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Physiological and Biomechanical Aspects of Sprint Skiing

Thesis for the degree of Philosophiae Doctor

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ABSTRACT

Sprint cross-country skiing is a physiologically and technically complex discipline, performed as a time-trial qualification race and three subsequent knock-out heats. The racing time in a single heat is 2-4 min and is comparable to other middle-distance sports. However, sprint skiing is performed in varied terrain at constantly changing intensities using multiple techniques involving the arms and the legs to various degrees. The overall objectives of the current thesis were to examine physiological and biomechanical aspects associated with sprint skiing performance in the skating technique in elite skiers: 1) while treadmill roller skiing in the laboratory (*studies I-IV*), 2) during sprint competitions on snow (*studies IV-V*) and 3) for relationships between laboratory characteristics and performance on snow (*studies IV-V*).

Studies I-III are comparative studies in which physiological characteristics, mechanical efficiency and gross kinematics during treadmill roller skiing were compared between male world-class and national level sprint skiers (*studies I-II*), and between men and women matched for performance level (*study III*). ***Study I*** showed that maximal aerobic capacity, gross efficiency and high speed capacity differentiated world-class from national level sprint skiers. The study also indicated that low and moderate intensity endurance training and maximal speed training is important in attaining an international level in sprint skiing. ***Study II*** demonstrated that world-class sprint skiers had a higher gross efficiency than national level skiers. A general linear relationship between work rate and metabolic rate existed, indicating that gross efficiency at moderate and high work rates provides useful information about cross-country skiers in standardized conditions during treadmill roller skiing. Furthermore, world-class skiers used longer cycle lengths and lower cycle rates at a given speed and generated higher maximal speeds. In ***study III***, men showed a 17% higher peak treadmill speed at a short and long incremental test compared to women. These gender differences were slightly greater than findings in comparable endurance sports. The majority of gender differences in performance could be explained by higher maximal oxygen uptakes and lower fat percentages in men. Men and women showed similar gross efficiency. However, women showed higher fractional utilization of maximal oxygen uptake at the anaerobic threshold.

In ***studies IV-V***, elite male skiers were analyzed for speeds, work rates, technique choices and gross kinematics during two sprint time-trial competitions on snow. Furthermore, the skiers were tested for physiological and kinematical characteristics in the laboratory. ***Study IV***

analyzed the time-trial of an international sprint competition. The results showed that performance on uphill and flat terrain strongly determined sprint time-trial performance, and that performance in the last half of the race differentiated most between skiers. Estimated work rates on an uphill section of the race were approximately 60% higher than the capacities which the skiers are able to cover aerobically. Peak oxygen uptake, gross efficiency, peak treadmill speed and peak cycle length were strongly related to sprint time-trial performance, particularly to the uphill and flat sections during the last part of the race. ***Study V*** analyzed a simulated sprint race by using a high end differential global navigation satellite system with simultaneous tracking of both GPS and GLONASS satellites. This provided an opportunity for more detailed analysis of cross-country skiing. Skiers encompassed a large speed range (2.9–12.9 $m \cdot s^{-1}$) and multiple transitions between skiing techniques (range: 21–34 transitions). The results demonstrated that performance in the uphill sections had the strongest correlation to sprint performance, and that the faster skiers used the G3 technique to a greater extent than the slower skiers.

Thus, this provides new knowledge on physiological and biomechanical aspects of sprint skating performance, particularly that both the maximal aerobic and peak speed capacities differed between world-class and national level sprint skiers. Furthermore, gross efficiency, while treadmill roller skiing provides relevant information strongly related to sprint performance level. Better skiers also employ longer cycle lengths at the same absolute speeds and at individual peak speeds. The gender differences in performance were slightly larger than expected; however, most of these differences could be explained by a higher maximal oxygen uptake and a lower fat percentage in men. Furthermore, the variations in speeds, work rates and techniques and, especially, speed in uphill and flat terrain are important to the skiers' total time-trial performance. Better sprint performance is related to more application of the G3 technique and to longer cycle lengths within this technique. Faster skiers showed higher peak oxygen uptake, gross efficiency and high speed capacity. These capacities were specifically correlated to the ability to maintain high speed on uphill and flat terrain throughout a sprint race.

Key words: aerobic capacity; anaerobic contribution; competition analysis; cross-country skiing; cycle length; cycle rate; efficiency; gender differences; metabolic rate, oxygen uptake; skating technique; speed; sprint skiing; terrain; training; world-class skiers; work rate.

SUMMARY IN NORWEGIAN

Sprintlangrenn er ein fysiologisk og biomekanisk kompleks disiplin som blir utført som ein prolog og tre etterfølgjande utslagsløp. Konkurransetidene i kvart enkelt heat er 2-4 min og kan samanliknast med andre mellomdistanseidrettar. Sprintlangrenn blir imidlertid gjennomført i kupert terreng og med varierande arbeidsintensitet og innslag av ulike teknikkar som involverer underkropp og overkropp i ulik grad. Den overordna målsetjinga med denne avhandlinga var å undersøke fysiologiske og biomekaniske aspekt som er assosiert med prestasjonen i sprint skøyting hos elite langrennsløparar: 1) på rulleskitredemølle i laboratoriet (*studia I-IV*), 2) i sprintkonkurransar på snø (*studia IV-V*), og 3) for samanhengar mellom laboratorium-karakteristikkar og sprintprestasjonen på snø (*studia IV-V*).

Studia I-III undersøker forskjellar i fysiologiske karakteristikkar, mekanisk effektivitet og kinematikk mellom mannlege verdsklasse og nasjonal klasse sprintlangrennsløparar (*studia I-II*) og mellom mannlege og kvinnelege sprintlangrennsløparar på tilsvarande prestasjonsnivå (*studie III*). ***Studie I*** viser at maksimal aerob kapasitet, mekanisk effektivitet og hurtigheit skil verdsklasse frå nasjonal klasse sprintlangrennsløparar. Studiet indikerer også at låg- og moderat-intensiv uthaldstrening og maksimal hurtigheitstrening er viktig for å nå internasjonalt nivå i sprintlangrenn. ***Studie II*** viser at verdsklasse sprintlangrennsløparar har betre mekanisk effektivitet enn løparar på nasjonalt nivå. Studiet viser ein generell lineær samanheng mellom arbeidsratar og energiforbruk og indikerer at målingar av mekanisk effektivitet gir nyttig og valid informasjon om langrennsløparar som blir samanlikna under standardiserte vilkår på rulleskitredemøller. Studiet demonstrerer også at verdsklasse løparane har lengre sykluslengder og lågare syklusfrekvens på ei gitt fart. ***Studie III*** viser at menn oppnår 17 % høgre fart enn kvinner både på ein kort og ein lang prestasjonstest med trinnvis aukande fart på rulleskitredemølla. Resultata indikerer at prestasjonsforskjellane mellom kjønna hovudsakleg kan forklarast av høgare maksimalt oksygenopptak og lågare feittprosent hos menn, og at forskjellane er noko større enn det litteraturen viser i andre tilsvarande uthaldsidrettar. Kvinner og menn har lik effektivitet, mens kvinner har høgare prosentvis utnytting av maksimalt oksygenopptak ved anaerob terskel.

I ***studia IV-V*** vart fart, arbeidsratar, teknikkval og kinematikk undervegs i sprintkonkurransar undersøkt. Vidare blei samanhengar mellom fysiologiske og kinematiske karakteristikkar i laboratoriet og sprintprestasjonen på snø undersøkt. I ***studie IV*** vart prologen i ein internasjonal sprintkonkurranse analysert. Resultata viser at prestasjonen i motbakke og i flatt terreng er sterke forklaringsvariablar for den totale prologprestasjonen. Studiet indikerer også at prestasjonen i siste halvdelen av løypa skil løparane mest. Estimerte arbeidsratar i motbakke indikerer eit totalt arbeid omlag 60% høgare enn det løparane klarer å dekke med aerob energi. Maksimalt oksygenopptak, mekaniske effektivitet, fartskapasitet og sykluslengde var sterkt relatert til sprintprestasjonen, og spesielt til farta i flatt terreng og motbakkar i siste halvdelen av løpet. I ***studie V*** vart ein simulert sprintprolog analysert ved bruk av ein høgteknologisk differensial GPS, med svært høg samplingsfrekvens og nøyaktigheit, som hadde samtidig mottak av GPS- og GLONASS-satellittar. Løparane gjennomførte sprintkonkurransen i variert terreng, noko som førte til eit spenn i hastigheiter frå 2.9 til 12.9 $m \cdot s^{-1}$ og som inkluderte 21–34 teknikkendringar. Motbakkeprestasjonen var høgast korrelert til total prestasjon, og betre skiløparar brukte dobbeldansteknikken i større grad, samanlikna med mindre gode løparar.

Samanfatta så bidreg denne avhandlinga med ny kunnskap om fysiologiske og biomekaniske aspekt av sprintlangrenn i skøyting. Det viser at både maksimal aerob kapasitet og fartskapasitet skil verdsklasse frå nasjonal klasse sprintlangrennsløparar. Det er også vist at målingar av mekanisk effektivitet på rulleskitredemølle gir valid informasjon og er sterkt relatert til prestasjonsnivået til løparane. Dei beste løparane bruker lengre sykluslengder både på same submaksimale fart og på si høgste individuelle fart. Forskjellane mellom mannlege og kvinnelege sprintløparar i prestasjon er noko større enn forventa. Det meste av desse kjønnsforskjellane kan forklarast av at menn har høgare maksimalt oksygenopptak og lågare feittprosent. Undervegs i sprintprologar viser løparane store variasjonar i fart, arbeidsratar og vekslar stadig mellom ulike teknikkar. Spesielt er farta i motbakkar og flatt terreng mot slutten av løpa betydningsfull for prologprestasjonen. Betre prologprestasjon er linka til meir bruk av dobbeldansteknikken og lengre sykluslengder innan denne teknikken. Betre utøvarar har også høgare maksimalt oksygenopptak, effektivitet og fartskapasiet, noko som vart relatert til evna til å oppretthalde høg fart i motbakkar og flatt terreng gjennom eit sprintløp.

Nøkkelord: aerob kapasitet; anaerobt bidrag; arbeidsrate; effektivitet; fart; kinematikk; kjønnsforskjellar; konkurranseanalysar; langrenn; metabolsk rate; oksygenopptak; skøyteteknikk; sykluslengde; syklusfrekvens; sprintlangrenn; terreng; trening; verdsklasseløparar.

LIST OF PUBLICATIONS

This thesis is based on the following articles and manuscripts, referred in the text by their Roman numerals. The articles are reprinted with permission from the publishers. This thesis also includes unpublished results.

I. **Sandbakk O**, Holmberg HC, Leirdal S, Ettema G (2010). The physiology of world-class sprint skiers. *Scand J Med Sci Sports*. doi 10.1111/j.1600-0838.2010.01117.x [Epub]

II. **Sandbakk O**, Holmberg HC, Leirdal S, Ettema G (2010). Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur J Appl Physiol*. 2010;109(3):473-81

III. **Sandbakk O**, Ettema G, Leirdal S, Holmberg HC. Which physiological and kinematic variables determine gender differences in sprint skiing performance? Manuscript

IV. **Sandbakk O**, Ettema G, Leirdal S, Jakobsen V, Holmberg HC. Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur J Appl Physiol.* Accepted.

V. Andersson E, Supej M, **Sandbakk O**, Sperlich B, Stöggl T, Holmberg H-C (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol.* doi10.1007/s00421-010-1535-2 [Epub]

ABBREVIATIONS

BLa	Blood lactate concentration
CL	Cycle length
CR	Cycle rate
CO_2	Carbone dioxide
d-GNSS	Differential Global Navigation Satellite System
FIS	Fédération Internationale de Ski (i.e., International Ski Federation)
GE	Gross efficiency
G3	One of the skating sub-techniques, referred to as V2 and double dance
HIT	High intensity endurance training
HR	Heart rate
HR_{max}	Maximal heart rate
LIT	Low intensity endurance training
MIT	Moderate intensity endurance training
OBLA	Onset of blood lactate accumulation (4 $mmol \cdot L^{-1}$)
P	Level of significance
r	Correlation coefficient
RER	Respiratory exchange ratio
SD	Standard deviation
STT	Sprint time-trial
TTE	Time to exhaustion
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen uptake
VO_{2peak}	Peak oxygen uptake
V_{peak}	Peak speed
V_{max}	Maximal speed
1RM	One repetition maximum

CONTENTS

CHAPTER IV

CHAPTER I

INTRODUCTION

Cross-country skiing has always been an important part of Nordic history, with the first evidence of skis dating back to about 2000 BC in Norway. The original use of cross-country skiing was for transport and travel over snow, but it has changed dramatically over time, particularly in the last century. Modern skiing is used for everyday exercise and is a popular sport with important races that are broadcast to millions of viewers worldwide. Competitive cross-country skiing always has been regarded as one of the most demanding endurance sports and has been on the Olympic program since the first Winter Olympics in Chamonix, France in 1924. Initially, competitive cross-country skiing included only classical time-trial races for men; international competition for women did not begin until 1952. From mid-1980s, a series of major changes have been introduced in cross-country skiing, starting with the introduction of the skating technique and thereafter different types of pursuit races, mass start races and sprint races. In modern skiing, skiers are challenged by a range of 1-90 km races, performed as individual time-trials, mass start races or knock-out heats. Furthermore, these races are performed at varied track topographies, challenging skiers to use different skiing techniques and employ their arms and legs to various extents. Because of these unique and challenging aspects, the scientific interest in cross-country skiing has grown tremendously in the last few decades.

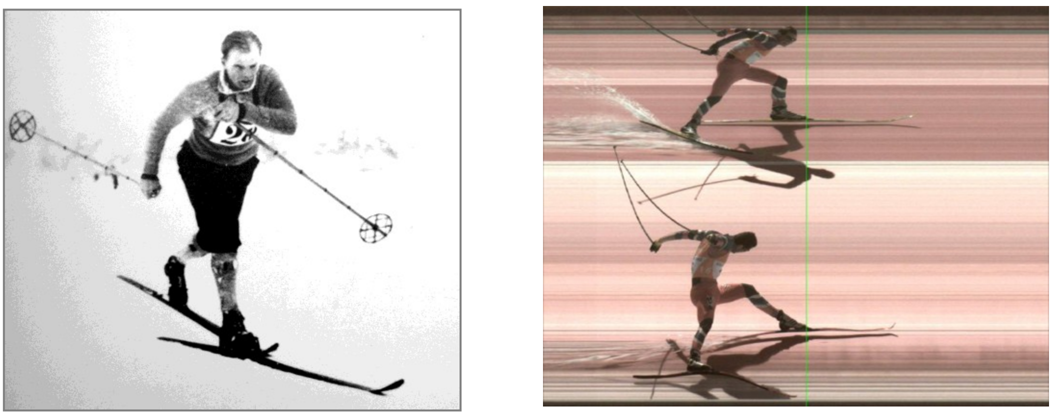

Figure 1. Equipment, ski techniques, and the competition program have evolved over the past century. The photos show Norwegian Olympic champions from the 1920s (Torleif Haug in an individual time-trial using the classical technique with heavy wooden skis) and the 2000s (Thomas Alsgaard and Frode Estil in the final sprint of a skating mass-start race. They are using lighter fiberglass skis that are optimized for skating).

The history of sprint skiing

Until recently, cross-country skiing competitions for men have ranged from 10 to 50 km (racing times from 25 min to 3 h) and for women from 5 to 30 km (racing times from 12 min to 2 h). During the 1990s, shorter "sprint" events were introduced, originating in "show competitions" that were performed in varying forms in cities after the official competitive season was finished. Sprint skiing was increasingly accepted as a discipline in cross-country skiing and included in the World Cup in the late 1990s. The first World Championship in sprint skiing was performed in Lahti, Finland in 2001 and the first Olympic event in Salt Lake City, USA in 2002. During these first years, the sprint competitions started with a time-trial qualification race (STT) where 16 skiers qualified for the knock-out heats with four skiers in each heat. These four skiers competed for the two first places which qualified them for the next heat all the way to the final. In addition, a team sprint was included in the 2005 World Championship in Oberstdorf, Germany with two skiers on each team, alternating in performing six rounds in total. These races started with semifinals in which the best six teams qualified for the finals.

