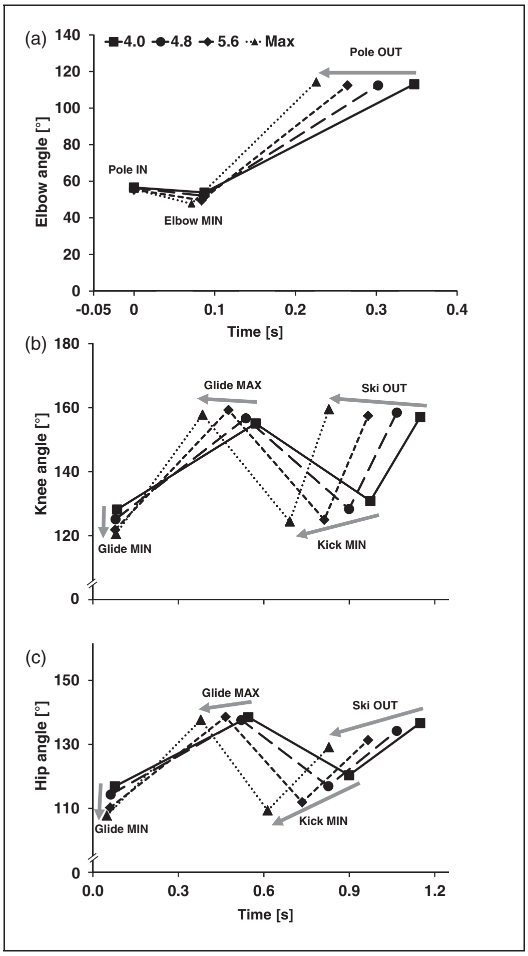

Figure 5. Elbow angle at first pole contact (Pole IN), minimum during poling (Elbow MIN), and at pole release (Pole OUT) (a), knee and hip angle at minimum after first ski contact (Glide MIN), maximum during the gliding phase (Glide MAX), minimum during the kick (Kick MIN) and ski release from snow (Ski OUT) (b and c, respectively) at three increasing submaximal speeds and V_{max}.

coefficients were quite similar in these studies compared to present (0.025 vs. 0.028). Friction coefficient has been shown to be constant during treadmill skiing even at edged ski situations during push-offs.[12,13] This is, however, probably not the case on-snow skiing where the ski penetrates to the snow during edging situations causing higher coefficient frictions especially at higher speeds and stronger push-offs thus probably limiting the usage of continuous increase in cycle length. This might at least partly explain the differences between the treadmill and on-snow skiing on cycle length but the topic requires further studies. Interestingly, some earlier studies also found cycle rate as the first governor of speed increase[7,8,32] with remaining and even decreasing cycle length starting from very low speeds up to the highest speeds. The main reasons for these controversial results may be the distinctly lower maximum skiing speeds which indicate that the skating technique and equipment have developed during last decade enabling higher speeds. The fact that cycle length currently plays a big role for controlling skiing speed indicates that skiing techniques as well as athletes' strength capacities[33] have developed during the last decades.

The duty cycle of the poles decreased from the slowest to two of the higher speeds supporting an earlier V2 skating study on roller skis on asphalt.[9] However, the values were ~5% lower in our case at all the speeds up to V_{max}. This can be influenced by different resistant forces like friction of the skis/roller skis and greater uphill angle of the terrain used. Both of these factors were greater in the present study indicating and highlighting the changes that have happened in skate skiing during the last decades. More recently Sandbakk et al.[12] reported similar duty cycles on ~1° and similar behaviour but higher values on the same uphill gradient compared to present study although submaximal speeds were lower in their study (from 1.7 m/s to 3.4 m/s). Decreasing duty cycles seems to be part of the skiers' strategy used at rather lower speeds, while predominantly increasing cycle length. Hereby, athletes need to produce forces at relatively shorter times, when skiing close to distance race speeds the duty cycles seem to find their optimal duration. However, different results are also presented. Our results are in controversy with Nilsson et al.[7] who reported constant relative phases across speeds.

Duty cycles of the legs increased between 4.8 m/s and V_{max}, which was slightly unexpected because during the recovery phase of V2 skating, the contralateral ski has ground contact. This is explained by the significant increase in the relative overlap time observed showing that the skiers are starting the glide phase of their contralateral leg earlier at higher speeds. We could say they start 'seeking ground contact' with the new glide ski at the highest speeds occurring during the late push-off phase of the other leg while body weight (COM) is transferred crossways from one side to the other. Based on our preliminary biomechanical 3D studies on fatigue (unpublished data) we speculate that this earlier ski plant or longer double stance phase may also lead to an earlier start of the COM transfer to the other side and the edging phase taking away pressure from the edge of the pushing ski. This might impair the force production and decrease skiing economy. Tangentially, V_{max} was negatively correlated to the relative overlap time in the current study vaguely indicating that faster skiers show less overlap and may control balance more securely at the highest speeds. Overall these are interesting subtopics that need to be examined in future studies using 3D kinematics, kinetics and physiological methods.

Pole and leg forces

Maximum pole forces increased through all speeds with a noticeable increase of 44% from the lowest speed up to V_{max} while similar maximum forces were found in recent studies on V2 skating.[28,29] Millet et al.[9] found similar pole force increases for V2 skating technique although maximum forces were ~10 percent lower compared to the current study. The distinct increase in maximum pole forces with increasing speed highlights the great importance of generated pole forces and thereby of arm and upper body work during V2 skating. From a mechanical point of view, the high significance of poling during V2 skating was shown by Smith et al.[11] who found that at a 5° inclination ~ two thirds of propulsion was due to pole forces acting proportionately in the skiing direction. The leg force production was shown to be less efficient due to non-optimal ski and edging angles in this technique at the present incline. In contrast, during V1 skating used on steeper uphills, less than half of the propulsive forces were generated by poling and leg forces that contributed more due to altered ski and edging angles at steep inclines.[11] Consequently, to predominantly pronounce the pole forces with increasing speeds represents a useful strategy among elite skiers when using V2 skating technique at low and moderate inclines, especially for skiers with high upper body capacities.

Maximum vertical leg forces of ~1300 N in the current study were in accordance with recent kinetic skating studies on snow[28,29] showing values ranging from 1299 to 1414 N. However, in contrast to the pole forces, the increase in maximum leg forces over speeds was significantly less (Figure 4(b)). Nonetheless, significant changes were found in the leg force minima, delta leg forces and rates of leg force development (Figure 4(b) and (c)). Interestingly, despite only minor increases in maximum leg forces, the delta leg force defined as the difference from the local force minimum to maximum leg force, doubled over speeds up to 160 %BW mainly due to an almost total unweighting prior to the kick phase (Figure 4(b)). In general, this unweighting can be considered a preparatory requirement for an efficient way of producing forces in a more eccentric manner (Table 1; Figure 5(b) and (c)) especially at high submaximal and maximal speeds using a stretch-shortening cycle pattern during push-offs[34] like in jumping[35] or running.[36] In cross-country skiing, the use of the stretch-shortening cycle has been shown in several techniques and for upper[16] as well as lower body.[8,18,37–39]

This has also been discussed for V2 skating as an efficient way to produce forces especially at maximum speeds. At maximum speed, when jumping from the ground and landing with a subsequent, more pronounced, eccentric phase is causing increased rates of force development[28,29,40] and efficient subsequent concentric phases during leg push-off. In the current study, average rate of leg force development showed an over threefold increase over speeds by an progressively clearer unweighting prior to the leg kick combined with a shortened relative time to maximum leg force, while rate of pole force development only showed a ~50% increase up to V_{max}. A more pronounced delta leg force production has also been shown for diagonal stride technique at different speeds[18] demonstrating that a pronounced unweighting before push-offs may be a useful strategy to gain the needed increased impulses of force. The observed increasing knee and hip angular flexion and extension velocities as well as ROM over the whole range of speeds describes a progressively pronounced stretch-shortening cycle pattern (Table 1; Figure 5(b) and (c)).

Joint kinematics

Regarding joint kinematics during V2 skating with increasing speeds, we can state that leg joint kinematics showed clear changes throughout the submaximal speeds but almost no changes from the last submaximal speed to maximum speed (Table 1; Figure 5(a) and (b)). Although not analysed in this study, the increased ROM as well as faster flexion-extension patterns at increasing speeds suggest a larger and faster displacement of the COM while the skiers move faster using the V2 skating technique. The question if a larger and faster vertical COM displacement during cross-country skiing is a waste of energy or the prerequisite to ski fast, has been positively answered in a recent study on diagonal skiing and double poling.[23] Results showed that the variability of skiing performance (individual V_{max}) could be explained up to 50% ($r^2 = 0.50$) by larger vertical downward displacements of the COM, larger downward velocities, greater changes in potential energy and larger kinetic energy during downward movements.[23] In addition, vertical COM movement measured with accelerometers has also been shown to aid more pronounced force transfer via rather rigid arms (small joint movement) and poles. This is enabled by higher COM position and thereby greater usage of the gravity.[24] The distinct increases in leg joint AVs in the current study during flexion phases of the V2 skating technique suggest an increasing mechanical efficiency of eccentric extensor muscle contractions with increasing stretch velocities, which has already been shown in early studies on human locomotion.[41]

Arms showed rather rigid behavior throughout the speeds with only decrease in angle minima during pole push. With shorter absolute time AVs, however increased. When considering elbow angles and comparing to recent studies on speed control using the double poling technique,[16,17] changes in angular displacements were smaller in the current study, although the basic mechanics in the arm push-off seem to be the same. During double poling, the pushing phase is started with straighter arms and continued by greater flexion and extension ROM. During V2 skating, arms are in a more flexed and fixed position keeping the elbow joint stiffer during the pole plant and the whole poling phase. Thus, arms may transfer more energy from the vertical movement of the body to the ground (large knee and hip ROM) rather than actively produce force which was also a conclusion by Myklebust et al.[24] However, using double poling, arms are a more active component during poling probably because arms and poles are the only way to produce and transmit propulsive forces whereas in V2, the legs are contributing to propulsion, even if to a smaller extent.[11] Interestingly, the role of large flexion–extension ranges of motion in the leg joints and thereby large vertical displacements of the COM in order to produce higher pole forces has also been demonstrated in studies by Holmberg et al.[21,42] showing the important role of leg movements for performance and economy during double poling. Distinct relative changes in elbow flexion (440%) and extension (90%) AVs indicate again, as already discussed for leg joint and leg muscles, an increasing role of stretch-shortening cycle patterns for arm extensor muscles as well as shoulder extensors, which have not been investigated in the current study. Due to the large contribution of pole forces to propulsion during the V2 skating technique,[11] these highly relevant aspects should be further analysed in future studies.

Conclusion

Longer cycle lengths and increasing cycle rates are used to generate higher speeds in V2-technique at submaximal speeds, while at speeds closer to maximum speeds, increasing cycle rate is the dominant factor. To be able to maintain both long cycle length and high cycle rate can be challenging but, however, is characterized as highly important prerequisites to reach really high speeds. Long cycle length is associated with generation of higher forces with poles and legs which seem to be related to greater vertical oscillation of the COM. This can be seen with increasing ranges of motions in knee and hip joints. This oscillation causes greater pole forces transferred via rather stiff elbow joint and greater leg forces generated via greater unweighting prior to the kick. These findings guide athletes to emphasize force and technique training, from which improved capacities could be refined into sport-specific skills in order to generate longer cycle lengths with submaximal speeds and to use high frequencies at maximal speeds while maintaining cycle length. Analysing the propulsive component of skate skiing would give additional valuable information on this topic. This interesting variable might provide a simple tool for analysing performance as well as economy of skiing, but calculations require 3D movement analysis, which are required in the future analysis.

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II

VALIDATION OF PORTABLE 2D FORCE BINDING SYSTEMS FOR CROSS COUNTRY SKIING

by

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Abstract

The aim of the present study was to design, construct, and scientifically validate a two-dimensional force measurement binding system for cross-country skiing. The system consists of two force measurement bindings. One binding was designed for analysing classic skiing (vertical and anterior-posterior [along the ski] force components) and the other one for skate (freestyle) skiing (vertical and medio-lateral [transverse to the ski] force components). Validation was accomplished by using a three step process 1) accuracy tests for the sensors in two temperatures, 2) sport-specific imitation jump test on standard force plates in a laboratory and 3) comparing the system against force measurement reference systems that are currently used when skiing on snow. During sport-specific imitation jumps, differences in peak forces and impulses between the classic binding and the reference systems ranged from 8.0 % to 19.9 % and were two to three times greater compared to differences between the skate binding and the reference systems (range: -5.9 to 5.5 %). However, high similarity coefficients were observed with both bindings (classic binding: 0.990 to 0.996; skate binding: 0.996 to 0.999) compared to the reference systems. Based on these results, the skate binding was shown to be fully valid for use in field measurements of skate skiing, whereas some improvements have to be performed in the construction and sensor placements for the classic binding (vertical as well as anterior-posterior force component).

1 Introduction

Force measurements in cross-country skiing have been conducted for over three decades using different methods. Two main approaches can be found from the earlier studies: 1) force measurements between the ski and the athlete with small force measurement plates or pressure insoles and 2) force measurements with systems buried under the snow. There are advantages and disadvantages to both approaches. With small force measurement plates attached to the skis, the forces can be measured in two [1-5] or three directions [6-10]. However, these kinds of force measurement plates add extra weight to the skis and although positioned close to the balance point of the ski they may still have a small effect on skiing. In addition, some limitations have been reported concerning the forces in medio-lateral and/or anterior-posterior direction [3,9]. Especially for analyses during roller skiing, strain gauges have been used and installed directly on the roller skies during classic skiing and skating measuring the forces in several dimensions [11-13]. Pressure insoles have been widely used in cross-country skiing research during the last decade due to the light-weight and minimal effect on the athletes' performances [14-17]. With pressure insoles, only the vertical force component can be measured and the measuring frequency of 100 Hz may be too low for some applications. The advantage of this method is the possibility to measure the center of pressure. Both force plates and pressure insole systems may influence athletes' performances due to the weight of the measurement systems (amplifiers, data loggers etc.). Data collecting and transmitting equipment are normally placed on a skier's waist with waist packs, while the included cables may slightly restrict movements and disturb skiing. However, the benefit of these systems is the possibility to measure several consecutive skiing cycles in one trial. In addition, these methods are not technique sensitive, so both skiing techniques (skating and classic) can be measured with these systems. Force platforms placed under snow allow an athlete to ski freely over the force measurement systems without any disturbing devices or cables attached. These systems allow measurement of only a few cycles per trial due to the length of the platform (6 m to 20 m) and it is in most cases only possible to investigate classic technique due to the construction of the system [2,18-20]. For skate skiing, Leppävuori [21] introduced a force measurement platform which was 2m long that could record one cycle per trial. In addition, measuring of skiing in different situations, e.g. varying track inclinations or the need of changing the measurement place, demands a great deal of time due to the big size and weight of those systems.

Classic technique with e.g. diagonal skiing technique can be analyzed with two dimensional force measurement systems since when moving straight forward along a classic skiing track only vertical as well as anterior-posterior (propulsive; along the ski) leg force components are mainly relevant. In contrast, skating techniques are more three-dimensional movements where all possible force components are important with a main focus on the vertical as well as the medio-lateral (transverse to the ski) force components. The medio-lateral direction of force is of special interest during skate skiing because the propulsive force is produced when the ski is edged. In a recent study [10] it was shown that the medio-lateral forces were higher using skis with a greater coefficient of friction, whereas no differences were observed in the vertical forces. This suggests that measuring only vertical forces is not enough to fully understand the requirements of skate skiing in different conditions and furthermore highlights the importance of measuring medio-lateral forces. In addition, with both vertical and medio-lateral force components a resultant ski force during skating can be calculated. Resultant forces from poles and legs are required in order to have the full benefit of three dimensional motion analyses. Using these two methods, it is possible to calculate the propulsive leg force component of skate skiing in any condition as described by Smith [22], acquiring the ski edging angle and the ski orientation angle from motion analyses and resultant forces from skis and poles. An accurate, valid, reliable and direct measurement of several leg force components combined with 3D kinematics will improve cross-country skiing specific motion analyses for technique optimization processes and the analyses of new ski or boot equipment, altogether in order to optimize skiing performance.

Even though forces have been measured in cross-country skiing with several different systems, there still is a great and from literature clearly justified need for a valid, accurate and light system synchronously measuring several force components. Such a system may respond to the high-level requirements of today's elite as well as recreational skiing. Earlier attempts in this working group to develop a 3D-force measurement system were partly successful. The constructed force binding could be easily transferred from one ski to another allowing for effective testing of different skis and athletes within a short period of time [9,10]. However, even though the system proved to be reliable for vertical and medio-lateral forces, there were still limitations concerning the measurement of the anterior-posterior forces acting along the ski [9] and additionally, there was still a need to make the system lighter and easier to use. Therefore, the aims of this study were to further develop the force measurement system by designing and building two separate two dimensional (2D) force bindings, one for kinetic classic skiing and one for skate skiing analyses. The functionality of these new systems should be tested 1) using accuracy tests separately for each force component with the sensors mounted in the front or rear parts of the binding and under lab as well as ski tunnel conditions, 2) using skiing imitation jump tests on standard force plates in a laboratory and 3) by skiing with the new system and comparing it against reference systems that are currently used in research investigating skiing on snow.

2 Materials and Methods

In this project, a custom-made force measurement system for cross-country skiing was designed and built. In order to test the functionality and validity of the new system, a three-step process was conducted. In the first step, the accuracy of the strain gauge sensors, mounted on the aluminum front and rear parts of the binding were tested separately and this was done in three temperature and mechanical stress conditions. In the second step, the system was compared against a standard 3D force plate in four different sport-specific imitation jumps in a laboratory and with and without extra load carried by the skier. Finally, the system was compared against systems that are currently being used during scientific measures in classic as well as skate skiing on snow.

2.1 Force binding

A custom-made force measurement system designed as a force binding (Figure 1) for recording several spatial components of forces during cross-country skiing was developed by the Neuromuscular Research Center, University of Jyväskylä, Finland. The force measurement system consisted of two force bindings in which one binding was specifically designed for analysing classic skiing techniques (classic binding) and the other for skate skiing techniques (skate binding). Both bindings contained parts for measuring front and rear foot forces in 2 dimensional spaces. Both bindings measured vertical forces (F_Z) in front and rear parts however the classic binding additionally gauged the anterior-posterior (along the ski, F_Y) force components and the skate binding the medio-lateral (transverse to the ski, F_X) force components (Figure 2). Based on experiences from the first 3D versions of the force binding [3,9] this separation was made to keep the construction of the plates more simple, to have less cross-talk between the sensors and so to get more accurate signals. The force binding was designed to move easily from one pair of skis to another by using the Rottefella (Rottefella as, Klokkarstua Norway) NIS (Nordic Integrated System) system. The NIS system allows removing or changing the place of the force binding without using screws. The total weight of both force bindings (classic plus skate binding) was 980 g, with 200 g weight for each rear and 290 g for each front part. Therefore the total added weight for one ski was 490 g. The total weight of the data capturing and transmitting equipment was 1050 g, which was distributed in parts as follows: amplifier 280 g; A/D-card and wireless transmitter 440 g; and battery pack 330 g that allows for several hours of measuring in cold conditions. The total weight of the whole measurement system was 2030 g. The used sensors mounted in the aluminum bodies of all rear and front parts of the force binding were based on resistance strain gauge technology where the resistance of the strain gauge is changed when it is stretched or compressed. A change in resistance caused a change in voltage over the gauge and these changes were comparable to changes in the applied force. In order to have reliable results, all force components were measured with a 4 strain gauge full bridge circuit. Signals were pre-amplified inside the force binding and transferred via wires to an amplifier (8-channel ski force amplifier, Neuromuscular Research Center, University of Jyväskylä, Finland). The amplifier was connected by separate cables for each force component (altogether 8 signal cables and one ground cable) for capturing data with the desired system. The amplifier was connected to a National Instruments wireless data acquisition and transmitting system, which consists of an A/D converter (sampling rate 1 kHz, NI 9205, National Instruments, Austin Texas, USA) and a wireless transmitter (WLS-9163, National Instruments, Austin Texas, USA). Data was transferred via WiFi to a receiver computer equipped with special data collecting software (LabVIEW 8.5; National Instruments, Austin Texas, USA).

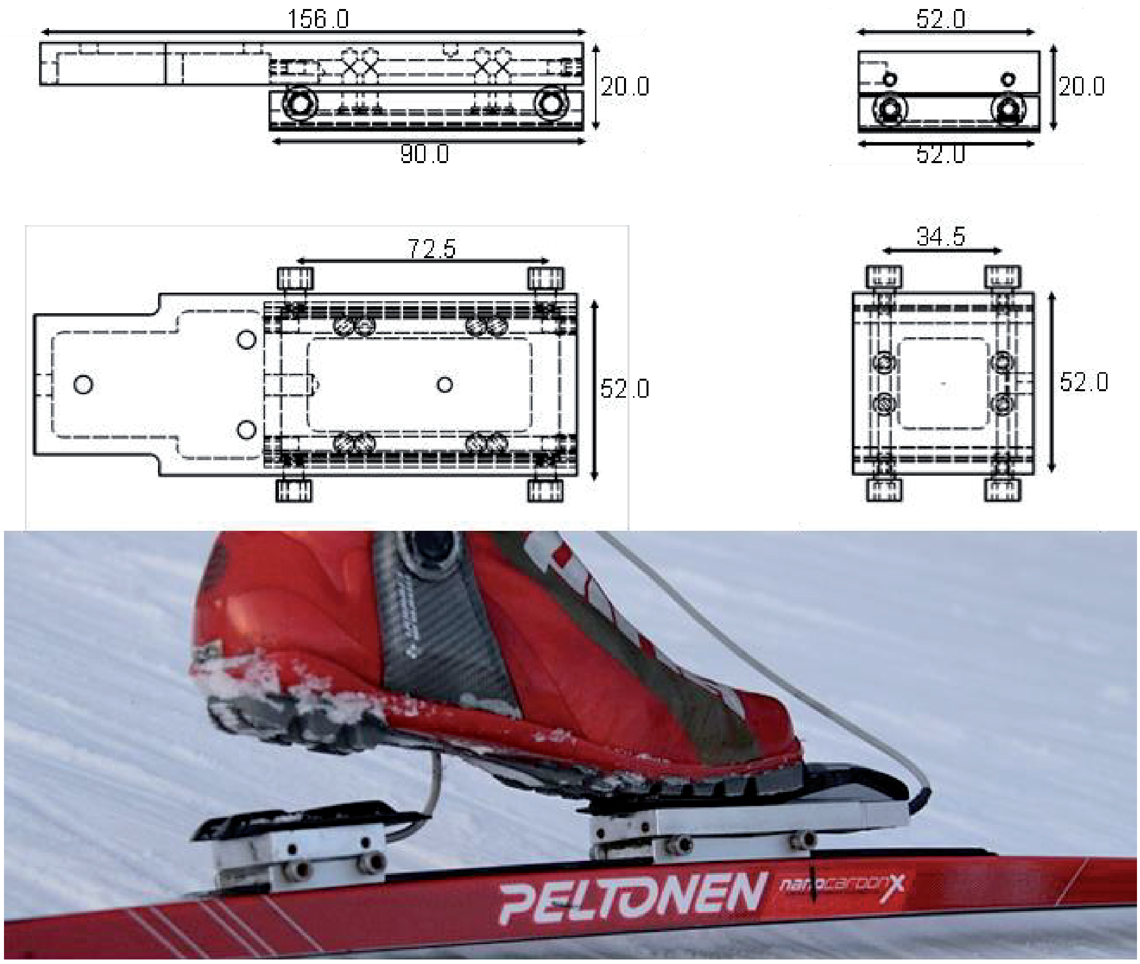


Fig. 1 Photograph and design drawing of the developed force measurement binding for cross-country skiing with dimensions of the front and rear part of the binding

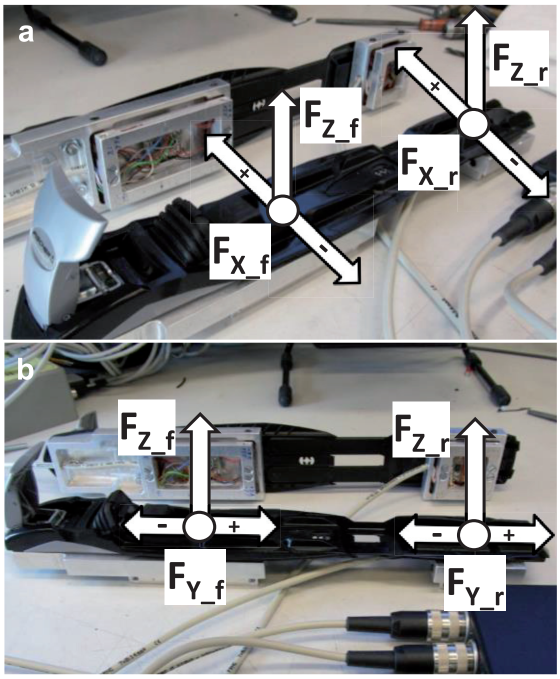


Fig. 2 (a) Vertical (F_Z) and medio-lateral (transverse to the ski) (+/- F_X) force components (skate binding) and (b) vertical (F_Z) and anterior-posterior (along the ski) (+/- F_Y) force components (classic binding) measurable separately by the front (f) and the rear (r) parts of both bindings

2.2 Calibration device

The calibration and the accuracy measurements for the rear and front parts of the force bindings were conducted with a special calibration device (Figure 3). The calibration device consisted of an amplifier, a screw vice where a commercial force sensor (Raute precision TB5, Nastola Finland) used as calibration sensor, was attached and an aluminum body where one part of the force binding was attached. The screw vice and body were attached to a thick aluminum base plate. The aluminum body could be attached to the base plate in three different positions to make the calibration of all three force components possible (Figure 3 a and c). The calibration sensor used as reference sensor and the amplifier were tested and calibrated in an accredited laboratory for force measurements (MIKES: The Centre for Metrology and Accreditation, Kajaani, Finland.). This sensor was confirmed to be reliable in the range of 0 to 1000 N with uncertainty ranging from 0.01 to 0.09 %. The calibration device was used in the accuracy tests during the first step of the validation process.

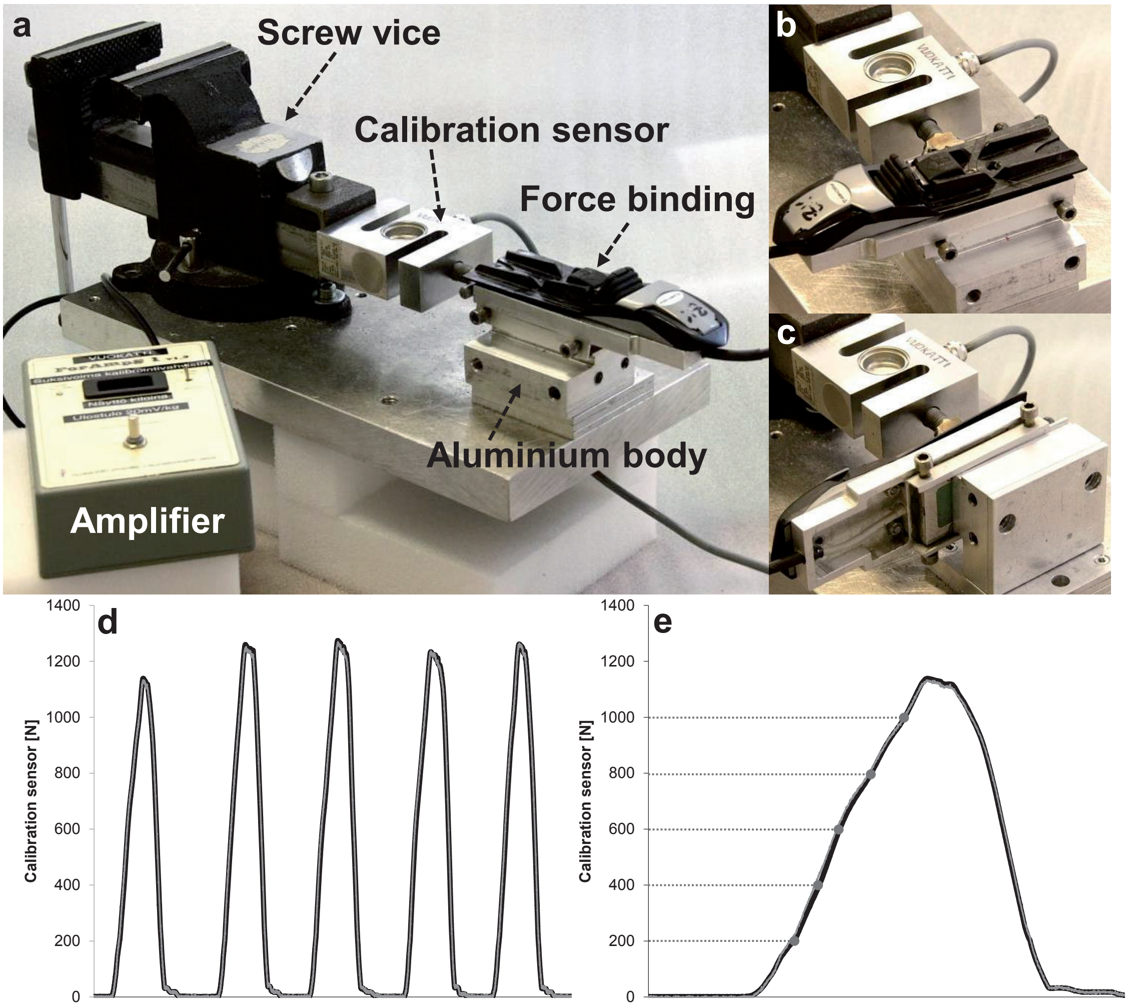


Fig. 3 Experimental set up for the calibration of the different force binding sensors: Adapted screw vice with mounted high precision reference sensor (Raute precision TB5, Nastola, Finland) and a part of the force binding with the amplifier, all mounted on a rigid aluminium body (a). The calibration sensor is pressed five times in succession (d) against the (a) anterior-posterior (F_Y), (b) medio-lateral (F_X) and (c) vertical (F_Z) force binding sensors determining voltage response at five increasing loads (e)

2.3 Reference systems in laboratory and field measurements

Sport-specific imitation jumps conducted during the second step of the validation process were performed in a laboratory over a 10 m long force plate row (8 plates of 1.25 x 0.60 m with natural frequency 180 ± 10 Hz for the vertical force component and 130 ± 10 Hz for the anterior-posterior force component, linearity ≤ 1%, cross-talk ≤ 2%; Raute Precision, Finland). The used force plate was based on strain gauge technology and has been used in numerous running studies, e.g. by Mero et al. [23].