Initially, the skating technique was predominant in sprint skiing. However, since 2005, the numbers of classical and skating races in the International Ski Federation (FIS) program have been similar. Another change, introduced in the 2005/06 season, was that 30 skiers qualified from the qualification time-trial race for the subsequent knock-out heats. The knock-out heats still allowed two skiers from each heat to qualify for the next round. The quarterfinals therefore had six skiers, the semifinals five skiers and the finals four skiers. Another change was introduced in 2006, with two skiers in each heat qualifying for the next round, but with the additional two best times regardless of heat going to the next round ("lucky losers"). Therefore, six skiers competed in all heats all the way to the final.

Today, modern sprint competitions are standardized as four separate races of 1200-1800 m (racing times from 2 to 4 min), starting with a STT, and thereafter heats with six skiers based on the knock-out system (FIS 2009). The duration of the breaks between the qualification race and the knock-out heats are normally between 1 and 2 hours; thereafter the breaks are approximately 30 min between the quarter-finals and semifinals and around 20 min between the semi-finals and the finals (see an example of a competition day in Appendix I).

Characteristics of sprint skiers

Physiological characteristics

Over the last decades, scientists have examined the characteristics of successful endurance athletes (Joyner and Coyle 2008; Saltin and Astrand 1967). In cross-country skiing, men and women have some of the highest values of maximal oxygen uptake (VO_{2max}) ever reported in the literature (Ingjer 1991). Such high values of VO_{2max} have not yet been found in sprint skiers. The current knowledge of sprint skiing suggest that sprint skiers only need a "required level" of maximal aerobic power (Stöggl et al. 2006; Stöggl et al. 2007a; Stöggl et al. 2007b). These studies propose that short duration speed and strength are most important for sprint performance.

With shorter racing times leading to higher average speeds, as well as the need for acceleration in the start and a high maximal speed at the finish have increased the importance of high speed capacities in sprint skiing compared to traditional races. This is confirmed by the abovementioned investigations of Stöggl et al. (2006; 2007a; 2007b). However, the role of aerobic capacity on sprint skiing performance is not yet clear. The average racing time in sprint skiing indicates that a large proportion of the total energy delivery must come from aerobic sources. This is further supported by other endurance sports with comparable racing times to sprint skiing, where 70-80% of the energy requirement is covered by aerobic energy delivery (Gastin 2001) and VO_{2max} has been shown to be of great importance to performance (Brandon 1995; Michael et al. 2008; Saltin and Astrand 1967; Secher 1993). Multiple races further increase the importance of the aerobic system (Glaister 2005). The aerobic system is therefore highly challenged to recover and tolerate a full day of competiton (see Appendix I). However, very little research has been conducted on sprint skiing yet, and the current knowledge is not verified for the skating technique, for sprint skiing on snow, and the characteristics of male or female world-class sprint skiers have not yet been examined.

Because of the complexity of sprint skiing, with four races over a varied terrain, different capacities may be advantageous for different aspects of a sprint race. For example, performance on different terrain may relate to different physical capacities, as studies on cycling have demonstrated that uphill riders have superior maximal oxygen uptake and flat terrain riders have superior maximal speed and power (Sallet et al. 2006). Furthermore, differences in pacing strategies may be used to accommodate for athletes' limitations in anaerobic and aerobic energy supply and utilization (Abbiss and Laursen 2008). Also, a higher aerobic capacity may help skiers recover between heats (Glaister 2005). The optimal composition of these different physiological capacities to optimize performance levels in sprint cross-country skiing is of practical interest, but is difficult to examine scientifically. An analysis of the world's best sprint skiers may thus serve as a model for the current benchmarks on the most important parameters. Accordingly, the influence of laboratory measured capacities for sprint performance on snow and their specific importance over the different sections of terrain in a sprint race needs to be studied further.

Cross-country skiers, unlike athletes in most other endurance sports which feature a greater homogeneity of athlete body types, show a large variation in body height and mass. These differences among skiers may be explained by the varying nature of the courses, with different terrains that may favor skiers with different body sizes. This is supported by investigations that show smaller skiers to be favored on uphill terrain and heavier skiers on flatter terrain (Bergh and Forsberg 1992; Bergh and Forsberg 2000).

Gender differences in endurance performance are shown to be 10-15% in elite runners, track cyclists, speed skaters and swimmers (Coast et al. 2004; Maldonado-Martin et al. 2004; Schumacher et al. 2001; Seiler et al. 2007). In order to explain differences in endurance performance, differences have been attributed to a multitude of physiological factors, such as VO_{2max}, anaerobic threshold and efficiency (Joyner and Coyle 2008). However, when comparing men and women, some of the differences in performance and physiological capacities can be attributed to genetics. Most studies therefore suggest that in comparisons between genders, variables should be expressed relative to lean body mass (Maldonado-Martin et al. 2004; van den Tillaar and Ettema 2004). When normalized for lean body mass, gender differences in muscular power in throwing has been shown to disappear (van den Tillaar and Ettema 2004), whereas the differences in endurance performance and VO_{2max} are reduced, but still significant (Calbet and Joyner 2010; Joyner 1993). Specially trained sprint cross-country skiers of both genders are well trained both in their upper and lower extremities, as well as for endurance, speed and strength capacities. Accordingly, sprint skiers are excellent subjects for evaluating gender differences employing whole body exercise in a wide range of physiological capacities.

Work economy and efficiency

Traditionally, cross-country skiers are tested for energy delivery capacity. However, the conversion of metabolic energy into work rates and speed is also of importance to the final performance. Generally, the most common definition used to express efficiency in endurance sports is gross efficiency (GE). Gross efficiency is defined as the ratio of work generated to the total energy expended (i.e., metabolic rate), expressed as a percentage (Sidossis et al. 1992). Gross efficiency is regarded as reflecting the efficiency of the entire human body in action and thus provides detailed insight into how work rate affects metabolic rate. However, one of the major challenges when studying efficiency in cross-country skiing is finding an accurate measurement of the work rate (van Ingen Schenau and Cavanagh 1990). Thus, work economy, expressed as aerobic metabolic rate or oxygen uptake per speed, is often studied when the work rate is unknown (Moseley and Jeukendrup 2001; Saunders et al. 2004).

A considerable number of studies have examined work economy in cross-country skiing (Hoff et al. 1999; Hoffman 1992; Hoffman et al. 1990a; Hoffman et al. 1990b; Hoffman et al. 1994; Mahood et al. 2001; Mikkola et al. 2007; Millet et al. 1998a; Millet et al. 2003; Millet et al. 1998b; Millet et al. 2002; Osteras et al. 2002). In general, these studies indicate that the aerobic energy cost discriminates between techniques and skiers of different standards. Furthermore, skiing economy is improved through strength and power training. Limited research has been done on mechanical efficiency in skiing (Hoffman et al. 1995; Niinimaa et al. 1978). However, the introduction of ski-specific laboratory testing using roller skis on treadmills has created opportunities for measuring work rate and metabolic responses that can serve as a model for cross-country skiing (Watts et al. 1993). One advantage of using efficiency is the possibility to compare the results across speeds and slopes and with other locomotion. The importance of efficiency for performance can therefore be investigated in the laboratory. Rationally, physical characteristics and technique affects efficiency, but this aspect has not yet investigated in cross-country skiing.

Kinematics

Sprint skiing challenges the athletes to master a wide range of speeds and slopes and to adapt their technique accordingly. Thus, skiers possess different skiing techniques and continuously change between them during a race. The skating technique has five predominant sub-techniques, known as gears (G1-5) (Nilsson et al. 2004a). The lower gears are used uphill, while the higher gears are used in easier terrain at higher velocities or in snow conditions with lower friction. Unpublished data from our group has shown that the G3 technique is predominant in international sprint races. G3 is used on moderate inclines and level terrain and involves one double pole push together with every leg push.

A few studies have compared kinematics between the different techniques in ski skating (Bilodeau et al. 1992; Nilsson et al. 2004a), whereas others have investigated how skiers adapt to increased speed and slope within these techniques (Bilodeau et al. 1996; Millet et al. 1998c; Millet et al. 1998e; Nilsson et al. 2004a; Rundell and McCarthy 1996; Stöggl and Muller 2009). Better skiers tend to use longer cycle length (CL) with a similar cycle rate (CR) and this difference has been suggested to be related to strength and power (Bilodeau et al. 1996; Lindinger et al. 2009; Stöggl et al. 2007a), as well as to technical aspects (Bilodeau et al. 1996; Stöggl and Muller 2009). Increases in ski skating speed have been associated with increases in both CL and CR (Millet et al. 1998c; Millet et al. 1998e), although other researchers report increases only in CR, especially from high to maximal speeds (Nilsson et al. 2004a). While push-off times appear to be dependent on speed in skiing (Millet et al. 1998e; Nilsson et al. 2004a), a more powerful push-off while maintaining recovery times may be crucial in the production of a longer CL and higher speeds.

Training

Distance cross-country skiers train according to a “polarized” endurance training model, with high volumes of low-intensity training and low to moderate volumes of high-intensity training (Gaskill et al. 1999; Rusko 1987; Seiler and Kjerland 2006). In addition, strength and power training reportedly improve work economy and performance in cross-country skiers (Hoff et al. 1999; Mikkola et al. 2007; Nilsson et al. 2004b; Osteras et al. 2002). At present, no studies have investigated the status of the best sprint skiers’ training.

Sprint race characteristics

Cross-country skiing competitions take place on varying terrain and at widely varying speeds, making it both physically and technically demanding (Saltin 1997; Smith 1992). During such races a skier must alter his or her rate of work and technique to suit the terrain (Bergh and Forsberg 1992; Kvamme et al. 2005; Norman and Komi 1987; Smith 1992). These variations in terrain, as well as in external conditions (e.g., snow structure, air temperature and humidity) thus require multiple transitions between different sub-techniques (“gears”) and adaptation to different speeds and slopes within these gears. Competition analyses of sprint skiing have been studied in simulated races, using the classical technique on snow or while roller skiing on a treadmill (Stöggl et al. 2007a; Zory et al. 2006). However, no studies have investigated sprint skating or examined an actual sprint competition on snow.

Stöggl et al. (2007a) showed peak values of 90-95% of VO_{2max} and 95-100% of maximal heart rate (HR_{max}) during a simulated classical sprint race on the treadmill. This study demonstrated that sprint performance strongly correlated to maximal speed, and that the fastest skiers produced longer CL in all techniques at equal CR. Furthermore, no changes in performance, HR, VO_2 and peak blood lactate concentration (BLa) over three following sprint heats were found. However, the removal of BLa decreased over the heats. BLa measured directly after sprint races has generally revealed peak values around 10-15 $mmol \cdot L^{-1}$ (Stöggl et al. 2007a; Zory et al. 2006). Zory et al. (2006) investigated a classical sprint simulation on snow for the effects of fatigue on kinematic parameters (cycle, phases, and joints angles) in the double poling technique. This study showed that the mean heat speed remained the same over the heats. However, the final sprint speed ("spurt") was significantly lower in the third heat compared to the first. No significant decreases in either CL or CR were found due to inter-individual differences.

These current measurements are limited to analyzing the final performance or mean speeds in parts of the races. More accurate measurements of the distribution of speed, gears and the adaptation of these techniques during cross-country skiing competitions would provide important information on where, when and why skiers gain or lose time during a race. In distance cross-country skiing, most research has focused on the capacity for performing on uphill terrain. Uphill terrain skiing is performed at work rates well above what can be produced purely aerobically (Norman and Komi 1987; Norman et al. 1989) and has been shown to be the most differentiating factor in distance races (Bergh and Forsberg 2000). These aspects are not yet examined in sprint skiing. However, in most sprint races one third of the distance is performed each on uphill, flat and downhill terrain. The largest portion of time to complete the course is therefore spent on uphill terrain, and it may be hypothesized that performance on the uphill terrain is also the most important factor in determining overall sprint skiing performance. However, sprint skiing has more flat terrain and higher average speeds than other cross-country skiing events, and performance on flat terrain may therefore be especially relevant for success. Downhill terrain may also directly, through speed and tactics, or indirectly, through economy and/or recovery, affect sprint skiing performance.

Aims

The main aims of the current thesis are presented below. More specific aims and hypotheses can be found in the articles.

The main aims of the current thesis are to:

1) compare world-class and national level sprint skiers for physiological characteristics, mechanical efficiency and kinematics in the skating technique during treadmill roller skiing in the laboratory (*studies I-II*);
2) examine performance differences and the main explanatory physiological factors between male and female sprint skiers (*study III*);
3) analyze speeds, work rates, technique choices and gross kinematics during sprint time-trial competitions and their associations to performance (*studies IV-V*);
4) investigate physiological, kinematic and anthropometrical determinants of sprint time-trial performance and specific associations to different aspects of the race (*studies I and IV*-V).

CHAPTER II

METHODS

Provided here is a summary of the methods and procedures utilized in this thesis. See the separate articles for more details.

Subjects

In total, 33 male and 8 female subjects volunteered to participate in the research for this thesis. All subjects were categorized as world-class or national level skiers (see Table 1 for the subjects' characteristics).

Table 1. The subjects' characteristics in the five different studies included in the current thesis.

Study	Men		Women	Age (yr)	Body height (cm)	Body mass (kg)	VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)
	WC	**NL**					
I-II	8	8		25 ± 3	186 ± 6	83.0 ± 6.4	68.2 ± 3.3
III			8	24 ± 2	168 ± 3	60.1 ± 4.7	60.8 ± 3.8
	4	4		26 ± 2	183 ± 5	83.3 ± 7.2	69.5 ± 3.7
VI	6	6		25 ± 3	185 ± 6	82.6 ± 6.6	70.0 ± 2.7
V	9	4		26 ± 4	181 ± 5	75.0 ± 6.7	73.4 ± 5.8

WC = world-class; NL = national level

The world-class skiers were all national team skiers in Norway and Sweden and included five World Champions and three Olympic Champions. All of the national level skiers ranked among the 10-30 best in the Norwegian or Swedish Cup Series. In *studies III-V*, the skiers were categorized as elite sprint skiers, which included a mix of world-class and national level skiers. All subjects gave their written consent to participate in the studies, which was pre-approved by the regional ethical committees of Norway and Sweden (see specific studies).

Instruments and materials

In the laboratory

Treadmill, roller skis and poles (studies I-V)

All roller skiing laboratory tests in *studies I-IV* were performed while skating on a motor-driven treadmill (Bonte Technology, Zwolle, the Netherlands) as shown in Figure 2. The classical roller skiing VO_{2max} test in *study V* was also performed on a treadmill (Rodby, Södertälje, Sweden). The treadmill belts consisted of non-slip rubber surface that allowed skiers to use their own poles with special carbide tips. To minimize variations in rolling resistance in *studies I-IV*, the skiers used the same pair of skating roller skis with standard wheels, which were pre-warmed before each test by 20 min of roller skiing on the treadmill. Rolling friction force were tested before the test periods, as previously described by Hoffman et al. (1990a). The incline and speed of the treadmill were calibrated using the Qualisys Pro Reflex system and the Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden).

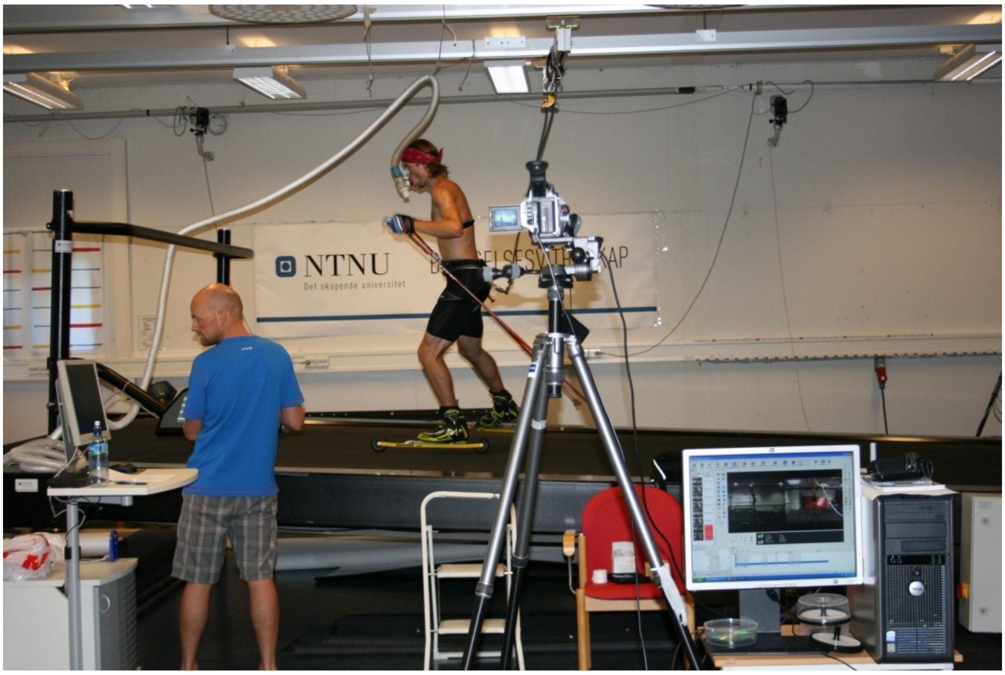

Figure 2. A subject being measured for gas exchange and simultaneously video filmed while skating on the treadmill.