In the third step of field measurements the following reference systems currently being utilized during scientific measures in classic as well as skate skiing on snow were brought to use: for classic skiing (diagonal style) the constructed force binding system was compared with a 20 m long force platform system (Neuromuscular Research Center, University of Jyväskylä, Finland), which consists of four parallel series of force plates for both skis and poles. The platform was composed of twenty 1 m long force plates which measure vertical (Fz) and anterior-posterior (Fy) components of force simultaneously along the platform from rows under skis and poles. These 1 meter long plates were connected to each other electrically in series row by row and voltage response was recorded with 1000 Hz. The measurement system was described in detail by Vähäsöyrinki et al. [20]. For comparing the force binding during skate skiing, a Pedar Mobile System (Novel GmbH, Munich, Germany) was used as a reference system. This system measures vertical ground reaction forces with pressure insoles, which include 99 capacitive sensors in each insole using a measurement frequency of 100 Hz. The insole data was transmitted via wires to a data logger. The calibration of the Pedar Mobile system was conducted using a special Pedar calibration device and these procedures were described in detail in several earlier cross-country skiing studies [14,15].

2.4 Accuracy measurements of the force binding sensors

The accuracy of the new force measurement system was tested by investigating the linearity and the repeatability of the force binding in calibration measurements in three different conditions against a calibration device: 1) laboratory (+22° centigrade); 2) ski tunnel (-5° centigrade); 3) 1 hour skiing in ski tunnel (-5° centigrade). In the calibration measurements, the rear and front parts were tested separately, each for both respective force components (Figure 2 a and b) in all described conditions which were a) pre and post measurements at 2-hour intervals in a laboratory as well as in a ski tunnel and b) also before and after 1 hour of skiing. The measurement equipment was placed and kept in the laboratory as well as in the ski tunnel for several hours before the measurements in order to be properly adapted to the temperature in each condition. The calibration for all components of forces was conducted by loading and unloading the appropriate binding part five times with each loading and unloading cycle lasting for approx. 2 seconds (Figure 3 d and e). To simulate the forces during natural skiing conditions all parts of the binding (all force components) were calibrated by 5 loads increasing by 200 N, 100 N and 50 N, up to 1000 N, 500 N and 250 N, respectively (Figure 3 e). Voltage response from the force binding data at appropriate points from five curves were collected and averaged. Figure 3 e shows an example of one calibration curve with appropriate points from the calibration sensor.

For linearity calculations, averaged values from the calibration sensor and the force binding were represented in the XY-coordinate system and a linear regression curve was drawn through all five points and R^2 values were calculated. Conversion factors to Newton were calculated from all five points with equation 1. A general conversion factor for each binding part was then achieved by calculating the average value of these five points.

$$\frac{F_{Calib}}{F_{Binding}} \tag{1}$$

Where F_{Calib} is the absolute (Newton) value from the calibration sensor and $F_{Binding}$ is the voltage value of the force binding.

The repeatability of the system was tested by calculating the relative difference of the conversion factor between pre and post tests for all the channels. These measurements were done to reveal the system's repeatability in two different constant temperatures. In addition, repeatability measurements were conducted to clarify the effect of mechanical stress (1 hour skiing) on the functionality of the force binding.

2.5 Comparison measurements during different jumps

In order to test the force binding in more applied situations, different modes of jumps simulating dynamic situations as well as diagonal and skate skiing were performed by one highly skilled male, National level cross-country skier: age = 44 years; height = 187 cm; body weight = 85 kg. A single subject design was chosen in order to keep the variability low between single imitation jump trials and thereby increasing the power for difference detection between all compared systems. Jumps and especially imitation jumps with skies plus force binding were and are highly demanding from a coordination point of view and had to be extensively trained properly even by the highly experienced skier. The individual-subject-analysis design was also used because the variations, especially in the used jump tasks, were considered to be the result of different strategies to perform the same imitation task by individual subjects, and not the result of more or less variations among individuals [24]. The skier was highly familiar with imitation exercises and with diagonal and skate skiing on skis during both training and testing. The athlete was fully informed about the nature of the study and procedures before giving his written informed consent to participate. The methods used and the experimental protocol of the study were approved by the University of Jyväskylä Ethics Committee. All jumps were performed on a force plate (Raute Precision, Finland). During all jumps including diagonal skiing and skating imitation jumps, the force bindings were attached to the skis and the subject used ski boots to better simulate a real skiing situation. Four kinds of jumps were done: squat jumps (SJ), counter movement jumps (CMJ), diagonal jumps (DJ) and skate jumps (SkJ). In all jump situations, absolute value signals from the front and back parts of the force binding were summed and compared to the force plate used as reference system.

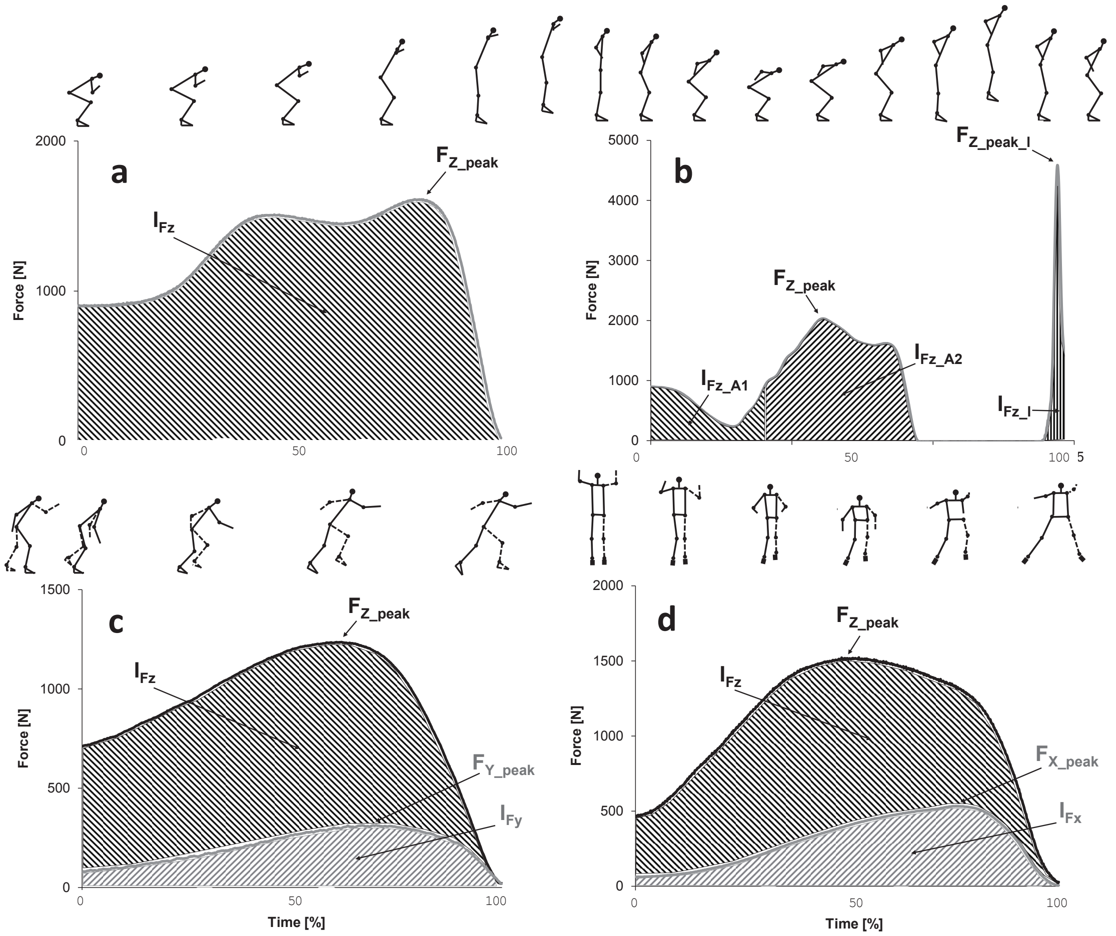


Fig. 4 Definitions of force variables during the two-legged squat (a) and countermovement (b) jumps and one-legged diagonal (c) and skating (d) imitation jumps in the lab

F_{Z_peak}, vertical peak force; I_{Fz_A1}, impulse of vertical force calculated for area 1 below the force curve (A1 = unweighting phase during CMJ); I_{Fz_A2}, impulse of vertical force calculated for area 2 below the force curve (A2 = impulse of force in deceleration + acceleration phase during CMJ); $F_{Z\_peak\_I}$, vertical peak force during landing impact; I_{Fz_I}, impulse of vertical force during landing impact; I_{Fz}, impulse of vertical force; F_{Y_peak}, anterior-posterior peak force; I_{Fy}, impulse of anterior-posterior force; F_{X_peak}, medio-lateral peak force; I_{Fx}, impulse of medio-lateral force

SJ and CMJ (Figure 4 a and b) were performed standing on and jumping from the force plate with both legs. The sum of the vertical signals from both types of force bindings were compared to the vertical signal from the force plate. From CMJs, landings were also analysed and compared to the force plate signal. DJs were performed in anterior-posterior (forward) direction on the force plate with one leg imitating the diagonal stride push-off phase (Figure 4 c). Vertical and anterior-posterior force components of the classic binding were analysed and compared to the corresponding signals of the force plate. SkJs were performed in the medio-lateral direction on the force plate (Figure 4 d) with one leg imitating the skate skiing push off phase. During SkJs the ski plus force binding were distinctly edged. In order to have comparable data from the force binding and the force plate, the following calculations were used for the vertical (equation 2) and medio-lateral (equation 3) directions (Figure 5). The calculations are based on ski edging angle analyses, which was acquired with a high-speed camera at 100 Hz (NXR-NX5E, Sony, Tokyo, Japan) and by using a specific 2D video analysis software (Dartfish, Fribourg, Switzerland).

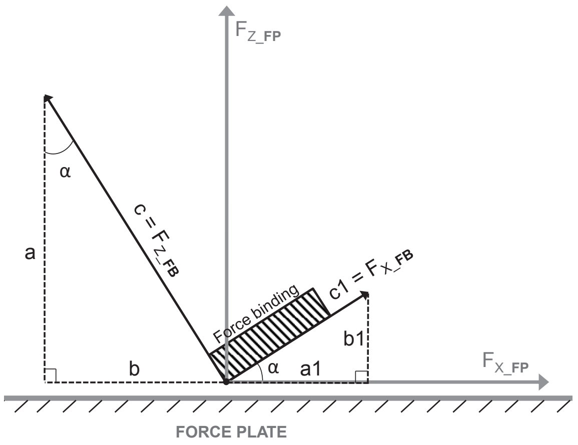


Fig. 5 Geometric scheme for the conversion of the vertical and medio-lateral binding forces (F_{Z_FB}; F_{X_FB}) during skating imitation jumps into vertical and medio-lateral force plate forces (F_{Z_FP}; F_{X_FP}) based on trigonometric functions in the right-angled triangle (equations 2 and 3)

$$F_{Z\_FP} = F_{Z\_FB} * \cos\alpha + F_{X\_FB} * \sin\alpha \tag{2}$$

$$F_{X\_FP} = F_{Z\_FB} * \sin\alpha + F_{X\_FB} * \cos\alpha \tag{3}$$

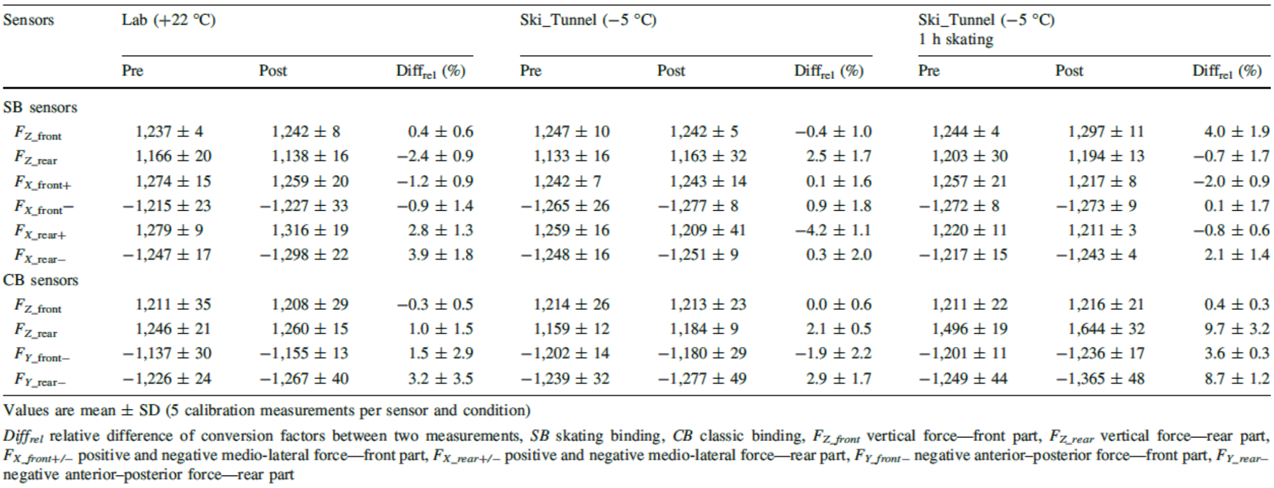
Where F_{Z_FP} and F_{X_FP} stand for the vertical and medio-lateral force components of the force plate and F_{Z_FB} and F_{X_FB} for the vertical and medio-lateral force components of the force binding. The calculations are also shown in Figure 5. From SkJs the calculated vertical and medio-lateral force components measured by the skate binding were compared to the vertical and medio-lateral signals from the force plate. If yaw rotations were observed between ski and force plate during SkJs, the particular jump was discarded from the results.

In all jump tests, each jump was carried out with 20kg extra load and without extra load to simulate heavier skier and/or stronger push offs. From each situation (SJ, CMJ, DJ and SkJ with and without extra load) 10 jumps were recorded for further analysis with both the systems (force binding and force plate). Peak forces and impulses (Figure 4 a to d) were calculated and absolute and relative differences between systems were investigated. In addition, similarity coefficients between the force binding and the force plate were calculated using Taylor polynomials [25] to show the similarity of the response between systems.

2.6 Comparison measurements during diagonal skiing and skating on snow

Finally the functionality of the force binding was tested in a skiing situation on real snow with diagonal skiing and skating techniques. In the skiing tests, the absolute signals from the front and rear part of the binding were also summed for achieving comparable signals to the used reference systems. The classic binding was tested using classic skiing diagonal stride technique on a 20 m long force platform system [20]. Vertical and anterior-posterior force components of the classic binding were compared to corresponding force signals from the long force platform. For skate skiing the V2-technique [22] was used when the skate binding was compared to the described pressure insole system. Pressure insoles measure only vertical forces and therefore only vertical forces could be compared between the systems. Due the lack of measurement systems, the medio-lateral direction could not be compared for the on snow skiing situation. With both techniques, the same skilled cross-country skier used medium speed (approx. 4 m/s for classic and 5 m/s for skating). With both skiing tests, again 10 subsequent cycles were averaged and analyzed and similarity coefficients were calculated.