Physiological measurements (studies I-V)

Gas exchange values were measured by open-circuit indirect calorimetry with calibrated gas analyzers. In *studies I-IV*, a Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany) was used and in *study V* an AMIS 2001 model C (Innovision A/S, Odense, Denmark). Both systems have previously been validated in the literature (Foss and Hallen 2005; Jensen et al. 2002) and have been tested versus the Douglas Bag method and shown valid at submaximal and maximal levels of exercise.

Heart rate was measured with a Polar S610 HR monitor (Polar Electro OY, Kempele, Finland). Blood lactate concentration was measured by a Lactate Pro LT-1710*t* kit (ArkRay Inc., Kyoto, Japan), as validated by Medbø and coworkers (2000) in *studies I-IV.* In *study V*, BLa was analyzed by a Biosen 5140 (EKFdiagnostic GmbH, Magdeburg, Germany) analyzer, calibrated before each measurement with control solutions.

Strength and anthropometrics (studies I-V)

In *studies I-II*, maximal isometric single-leg squats were recorded on a force plate (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland) and upper body one repetition maximum (1RM) was tested in a LAT MACH machine (Technogym, Gambettola, Italy) with a semi-pronated rowing handlebar.

Body fat percentages were estimated using a Holtain Skinfold caliper PE025 (Holtain Ltd., Crosswell, UK), according to Withers et al. (1987) in *studies I-II and IV* and according to Durnin and Womersley (1973) in *study III*. In *study V*, total mass, fat mass and lean mass was measured by using the Lunar iDXA (GE Healthcare, Madison, WI, USA) and analyzed by the iDXA software (Encore 2007, Version 11).

Kinematics (studies II-IV)

To measure kinematics in *studies II-IV*, two synchronized 50 Hz video cameras (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) were fixed to the front and on the side of the treadmill, enabling a total view of the subjects and the whole movement range of the poles. All the video recordings were analyzed in DartFish ProSuite 4.5 (DartFish Ltd., Fribourg, Switzerland).

In the field

Sprint track, skis and poles (studies IV-V)

Two sprint competitions were performed on snow. In *study IV*, a FIS sprint competition in the skating technique was performed on an 1820 m track with varied topography; approximately

1/3 flat, 1/3 uphill and 1/3 downhill, with a total climb of 35 m and a maximal height difference of 24 m. Each lap was divided into 9 different sections (S1-S9) according to the terrain's properties, marked by reference poles on the side of the track. In *study V*, a simulated STT competition was performed in a 1425 m (2 x 712.5 m) approved course for international sprint competitions with varied topography. The course terrain was approximately 1/3 flat, 1/3 uphill and 1/3 downhill but included more frequent and steeper hills than the course in *study IV*. The maximal height difference was 17 m with a total climb of 26 m per lap (in total 52 m). Each lap was divided into 10 different sections (S1-S10) according to terrain properties.

In *studies IV-V*, all subjects used their own racing poles and skis with standardized stone ground and waxing. The friction coefficient of the skis in *study IV* was based on measurements of decelaration of a skier on flat terrain using two pairs of photocells (Speedtrap II Timing System, Brower Timing Systems, Draper, USA) and the air drag coefficient was estimated from measurements in a wind tunnel according to Leirdal et al. (2006) (see *study IV* for details).

Time and speed measurements (studies IV-V)

In *study IV*, time measurements in the nine sections of the competition were captured with time synchronized 50 Hz video cameras (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan). The measurements of total times differed by 0.12 ± 0.03 s from the official total racing times. During the simulated sprint competition in *study V*, a differential global navigation satellite system (d-GNSS) was used to continuously analyze speed (see Figure 3).

The rover and reference station for the d-GNSS system consisted of 1) Leica GX1230 GG, 72 channel, dual frequency L1/L2 receivers, 2) Leica AX1202 GG survey antennas and (3) Leica GFU14 Satelline 3AS radio modems (Leica Geosystems AG, Heerbrugg, Switzerland). The system simultaneously received signals from both American and Russian global navigation systems (GPS and GLONASS) and surveyed positions with 1 cm + 1 ppm and 2 cm + 1 ppm horizontal and vertical accuracy respectively, at a 20 Hz sampling rate in the real time kinematics mode. The rover was stacked into a specially designed small backpack carried by the skiers (total weight ~ 1.64 kg).

Figure 3. The d-GNNS used in *study V*. The reference station is shown on the left side, and the backpack carried by the athlete is shown on the right side.

Kinematics (studies IV-V)

In *study IV*, a panning 50-Hz Sony video camera (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) monitored the skiers for 6 consecutive cycles during the mid-part of one uphill section to allow determination of the gross kinematic parameters (i.e. CL and CR). In *study V*, the skiers were filmed continuously with one camcorder (Panasonic NV-GS 280, Panasonic Corp., Osaka, Japan) from a ski-mobile that followed the skier from behind. All video analyses were carried out in Dartfish Pro Suite 4.5.

Maximal speed and acceleration (studies I and V)

In *study I*, acceleration in the skating G3 technique while roller skiing was tested in a 30-m maximal sprint at a 1% inclination outdoors on a straight asphalt track using two fixed light sensors (Newtest Powertimer 300, Oulu, Finland). In *study V*, a 20-m maximal speed test in flat terrain on snow in the skating G3 technique and a 20-m acceleration test in DP were performed were the maximal and peak velocities from d-GNSS readings were assessed.

Test protocols and measurements

In the laboratory

Submaximal tests (studies I-IV)

To measure physiological responses and kinematics, one (*studies I and IV*) or three (*study II-III*) submaximal 5-min stages at a constant speed whilst roller ski skating on the treadmill was performed. Blood lactate concentration was measured immediately after each stage. Gas exchange (i.e., VO_2 and VCO_2), HR, cycle length and rate were determined by the average of the last minute during each stage. Metabolic rate and GE was calculated from the abovementioned values (see calculations below).

Maximal aerobic capacity tests (studies I-V)

Peak and maximal aerobic capacity were tested in incremental tests in the skating G3 technique (*studies I-IV*) and in diagonal skiing (*study V*) with increasing speed and/or slope every minute (see Figure 4). Time to exhaustion (TTE) was recorded at the time the subject failed to keep the roller skis' front wheels ahead of a marker placed 4 m from the front of the treadmill, which determined the skiers' individual treadmill performance level.

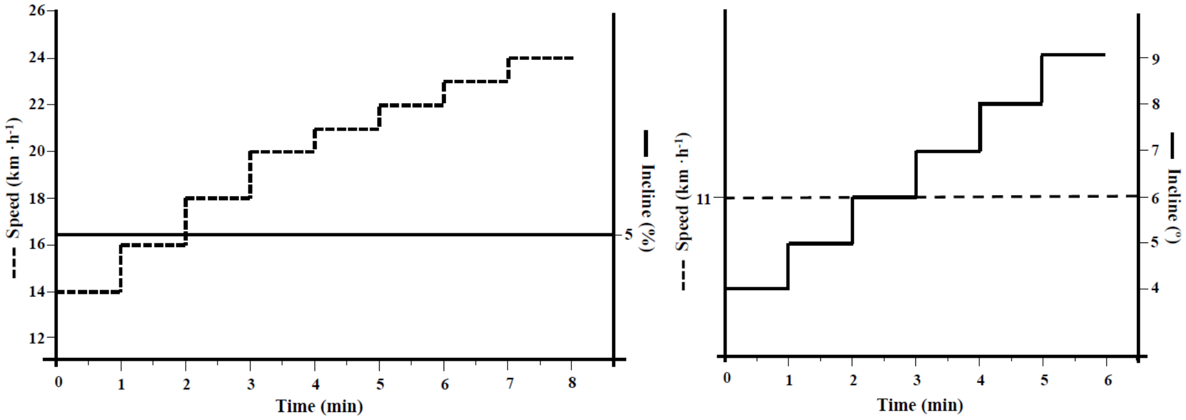

Figure 4. The two different test protocols used to measure peak oxygen uptake in *studies I-IV* (on the left side) where speed was increased at a stable inclination and in *study V* where inclination was elevated at a stable speed.

The tests were considered to be a maximal effort if two of the following three criteria were met: (1) a VO_2 plateau with increasing exercise intensity, (2) respiratory exchange ratio (RER) above 1.10, and (3) BLa exceeding 8 $mmol \cdot L^{-1}$. VO_2 was measured continuously, and the average of the three highest 10-s consecutive measurements defined peak maximal oxygen uptake (VO_{2peak}) or VO_{2max}. VO_2 plateau time was calculated as the time between the start and the end of the VO_2 plateau, according to Brink-Elfegoun et al. (2007). The highest HR values during the tests were defined as peak HR (HR_{peak}). In studies I and III, BLa was measured 1, 3, 6, and 10 min after finishing the test and the highest value determined peak BLa. The skiers skied at 2 $m \cdot s^{-1}$ between the BLa measurements. Lactate recovery was calculated as peak BLa minus BLa 10 min after finishing the test. Furthermore, peak CL was determined during the last completed 30-s work load in *studies II-IV*.

Peak treadmill speed tests (studies I-IV)

Maximal treadmill speed (called V_{max} or V_{peak}) was tested in the G3 technique in incremental tests to exhaustion in *studies I-IV*, initiated with 30 s of medium intensity. Speed was thereafter increased every 10 s by 0.3 m/s until exhaustion (see Figure 5). Peak treadmill speed was calculated as $v = V_f + [(t \cdot T^{-1}) \cdot V_d]$, where V_f is the speed of the last completed workload, t is the duration of the last workload, T is the standard duration of each workload and V_d is the speed difference between the last two workloads (Holmberg et al. 2005).

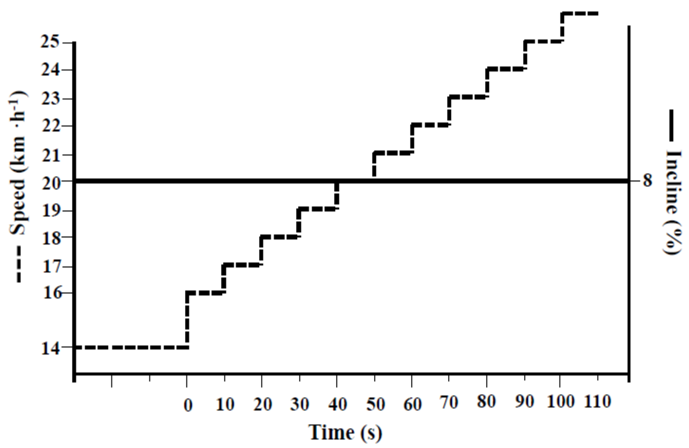

Figure 5. The test protocol used to measure peak treadmill speed where speed was increased at a stable inclination.

Strength tests (studies I-II)

A maximal isometric single-leg squat test was performed under a fixed metal bar for the right and left leg respectively. The bar was regulated for each subject to obtain a knee angle of 125°. The skiers were instructed to push maximally for 3 s. Maximal isometric one-leg strength was taken as the highest average force over one second. An upper body one repetition maximum poling test was performed sitting with locked legs, poling maximally when holding a semi-pronated rowing handlebar with both hands, starting with the arms fully extended with an angle of 125° between the arms and the trunk, and ending with the elbows passing the major trochanter at the hip region. Maximal upper body strength was determined by the heaviest accepted trial, as evaluated by two independent investigators.

In the field

Sprint time-trial races (studies IV-V)

In *study IV*, total performance, performance in nine different sections of terrain, as well as estimated work rates and kinematics in one uphill section were analyzed in the STT. Section times and gross kinematics were measured by video analysis and work rates were estimated based on work against gravity, friction on snow and air resistance (see calculations below). Performance and kinematics were compared between skiing on snow and roller skiing (see Figure 6 for illustrations of ski skating on snow and roller skiing on asphalt). During the simulated STT in *study V*, speed and CR was measured continuously by simultaneous d-GNSS and video analyses during the time trial, HR was measured continuously and BLa was measured 1, 3 and 5 min after the finish. Analyses of the skiers' CL were performed in three specific sections per lap: the two major uphills and a flat section.

Figure 6. Skiing on snow (left side) and roller skiing on asphalt (right side), where similar shoes and poles are used, but the pole tips are modified for skiing on snow and for roller skiing on asphalt.

Maximal speed and acceleration tests (studies I and V)

In *study I*, acceleration on asphalt was performed with the starting position standardized and time measurement started when the skiers' front foot passed the first light sensor at the starting line and stopped when the front foot passed the second light sensor after 30 m. 30m mean acceleration was calculated as $2 \cdot s \cdot t_s^{-2}$ (s = 30 m and t_s = 30 m test time).

Acceleration and speed tests on snow were performed in *study V*: 1) a 20-m maximal speed test using the skating G3 technique where the skiers performed a 100-m run-up before the 20-m measurement zone and were instructed to reach maximal speed when entering the measurement zone, and 2) a 20-m start test using the double poling technique where the skiers used a self-selected starting position and were told to accelerate maximally for 20 m. Both 20-m tests were carried out twice in flat terrain, each separated by four minutes of light activity. The peak speeds from d-GNSS readings were declared as maximal for each skier.

Sprint performance level (studies I-V)

Individual overall FIS points from sprint FIS races provided a quantitative assessment of performance level differences between the skiers. According to FIS (2009), a skier's rank is relative to a 0 point standard established by the top ranked skier in the world. A skier's total points for a given race are determined by adding race points (from comparing the individual skier's time to the winner's time) and race penalty based on the five best competitors' FIS points in the competition.

Efficiency and power calculations

Gross efficiency (*studies I-IV*)

Gross efficiency was calculated as the work rate divided by the total metabolic rate under steady-state conditions during 5-min submaximal stages on the treadmill. The work rate was calculated as the sum of power against gravity (P_g) and friction (P_f), with incorporated calculation of differences between the treadmill's and the skis speed due to the angling of the skis when skating. Moreover, adjusted body masses were calculated due to the active use of the poles, affecting the mean normal forces on the skis (see *studies II and IV* for exact calculations). The aerobic metabolic rate was determined from VO_2 and VCO_2 using the RER value and standard conversion tables (Peronnet and Massicotte 1991). The anaerobic metabolic rate was determined on the basis of the BLa measured immediately after the test as described by di Prampero and Ferretti (1999). An increase in BLa of 1 $mmol \cdot L^{-1}$ was considered equivalent to 3 $mL \cdot kg^{-1}$ of oxygen consumed with an RER value of 1.0.

Power balance model (*study IV*)

To estimate the contribution of aerobic and anaerobic power on one uphill section of the STT in *study IV*, a modified power balance model was employed (de Koning et al. 2005). Anaerobic power (P_{an}) was calculated as total work rate (P_{tot}) minus peak aerobic power (P_{ae}), with P_{ae} being the product of peak aerobic metabolic rate (Q_a, i.e., the energetic equivalent of VO_2 at VO_{2peak}) and GE (Eq. I). Accordingly,

Eq. I

$$P_{an} = P_{tot} - P_{ae} \quad \text{(Ia)}$$

$$P_{an} = P_{tot} - Q_a \cdot GE \quad \text{(Ib)}$$

P_{tot} was estimated for one uphill section performed straightforward at stable inclination and speed (< 5% range) over this entire section. P_{tot} was calculated as the sum of power against gravity (P_g), friction (P_f) and air drag (P_d), with v being the average speed, α the angle of incline, μ_s the coefficient of friction, p the density of the air, A the exposed frontal area of the skier and C_d the drag coefficient (Eq. II). Because the skis angled outwards while skating and skiers apply their body mass to the poles while poling, thereby reducing the mean normal force on the skis during a cycle, the work rate calculations were adjusted for this in *study IV*.

Eq. II

$$P_{tot} = P_g + P_f + P_d \quad \text{(IIa)}$$

$$P_{tot} = m \cdot g \cdot \sin(\alpha) \cdot v + (1 - 0.05) \cdot m \cdot g \cdot \cos(\alpha) \cdot \mu_s \cdot v_{ski} + 0.5 \cdot p \cdot v^3 \cdot A \cdot C_d \quad \text{(IIb)}$$

Technique definitions and kinematics

In *studies IV-V*, the different skiing techniques were designated as G2, G3, G4, G5, G6 and G7 (see Figure 7). G2, a technique for skiing uphill, involves an asymmetrical double pole push in connection with every other leg push. G3, used on moderate inclines and level terrain, involves one double pole push together with every leg push. G4, a symmetrical double pole push in connection with every other leg push is used on level terrain. G5 is downhill skating in a low position with only using the legs. G6, a technique for curves in which leg work is performed with or without poling and G7 downhill skiing in a low stance position without leg or pole push. A gear transition was defined as the first leg stroke in the new technique after a change.

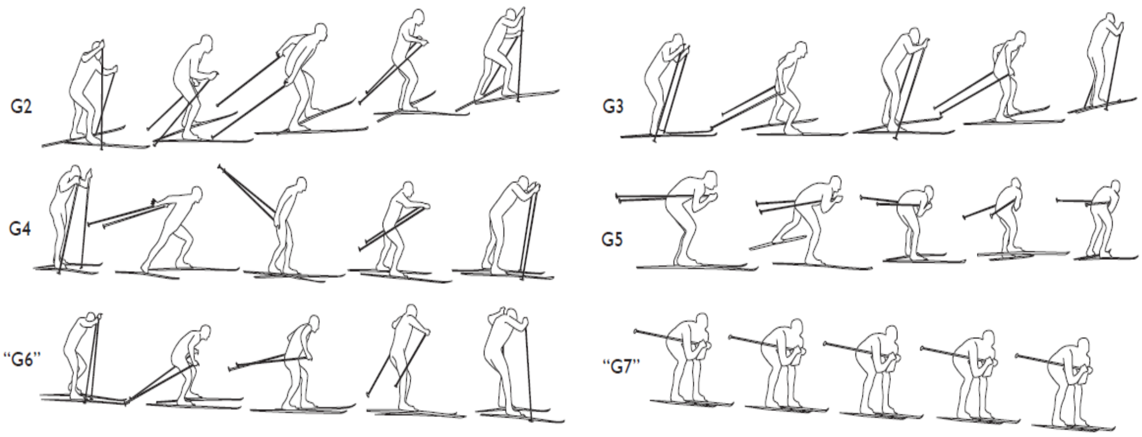

Figure 7. The six main sub-techniques ("gears") used in the skating technique in cross-country skiing.

In *studies II-V*, one movement cycle was defined as a complete left and right leg stroke, together with the contingent poling action according to the specific technique. One cycle was defined for every second pole plant of the left pole and all kinematic variables were averaged over 6 cycles. Cycle time and CR were measured between every second pole plant. CL was determined by dividing the subject's speed by CR. All further variables in *study IV* on the treadmill were analyzed according to Stöggl and Müller (2009). The pole push-off time started with the pole plant and ended when the pole lost ground contact. The push-off time of the leg started with pole plant and ended when the roller ski lost ground contact. Recovery times for the legs and the poles were calculated as cycle time minus push-off time.

Training diary analyses

Training history in *study I* was recorded based on the skiers' training diaries and categorized into different intensity zones according to the session goal method (Seiler and Kjerland 2006). Endurance training intensity was monitored by heart and categorized into three intensity zones, according to a modification of the Norwegian Olympic system's intensity scale: 1) low intensity (LIT; 1.5 to 2.5 mmol·L^{-1} BLa, 60-81% of HR_{max}), 2) moderate intensity (MIT; 2.5 to 4 mmol·L^{-1} BLa, 82-87% of HR_{max}), and 3) high intensity (HIT; > 4 mmol·L^{-1} BLa, > 88% of HR_{max}). These intensity zones were individualized on the basis of a traditional test protocol for Norwegian cross-country skiers (Ingjer 1991). If an individual's intensity zone, based on % of HR_{max} differed considerably from that based on BLa, the average was used to determine the individual zone. In addition, maximal speed training (-30 s), strength training and training time in the skating technique (roller skiing and skiing) were recorded. The training duration registered during interval training, as well as strength and speed training included rest intervals according to the Norwegian Ski Federations standards.

Statistics

In all studies the data were checked for normality and presented as mean and standard deviation (SD). *Studies I and IV-V* presented correlations between variables analyzed using Pearson's product-moment correlation coefficient (r) and Spearman's rho when variables deviated from a normal distribution. Linear regression lines were compared in accordance with Crowder and Hand (1990) in *studies I and III*. In *study IV*, stepwise multiple regression analyses were used to predict STT performance from physiological and kinematic variables. Potential interactions and confounders were analysed according to Kleinbaum et al. (1998). The coefficient of variation ($100 \cdot SD \cdot mean^{-1}$) within each section was also calculated in *studies IV-V*. In *studies I-III*, comparisons between groups were analyzed using the independent t-test procedure. The one-way ANOVA for repeated measures were used in *studies II and V*, followed up by Tukey's HSD post hoc test in *study V* and by an F test for the residual sum of squares, using pooled and individual values according to Crowder and Hand (1990) in *study II*. When the selected variables deviated from normal distribution, the Wilcoxon signed-rank test was applied (*study V*). Intraclass correlation coefficients tested repeated measurements of the dependent variables in *study IV*. Statistical significance was set at $P < 0.05$ in all studies. Bonferroni alpha levels, adjusted for the number of variables tested against each other, were used to examine correlations in *study IV*. All statistical tests were processed using SPSS 11.0 Software for Windows (SPSS Inc., Chicago, USA).

CHAPTER III
RESULTS

Study I: The physiology of world-class sprint skiers

Specific aims and design

The purposes of the study were 1) to compare physiological characteristics in world-class and national level sprint cross-country skiers, and 2) to examine determinants of sprint skiing performance.

To measure physiological response and performance, three treadmill roller ski tests were performed: 1) a submaximal test, 2) a VO_{2peak} test and 3) a V_{peak} test. The skiers were also tested for acceleration, as well as lower and upper body maximal strength. The standard of sprint skating performance was determined by FIS points, and the training distribution was quantified from training diaries.

Results

World-class skiers had 8% higher VO_{2peak} and performed twice as long VO_2 plateau time at the VO_{2peak} test compared to national level skiers (Figure 8, both $P < 0.05$).

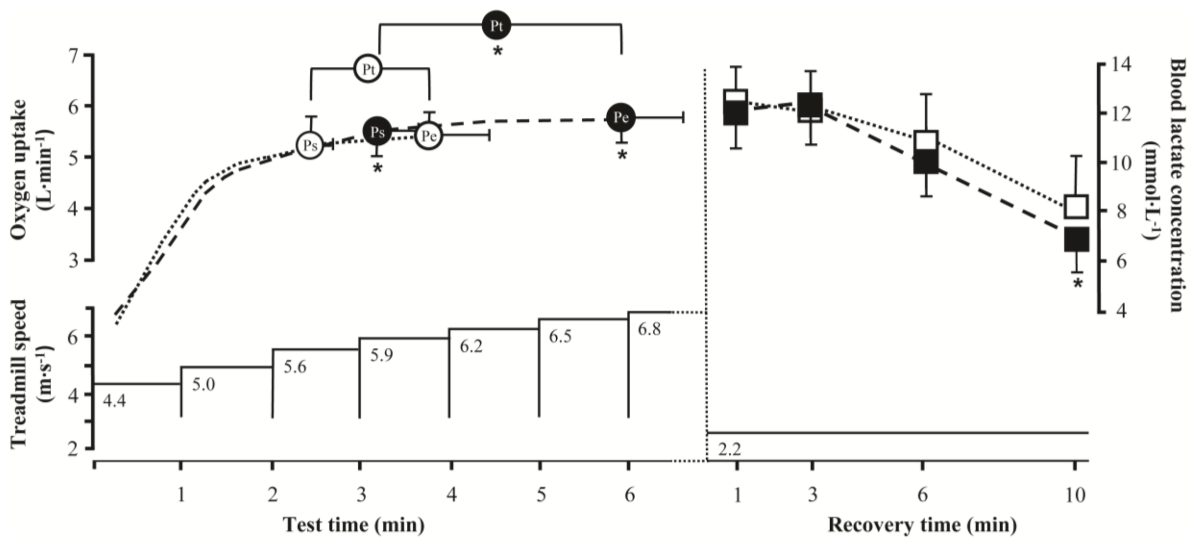

Figure 8. Oxygen uptake (circles) measured continuously during an incremental protocol to exhaustion (VO_{2peak} test), and blood lactate concentration (squares) measured directly after finishing the test in eight world-class (filled symbols) and eight national level (open symbols) sprint cross-country skiers (vertical bars indicate SD). Ps, start of VO_2 plateau; Pe, end of VO_2 plateau; Pt: VO_2 plateau time. Significant group differences, * $P < 0.05$.

World-class skiers did not differ in work economy, but they showed higher GE at the submaximal test than the national level skiers ($P < 0.05$). Also, an 8% higher V_{peak} was shown in world-class skiers ($P < 0.05$). However, world-class and national level skiers did not differ in acceleration, and upper and lower body maximal strength.

VO_{2peak}, GE, and V_{peak} significantly correlated with performance (i.e., TTE and FIS points) in all skiers when pooled (all $P < 0.05$). However, the groups showed different regression lines and most within-group correlations were not significant.

World-class skiers performed more low and moderate-intensity endurance training and speed training (Table 2, both $P < 0.05$). See Appendix II for a practical example of a training week for a world-class skier during this period.

Table 2. Total training performed in the six months previous to the laboratory measurements in world class and national level sprint cross-country skiers (mean and SD).

	World-class (*n* = 8)		**National level (*n* = 8)**	
	Training hours	**% of total training**	**Training hours**	**% of total training**
LIT	340 ± 23**	76.4 ± 4.6	254 ± 94	73.1 ± 12.0
MIT	29 ± 12**	6.5 ± 2.2*	14 ± 6	4.4 ± 2.4
HIT	19 ± 3	4.4 ± 0.8	19 ± 8	5.6 ± 2.1
Speed	16 ± 7**	3.7 ± 1.5*	7 ± 3	2.3 ± 1.2
Strength	39 ± 14	8.8 ± 2.9	31 ± 14	9.4 ± 3.7
Total	445 ± 27**	100	341 ± 90	100

LIT, low intensity endurance training; MIT, moderate intensity endurance training; HIT, high intensity endurance training. Significant group differences, * $P < 0.05$ and ** $P < 0.01$.

Study II*: *Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers

Specific aims and design

The purpose of the study was to examine metabolic rate and GE in roller ski skating, from moderate to high work rates, while also comparing world-class and national level sprint skiers. Furthermore, we measured gross kinematics (i.e., cycle length and rate) and the physiological characteristics (i.e., maximal speed, maximal strength, and VO_{2peak}) of the skiers.

Physiological responses and kinematics were measured during three submaximal 5-min stages at 14, 16 and 18 km·h^{-1} on a 5% incline while roller ski skating on a treadmill. Furthermore, the skiers were tested for TTE, VO_{2peak} and maximal speed on the treadmill, as well as maximal leg and upper body strength in the laboratory. Performance level in sprint skating on snow was determined by FIS points.

Results

World-class skiers did not differ from national level skiers in VO_2 or aerobic metabolic rate, but showed lower RER, BLa and anaerobic metabolic rate at all given speeds (all $P < 0.05$). GE was therefore better in world-class skiers at all speeds (Figure 9, $P < 0.05$). The small effect of speed on GE was not significant ($P = 0.073$).

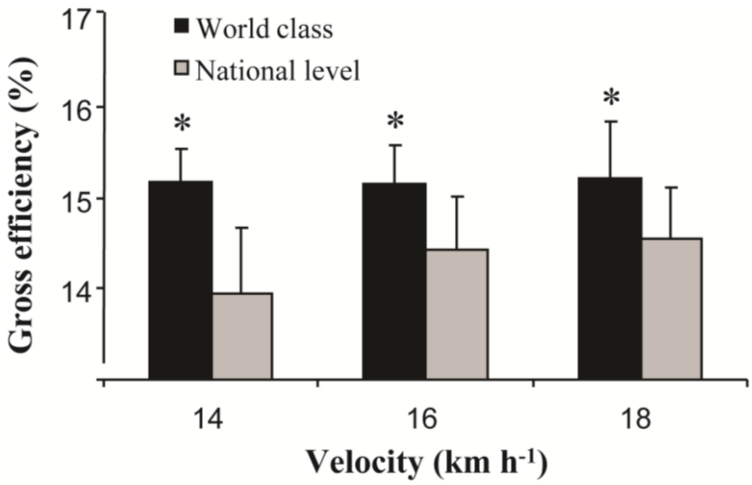

Figure 9. Gross efficiency in world-class and national level sprint cross-country skiers during 5-min stages at 14, 16 and 18 km h^{-1} at a 5% incline using the skating G3 technique in treadmill roller skiing (mean and SD). Significant differences between groups are indicated by * = $P < 0.05$.

The GE at approximately 15% in this study, is close to what is found in speed skating (de Koning et al. 2005) and slide boarding (Leirdal et al. 2006), but lower than in cycling which Ettema and Lorås (2009) have measured at around 20%.

Furthermore, the present study reveals a general linear relationship and strong individual trends between work rate and metabolic rate, with no significant effect of work rate on GE (Figure 10A-B).

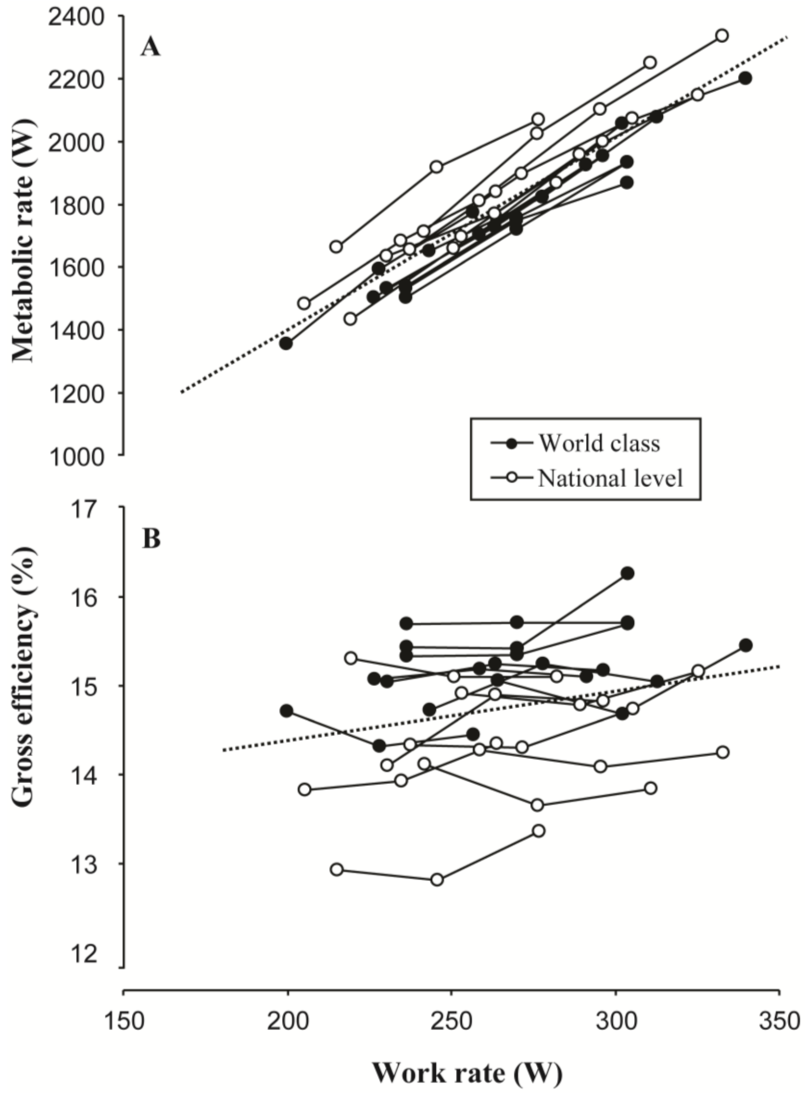

Figure 10A-B. Metabolic rate (A) and gross efficiency (B) plotted against work rate (individual data) in world-class and national level sprint cross-country skiers during 5-min stages at 14, 16 and 18 km·h^{-1} at a 5% incline using the skating G3 technique in treadmill roller skiing. Trend lines (dashed lines) are estimated based on linear regression for the entire data set.