Table 1 Comparison of the conversion factors (Volt to Newton) from two-time calibration measurements with a 2 hours break in between (pre vs. post) in three different conditions, i.e. in 1) the laboratory (+22°), 2) the ski tunnel (-5°) and 3) the ski tunnel (-5°) with 1 h skating (mechanical load) in between



Sensors	Lab (+22 °C)			Ski_Tunnel (−5 °C)			Ski_Tunnel (−5 °C) 1 h skating		
	Pre	Post	$Diff_{rel}$ (%)	Pre	Post	$Diff_{rel}$ (%)	Pre	Post	$Diff_{rel}$ (%)
SB sensors									
F_{Z_front}	1,237 ± 4	1,242 ± 8	0.4 ± 0.6	1,247 ± 10	1,242 ± 5	−0.4 ± 1.0	1,244 ± 4	1,297 ± 11	4.0 ± 1.9
F_{Z_rear}	1,166 ± 20	1,138 ± 16	−2.4 ± 0.9	1,133 ± 16	1,163 ± 32	2.5 ± 1.7	1,203 ± 30	1,194 ± 13	−0.7 ± 1.7
F_{X_front+}	1,274 ± 15	1,259 ± 20	−1.2 ± 0.9	1,242 ± 7	1,243 ± 14	0.1 ± 1.6	1,257 ± 21	1,217 ± 8	−2.0 ± 0.9
F_{X_front-}	−1,215 ± 23	−1,227 ± 33	−0.9 ± 1.4	−1,265 ± 26	−1,277 ± 8	0.9 ± 1.8	−1,272 ± 8	−1,273 ± 9	0.1 ± 1.7
F_{X_rear+}	1,279 ± 9	1,316 ± 19	2.8 ± 1.3	1,259 ± 16	1,209 ± 41	−4.2 ± 1.1	1,220 ± 11	1,211 ± 3	−0.8 ± 0.6
F_{X_rear-}	−1,247 ± 17	−1,298 ± 22	3.9 ± 1.8	−1,248 ± 16	−1,251 ± 9	0.3 ± 2.0	−1,217 ± 15	−1,243 ± 4	2.1 ± 1.4
CB sensors									
F_{Z_front}	1,211 ± 35	1,208 ± 29	−0.3 ± 0.5	1,214 ± 26	1,213 ± 23	0.0 ± 0.6	1,211 ± 22	1,216 ± 21	0.4 ± 0.3
F_{Z_rear}	1,246 ± 21	1,260 ± 15	1.0 ± 1.5	1,159 ± 12	1,184 ± 9	2.1 ± 0.5	1,496 ± 19	1,644 ± 32	9.7 ± 3.2
F_{Y_front-}	−1,137 ± 30	−1,155 ± 13	1.5 ± 2.9	−1,202 ± 14	−1,180 ± 29	−1.9 ± 2.2	−1,201 ± 11	−1,236 ± 17	3.6 ± 0.3
F_{Y_rear-}	−1,226 ± 24	−1,267 ± 40	3.2 ± 3.5	−1,239 ± 32	−1,277 ± 49	2.9 ± 1.7	−1,249 ± 44	−1,365 ± 48	8.7 ± 1.2

Values are mean ± SD (5 calibration measurements per sensor and condition)

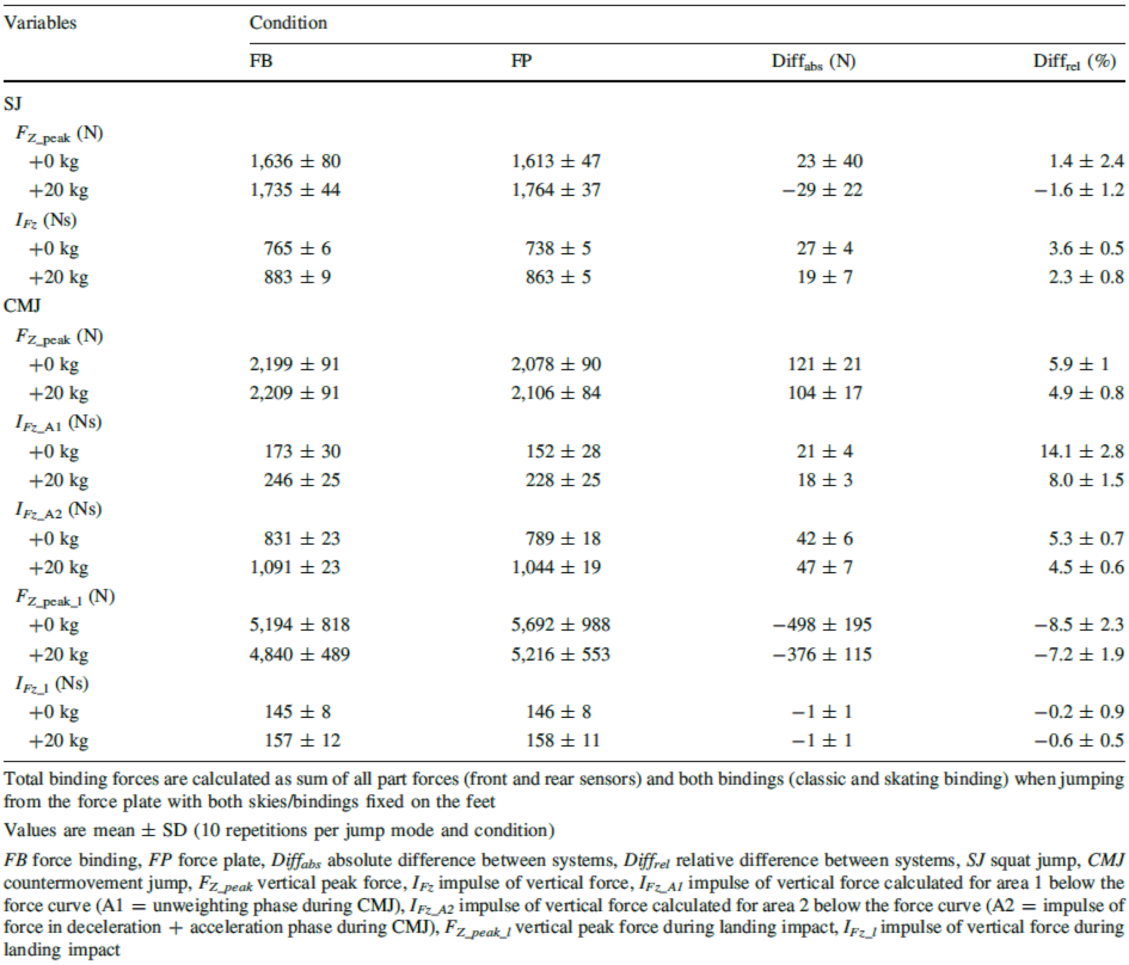
$Diff_{rel}$ relative difference of conversion factors between two measurements, *SB* skating binding, *CB* classic binding, F_{Z_front} vertical force—front part, F_{Z_rear} vertical force—rear part, $F_{X\_front+/-}$ positive and negative medio-lateral force—front part, $F_{X\_rear+/-}$ positive and negative medio-lateral force—rear part, F_{Y_front-} negative anterior–posterior force—front part, F_{Y_rear-} negative anterior–posterior force—rear part

2.7 Data proceeding and statistical analyses

All data processing was conducted using IKE-master v. 1.34-software (IKE Software Solutions, Salzburg, Austria) and descriptive statistics with mean values and standard deviations were calculated using Microsoft Office Excel 2010 (Microsoft Corporation, Redmond, Washington, USA).

Similarity coefficients were calculated using MATLAB (The MathWorks, Natick, MA, USA) from time normalized curves between the force binding and the reference systems. In contrast to standard correlation coefficient calculations for time-discrete values, similarity coefficients are used with time series and they are mathematically based on Taylor polynomials [25]. The similarity coefficients were classified as follows -1 < similarity <1, where -1 means entirely contrary time histories, 0 means no similarity, and 1 means high similarity.

Table 2 Comparison of force variables between the cross-country skiing specific force bindings and a standard force plate during squat and countermovement jumps without and with 20 kg extra weight



Variables	Condition			
	FB	FP	$\mathrm{Diff}_{\mathrm{abs}}$ (N)	$\mathrm{Diff}_{\mathrm{rel}}$ (%)
SJ				
F_{Z_peak} (N)				
+0 kg	1,636 ± 80	1,613 ± 47	23 ± 40	1.4 ± 2.4
+20 kg	1,735 ± 44	1,764 ± 37	−29 ± 22	−1.6 ± 1.2
I_{Fz} (Ns)				
+0 kg	765 ± 6	738 ± 5	27 ± 4	3.6 ± 0.5
+20 kg	883 ± 9	863 ± 5	19 ± 7	2.3 ± 0.8
CMJ				
F_{Z_peak} (N)				
+0 kg	2,199 ± 91	2,078 ± 90	121 ± 21	5.9 ± 1
+20 kg	2,209 ± 91	2,106 ± 84	104 ± 17	4.9 ± 0.8
I_{Fz_A1} (Ns)				
+0 kg	173 ± 30	152 ± 28	21 ± 4	14.1 ± 2.8
+20 kg	246 ± 25	228 ± 25	18 ± 3	8.0 ± 1.5
I_{Fz_A2} (Ns)				
+0 kg	831 ± 23	789 ± 18	42 ± 6	5.3 ± 0.7
+20 kg	1,091 ± 23	1,044 ± 19	47 ± 7	4.5 ± 0.6
$F_{Z\_peak\_l}$ (N)				
+0 kg	5,194 ± 818	5,692 ± 988	−498 ± 195	−8.5 ± 2.3
+20 kg	4,840 ± 489	5,216 ± 553	−376 ± 115	−7.2 ± 1.9
I_{Fz_l} (Ns)				
+0 kg	145 ± 8	146 ± 8	−1 ± 1	−0.2 ± 0.9
+20 kg	157 ± 12	158 ± 11	−1 ± 1	−0.6 ± 0.5

Total binding forces are calculated as sum of all part forces (front and rear sensors) and both bindings (classic and skating binding) when jumping from the force plate with both skies/bindings fixed on the feet

Values are mean ± SD (10 repetitions per jump mode and condition)

FB force binding, *FP* force plate, *Diff*Diff_{abs} absolute difference between systems, Diff_{rel} relative difference between systems, *SJ* squat jump, *CMJ* countermovement jump, F_{Z_peak} vertical peak force, I_{Fz} impulse of vertical force, I_{Fz_A1} impulse of vertical force calculated for area 1 below the force curve (A1 = unweighting phase during CMJ), I_{Fz_A2} impulse of vertical force calculated for area 2 below the force curve (A2 = impulse of force in deceleration + acceleration phase during CMJ), $F_{Z\_peak\_l}$ vertical peak force during landing impact, I_{Fz_l} impulse of vertical force during landing impact

3 Results and discussion

3.1 Accuracy of the force binding sensors

The accuracy tests showed high linearity in all situations (pre and post tests in the laboratory, ski tunnel and 1 hour skiing) with the range of R^2 values from 0.9981 to 1.0000 where the lowest values were observed after one hour of skiing in the rear part of the classic binding. The repeatability results between pre and post tests in three different conditions (laboratory, ski tunnel and 1 hour skiing) are shown in Table 1. In the laboratory tests, the highest difference in the conversion factors between pre and post tests were 3.9 % (skate binding, rear part, medio-lateral direction) with the range of all sensors varying between -2.4 % and 3.9 %. The repeatability measurements in the ski tunnel revealed equal differences compared to laboratory measurements with the largest difference of -4.2 % (skate binding: rear part, medio-lateral force component) and the range of all sensors varying between -4.2 % and 2.9 %. One hour of skiing caused greater differences in the conversion factors between pre and post tests compared to previous measurements resulting in 9.7 % as the largest value (classic binding: rear part, vertical force component) and with a range of -2.0 % to 9.7 % for all sensors. In addition, conversion factor levels were larger in this rear force channel compared to other tests (laboratory and tunnel tests without skiing) while conversion factor levels in other channels remained rather constant, although the reason for this is unclear. These results suggest that skiing had some mechanical effects on the rear part sensor of the classic binding with no negative effects found for the constructed skate binding. This was possibly due to a different construction and placing of the strain gauges, which probably led to a different level of sensitivity to mechanical loading between the bindings.

3.2 Comparison of force binding to force plate during jumps

SJ and CMJ were performed with both legs on the force plate and signals from both bindings were summed to obtain the total vertical force, which was comparable to the vertical force component of the force plate. Results of SJ and CMJ are presented in Table 2 and differences are always shown and discussed between force plate and force binding. The relative differences in maximum vertical forces were greater for CMJ (approx. 6 %) compared to SJ (-1.6 to 1.4 %). The differences in impulses of force were similar during SJ (approx. 3 %) and deceleration-acceleration phase of the CMJ (approx. 5 % for area [A] 2, Figure 4b). The greatest differences in CMJ were observed in the impulse of force during the unloading phase (8 % to14 %, area [A] 2, Figure 4b). Due to the lower absolute values during the unloading phase, the relative differences were greater for A1 compared to A2. All in all, the absolute differences stayed quite constant (Figure 6 a and d, Table 4) during both jumps with mean absolute differences for SJ of approx. 74 N and for CMJ of approx. 77 N indicating that the error was constant during jumps and the movement itself was not affecting the error.