The analysis for repeated measures revealed that all subjects had a similar slope of the regression line (P = 0.595), but the offset (regression intercept) varied (P < 0.001). The same conclusion applied when comparing the two groups (slope: P = 0.872; offset: P < 0.001).

As seen in cycling, a linear metabolic–work rate relationship with an offset also exists. Such data provides a curvilinear relationship between GE and work rate as shown in Figure 11. Therefore, GE plateaus above a certain work rate and the further effect of an increased work rate on GE is minimal.

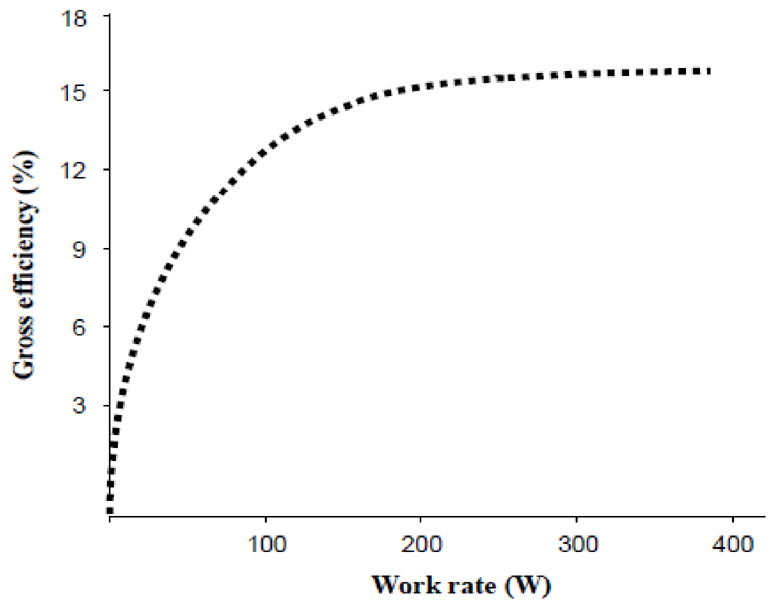

Figure 11. A theoretical model of gross efficiency (GE) plotted against work rate for a cross-country skier during treadmill roller skiing in the skating G3 technique.

World-class skiers skated with longer CL at lower CR at all submaximal speeds and longer CL at similar CR at peak speed than the national level skiers (Figure 12A-B, all $P < 0.05$). In addition, world-class skiers also had higher maximal speeds, VO_{2peak} and TTE (all $P < 0.05$).

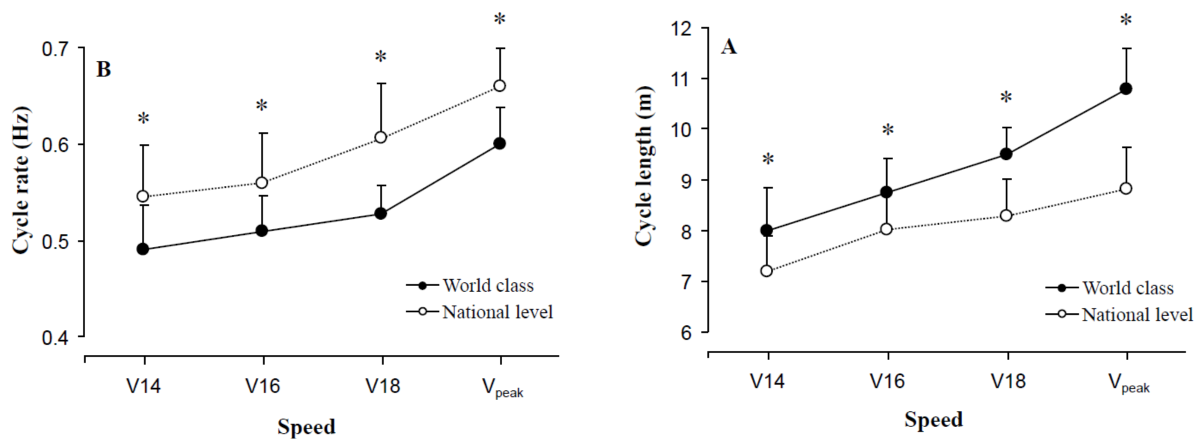

Figure 12A-B. Cycle length (A) and cycle rate (B) in world class (filled circles) and national level (open circles) sprint cross-country skiers during 5-min stages at 14, 16 and 18 $km \cdot h^{-1}$, as well as at the skiers' last completed speed at the VO_{2peak} test (V_{peak}), at a 5% incline using the skating G3 technique in treadmill roller skiing. Vertical bars indicate SD. Significant differences between groups are indicated by * = $P < 0.05$.

Study III*: *Which physiological and kinematic variables determine gender differences in sprint skiing performance?

Specific aims and design

The present study compared performance, physiological and kinematic characteristics of male and female world-class sprint cross-country skiers.

All subjects were tested for performance, physiological response and kinematics using three treadmill roller ski tests employing the G3 skating technique: 1) three 5-min submaximal stages, 2) a ~5-min maximal aerobic capacity (VO_{2max}) test, and 3) a ~1-min maximal treadmill speed (V_{max}) test.

Result

Men reached 17% higher peak speed than women in both the ~5 min VO_{2max} and the ~1 min V_{max} incremental tests (both $P < 0.05$). When normalized for lean body mass, the gender differences in peak work rate in both tests were reduced by 50% compared to when normalized for total body mass, but remained significant (Figure 14 A-B, all $P < 0.05$). Peak work rate in the VO_{2max} test is plotted against VO_{2max} in Figure 13.

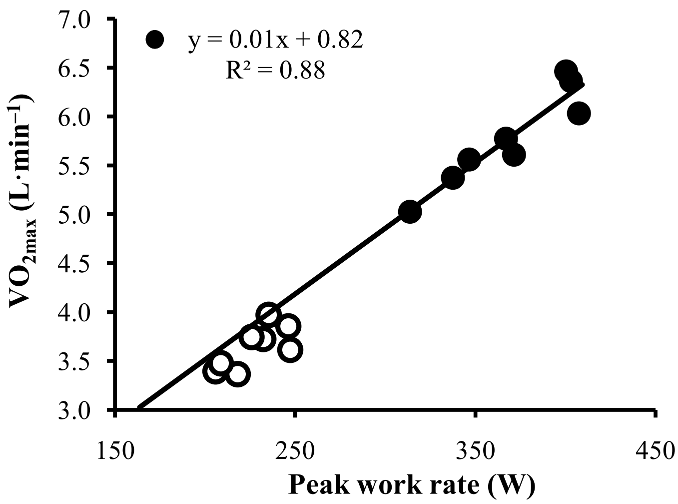

Figure 13. VO_{2max} plotted against peak work rate on the same test in male and female elite sprint cross-country skiers while treadmill roller-ski skating. Individual data and significant trend lines, based on linear regression, are shown for men (filled circles and straight line) and women (open circles).

VO_{2max} was 14% and 7% higher in males when normalized for total and lean body mass, respectively (Figure 14C-D, both $P < 0.05$). Women utilized around 5% higher fraction of VO_{2max} at OBLA ($P < 0.05$).

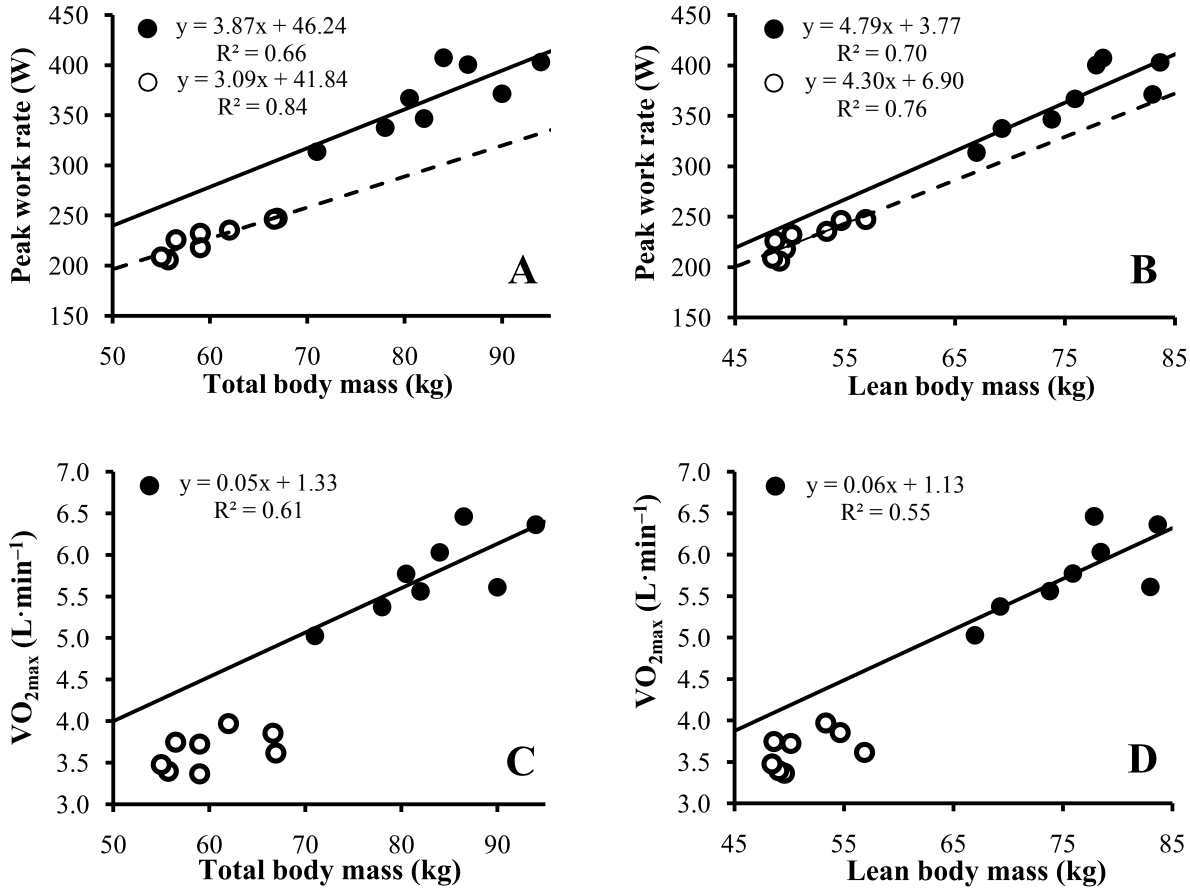

Figure 14A-D. Peak work rate and VO_{2max} plotted against total and lean body mass in male and female elite sprint cross-country skiers while treadmill roller-ski skating. Individual data and significant trend lines based on linear regression are shown for men (filled circles and straight line) and women (open circles and dashed line).

The relationship between metabolic rate and work rate at the same speed was strongly linear within both genders, and there were no significant gender differences between slopes or intercepts (see Figure 15). Gross efficiency and work economy at submaximal speed did not differ between genders. Furthermore, male skiers employed 11% longer cycle lengths at lower cycle rates at the same absolute submaximal speed, and 21% longer cycle length at similar cycle rates at peak speed as compared to the females (all $P < 0.05$).

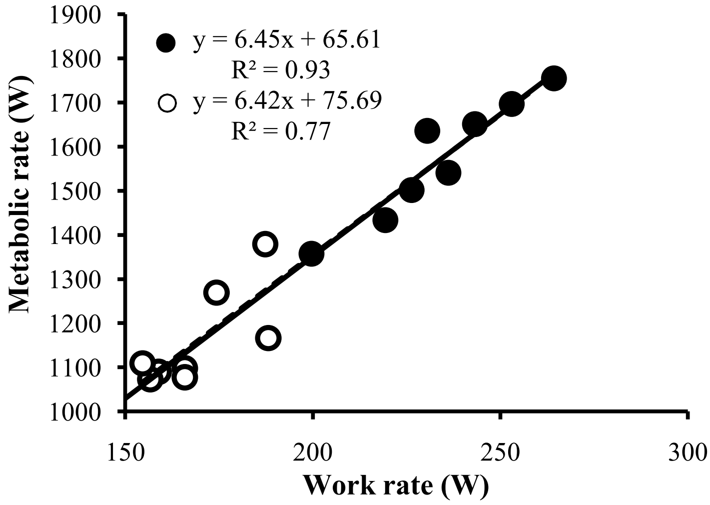

Figure 15. Submaximal metabolic rate plotted against work rate in male and female elite sprint cross-country skiers while treadmill roller-ski skating. Individual data and significant trend lines, based on linear regression, are shown for men (filled circles and straight line) and women (open circles and dashed line).

Study IV: *Analysis of a sprint ski race and associated laboratory determinants of world-class performance*

Specific aims and design

The present study was designed to investigate an international FIS sprint skating competition in cross-country skiing for 1) STT performance in relationship to the amount of time spent on different terrains, 2) work rate and kinematics in uphill terrain and 3) the relationship of these parameters to physiological and kinematic characteristics utilizing roller ski skating in the lab.

Initially, a sprint time-trial was investigated with respect to overall performance and time spent on nine different sections of terrain, as well as kinematics and estimated work rates for one section representative of the uphill terrain. One week later, the subjects were assessed for physiological and kinematic variables while treadmill roller ski skating in the laboratory.

Results

Uphill, flat, downhill and curve section times represented 36%, 27%, 30% and 7% of STT time, respectively. The relationship between time spent on different sections of terrain and total STT performance is shown in Figure 16A. Specifically, the time spent on the last two uphill and last two flat sections correlated with STT performance (all r = ~-0.80, $P < 0.001$). Section time was negatively correlated with CL (r = -0.75, $P < 0.01$) and the estimated work rate was ~160% of peak aerobic power in the selected uphill section.

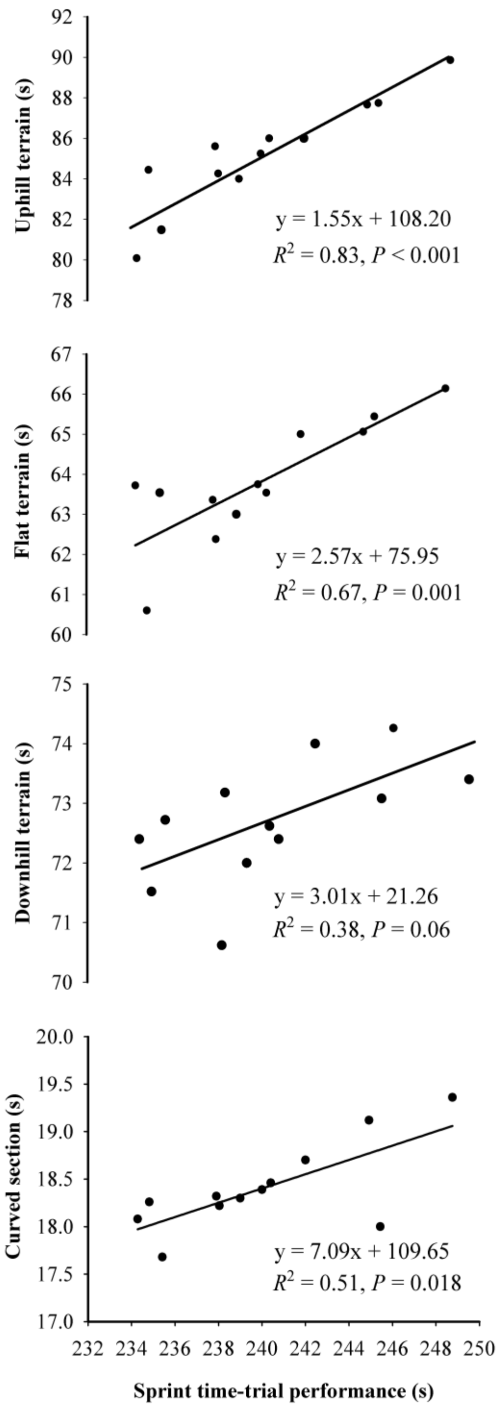

Figure 16A. Sprint time-trial performance in relationship to the time spent in different sections of terrain for the 12 elite male sprint cross-country skiers. The data points represent the individual skiers and the lines were obtained by linear regression.

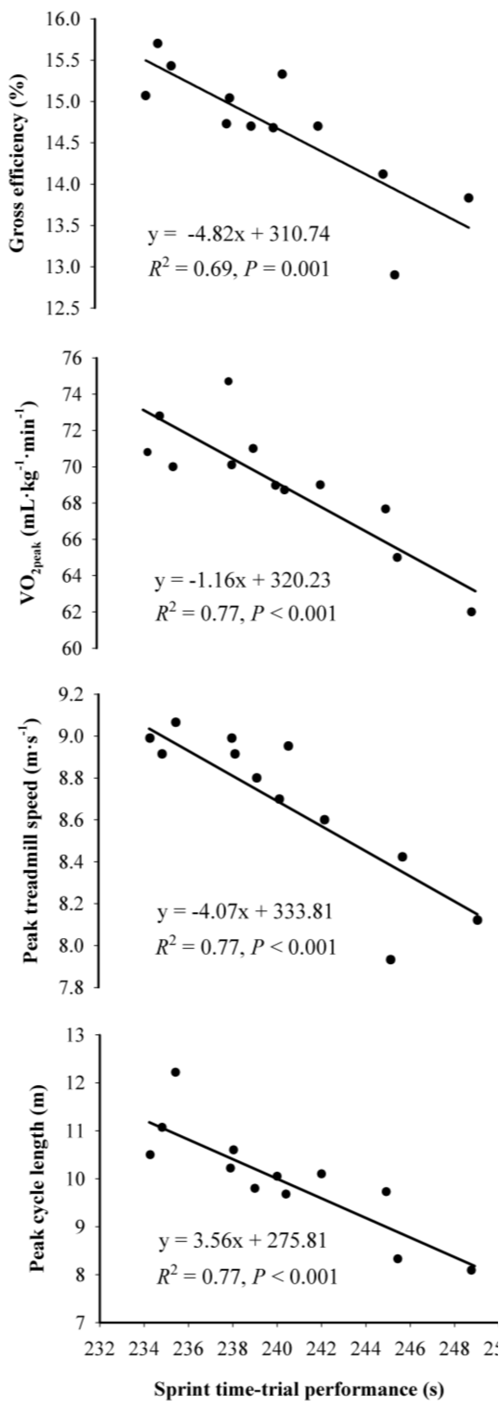

Figure 16B. Sprint time-trial performance in relationship to physiological and kinematic variables for the 12 elite male sprint cross-country skiers. The data points represent the individual skiers and the lines were obtained by linear regression.

VO_{2peak}, GE, V_{peak} and peak CL correlated negatively with STT performance (Figure 16B, all r= ~-0.85, $P < 0.001$). Specifically, VO_{2peak} and GE correlated with the last two uphill and last two flat section times, whereas V_{peak} and peak CL were correlated with times spent on uphill, flat and curve sections during the entire STT (all r = ~-0.80, $P < 0.01$).

Study V*: *Analysis of Sprint Cross-Country Skiing using a Differential Global Navigation Satellite System

Specific aims and design

The aims of the study were: 1) to examine skiing velocities, gears and CR during a STT and their relationship to performance using a differential global navigation system together with 2-D video recording and 2) to examine the relationship of sprint time-trial performance with aerobic power, maximal skiing speed and body composition.

First, the skiers' body composition and VO_{2max} in the laboratory were measured. Thereafter, three cross-country skiing performance tests on snow were performed: two 20-m maximal speed tests followed by a 1.43 km skating sprint time trial (Figure 17).

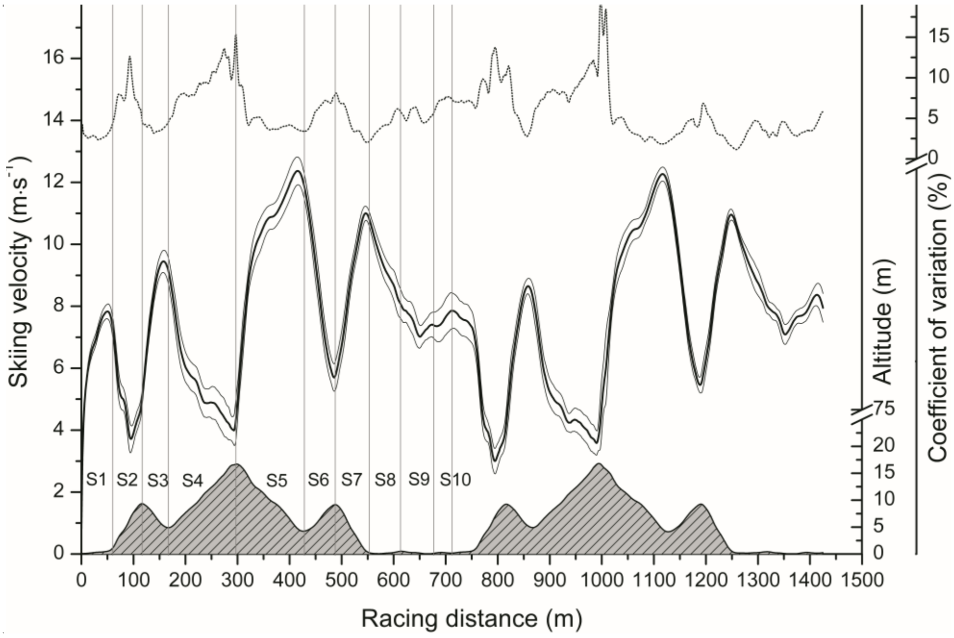

Figure 17. The a) skiing speed (solid line), b) altitude profile (grey area under the curve) and c) coefficient of variation (dashed line) plotted against horizontal distance (m) for both laps.

Results

The STT encompassed a large speed range (2.9-12.9 m·s-1) and multiple transitions (21-34) between skiing gears (see Figure 17 and 18A-D for more detailed distributions).

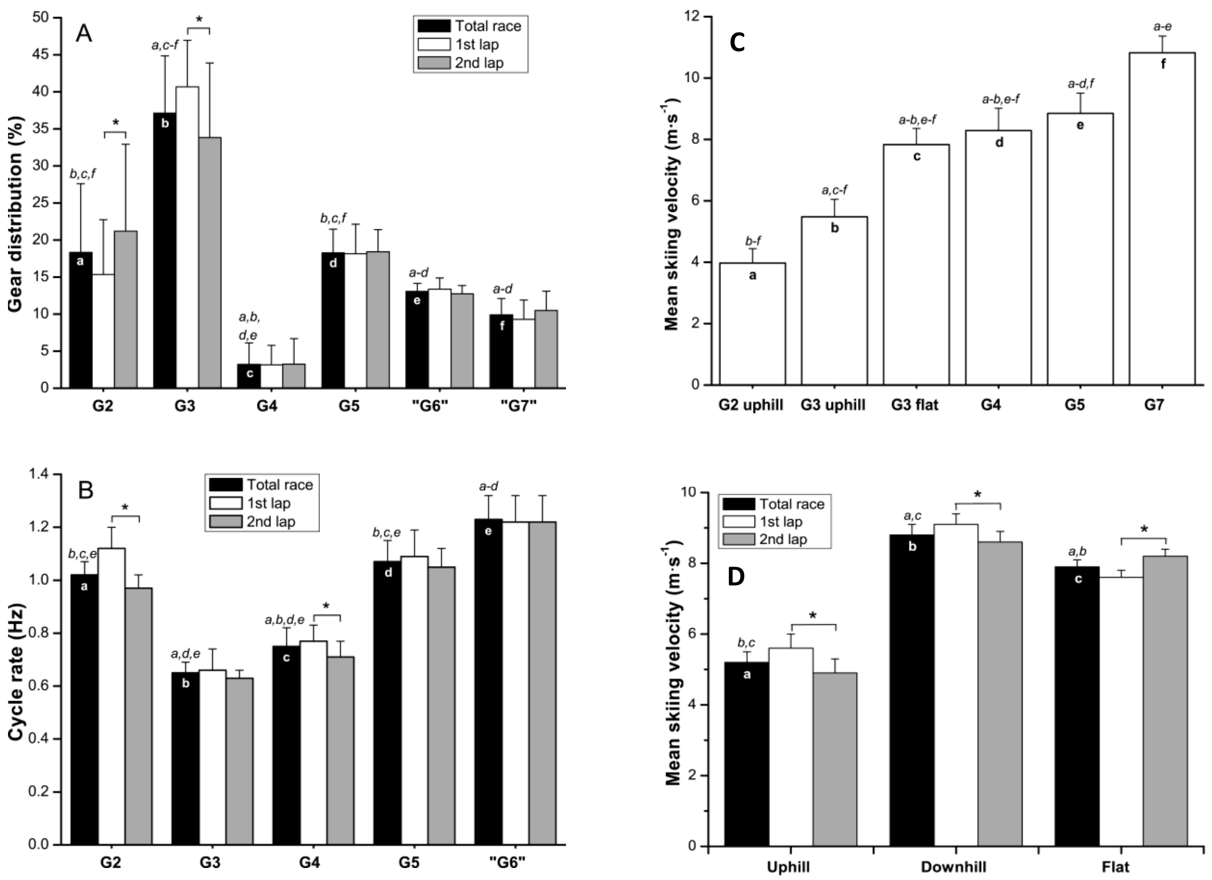

Figure 18A-D. A) Gear distribution, B) cycle rate and C) mean speed within the different skating techniques and D) racing speed in different sections of terrain in 9 elite skiers performing a sprint time-trial. See paper V Figures 3-5 for explanations of the symbols indicating significant differences between variables.

Skiing speed in the uphill sections was related to gear selection between G2 and G3. STT performance was most strongly correlated to uphill time ($r = 0.92$, $P < 0.05$), the percentage use of G2 ($r = -0.72$, $P < 0.05$), and double poling maximal speed ($r = -0.71$, $P < 0.05$). The speed decrease in the uphills from the first to the second lap was correlated with VO_{2max} ($r = -0.78$, $P < 0.05$). Maximal speed in double poling and G3 were related to percent of racing time using G3.

CHAPTER IV

GENERAL DISCUSSION

The current thesis provides new information on the physiological and biomechanical aspects of skating performance in sprint skiing. The world's best sprint skiers were examined in the laboratory and during an international sprint competition on snow. This thesis developed models for measuring work rate and mechanical efficiency during treadmill roller skiing; these models were then modified so that they could also be utilized for skiing on snow. Also examined for the first time within this thesis were the characteristics of female sprint skiers and the gender differences in modern cross-country skiing. Furthermore, the specific speed, and the distribution of techniques and kinematics were examined during a competition on snow through the use of an advanced differential global navigation satellite system.

These five studies together demonstrate that world-class skiers have higher maximal oxygen uptake, peak speed capacities, and gross efficiency during treadmill roller skiing than national level skiers. In addition, world-class skiers tended to ski with longer cycle lengths at both submaximal and peak speeds. These variables strongly correlated to sprint time-trial performance on snow, when the uphill and flat terrain in the last stages of the race had the greatest impact on overall performance. The laboratory-measured physiological and biomechanical capacities were also most important for the last stages of the sprint race. Although performance differences between men and women were slightly greater in sprint skiers than was expected based on previous studies from other comparable sports, the majority of the differences attributed to gender could be explained by maximal oxygen uptake and fat percentage.

Characteristics of sprint skiers

The current thesis provides novel information on the physiological and kinematic differences between male world-class and national level sprint skiers (*studies I-II*), and how these factors impact sprint performance (*studies I and IV*). This research also considered similar issues with respect to gender among elite sprint skiers (*study III*). The combined analyses of laboratory measurements and performance in different parts of the sprint races on snow in *studies IV-V* allowed for further specification of the importance of the different capacities to different aspects of the races. The following characteristics pertain exclusively to male sprint skiers except within the section which specifically addresses gender differences and female characteristics and is noted as such.

Physiological characteristics

In general, the studies demonstrated that both aerobic characteristics and maximal speed abilities are important factors in sprint skiing performance. *Studies I-II* revealed for the first time in cross-country skiing a sharp difference in VO_{2peak} and VO_2 plateau time between world-class and national level sprint skiers. In *study IV*, VO_{2peak} significantly impacted the overall STT performance and was specifically linked to performance on uphill and flat terrain, particularly in the latter stages of the race. Although *study V* revealed an insignificant correlation between VO_{2peak} and overall STT performance, it nonetheless showed that VO_{2peak} affected the ability to maintain uphill speed on the second lap of the STT.

The importance of aerobic characteristics for sprint skiing performance contrasts with the findings from the studies conducted by Stöggl et al. (2006; 2007a) on classical sprint skiing. Other studies on distance cross-country skiing (Holmberg et al. 2007; Ingjer 1991; Saltin and Astrand 1967), as well as for elite athletes in sports with comparable racing times as sprint skiing, such as running, rowing and kayaking (Brandon 1995; Michael et al. 2008; Secher 1993), have demonstrated the significance of VO_{2max} to performance. The importance of VO_{2peak} on sprint skiing performance is further supported by two recent studies involving the skating technique, which demonstrate that high aerobic power is associated with performance throughout a succession of heats (Mikkola et al. 2010; Vesterinen et al. 2009). The results from our studies shows VO_{2peak} to be important for the qualification race as well, and particularly for the ability to maintain speed during a STT. These findings are not surprising, as Gastin (2001) revealed for sport performances with similar racing times to a single sprint heat that aerobic energy release accounted for 70 to 80% of the total energy. It is also likely that the aerobic contribution further increases during multiple high intensity periods of work (Glaister 2005). Thus, from a physiological point of view, the term “sprint” skiing seems somewhat misleading because of the greater role of aerobic capacities on sprint skiing performance.

The insignificant relationship between VO_{2peak} and overall STT performance revealed in *study V* contrasted with the results from *studies I-II and IV* where VO_{2peak} was a highly significant differentiator between performance levels and significantly related to STT performance. The differences between the importance of VO_{2peak} in *studies I-II and IV* versus *study V*, may be caused by a longer duration of the STT in *study IV*. Also, a more mixed group of both sprint and distance skiers were among the subjects in *study V* compared to only specially trained sprint skiers in *study IV*. When comparing VO_{2peak} in sprint and distance skiers with similar performance levels (unpublished data from our lab), VO_{2peak} seems slightly more important for distance skiers. Compared to other studies of world-class distance skiers (Bergh 1987; Holmberg et al. 2007; Ingjer 1991), the world-class sprint skiers under study in this thesis showed lower VO_{2peak} in $mL \cdot kg^{-1} \cdot min^{-1}$. However, VO_{2peak} in $L \cdot min^{-1}$ sprint skiers seems similar to the earlier findings of distance specialists. Sprint skiers are challenged in generating high speeds, which might favor heavier skiers with more muscle mass. A high VO_{2max} in absolute values might therefore be a prerequisite for performance in sprint skiing in order to compensate for a higher body mass. Also, a flatter terrain profile in sprint skiing may reduce the negative effect of a higher body mass, as earlier indicated by Bergh and Forsberg (5).

World-class skiers show a longer VO_2 plateau time than national class skiers, as demonstrated in *study I*. This difference may be influenced by fractional utilization of oxygen and skiing efficiency, which have been shown to contribute to the level of success of athletes in most endurance sports (Joyner and Coyle 2008). However, VO_2 plateau time may also be influenced by differences in the ability to generate anaerobic power. In *studies I and IV* it was hypothesized that a higher contribution of anaerobic energy separates sprint skiers of different performance levels, as Stöggl et al. (2007a) had previously suggested. An improved method of measuring anaerobic work is still needed in order to conclude that anaerobic capacity differentiates between different performance levels (Bangsbo 1998).

An interesting physiological aspect of cross-country sprint skiing is the ability for athletes to recover during the downhill sections of the races as well as between the heats. In *study I* a better BLa recovery was evident in world-class compared to national level skiers. In *study IV* the importance of a fast recovery was highlighted by the high anaerobic contribution during the uphill part of the race and a limited time to recover in the downhill parts. Faster skiers were not significantly faster downhill, but maintained speed better during the race. It was hypothesized that a fast recovery downhill may be linked to performance in the following parts of the race. The ability to reduce BLa after high-intensity work has been shown to relate to performance in cyclists during prolonged exercise with variable intensity (Björklund et al. 2007).