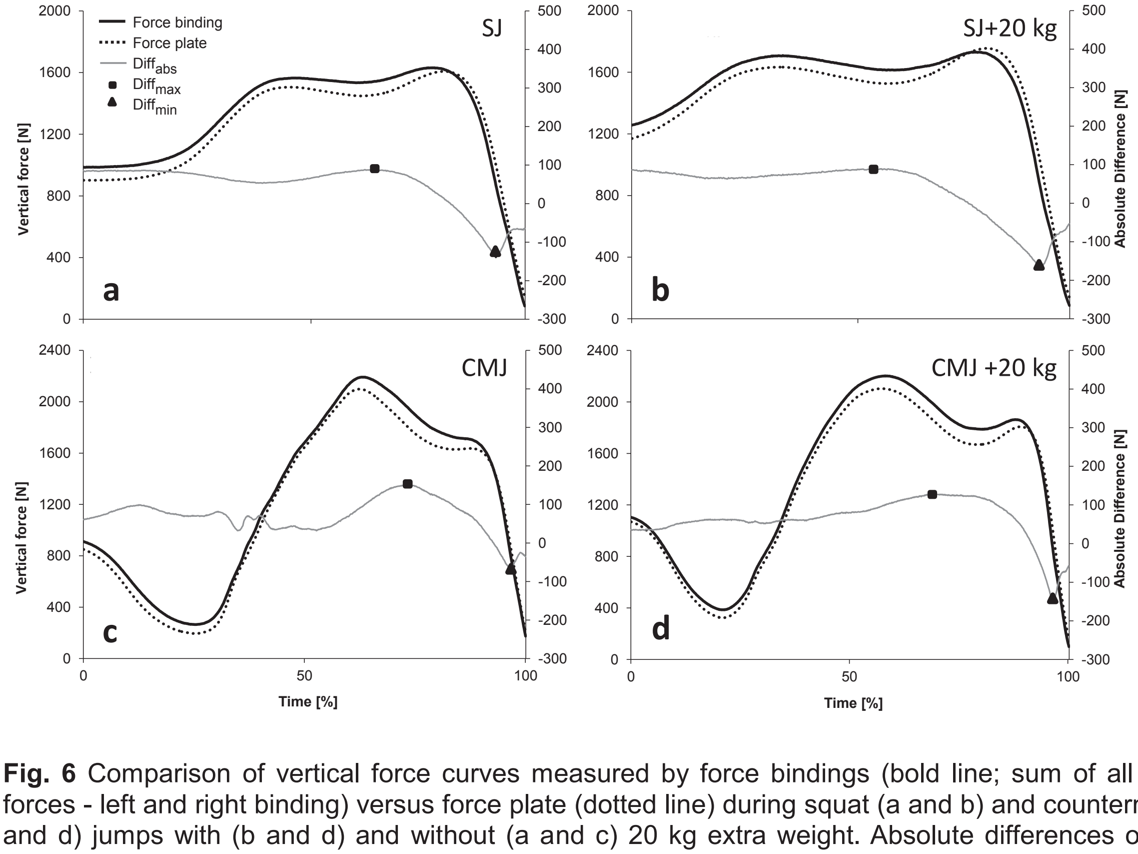
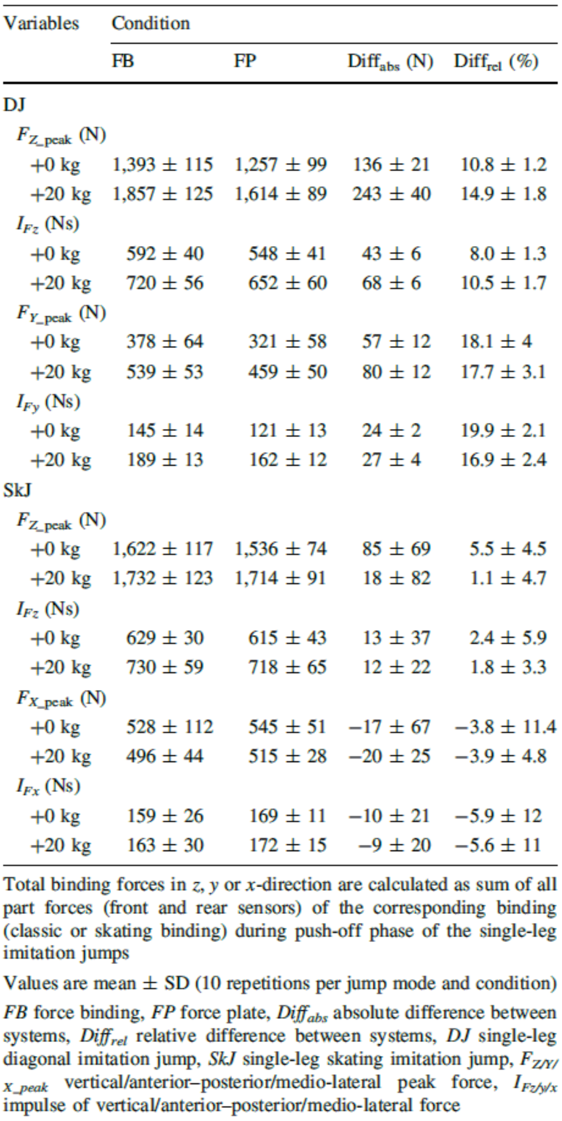


Fig. 6 Comparison of vertical force curves measured by force bindings (bold line; sum of all vertical part forces - left and right binding) versus force plate (dotted line) during squat (a and b) and countermovement (c and d) jumps with (b and d) and without (a and c) 20 kg extra weight. Absolute differences over time are demonstrated (grey line)

The landing situation during CMJ caused extremely high peak forces (over 5000 N), which were approx. fourfold compared to forces recorded during skate cross-country skiing at maximum velocity [17,26,10,21]. Nevertheless, the differences between the force plate and the force binding were approx. -8 % at the peak force and only approx. 0.5 % for the impulse of force during the landing situation. Both of these results appear to be low for such extreme loads suggesting that even higher loads do not negatively affect due to the robust construction of the binding.

DJs and SkJs were more specific imitation jumps for cross-country skiing that simulate diagonal and skating push-off phases. These jumps were performed on the force plate using only one leg with the classic or skate binding attached to a ski. Results of the DJ and SkJ are shown in Table 3. The greatest differences during skiing imitation jumps were recorded during diagonal jumps (Figure 7). Differences in peak forces were approx. 10 % to 15 % for the vertical and approx. 18 % for the anterior-posterior force components. For the vertical components forces were slightly overvalued around the highest forces (Figure 7 a and b) and for the anterior-posterior force component during the whole jump (Figure 7 c and d). This indicated that a more natural movement, where the center of pressure is moving along the force binding (simulating the diagonal stride push-off) is causing an error in the vertical direction during push-off discussed in detail when comparing the errors of both bindings. This effect is smaller in the direction along the ski/binding, however there was a constant absolute error during the push-off phase probably due to a cross-talk effect. These differences also caused higher impulses of force with the force binding in vertical (approx. 10 %) and anterior-posterior (approx. 20 %) force components.

Table 3 Comparison of force variables between the cross-country skiing specific force bindings and a standard force plate during imitation jumps for diagonal skiing and skating technique without and with 20 kg extra weight



Variables	Condition			
	FB	FP	Diff_{abs} (N)	Diff_{rel} (%)
DJ				
F_{Z_peak} (N)				
+0 kg	1,393 ± 115	1,257 ± 99	136 ± 21	10.8 ± 1.2
+20 kg	1,857 ± 125	1,614 ± 89	243 ± 40	14.9 ± 1.8
I_{Fz} (Ns)				
+0 kg	592 ± 40	548 ± 41	43 ± 6	8.0 ± 1.3
+20 kg	720 ± 56	652 ± 60	68 ± 6	10.5 ± 1.7
F_{Y_peak} (N)				
+0 kg	378 ± 64	321 ± 58	57 ± 12	18.1 ± 4
+20 kg	539 ± 53	459 ± 50	80 ± 12	17.7 ± 3.1
I_{Fy} (Ns)				
+0 kg	145 ± 14	121 ± 13	24 ± 2	19.9 ± 2.1
+20 kg	189 ± 13	162 ± 12	27 ± 4	16.9 ± 2.4
SkJ				
F_{Z_peak} (N)				
+0 kg	1,622 ± 117	1,536 ± 74	85 ± 69	5.5 ± 4.5
+20 kg	1,732 ± 123	1,714 ± 91	18 ± 82	1.1 ± 4.7
I_{Fz} (Ns)				
+0 kg	629 ± 30	615 ± 43	13 ± 37	2.4 ± 5.9
+20 kg	730 ± 59	718 ± 65	12 ± 22	1.8 ± 3.3
F_{X_peak} (N)				
+0 kg	528 ± 112	545 ± 51	−17 ± 67	−3.8 ± 11.4
+20 kg	496 ± 44	515 ± 28	−20 ± 25	−3.9 ± 4.8
I_{Fx} (Ns)				
+0 kg	159 ± 26	169 ± 11	−10 ± 21	−5.9 ± 12
+20 kg	163 ± 30	172 ± 15	−9 ± 20	−5.6 ± 11

Total binding forces in *z*, *y* or *x*-direction are calculated as sum of all part forces (front and rear sensors) of the corresponding binding (classic or skating binding) during push-off phase of the single-leg imitation jumps

Values are mean ± SD (10 repetitions per jump mode and condition)

FB force binding, *FP* force plate, Diff_{abs} absolute difference between systems, Diff_{rel} relative difference between systems, *DJ* single-leg diagonal imitation jump, *SkJ* single-leg skating imitation jump, $F_{Z/Y/X\_peak}$ vertical/anterior–posterior/medio-lateral peak force, $I_{Fz/y/x}$ impulse of vertical/anterior–posterior/medio-lateral force

Differences in SkJ using the skate binding were less than half compared to DJ using the classic binding. Regarding peak vertical forces, differences between force plate and the skate binding were 5.5 % or less and peak medio-lateral forces -3.9 % or less. In addition, the differences between the force measurement systems varied within the jump (Figure 8 a to d), which also resulted in small differences in impulses of force (vertical: approx. 2 %; medio-lateral: approx. -6 %). The results from the skate binding can be considered as promising and acceptable for highly dynamic situations, especially since these values were calculated using angular data from a high-speed camera to transform the forces into the same coordinate system as the force plate.

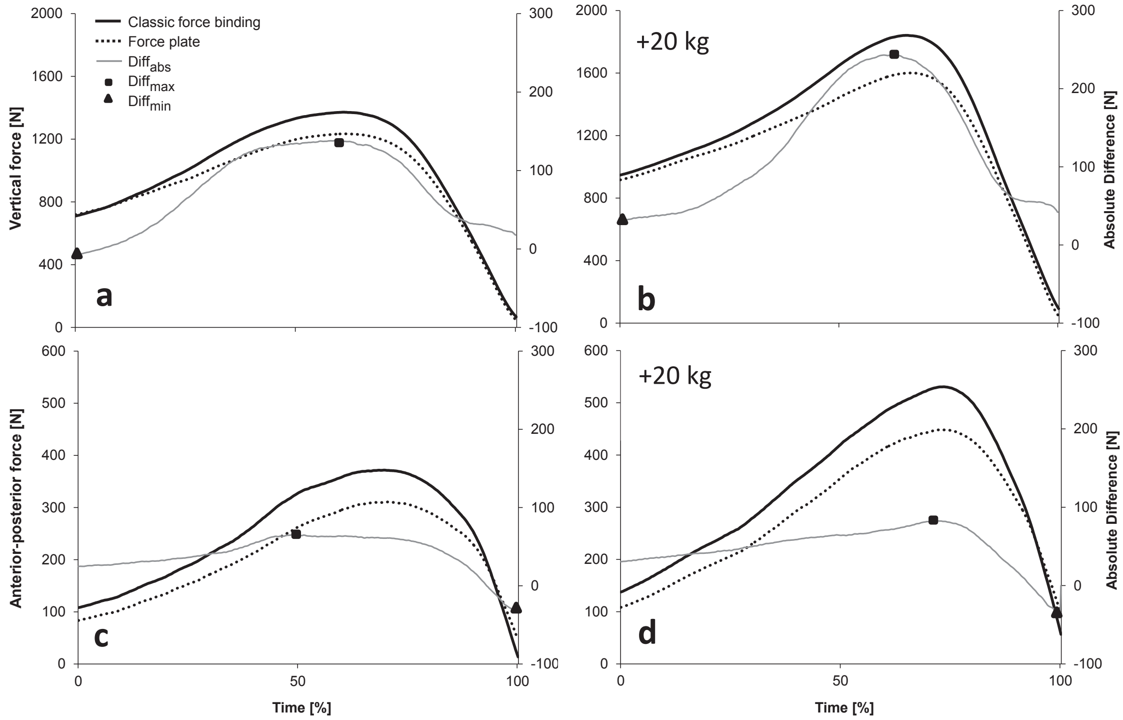


Fig. 7 Comparison of vertical (a and b) and anterior-posterior (c and d) force curves measured using the classic binding (bold line; sum of corresponding front and rear part forces) versus the force plate (dotted line) during diagonal imitation jumps with (b and d) and without (a and c) 20 kg extra weight. Absolute differences over time are demonstrated (grey line)

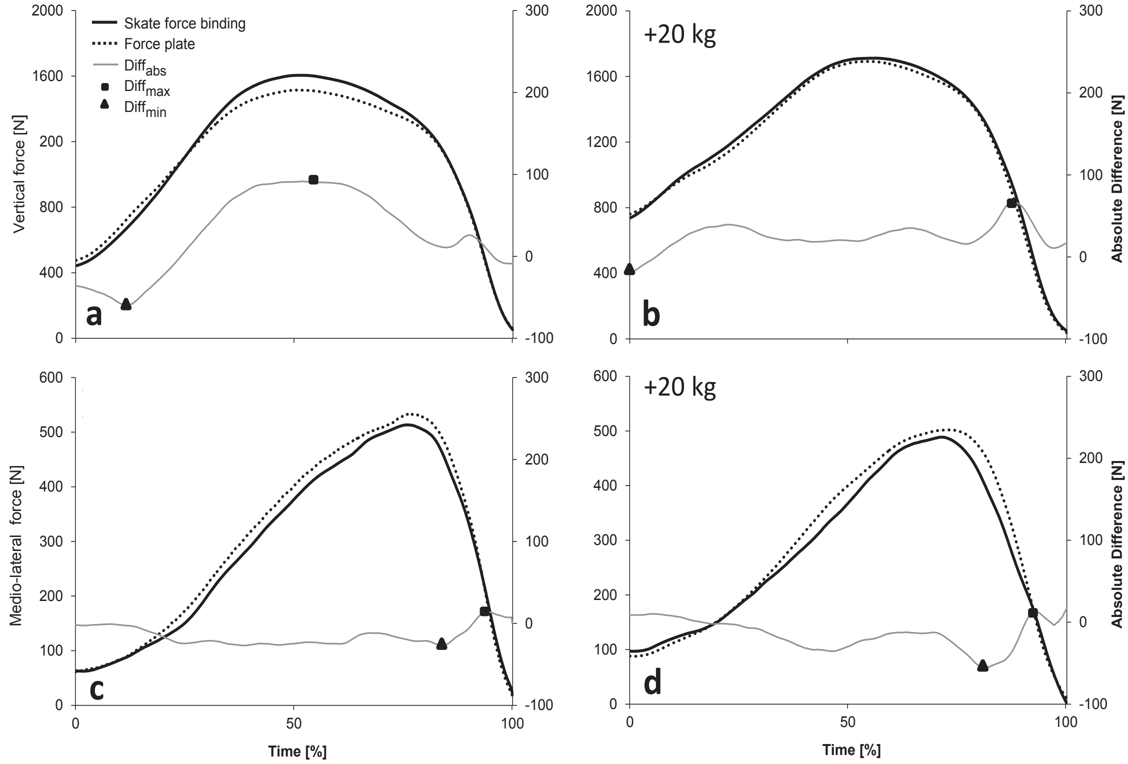
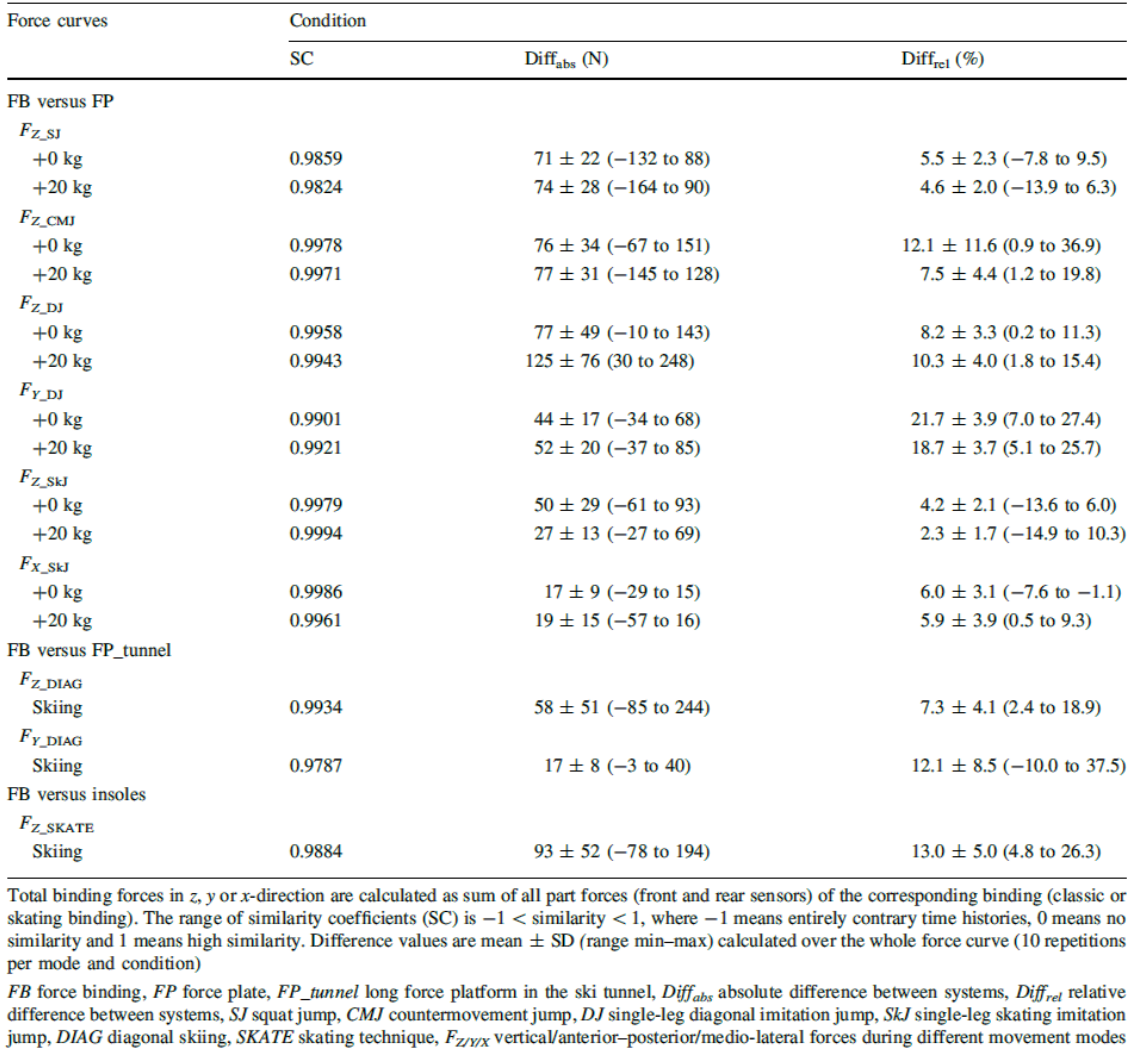