Overall, the current thesis also demonstrate the importance of high-speed abilities for STT performance, illustrated by differences in peak treadmill speed between world-class and national level skiers in *studies I and II*, as well as the relationship of V_{peak} on sprint performance in *study IV*. The relationship between this type of incremental treadmill maximal speed test and sprint performance are supported by other studies (Stöggl et al. 2006; 2007a). Specifically in *study IV*, V_{peak} correlated negatively with the time spent on all uphill, flat and curved sections of the STT, except for the initial section of the course. The non-significant correlation between V_{peak} and the initial section may indicate that faster skiers used a pacing strategy in order to use a lower percentage of their speed capacity during the first section of the STT. The low influence of the initial section on overall performance may also reflect that skiers' capacity to accelerate is not a differentiating factor among elite sprint skiers, as pure acceleration and maximal strength did not differ between the groups or relate to any performance variables in *studies I-II*. These findings contrast with those of Stöggl et al. (2006; 2007b) investigating a more mixed group of both sprint and distance skiers compared to the subjects in *studies I-II*. In *study V*, maximal speed and acceleration did not correlate to overall STT performance. However, maximal speed in G3 was related to the percentage of time using G3 in the STT and acceleration in double poling correlated with performance in the uphill sections of the STT, which may reflect the greater role of upper body power for uphill performance in skating. A large proportion of total propulsive forces in the forward direction are shown to be generated from the upper body during uphill skating (Smith 1992), which is more pronounced when using G3 compared with G2 (Millet et al. 1998e; Smith 1992).

No relationships between body composition and overall STT performance were revealed during the course of this research. One specific correlation, however, was found in *study V*, with a relationship between the skier's absolute values of lean body mass and performance in the starting section of the STT. The non-significant effects of body composition in the current thesis may reflect a homogenous group of skiers; in more heterogeneous group of skiers, the influence of body composition on racing performance appears to be more pronounced. For example, a positive relationship between absolute lean body mass and performance in a 10-km skating distance race was found in junior skiers (Larsson and Henriksson-Larsén 2008). Furthermore, the skier's absolute lean mass in the arms was related to the overall race outcome and the relative lean arm mass was correlated with performance on the uphill sections of the track. The influence of body mass on performance may also depend on the distribution of flat, downhill and uphill terrain, and on the steepness of the uphill and downhill parts. However, Bergh and Forsberg (1992) states that heavier skiers are faster in all types of terrain except the steep uphill, but they also suggest that other factors are more important than body mass for cross-country skiing performance. Future studies should evaluate how differences of muscle mass in the upper- and lower extremities and related propulsive power versus energy cost of this extra body mass influence cross-country skiing performance.

Work economy and efficiency

This thesis also provides a greater understanding on the role of mechanical efficiency on cross-country skiing performance and highlights GE as an important determinant of sprint performance. World-class skiers did not differ from national level skiers in aerobic metabolic rate in *study II*, but the world-class skiers demonstrated a lower anaerobic metabolic rate and higher GE at submaximal speeds. Additional results from *studies I and IV* revealed a greater importance of GE to treadmill performance and to STT performance on snow than previously known. In *study IV*, GE was most strongly related to performance on uphill and flat terrain during the latter part of the STT. On these latter uphill and flat sections of the race the G3 technique was used at an incline similar to when GE was measured. This relationship might seem surprising because GE was measured at a work rate well below the competition work rate; however, the curvilinear relationship between GE and work rate as shown in Figure 11 indicates that inter-individual GE measurements from the submaximal test have minimal errors when transferred to a competition work rate.

The current literature on the role of work economy and efficiency on performance in other endurance sports shows contradictory results in the literature. For example, a consensus exists in running that better athletes have better work economy (Saunders et al. 2004). Yet, in cycling this relationship is less clear, and higher efficiency in better cyclists may largely be explained by higher work rates (Ettema and Loras 2009). Taking into consideration this difference between running and cycling, one may hypothesize that the complexity of the movement plays a role in the relationship between efficiency and performance level. Because of the technical complexity in cross-country skiing, it may be hypothesized that the magnitude of muscle power transferred into external power and speed may differ between skiers of different levels. Performance will therefore be affected by efficiency.

Several previous studies have examined work economy in cross-country skiing (Hoff et al. 1999; Hoffman 1992; Hoffman et al. 1990a; Hoffman et al. 1990b; Hoffman et al. 1994; Mahood et al. 2001; Mikkola et al. 2007; Millet et al. 1998a; Millet et al. 2003; Millet et al. 1998b; Millet et al. 2002; Osteras et al. 2002). However, one advantage of using efficiency is the possibility to compare the results across speeds and slopes and with other locomotion. The efficiencies found in *studies I-IV* are close to those results found in speed skating (de Koning et al. 2005) and slide boarding (Leirdal et al. 2006) with ~15%, but lower than results observed in cycling with ~20% (Ettema and Loras 2009).

In the present thesis, we adopted the standpoint that any baseline subtraction is essentially flawed (Cavanagh and Kram 1985; Ettema and Loras 2009), and we used GE to express efficiency of the whole body as an energy converting system that works against environmental resistance. *Study II* revealed a general linear relationship and strong individual trends between work rate and metabolic rate. This relationship appears consistent outcome with other studies (Ettema and Loras 2009) and may be regarded as an example of the Fenn effect as described for a muscle contraction (Fenn 1924). Thus, it seems that the same effect found in an isolated muscle contraction is also transferable to the entire system (human body) during cross-country skiing. All subjects, independent of group membership, showed a similar slope of the metabolic-work rate relationship, although some individual differences in the intercept existed. When adopting delta efficiency, with the change in work rate divided by change in metabolic rate, as suggested by Moseley and Jeukendrup (2001), one would have conclude that both world-class and national level sprint skiers have similar delta efficiency.

One of the major challenges when studying efficiency in outdoor sports is finding an accurate measurement of the (external) work rate (van Ingen Schenau and Cavanagh 1990). The introduction of ski-specific laboratory testing using roller skis on treadmills provides a model for cross-country skiing (Watts et al. 1993) and enables work rate and metabolic response to be measured. The effect of possible uncertainties was minimized by all skiers using the same technique and equipment and performing at the same speeds and incline. To improve the model some calculations and simplifications were nonetheless performed in *studies II-IV*. Power against gravity can be determined accurately, whereas power against friction includes some assumptions and simplifications. First, the mean normal force determines the mean frictional force when assuming a constant friction coefficient. With the skating movement during cross-country skiing, the normal forces on the skis change during a movement cycle, and, more importantly, a considerable fraction of the normal force is taken by the poles. In *studies II-IV*, we have used the data from Millet (1998a and b) to reduce the errors caused by speed and slope differences. Second, the movement direction of the roller skis during skating is not aligned to the movement of the treadmill belt, which affects the skier's actual rolled distance and speed compared to the treadmill belt. Therefore, the ski orientation angle when the roller skis move faster than the treadmill belt during skating affects the measurements of efficiency ($v_{ski} = v_{belt}/\cos(\text{orientation angle})$). The latter error was estimated to maximally affect GE by 0.1% in *study II* and *study IV* also accounted for this error (see specific study for more information). Finally, because skating is performed with an edging of the skis, we checked the effects of edging the skis on μ which showed an effect of angling on μ of less than 2% (see *study II* for details). One additional limitation in *study IV* is that GE was measured on the treadmill and not on snow. However, the G3 skating technique at a similar inclination was used at both conditions, and strong relationships were found between GE and performance on snow. The difference between roller skiing and skiing on snow is an important topic for future examinations.

Traditionally, the metabolic rate used to calculate efficiency is based on oxygen uptake in steady-state aerobic conditions (Ettema and Loras 2009; Hoffman et al. 1995; Niinimaa et al. 1978). When using GE to predict performance at high, competition intensities, it is implicitly assumed that inter-individual differences in efficiency are independent of work rate. As seen in Figure 11, measurements should therefore be performed above a certain threshold to reach a plateau in GE. In *study II* only small, insignificant group differences in VO_2 were found, but when converting VO_2 and RER to aerobic metabolic rate and including anaerobic metabolic contribution in the calculations, the differences between world-class and national levels sprint skiers were highly significant. Thus, we conclude that the anaerobic contribution is important when interpreting metabolic–work rate relationships. The metabolic rates measured in the current thesis were calculated by the method recommended by di Prampero and Ferretti (1999), which calculates the anaerobic metabolic rate from blood lactate levels. Although this method is considered less accurate than its aerobic counterpart it is nonetheless still reliable (di Prampero and Ferretti 1999).

In *study II* a greater efficiency in world-class skiers was linked to longer CL at lower CR in the athletes. The higher metabolic rate in national level skiers may be related to their higher cycle rate and thus be independent of work rate. It seems reasonable to suggest that efficiency is related to technique in relatively complex technical endurance sports such as cross-country skiing. Significant relationships between GE, CL and performance were also found in *study IV*.

Kinematics

Cross-country skiing is a sport that comprises many different skiing techniques which skiers change during a race according to the track topography and their speed in order to maintain high work rates (Bilodeau et al. 1992; Nilsson et al. 2004a). Cycle length and CR may be regarded as two coupled outcomes in a kind of "gearing principle" when controlling speed in cross-country skiing. This thesis investigated CL and CR in *study II*, as well as gear choice and CL and CR within these gears in *studies IV-V*. Moreover, the relationship between performance and kinematics on the treadmill and on snow was evaluated in *study IV*.

Studies IV-V highlighted G3 as the predominant technique used in sprint skiing, followed by G2. The G3 technique was also examined in *studies I-IV* in the laboratory. The current thesis confirms that performance and kinematics while G3 skating on the treadmill are likely relevant to kinematics and performance on snow (*study IV*). Gross kinematics (i.e., CL and CR) at similar speeds did not differ between roller skiing and skiing uphill in the STT, which may not be surprising because the fundamental principles of propulsion are the same. Nevertheless, the possible differences between effectiveness of the various phases of skating movement between roller skiing and skiing, such as friction while edging the skis when gliding and the distribution of the upper and lower body during the skating cycle, should be further investigated. These aspects may have an impact on how skiers could optimize roller ski training and utilize it as technical training for skiing on snow.

Furthermore, this thesis confirms earlier findings that a long CL strongly correlated to skiing speed and performance (Bilodeau et al. 1996; Rundell and McCarthy 1996). In *studies II and IV*, the fastest skiers on the treadmill and during the STT showed the longest peak CL. Several physiological and kinematic aspects influence the skiers speed during exhausting exercise. Therefore, the cause and effect between speed and CL is difficult to assess. Nonetheless, the world-class skiers in *study II* used longer CL at lower CR performing at the same sub-maximal speeds. It may therefore be suggested that better skiers have a higher self-selected CL at all speeds.

Several factors may affect how skiers regulate CL and CR to obtain their individual speed during a race. *Study V* shows that reduced speed from the first to the second lap were related to both CL and CR in the G3 technique, but in the G2 technique only CR was reduced, which may indicate a difference between these two techniques in how speed is regulated. In the final spurt of this race, the increased speed was induced exclusively by a higher CR. Increased speed by CR in the spurt is supported by Vesterinen et al. (2009), investigating three sprint heats on a flat tartan track using the skating G3 technique. This increase in CR might be explained by an ongoing fatigue during a sprint race, which has been shown to reduce upper and lower body force (Zory et al. 2006; Zory et al. 2009). This may thereby have reduced the possibility to increase CL. Also earlier studies investigating how skiers control speed within the different skating techniques display contradictory results, and increases in speed is associated with increases in both CL and CR (Millet et al. 1998e), as well as increases only in CR (Nilsson et al. 2004a; Stöggl and Muller 2009). There might also exist differences in how skiers increase and decrease speed during races when involving skating techniques with various degrees of involvement of the upper and lower extremities, as well as differences in the surface where propulsion takes place. These aspects of skiing need further examination.

Training

Traditionally, cross-country skiers have trained according to a “polarized model” with high volumes of low intensity and moderate volumes of high intensity endurance training (Seiler and Kjerland 2006). *Study I* found, during six months of preparation training before the competitive season, such a polarized training pattern in the national level skiers but not among world-class skiers. During this 6-month period, world-class skiers trained more LIT and MIT than national level skiers, which might indicate that LIT and MIT are important “base training” intensities in elite sprint skiers during this period of the year. The effectiveness of such training intensities are supported by several studies on elite endurance athletes, in which LIT (Esteve-Lanao et al. 2005; Fiskerstrand and Seiler 2004) and MIT (Mader 1991; Weltman et al. 1990) are suggested as important training intensities for improving performance over time. This training pattern found among the world-class sprint skiers seems successful. Assuming that the differences in training characteristics between world-class and national level skiers in *study I* contribute to performance differences, the present thesis indicates that LIT and MIT, and not HIT, were the differentiating factors. In contrast, most studies report HIT to be the most effective training intensity in highly trained endurance athletes (Gaskill et al. 1999; Laursen and Jenkins 2002).

Upon further investigation of the following months of training shows an increasingly polarized training pattern leading up to and during the competition period, with reductions in the total volume of both LIT and MIT and increases of HIT among both groups of sprint skiers. In this context the effect of the six month "base training" period on the subsequent more intensified training pattern during the competitive season may play a major role in optimizing performance. The accumulated effect of training over time among elite athletes is an important aspect which still requires further investigation.

Several studies have previously demonstrated the effects of maximal strength and power training on cross-country skiing performance and work economy (Hoff et al. 2002; Mikkola et al. 2007; Nummela et al. 1996; Osteras et al. 2002). *Study I* of this thesis examined differences in the amount of strength and speed training among world-class and national level skiers. No differences in the volumes of strength training were found between these two groups. However, world-class skiers trained more speed training in their regimen than national level skiers. The effects of speed training have not yet been investigated in sprint skiing, but a positive effect of this type of training on peak power and 6-min double poling performance have been reported by Nilsson et al. (2004b). While peak speed and strength is regarded a crucial factor for sprint skiing performance, the effects of these types of training should be further investigated.

Gender differences

In *study III*, men reached a 17% higher peak speed than women in both the ~5 min VO_{2max} and the ~1 min V_{max} incremental tests. These differences in performance between men and women were approximately 5% greater than observed in other endurance sports, such as running, cycling, speed skating and swimming (Coast et al. 2004; Maldonado-Martin et al. 2004; Schumacher et al. 2001; Seiler et al. 2007). One possible limitation of the performance tests in *study III* was the use of peak speed on incremental protocols, which differed from the other endurance sport studies, which utilized time during a race to assess performance. These comparisons with studies on other endurance sports are nonetheless regarded valid because the tests used in *study III* strongly correlated to sprint time-trial performance in *study I and IV*. Also, the relative differences in peak speed between men and women in the current study are equivalent with the differences in mean speed during male and female sprint time-trials during the two previous World Cup seasons (FIS 2009).

One possible explanation for these greater performance differences between male and female skiers is the large involvement of the upper body while skiing (Holmberg et al. 2005; Smith 1992). Several studies have highlighted the importance of upper body strength and endurance capacity and sufficient upper body muscle mass to ski at an elite level (Hoff et al. 1999; Holmberg 2009; Larsson and Henriksson-Larsén 2008; Stöggl et al. 2010; Terzis et al. 2006). Whether male skiers are better trained in their upper body or have upper body composition advantages over female skiers is an important question for further examination.

When further analyzing how body size explain the differences between male and female sprint skiers, the results in study II indicated that work rate and VO_2 variables should be normalized for total and lean body mass with a mass exponent of one, in support of the conclusions of Batterham et al. (1999). After normalizing for lean body mass, the differences between male and female peak work rate on both performance tests were reduced by 50% compared to when normalized for total body mass. Although normalization for lean body mass diminished differences in performance between men and women, the results were still significant, indicating than other factors than body mass and fat percentage are also important. In this connection, differences in 1) VO_{2max}, 2) fractional utilization of VO_{2max} and 3) gross efficiency were suggested as potential explanatory factors for performance differences among sprint skiers in *studies I-II*.

While men employed 59% higher absolute VO_{2max}, these differences between male and female skiers were reduced to 14% when normalized for total body mass. These gender differences in VO_{2max} are in agreement with investigations throughout the decades investigating elite cross-country skiers at traditional distances (5-50 km) (Ingjer 1991; Åstrand 1956). However, the difference in VO_{2max} between male and female cross-country skiers is greater than the ~10% difference found in elite endurance athletes in other sports (Calbet and Joyner 2010). Most studies explain gender differences in VO_{2max} by a higher body fat percentage and lower hemoglobin and hematocrit levels in women (Calbet and Joyner 2010; Joyner 1993; Åstrand 1956). In *study III*, the difference in VO_{2max} between male and females skiers were reduced to 7% when normalized for lean body mass. Furthermore, the women's hemoglobin levels were around 10% lower than the men's (13.5 versus 15.0 $g \cdot dL^{-1}$), which may explain the majority of the remaining gender differences in VO_{2max}.