Fig. 8 Comparison of vertical (a and b) and medio-lateral (c and d) force curves measured by the skate binding (bold line; sum of corresponding front and rear part forces) versus force plate (dotted line) during skating imitation jumps with (b and d) and without (a and c) 20 kg extra weight. Absolute differences over time are demonstrated (grey line)

The smaller differences observed in the skate binding compared to the classic binding may have occurred due to the different constructions and designs of the two bindings as well as the mechanically different movements and mechanical stresses acting on the bindings during these specific jumps. During DJ push-off the center of pressure is moving forward along the force binding and the maximum force is produced when the subject’s heel is lifted from the rear plate of the force binding. This might create a moment acting on the front part of the classic binding, which possibly causes a greater error. During SkJ the push-off force is almost perpendicular to the skate binding and the acting angle of force in relation to the force binding is not changing as much as during DJ, which might cause less moments.

Mean absolute differences between the force plate and the force binding for vertical force components (Table 4) were lower for SkJ (approx. 27 N to 50 N) and higher for DJ (77 N to 125 N) when compared to SJ (71 N to 74 N) and CMJ (76 N to 77 N). These results support the suggestion that the vertical force sensors of the classic binding measured forces too high. This can be seen in the higher differences compared to the force plate during DJ, which were performed only with the classic binding. Mean differences were smaller during SJ and CMJ compared to DJ, which is probably caused by the use of both bindings and the summing of the force signals during SJ and CMJ, which presumably reduced the error of these jumps. The smallest mean differences were observed during SkJ, which were performed only using the skate binding. These results highlight the different behavior of these two bindings during sport-specific movements.

Table 4 Similarity coefficients and differences between time normalized force curves recorded by different measurement systems during various jump and imitation exercises (with and without 20 kg extra weight) in laboratory conditions and during diagonal and skating skiing on snow



Force curves	Condition		
	SC	$\mathrm{Diff}_{\mathrm{abs}}$ (N)	$\mathrm{Diff}_{\mathrm{rel}}$ (%)
FB versus FP			
F_{Z_SJ}			
+0 kg	0.9859	71 ± 22 (−132 to 88)	5.5 ± 2.3 (−7.8 to 9.5)
+20 kg	0.9824	74 ± 28 (−164 to 90)	4.6 ± 2.0 (−13.9 to 6.3)
F_{Z_CMJ}			
+0 kg	0.9978	76 ± 34 (−67 to 151)	12.1 ± 11.6 (0.9 to 36.9)
+20 kg	0.9971	77 ± 31 (−145 to 128)	7.5 ± 4.4 (1.2 to 19.8)
F_{Z_DJ}			
+0 kg	0.9958	77 ± 49 (−10 to 143)	8.2 ± 3.3 (0.2 to 11.3)
+20 kg	0.9943	125 ± 76 (30 to 248)	10.3 ± 4.0 (1.8 to 15.4)
F_{Y_DJ}			
+0 kg	0.9901	44 ± 17 (−34 to 68)	21.7 ± 3.9 (7.0 to 27.4)
+20 kg	0.9921	52 ± 20 (−37 to 85)	18.7 ± 3.7 (5.1 to 25.7)
F_{Z_SkJ}			
+0 kg	0.9979	50 ± 29 (−61 to 93)	4.2 ± 2.1 (−13.6 to 6.0)
+20 kg	0.9994	27 ± 13 (−27 to 69)	2.3 ± 1.7 (−14.9 to 10.3)
F_{X_SkJ}			
+0 kg	0.9986	17 ± 9 (−29 to 15)	6.0 ± 3.1 (−7.6 to −1.1)
+20 kg	0.9961	19 ± 15 (−57 to 16)	5.9 ± 3.9 (0.5 to 9.3)
FB versus FP_tunnel			
F_{Z_DIAG}			
Skiing	0.9934	58 ± 51 (−85 to 244)	7.3 ± 4.1 (2.4 to 18.9)
F_{Y_DIAG}			
Skiing	0.9787	17 ± 8 (−3 to 40)	12.1 ± 8.5 (−10.0 to 37.5)
FB versus insoles			
F_{Z_SKATE}			
Skiing	0.9884	93 ± 52 (−78 to 194)	13.0 ± 5.0 (4.8 to 26.3)

Total binding forces in *z*, *y* or *x*-direction are calculated as sum of all part forces (front and rear sensors) of the corresponding binding (classic or skating binding). The range of similarity coefficients (SC) is $-1 <$ similarity < 1, where −1 means entirely contrary time histories, 0 means no similarity and 1 means high similarity. Difference values are mean ± SD (range min–max) calculated over the whole force curve (10 repetitions per mode and condition)

FB force binding, *FP* force plate, *FP_tunnel* long force platform in the ski tunnel, Diff_{abs} absolute difference between systems, Diff_{rel} relative difference between systems, *SJ* squat jump, *CMJ* countermovement jump, *DJ* single-leg diagonal imitation jump, *SkJ* single-leg skating imitation jump, *DIAG* diagonal skiing, *SKATE* skating technique, $F_{Z/Y/X}$ vertical/anterior–posterior/medio-lateral forces during different movement modes

Generally observing, all laboratory imitation jumps (SJ, CMJ, DJ and SkJ) showed high similarity coefficients (Table 4) in all situations with the lowest value of 0.982 from SJ with 20 kg extra load to the highest value of 0.999 from the vertical force component of SkJ with 20 kg extra load. This suggests a nice force curve reproduction in terms of specificity of different sport specific tasks, a fact that may get essential when comparing inter-individual technique strategies during push-off and gliding phases in cross-country skiing techniques.

3.3 Comparison measurements during diagonal skiing and skating on snow

The mean differences between the long force platform and classic binding (Figure 9 a and b) during diagonal stride over a total ground contact phase were 58 N and approx. 7 % for the vertical force component and 17 N and approx. 12 % for the anterior-posterior force component. These results are quite well in line with differences in DJ (77 N and 7.5 % for the vertical and 44 N and 21.7 % for the anterior-posterior component). The results of the skiing comparisons are presented in Table 4. There may be several reasons which might cause uncertainty in these results, for example a slight ski edging during diagonal skiing over the force platform, which could not be controlled but may have caused shifts between the coordinate systems of the force binding and the long force platform. Therefore, these results can be considered as only indicative.

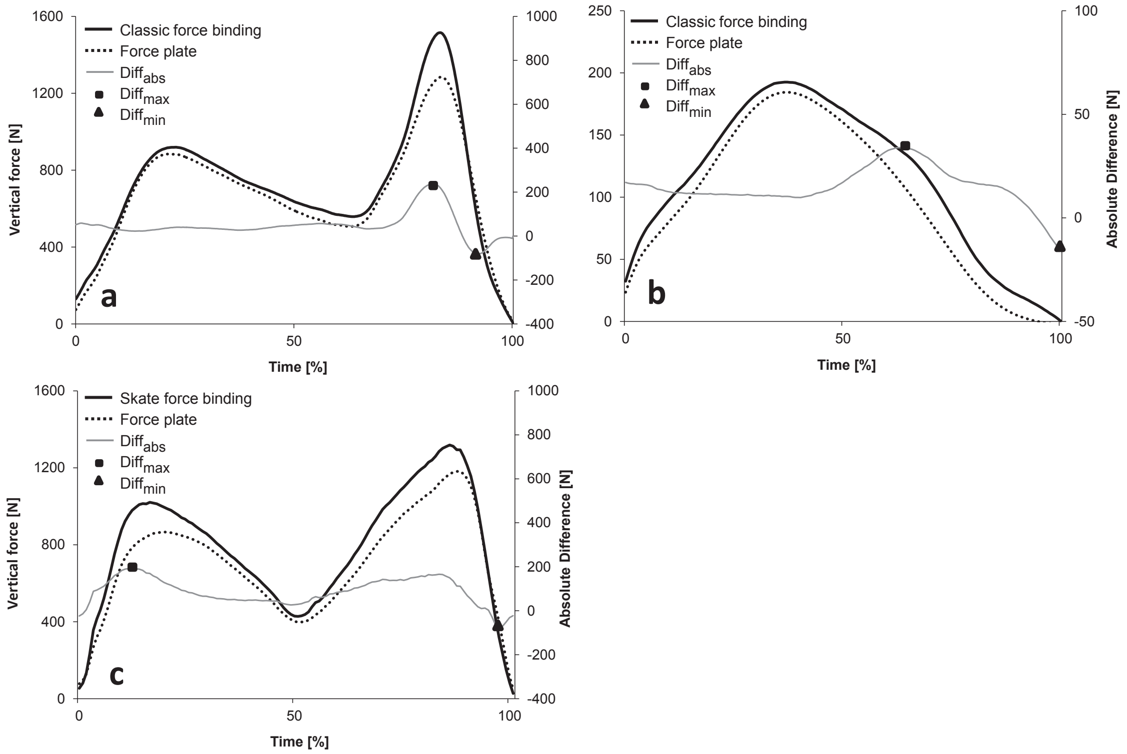


Fig. 9 Comparison of vertical (a) and longitudinal (b) force curves measured by the classic force binding (bold line; sum of corresponding front and rear part forces) versus the long force platform mounted in snow (dotted line) during classic skiing in the ski tunnel, and comparison of vertical (c) force curves measured by skate binding versus Pedar pressure insoles during skating on snow. Absolute differences over time are demonstrated (grey line)

During skate skiing, the mean difference between Pedar insoles and the skate binding over ground contact was 93 N and 13.0 % for the vertical force component. Lindinger 2005 [15] and other studies [14,27] reported lower values measured by the Pedar system compared to other standard force plates with values of -1,5 % to -6 % at peak values during skating push-offs and up to -14% in other phases of the ground contact. Interestingly and in contrast to the study of Lindinger 2005 [15], results of the current study showed that the highest differences between systems were recorded during maximum force (Figure 9 c) which may also indicate that the skate binding may measure slightly too high values due to unknown mechanical reasons. In studies of other winter sports, e.g. alpine skiing [28,29], Pedar insoles have also been reported to show lower values compared to other systems.

Despite these limitations we again observed high similarity coefficients when comparing with both reference systems during skiing on snow (classic: vertical 0.993, anterior-posterior 0.979; skating: vertical 0.988) which supports the assumption that the force bindings are valid and reliable also in field conditions. Similarity coefficients have been also used elsewhere when comparing force measurement systems. For example Stricker et al. [28] reported similarity coefficients ranging from 0.974 to 0.977 between custom made 3D dynamometer and Pedar pressure insoles during alpine skiing.

Overall, when examining the mean differences (Table 4) in all situations, the greatest differences between the force binding and any used reference system were observed in the classic binding during DJ situations (approx. 20 %). Much lower differences were found from skiing (skate: vertical 13 %; diagonal: anterior-posterior 12.1 %) as well as in CMJ (12.1 %; with 20 kg extra load) and SJ (10.3 %; with 20 kg extra load). All other differences were less than 10 %. Mean differences during SkJ using the skate binding were 6 % or less for both measured force components and load situations.

4 Conclusion

In summary, it can be concluded that through all steps of the validation process there was a difference in the functionality between classic and skate binding constructions. Sensor tests in our laboratory showed high linearity for both bindings, while repeatability tests indicated small differences between pre and post-tests in both laboratory and ski tunnel measurements. Mechanical stress caused by one hour of skiing showed some effects on the classic binding sensors. Greater differences were observed for the classic binding compared to the skate binding in comparison to the force plate when performing different modes of jumps with less accuracy observed during DJ at higher forces. The comparison of the force binding to a reference system during on snow skiing showed high similarity correlations for both classic and skate bindings, indicating a high validation level in terms of specific reconstruction of the task specific ground reaction forces in several relevant force components. The lower accuracy of the classic binding compared to the skating binding are most likely due to different mechanical properties caused by the construction and making the binding more sensitive for measurement errors especially during diagonal imitation type jumps. Further improvements are therefore needed for the classic binding. The most crucial point will be to prolong the front part of the classic binding. This would enable the pressure of the body to be distributed over a longer portion of the binding during the push-off phase and therefore causing a lower moment. In addition, the placements of the strain gauges need to be re-considered. These points are taken into account in the planning of the next version of the classic binding. The skate binding, on the other hand, was shown to be reliable during all measurements from sensor tests to more applied jumping tests and skiing on snow. Based on these results, the skate binding was shown to be valid and reliable for use in cross-country skiing skate technique measurements with differences of 6 % or less in all tested situations.

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Conflict of interest

The authors have no financial relationship with the organization that sponsored the research. The authors declare that they have no conflict of interest.

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III

CHANGES IN BIOMECHANICS OF SKIING AT MAXIMAL VELOCITY CAUSED BY SIMULATED 20-KM SKIING RACE USING V2 SKATING TECHNIQUE

by

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ORIGINAL ARTICLE

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Changes in biomechanics of skiing at maximal velocity caused by simulated 20-km skiing race using V2 skating technique

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This study investigated how the fatigue caused by a 20-km simulated skating cross-country skiing race on snow affects the final spurt performance from a biomechanical perspective. Subjects performed a 100-m maximal skiing trial before and at the end of the simulated race. Cycle characteristics, ground reaction forces from skis and poles, and muscle activity from eight muscles were recorded during each trial. Results showed that subjects were in a fatigued state after the simulated race manifested by 11.6% lower skiing speed ($P<.01$). The lower skiing speed was related to an 8.0% decrease in cycle rate ($P<.01$), whereas cycle length was slightly decreased (tendency). In temporal patterns, relative kick time was increased (10.9%, $P<.01$) while relative poling time was slightly decreased (tendency). Vertical ski force production decreased by 8.3% while pole force production decreased by 26.0% (both, $P<.01$). Muscle activation was generally decreased in upper (39.2%) and lower body (30.7%) (both, $P<.01$). Together these findings show different responses to fatigue in the upper and lower body. In ski forces, fatigue was observed via longer force production times while force production levels decreased only slightly. Pole forces showed equal force production times in the fatigued state while force production level decreased threefold compared to the ski forces.

KEYWORDS
fatigue, force measurements, XC-skiing

1 | INTRODUCTION

During the last 10-15 years, there have been changes to the FIS (International Ski Federation) World Cup as well as World Championships and Olympic Games race calendars emphasizing the importance of skiers' abilities to produce high power. Nowadays, there is only one race with an interval start in the World Championship and Olympic Games race calendar: 10 and 15 km for ladies and men, respectively.[1] During the 2015-2016 World Cup season, there were only 8 interval start races of 37 races.[2] Other races include sprints (1.2-1.8 km), handicap and mass starts, and different relays where the ability to ski fast several times (man-to-man fights for positions during the race and in the final spurt) during a race is essential for good results. Even these race forms are different and the fatigue accumulated by repeated sprint and distance events might differ nowadays an extremely good capacity to produce high speeds even in fatigued state is required from the athletes. With this in mind, researchers have recently focused a lot on sprint skiing and have also guided athletes and coaches to concentrate more on the ability to ski fast and to perform strength training, especially for improving upper body capacity.[3]

Fatigue and the effects of it have been studied quite extensively in XC-skiing. In sprint and distance skiing, fatigue has been observed via increased end spurt times in final heats,[4-6] decreased cycle rate,[5,7,8] and increased poling time[4,7] at the end part of the race. In terms of muscle activity (EMG) during sprint skiing, fatigue is showed with lower values in frequency analysis[9] between the first and last heat and with lower iEMG values from arms and legs during the end spurt of a simulated sprint race compared to a pre-speed test.[5] Force measurements during sprint and distance skiing simulations are rare, however, Mikkola et al.[4] reported lower peak vertical and partly horizontal (only last heat) pole force at the end of the sprint heats compared to the start of the sprint heats and Halonen et al.[7] reported a general decrease in force variables. In distance skiing race analyses, cycle length has reported to decrease at the late part of the race while cycle rate remains unaltered[10-12] when using the skating technique.

However, cycle rate and length do not appear to change between the heats in a sprint competition.[5,6,8] When comparing trials with maximal effort before and after a sprint race simulation, decreasing speed is caused by decreasing cycle rate while cycle length remains unaltered.[4,5] Studies of the effects of fatigue in final spurt on distance race simulations were not found. In addition to FIS World Cup race distances, fatigue in Marathon skiing (40-90 km) has been reported as decreased MVC and/or EMG amplitude values immediately after the race compared to pre-race values.[13-15] An additional reason also for decreased performance with fatigue is compromised coordination, which is observed as unstable movements in the arms and legs that lead to a decrease in speed.[16]

How fatigue is manifested and how it affects XC-skiing is quite well established in sprint skiing in terms of cycle characteristics and muscle activation in addition to possible changes in force production. How fatigue caused by a skating distance race affects athletes' performance, and how it is recognized in cycle characteristics, muscle activity, and especially force production remains unanswered and a comprehensive approach with force and EMG measurements is needed. The aim of our study was to find out how the fatigue caused by a 20-km skating race simulation completed by XC-skiing on snow affects the final spurt performance from a kinematic (cycle characteristics), kinetic (ground reaction forces), and muscle activity point of view. Our hypothesis was that maximal performance after the simulated race would be compromised by fatigue resulting from decreased muscle activity (EMG) and force production from lower and upper body leading to decreased cycle time and thus to decreased maximal skiing speed.

2 | MATERIALS AND METHODS

2.1 | Subjects

Nine Finnish National level male skiers (28.4±6.3 years 74.5±5.7 kg, 176.6±4.5 cm, FIS points 136±42) participated in the study. All of them were informed beforehand about the measurement protocols, and they all gave their written consent to participate in the study. All procedures used during the study were preapproved by the ethics committee of the University of Jyväskylä.

2.2 | Overall design

Subjects performed a 20-km-long XC-ski skating race simulation in the Vuokatti ski tunnel where ambient conditions were constant (temperature: −5°C, air humidity: 85%) offering equal conditions over the whole measurement period of 5 days. The simulated race was performed as an individual race so that only one subject was racing at the time, skiers were instructed and encouraged to do their best as they would do in real competition. A standard warm up of 15 minutes was performed with moderate training speed (approx. 70% of max. HR). The race consisted of ten 2-km laps and a total climb (TC) of 45 m per lap totaling 450 m of TC over the whole race. The total climb was approx. two-thirds in the current study when compared to world cup tracks TC:s (Ruka 4×5 km, 698 m; Lillehammer 8×2.5 km, 760 m; Toblach 4×5 km, 668 m).[17] To find out how a race affects athletes, XC-skiing performance trials with maximal skiing speed were performed before the race (Pre) and during the final spurt at the end of the race (Post). Pre and Post tests were performed using the V2 technique (also called as gear 3, G3), where one poling action with both arms is performed for every leg kick on a 100-m-long uphill with a gradient of 4°. Both test were performed twice, and the better trial in both situations, characterized by higher speed, was selected for further analyzes.

2.3 | Measurement devices

All subjects skied with the same pair of skating skis (Peltonen Supra; Peltonen Ski Oy, Heinola, Finland) prepared with the same wax (Violet Rex Olympic; Oy Redox Ab, Hartola, Finland) and waxing procedures to standardize gliding properties. To measure the ski and pole forces, the skis were equipped with force sensors between the ski and binding (Force binding, Neuromuscular Research Center, University of Jyväskylä) and the poles were equipped with force sensors placed inside the pole handgrip (VELOMAT Messelektronik GmbH, Kamenz, Germany). Force bindings measured forces from vertical and transversal directions. Validity and calibration procedures for the force bindings used in this study are reported in detail by Ohtonen et al.[18] The pole force sensor measured axial forces and the calibration of the sensor was conducted by loading the pole equipped with the sensor against a force plate (Neuromuscular Research Center, University of Jyväskylä) with forces approx. equal to forces as measured during V2 skating (approx. 250 N). The pole with the sensor was pressed five times against a force plate in the vertical direction, and the values from the force plate and pole force sensor were recorded to calculate the appropriate conversion factor from analog voltage response of the pole force sensor to Newtons. All subjects used similar carbon race poles (KV+, Dongio, Switzerland) adjusted to their own normal pole length. Surface EMG was recorded simultaneously with the forces using an EMG suit (Myontec Ltd., Kuopio, Finland). EMG was measured from the following muscles and muscle groups: calf, quadriceps femoris, hamstrings, gluteus, triceps brachii, latissimus dorsi, pectoralis major, and rectus abdominals. The EMG suit has been shown to be a valid measurement device compared to traditional surface electrodes.[20] All forces and EMG were measured during skiing with the same data acquisition board (sampling rate 1 kHz, NI 9205; National Instruments, Austin, TX, USA) and was thereby synchronized. The data acquisition board was attached to a wireless transmitter (WLS-9163; National Instruments) and carried by the subject using a waist bag. Data were transferred wirelessly to a PC computer equipped with custom-made data collecting software (LabVIEW 2010; National Instruments). Extra weight caused by the measurement and data collecting equipment totaled 2230 g that was distributed as follows: force bindings (total left and right) 980 g, pole force sensors (total left and right) 200 g, data collecting and transmitting equipment 1050 g. All trials were also recorded with laser radar (Jenoptik LDM 300 C SPORT, Jena, Germany) to measure the skiers' speed through the measurement station.

2.4 | Measured and calculated variables

An example of raw force data curves with selected cycle and force variable definitions is presented in Figure 1. Analyzed variables in this study include the following: skiing speed through the measurement station, cycle time and poling cycle time (defined from right ski/pole contact to subsequent right ski/pole contact) and cycle rate (Hz, defined as cycle time^{-1}) and cycle length (m, defined as product of speed and cycle time). To resolve if there were changes in temporal patterns of the cycle, the cycle time was divided into ground contact time (right ski on snow contact) and leg recovery time (right ski not on snow). Moreover, ground contact time was divided into glide time (from right ski snow contact to force minima prior to the kick) and kick time (force minima during ground contact until the end of ground contact). Unloading phase (from force maximum to minimum during glide) during ground contact is part of the glide time (Figure 1). Poling cycle time was analyzed for temporal patterns by dividing the whole poling cycle time to poling time (time of actual poling action) and poling recovery time (rest of the poling cycle). All temporal patterns of the cycle are presented as percentage of cycle time (%CT). In addition, some variables (ground contact time, kick time, leg recovery time, and poling recovery time) are also presented as absolute values. Peak, delta, impulse, and average ground reaction force for vertical and transversal directions as well as for axial pole force were calculated (Figure 1). Peak force was defined as highest force during kick for ski forces and the highest active force after impact, caused by the hit of the poles to ground, for pole forces. Delta leg force was calculated only for vertical ski force and is defined as force difference between the force minima during ground contact time and peak vertical ski force.[21] Impulses for ski and pole forces were defined as area under the force curve during kick time and poling time, respectively. Average forces for ski and pole were calculated over the cycle time for ski forces and poling cycle time for pole forces. All force variables are expressed relative to body weight (%BW). Average rate of force development (RFD) was calculated for vertical ski force and pole force by dividing the delta vertical ski force and peak pole force with time from the beginning of the force development to the peak of force, respectively. Average RFD:s are expressed as N/s. The ratio between pole force and vertical ski force was calculated for peak vertical forces (pole/ski) and average RFD:s (RFD pole/RFD ski) and expressed as the percentage of pole variable from ski variable. The raw EMG signals were band-passed (10-500 Hz) and rectified. The root mean

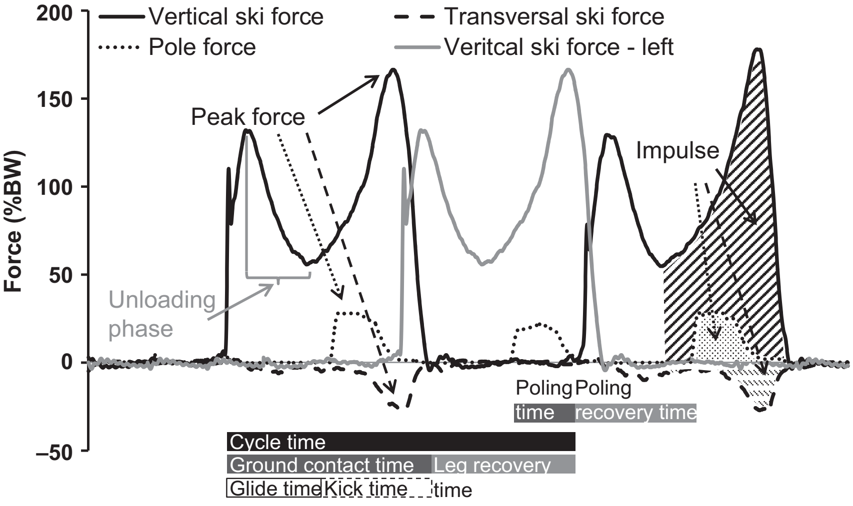

FIGURE 1 Example figure of the raw data with cycle and force variable definitions

square (rms) for EMG signals was calculated during the kick time for the lower body muscles and during the poling time for upper body muscles. The skiing EMG:s are expressed as percentage of the rms EMG during isometric maximal voluntary contraction (%MVC) conducted separately for all the muscle groups before the skiing measurements. In addition to separate muscle groups, an average of normalized lower body and upper body muscle activity was calculated. All skiing variables were calculated over nine consecutive skiing cycles and averaged.

2.5 | Data and statistical analyses

All data were analyzed with IkeMaster 1.38a (University of Salzburg, Salzburg, Austria) and Microsoft Office Excel 2010 (Microsoft corporation, Redmond, WA, USA). Statistical analyses were performed with PASW Statistics 18 (IBM, Armonk, NY, USA). Differences between Pre and Post skiing test were analyzed with repeated-measures ANOVA for skiing speed, cycle variables, forces from skis and poles as well as for EMG:s. Significance level was set to $P<.05$.

3 | RESULTS

Average race time in the simulated race was 1:00:33. Maximal skiing speed decreased from 6.13±0.34 to 5.42±0.43 m/s from Pre to Post test representing a decrease of 11.6% ($P<.01$).

Cycle characteristics, ground reaction forces, and muscle activities in Pre and Post tests are showed in Table 1. Decreased skiing speed was caused by 8.9% increase in cycle time, ($P<.01$) and thus by 8.0% decrease in cycle rate ($P<.01$). Also a tendency of 3.9% decrease in cycle length ($P<.07$) was observed. Absolute ground contact time and kick time increased by 10.5% and 21.0%, respectively (both $P<.01$), and absolute leg recovery time showed tendency to increase by 6.1% ($P=.09$) while absolute poling time showed no differences and absolute poling recovery time increased by 9.9% ($P<.01$). Temporal patterns (relative cycle values) showed changes with 10.9% rise in kick time ($P<.01$) and tendencies with 3.4% and 2.3% (both, $P<.10$) decrease and increase in poling time and poling recovery time, respectively, during Post test.

Ski forces decreased by 8.1% and 13.4% in peak vertical ski force and delta vertical ski force (both, $P<.01$). Average vertical ski force decreased 12.0% ($P<.01$) while the impulse of vertical ski force increased by 6.1% ($P<.05$). Transversal ski forces (peak, impulse, and average) showed a nonsignificant average change of 7.2%. Pole forces showed 24.9%, 19.9%, and 2.6% lower values in peak, impulse, and average forces, correspondingly (all, $P<.05$), during Post test. Average rate of force development decreased by 31.2% and 31.4% in ski and pole forces (both, $P<.01$). The ratio between peak pole and peak vertical ski force showed a tendency to decrease with 18.5% ($P=.08$). The behavior of the peak vertical ski force and relative kick time as well as peak pole force and relative poling time are presented in Figure 2.

Between Pre and Post test, lower body muscle activity decreased in calf, quadriceps, hamstrings, gluteus, and total average of lower body activity with 25.8%, 32.5%, 35.5%, 25.4%, and 30.7%, correspondingly (all, $P<.01$). Similarly in upper body triceps, latissimus dorsi and total average of upper body showed lower muscle activity in Post test by 32.0%, 56.2%, and 39.2%, respectively (all, $P<.01$). No significant differences were observed between the changes in lower and upper body muscle groups.

4 | DISCUSSION

This study investigated the effects of a 20-km skating race simulation completed by XC-skiing on snow on end spurt performance from a kinematic, kinetic, and muscle activity perspective. Based on the lower speed in the Post test, the results suggest that athletes were in fatigued state after the simulated race. The fatigue is causing impaired functionality of the muscles which is seen with lower EMG activity causing lower force production and movement frequency. When reflecting our results to the hypotheses, our main findings were that after simulated 20 km ski skating race (a) cycle rate decreased and cycle length showed a tendency to be diminished. (b) Force production decreased in a different way between pole and ski forces: Peak pole force production decreased more compared to peak vertical ski forces. However, while poling time was preserved (and even slightly decreased, tendency), kick time was increased causing a similar decrease in average RFD with arms and legs (Figure 2). (c) EMG activity decreased more with relevant upper body muscle groups contributing to poling compared to lower body muscle groups.

4.1 | Speed, cycle and force characteristics

Maximal skiing speed measured at the beginning and at the end of the simulated race has reported to decrease 14%-16%[4,5] in sprint skiing using V2 and double poling (DP) techniques, respectively. In distance skiing, Halonen et al.[7] reported 9% decrease on snow with DP technique. The 12% decrease in maximal skiing speed observed in this study is comparable with these results. The decrease in speed from a cyclic point of view was caused by a decrease in cycle rate and a minor decrease (tendency) in the cycle length. Vesterinen et al.[5] noted same phenomenon in sprint skiing with a decrease in cycle rate at the end part of sprint heats, caused by an increase in both absolute poling time and recovery time, as well as with constant cycle length within

TABLE 1 Kinematic, kinetic, and muscle activity variables from Pre and Post measurements and differences between them. Significance is determined between Pre and Post measurements

Variable	Unit	Pre	Post	Difference (%)
Cycle characteristics				
Cycle time	[s]	1.41±0.06	1.53±0.07	8.9±4.7**
Cycle rate	[Hz]	0.71±0.03	0.65±0.03	−8.0±4.2**
Cycle length	[m]	8.64±0.61	8.30±0.73	−3.9±5.4$^{\#}$
Ground contact time, relative	[%CT]	60.25±1.92	61.21±3.93	1.5±3.9
Ground contact time, absolute	[s]	0.85±0.04	0.94±0.08	10.5±6.2**
Glide time, relative	[%CT]	35.17±2.20	33.41±2.85	−4.9±6.7$^{\#}$
Kick time, relative	[%CT]	25.09±1.69	27.79±2.05	10.9±6.2**
Kick time, absolute	[s]	0.35±0.03	0.43±0.04	21.0±9.9**
Leg recovery time, relative	[%CT]	39.75±1.92	38.79±3.93	−2.6±6.8
Leg recovery time, absolute	[s]	0.56±0.04	0.59±0.05	6.1±8.9$^{\#}$
Poling time, relative	[%CT]	38.59±3.98	37.20±3.97	−3.6±4.9$^{\#}$
Poling recovery time, relative	[%CT]	61.41±3.98	62.80±3.98	2.3±3.0$^{\#}$
Poling recovery time, absolute	[s]	0.44±0.04	0.48±0.04	9.9±6.1**
Ground reaction forces				
Peak vertical ski force	[%BW]	202.48±10.28	185.99±20.51	−8.3±6.9**
Delta vertical ski force	[%BW]	197.00±10.44	170.82±23.91	−13.4±9.8**
Impulse of vertical ski force	[%BW]	42.26±2.60	44.73±1.92	6.1±5.4*
Average of vertical ski force	[%BW]	119.87±8.13	105.44±8.53	−12.0±4.6**
RFD of vertical ski force	[N/s]	6859±1046	4685±1155	−31.2±16.0**
Peak pole force	[%BW]	35.9±4.40	26.03±6.42	−24.9±17.4*
Impulse of pole force	[%BW]	5.30±0.70	4.40±1.09	−19.9±17.6*
Average of pole force	[%BW]	19.47±2.39	15.46±3.16	−22.6±2.9*
RFD of pole force	[N/s]	2198±391	1532±300	−31.4±16.6**
Peak pole force/Peak vertical ski force	[%]	16.79±2.42	14.00±3.90	−18.5±19.1$^{\#}$
RFD pole/RFD ski	[%]	33.27±7.01	35.56±14.63	1.46±28.0
Muscle activity				
Calf	[%MVC]	98.5±38.2	72.9±27.7	−25.8±16.1**
Quadriceps	[%MVC]	115.2±36.0	78.9±30.9	−32.5±10.1**
Hamstrings	[%MVC]	104.4±44.6	70.8±41.5	−35.5±16.5**
Gluteus	[%MVC]	75.9±40.6	55.5±26.2	−25.4±10.3**
Lower body	[%MVC]	98.5±27.3	69.5±24.2	−30.7±11.2**
Triceps	[%MVC]	112.3±57.7	72.9±32.0	−32.0±9.4**
Latissimusdorsi	[%MVC]	154.2±45.3	63.3±20.7	−56.2±6.5**
Pectoralis	[%MVC]	135.6±131.6	64.8±51.3	−38.1±21.5$^{\#}$
Abdominal	[%MVC]	98.6±36.2	87.0±44.2	−11.8±22.5
Upper body	[%MVC]	123.8±38.3	72.0±19.1	−39.2±9.7**

RFD of vertical ski force, average rate of vertical ski force development; RFD of pole force, average rate of pole force development; Peak pole force/Peak vertical ski force, ratio between peak pole force and vertical ski force; RFD pole/RFD ski, ratio between average rate of pole force development and average rate of vertical ski force development; s, second; Hz, Herz (s^{-1}); m, meter; %CT, percent of the cycle time; %BW, percent of the body weight; %MVC, percent of the maximal voluntary contraction.

Data are presented as the mean±SD.

Significance is determined with ANOVA.

$^{\#}P<.10$, $^{*}P<.05$, $^{**}P<.01$, different to Pre test.

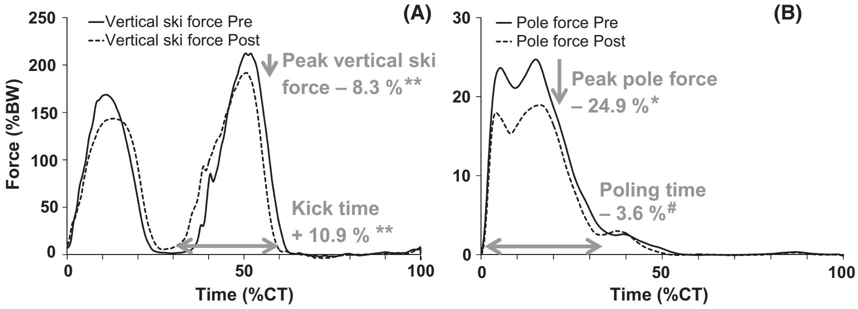

FIGURE 2 Ski (A) and pole (B) force curves averaged over nine cycles from one representative subject. Mean changes from all subjects between Pre and Post test are presented for kick time and peak vertical ski force as well as for poling time and peak pole force for showing the different behavior of the ski and pole forces when fatigued. $^{\#}P<.10$; $^{*}P<.05$; $^{**}P<.01$

the heats using V2-technique while roller skiing. Absolute poling recovery time also increased in our study while absolute poling time, in which large individual differences were observed, showed no differences. However, when observing leg patterns, we noted an increase in absolute ground contact time and leg recovery time (tendency) indicating that increased cycle time is divided equally into absolute ground contact time and leg recovery time. This indicates that the cyclic pattern changes are different in upper (increase only in absolute pole recovery time, not in poling time) and lower (increase in absolute ground contact time and leg recovery time) body due the fatigue in the current study. Also studies from DP on snow during sprint[4,6] and distance skiing[7] have reported similar changes, but with only in increased poling time with no significant changes in cycle rate. In addition to basic cycle variables, this study also focused on clarifying whether there are any changes in the temporal patterns within the cycle manifested by fatigue. In fatigued state, athletes demonstrated equal relative ground contact time and recovery time with legs compared to non-fatigued state. However, patterns inside the ground contact time changed, glide time showed a tendency to decrease and kick time increased by 11% (Figure 2. This highly relevant finding (increase of the kick time) causes 70% of the increase in cycle time while the duration of the kick time is only approx. 25% of the cycle time. This is partly explained by the impaired unloading phase during the ground contact time in the Post test when the skiers are fatigued and was demonstrated by an increase in the difference between peak and delta vertical ski force in Pre and Post tests from 5% to 15%. In a recent study from our group,[21] an increase in relative kick time was observed with high speeds compared to slower speeds indicated that production of a fast push-off phase is critical and could be a discriminating factor between athletes during high-speed XC-skiing. This also highlights the importance of this part of the cycle where the push-off of the leg is produced and propulsion is created. However, while the relative kick time was increased when fatigued, the relative poling time was slightly decreased (tendency) (Figure 2) in the present study. This different behavior of the upper and lower body is interesting and indicates different mechanisms for how the upper and lower body reacts to fatigue in cycle characteristics point of view and is also discussed later on force production perspective.

Peak vertical ski forces were slightly higher but still at a rather equal level in our study (1478 N and 1355 N in Pre and Post test, respectively) when compared to earlier V2 studies with direct force measurements showing values from 1299 N to 1414 N.[18,19,21-23] On the other hand, peak pole forces were lower in our study (247 N and 188 N, Pre and Post) compared to earlier pole force measurements from V2-technique, which varied approx. 270 to 300 N.[21,22,24]

A search of the literature did not reveal studies on XC-skiing (sprint or distance skiing) observing fatigue-induced changes in leg forces during skating skiing. In our study peak, vertical ski force decreased by 8% while delta leg force decreased by 13% indicating, as described earlier, that the unloading was compromised while fatigued. This leads to an increase in the kick time by changing the initial point of the kick to occur earlier in the ground contact phase. This is interesting because the unloading phase, which has been reported to be an important part of the cycle for generating higher forces with the arms and legs, is also linked to performance.[21,25] The impulse of the vertical ski force increased by 6%, and this is due to increase in the kick time, not by an increase in force. However, average vertical leg force, which takes into account also the changes in cycle time, decreased by 12% also indicating that the ability to maintain forces is highly compromised after the 20-km simulated race.

While ski forces decreased approx. 10%, pole forces showed distinctly greater changes varying from 20% to 26% in peak, impulse, and average pole force. A decrease in impulse of pole force compared to increase in impulse of vertical leg force demonstrates the different behavior of the lower and upper body with fatigue caused by increasing kick time and slightly decreased (tendency) poling time. Concerning pole forces our results are well in line with Mikkola et al.[4] studying sprint simulation using DP. They observed a decrease of approx. 20%-24% in peak and average forces between the start and end phases of each heat. However, impulses in their study did not differ, whereas we noted decreases of 20% due to slightly decreased poling time in our study. Halonen et al.[7] discovered decreases of approx. 14% in peak forces after a simulated 6-km double poling race. Nonetheless, race time in Halonen et al.[7] was approx. one-third of that in the present study, which might explain the smaller decreases in pole forces. However, in all these cases, subjects were instructed to ski as they would do in race situation and thereby the effect of race time should be smaller due to higher intensity during shorter races.

Ratios of peak forces decreased by 19% from Pre to Post test showing that pole forces decreased more compared to ski forces during this 20-km simulated race, thereby confirming the different response to fatigue with upper and lower body. When combining our results from the changes in cycle characteristics and ground reaction forces, we noticed that the changes in average RFD in upper and lower body are rather similar with decreases of approx. 31% and no changes in the ratio of the RFD:s. This demonstrates that the different mechanisms of fatigue in the upper and lower body cause similar changes in RFD:s of force. In our study, pole forces decreased threefold compared to ski forces. Changes in the different fatigability of the upper and lower body have also been reported by Boccia et al.[13] with non-sport-specific movements showing greater decreases in fast force production (RFD during MVC) with arms compared to legs (decrease of 26% with arms while no changes with legs) after classical marathon ski race. As it has been shown earlier in V2-technique, arms are contributing two-thirds while legs only on third to propulsion force[26] which actually propels the skier forward. Propulsion was not measured in this study, but due to changes in the ratio between the arms and legs, fatigue is likely to have some effect on the propulsion distribution generated by arms and legs. However, the decreases in propulsion might be greater than the decreases in just the peak forces of the legs due to compromised coordination and unstable movements[16] of leg forces when fatigued. This interesting topic with effects of fatigue on propulsion needs further investigation. Transversal forces showed no changes in this study. However, these transversal forces might play an important role when calculating propulsion.[27]

4.2 | Muscle activity

This study aimed to describe the general effects of fatigue, analyzing whether fatigue was central, or peripheral origin was not possible to determine with the methods used in this study. Few actual race analyses have been conducted where EMG:s have been measured before and after the marathon skiing race using isometric MVC in a force dynamometer. Results observed during MVC tests before and after a race showed approx. 30% decreases in EMG activity[14,15] with leg muscles, which are comparable to our results. Also a recent study shoved smaller changes after marathon race with 10% (elbow) to 20% (knee) decreases.[13] In our study, the latissimus dorsi muscle showed the highest relative values (150%) compared to MVC in Pre test. This result is in agreement with Halonen et al.[7] highlighting the importance of this muscle during poling action in V2 skating as well as DP where the poling action is rather similar. Our study also noted the greatest decreases due to fatigue (over 50%) in this muscle, which is highly relevant during the whole push-off phase. The importance of the latissimus dorsi, pectoralis, and teres major (not investigated in this study) muscles to double poling action has been shown by Holmberg et al.[28] and Lindinger et al.[29] The pectoralis muscle showed the second highest decrease with 36% (tendency) in our study. Compromised muscle activity due to fatigue in these highly important muscles contributing to poling action of double poling and V2 is likely causing a less stable push-off action during poling and the force might "leak" out due the "softness" of these muscles. As showed earlier, pole forces in V2 technique are partly generated by lifting the center of mass (COM) into a high position with the legs and then "dropping" the body mass onto the poles while the torso and arms must form a stable frame so that the force is transmitted to the poles.[21,25] This also highlights the importance of the latissimus dorsi, pectoralis, and triceps brachii muscles. Therefore, if the stability of these muscles is compromised, the force is not likely optimally transferred to the poles. The decrease in the EMG activity of the latissimus dorsi muscle among other muscles in the upper body is probably linked to a greater decrease in pole forces where upper body EMG decreased by 39% compared to ski forces, whereas lower body EMG decreased by 31%. Still there was no statistical difference between the changes in upper and lower body in fatigued state. However, Vesterinen et al.[5] did not notice changes in latissimus dorsi muscle in a simulated sprint race. Nonetheless, they found a decrease of approx. 18% in sum iEMG from triceps brachii and vastus lateralis representing a general EMG for the whole body, which is smaller compared to ours.

5 | PERSPECTIVE

Twenty-kilometers skating XC-skiing causes fatigue, which is observed as decreasing speed after a race. This reduction in speed is caused by decreased EMG activity, which leads to compromised force production and decreased movement frequency. Different kinds of fatigue-induced responses are observed with the lower and upper body: Kick time is increased while poling time is preserved and pole forces are decreased threefold in comparison with ski forces (Figure 2). Increased kick time is caused partly by an impaired ability to use unloading prior the kick. Greatly decreased pole forces are due to a compromised ability to maintain a stable upper body.

Practical implications for coaches and athletes based on this study are to perform technique training sessions in a fatigued state and with high speeds to create adaptations and stabilize technique. Special focus should be put on to achieve total unloading to maximize rapid force production during kick phase as well as to maintain rigid upper body position during poling to minimize pole force reduction when fatigued.

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IV

EFFECT OF 20 KM SIMULATED RACE LOAD ON PROPULSIVE FORCES DURING SKI SKATING

by

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