Women showed a higher fractional utilization of VO_{2max} at OBLA in *study III*. This finding is supported by earlier investigations, suggesting that women partly compensate for a lower VO_{2max} with a higher fraction of VO_{2max} at anaerobic threshold (Maldonado-Martin et al. 2004). One possible explanation for differences in fractional utilization of VO_{2max} at OBLA may be differences in substrate oxidization between genders (Jeukendrup and Wallis 2005).

Gross efficiency and work economy were similar in men and women in *study III*. The relationship between metabolic rate and work rate was strongly linear for both genders, and no significant differences existed between slopes or intercepts between male and female subjects. Previous comparisons in work economy and GE for men and women have yielded various results (Coast et al. 2004; Helgerud et al. 1990; Hoffman et al. 1995; Maldonado-Martin et al. 2004). In *study II* we suggested that CL and technique-specific power were related to the differences in GE between male world-class and national level skiers. In contrast to this suggestion, *study III* shows that men and women have large differences in peak CL and peak treadmill speed, but not in GE or work economy. These findings indicate that GE differs between performance levels, but not between men and women at equivalent performance levels.

Study III compared for the first time in cross-country skiing kinematics between men and women. Men employed 11% longer CL at lower CR compared to women at the same absolute speed. The differences in CL between male and female skiers increased twofold, up to 21%, at peak speed, whereas their CR were similar. Because GE did not differ between genders in the current study and no significant relationships between kinematics and any measures of body size were found, the differences in cycle length are probably linked to the skiers' physical capacities. However, gender differences in kinematics need further examination.

Sprint race characteristics

The analyses of sprint time-trials in *studies IV-V* provide new information on where and why athletes gain or lose time during a race. *Study IV* analyzed the time-trial of an international sprint race for time spent on nine different sections of terrain, as well as work rates and kinematics during one specific uphill section. To provide more detailed information on speeds and kinematics during a race, the combination of d-GNSS and video was used to analyze the distribution of gears, the number of transitions and gross kinematics in *study V*.

Speeds and work rates

A unique aspect of cross-country skiing is the large variation in speed during a race, explained by the wide variety in topography. In *study IV*, the mean STT speed was 7.6 $m \cdot s^{-1}$, with variations from 5 to 10 $m \cdot s^{-1}$ across the nine different sections of terrain. When speed was continuously measured, the mean STT speed in *study V* was 6.9 $m \cdot s^{-1}$, with variations from 2.9 to 12.9 $m \cdot s^{-1}$. The skiing times on the uphill sections were the main determinants for both races' overall results. The importance of performance on uphill skiing for the overall race results has previously been observed over longer distances (above 10 km) in cross-country skiing by Berg and Forsberg (1992). However, *studies IV-V* are the first studies which demonstrate the importance of uphill performance in sprint skiing. In *study V*, the highest variations in skiing speeds were found at the end of every uphill section and the subsequent transition into the downhill section. Hence, skiers seem to lose or gain most time at these parts of the track, including the transitions between different gears during these parts of the race.

In *study V*, only uphill performance significantly correlated to overall STT performance, whereas in study IV both uphill and flat terrain contributed in determining overall STT performance. The significance of the performance on flat terrain in the overall performance was demonstrated in cross-country skiing for the first time in *study IV*. More flat terrain, especially in the end of the race in *study IV* as compared to more frequent uphill sections in *study V* may explain the more pronounced importance of flat terrain to overall performance in *study IV*. In comparison to earlier studies on distance cross-country skiing, the contribution of flat terrain skiing to overall performance is a new finding that may be explained by the flatter nature of sprint skiing tracks and the more pronounced significance of skating on flat terrain during sprint skiing. Despite the importance of flat terrain in *study IV*, it is noteworthy that the time spent on the initial 180-m flat section of the STT did not significantly correlate to performance. This observation indicates that the time required to achieve maximal speed from a standing position may not differ significantly between elite sprint skiers, a conclusion supported by the findings in *study I* on similar performances by world-class and national level sprint skiers in connection with a 30-m acceleration test.

Performance on the downhill sections did not reveal any significant correlation to overall STT performance in any of the studies in this thesis. The downhill sections involved in these studies were relatively straightforward and not technically difficult, allowing the skiers to glide most of the time in the deep stance typically used downhill (i.e., the G7 technique). These sections may therefore have been used primarily for recovery. Although the studies conducted for this thesis did not yield any major conclusions regarding the impact of downhill terrain on performance, the downhill may still be important even though we do not find correlations to time measurements. Because, as shown in *study I*, better sprint skiers recover more rapidly, the downhill sections may have exerted an indirect impact on the time spent on the subsequent flat and uphill sections of the race. Interestingly, the lowest variation of speed among the skiers was found at the end of the downhill sections where the skiing speeds were highest. This observation may support the notion that the properties of the skis used in the studies were homogenous among the skiers and not a discriminatory performance factor in *studies IV-V*.

Studies IV-V indicated that the skiers used a positive pacing strategy, which agrees with previous studies indicating that such a strategy could be beneficial for sports events with work durations of ~1.5 - 4 minutes (Abbiss and Laursen 2008; Bishop et al. 2002; de Koning et al. 1999; Jones et al. 2007). In *study V*, the skiers used a positive pacing strategy in the uphill and downhill sections, with ~13% and ~5% decline in speed during the second lap. On the flat sections a negative pacing strategy was observed, with ~8% higher speed on the second lap. However, the latter was explained by great differences in speed on section one between the two laps, where skiers accelerated from standing still during the first lap and possessed a high entrance speed into this section on the second lap. Furthermore, differences in pacing strategy related to the physiological characteristics of the skiers were found in *study V*, where skiers with different aerobic and maximal speed showed different pacing strategies. The skiers with the highest aerobic power, but with moderate V_{max}, showed more even pacing strategies compared to skiers with the highest V_{max} but moderate aerobic power.

In *study IV*, the work rate in the selected uphill section was approximately 160% of the laboratory peak aerobic power produced by the skiers. This indicates that ~40% of the energy on uphill terrain is produced anaerobically, which appears remarkably high. In other endurance sports involving racing times comparable with the STT investigated in *study IV* (i.e., approximately 4 min), about 20-30% of the total energy requirement during competitions is supplied by anaerobic energy processes (Gastin 2001). Despite the intense work rate during the uphill section analyzed, the relative anaerobic and aerobic energy contributions during the entire STT might be similar to those contributions observed in other endurance sports as a result of lower work rates on flat and downhill terrain during sprint skiing. A rough estimation of the work rates on flat terrain observed in *study IV*, indicate rates of work slightly greater than peak aerobic power, i.e., considerably lower than on uphill terrain. Because of the passive nature of the downhill sections, the metabolic costs on this terrain are well below peak aerobic power. The lower metabolic costs of downhill terrain indicates that the varying terrain associated with cross-country skiing allow skiers to recover while going downhill, thereby enabling them to generate more pronounced anaerobic power when skiing uphill. Such variations in power output on different terrains and under varying external conditions in connection with bicycling has previously been shown to optimize performance (Swain 1997). Two earlier studies indicated that elite cross-country skiers performed well above peak aerobic power during 15 km and 30 km races in the classical technique (Norman and Komi 1987; Norman et al. 1989). Work rates on level terrain were approximately 50% lower than on steep uphill terrain (Norman and Komi 1987).

Technique

One challenge in cross-country skiing is choosing an optimal gear based on the terrain profile and the skier's work capacity. The distributions of the main skating techniques in *studies IV-V* demonstrated the importance of the G3 technique as the predominant technique, followed by the G2 technique. A previous study by Kvamme et al (2005), comparing G2 and G3, suggested that the decisive factor in skiers' selection of which technique to use is the level of incline. S*tudy V* indicates that skiers' gear selections are not only determined by incline, but also by skiing speed and the length of the uphill slopes. A unique aspect of cross-country skiing is the frequent transition between the different gears. In the 1.45 km sprint time trial in *study V* the skiers performed between 21 and 34 gear transitions. These many transitions, involving the upper and lower body muscles to various degrees, were investigated for the first time in cross-country skiing in the research conducted for this thesis. In comparison, triathlon involves three different exercise modes (swimming, cycling and running) involving two transitions. This sport has received significant interest, as triathletes perceive difficulties in the transitions, especially from cycling to running (Bentley et al. 2002). The fastest skiers in *study V* used fewer transitions than the rest of the subjects studied. The use of fewer transitions was related to the ability to maintain G3 uphill without "gearing down" to G2.

While transitions in cross-country skiing are probably not as challenging as the transitions in triathlon, the extra energy costs and time lost while changing gear versus the unloading and variations of muscle load is highly interesting both from a physiological, biomechanical and motor control perspective and should be further investigated.

In *study V*, the skiers used ~137 movement cycles during the sprint race, representing a mean CR of 0.85 Hz. The highest CR were observed in G2, G5 and G6, whereas the lowest CR were used in the high speed techniques G3 and G4. Along with the decrease in mean speed in the long uphills from the first to the second lap, skiers also utilized more G2 instead of G3 in uphill terrain. This aspect might be attributed to the higher contribution of upper body work when using G3 compared with G2, as shown in a previous investigation by Millet et al. (1998d). Consequently, ongoing fatigue in the upper body may contribute to skiers' switch from G3 to G2 to unload the upper body muscles with a greater use of the legs. Gear selection on flat terrain showed little variation, possibly explained by prioritization of the uphill sections by the skiers because the track profile used in this study included a downhill section immediately after each uphill section. In sprint tracks where flat sections have a larger proportion, or when flat sections directly follow the uphill, there may be a different pattern to gear selection on flat terrain.

Practical implications

Successful performance development demands a goal-oriented process. To improve this process greater knowledge on the specific demands behind an outstanding performance, a detailed analysis of the current capacity and the training strategies to improve this capacity towards the goal are useful tools. The aim of this thesis was to increase the understanding of sprint cross-country skiing, evaluate relevant capacity testing for this sport and investigate the capacities and training among world-class sprint skiers.

This thesis shows that better sprint skiers have higher peak aerobic capacity, a more efficient technique, as well as greater speed abilities. Specifically, these capacities are most strongly coupled to a higher speed during the flat and uphill sections of a sprint race. Performance on the last half of an STT, as well as the last parts of all uphill sections differentiates world-class from national level sprint skiers. Better skiers more frequently use the G3 technique and use fewer transitions between the different techniques during a race. Furthermore, better skiers generally skate with longer CL, but they have the ability to increase CR when needed during a sprint race. If assuming that the training characteristics in world-class skiers contribute to these performance differences, this thesis may also provide some guidelines for future elite sprint skiers.

The current thesis also demonstrated that gross efficiency measured by treadmill roller skiing provides useful information about cross-country skiing performance when compared with standardized conditions. Coaches and skiers should consider changes in both energy delivery capacity and mechanical efficiency when evaluating the training progress. Finally, competition analyses might be a useful tool in optimizing performance in elite skiers. For example, the d-GNNS can provide continuous speed profiles, showing skiers exactly where they gain or lose time on the course compared to other skiers.

CONCLUSIONS

Study I

- Maximal aerobic capacity, gross efficiency and high speed capacity differentiate world-class from national level sprint skiers, and these variables seem to determine sprint skiing performance.
- World-class skiers include more low and moderate-intensity endurance training and maximal speed training in their conditioning, which indicates that these training methods are important to achieve an international level in sprint skiing.

Study II

- In addition to the higher energy delivery capacity, world-class sprint skiers have a higher gross efficiency than national level skiers.
- World-class skiers use longer cycle lengths and lower cycle rates at a given speed and generate higher maximal speeds than national level sprint skiers. Therefore, the higher efficiency in world-class skiers may be linked to technique and technique-specific power.
- The study revealed a general linear relationship between work rate and metabolic rate (i.e., a "Fenn effect"), indicating that gross efficiency at moderate and high work rates provides useful information about cross-country skiers compared in standardized conditions during treadmill roller skiing.

Study III

- Male and female elite sprint skiers have 17% difference in peak speed on both a short and long incremental test. This difference in sprint skiing is slightly larger than other research on comparable endurance sports.
- These differences between male and female skiers can primarily be explained by higher maximal oxygen uptake and lower fat percentage in men.
- Men and women showed similar gross efficiency, whereas men used 11% longer cycle lengths at lower cycle rates at the same submaximal speed and 21% longer cycle lengths at similar cycle rates at peak speed.

Study IV

- Performance on uphill and flat terrain has the greatest impact on sprint time-trial performance, and the last part of a sprint race contains the greatest differential among skiers.
- Estimated work rates were around 160% of peak aerobic power during the uphill section of the race, whereas cycle length and speed were tightly coupled.
- Peak oxygen uptake, gross efficiency, peak treadmill speed and peak cycle length when treadmill roller skiing strongly correlate to sprint time-trial performance on snow, particularly on the uphill and flat sections during the last part of the race.

Study V

- Performance on the uphill sections correlates to overall sprint time-trial performance, particular because the better skiers used the G3 technique to a greater extent and the slower skiers used G2.
- Better skiers have a higher entrance speed into the uphill sections and a smaller decrease in racing speed during the uphills. The largest variations in speed are found in the last parts of the uphills and the transitions to flat terrain.
- The maximal speed tests in double poling and G3 correlated to the percentage of racing time using G3, indicating the significance of the upper body and movement specific power in uphill terrain. VO_{2max} correlates to the ability to maintain uphill racing speed from the first lap to the second lap.
- The high end d-GNSS with a high sampling rate and accuracy with simultaneous tracking of both GPS and GLONASS satellites provides opportunities for more detailed analysis of cross-country skiing and could also be useful in other outdoor sports.

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APPENDIX

Appendix I. An actual competition day for an elite sprint skier.

	Activity	Duration	Intensity
07.00	Breakfast		
08.00	Morning run	30 min	Low intensity and 4 x 15 s strides with 3 min breaks in between
09.30	Lunch		
10.00	Relax and competition briefing		
11.30	Transportation to the competition stadium		
12.00	General warm-up and ski testing while skiing on snow	30-45 min	First 15 min at 70% HR_{max}, thereafter at 70-80% HR_{max}
12.45	Specific warm-up while skiing on snow	20-25 min	2 x 3 min at 90% HR_{max} and 3 x 15 s maximal sprints, all with 3 min low intensity in between
13.00	Easy running and walk to the start	10-15 min	Low intensity
13.15	**Qualification race**	3-4 min	Maximal intensity: 95-100% HR_{max}, blood lactate > 10
13.20	Nutrition and dry clothes	5 min	
13.35	Recovery: easy running	10-15 min	60-70% HR_{max}
14.00	Relax, competition briefing and nutrition		
15.00	Warm-up while skiing on snow	30 min	15 min 70-80% HR_{max}, thereafter 3 x 15 s maximal sprints with 3 min at low intensity in between
15.30	Easy running and walk to the start	10-15 min	
15.45	**Quarterfinal**	3-4 min	Maximal intensity: 95-100% HR_{max}, blood lactate > 10
15.50	Nutrition and dry clothes	5 min	
16.00	Recovery: easy running	15-20 min	60-70% HR_{max}
16.20	Activation sprints while running and going to the start	10-15 min	2-3 x 15 s activation sprints with 3 min of low intensity in between
16.30	**Semifinals**	3-4 min	Maximal intensity: 95-100% HR_{max}, blood lactate > 10
16.35	Nutrition and dry clothes	5 min	
16.45	Recovery: Easy running and walk to the start	15 min	60-70% HR_{max}
16.55	**Final**	3-4 min	Maximal intensity: 95-100% HR_{max}, blood lactate > 10
17.00	Nutrition and dry clothes	5 min	
17.20	Recovery: easy running	15-20 min	60-70% HR_{max}
17.30	Prize giving ceremony		
18.00	Transport		
18.30	Dinner		
20.00	Relax and debriefing		
22.00	Going to bed		

Appendix II. Example of a training program for a male world-class sprint skier. This training week corresponded to approximately 70% low intensity endurance training, 10% moderate intensity endurance training, 5% high intensity endurance training, 5% speed training and 10% strength training, according to the session goal model used in the current thesis.

Monday	I.	Warm-up + moderate intensity: 5·8 min roller ski skating
	II.	Warm-up (running) + maximal strength training 1 h
Tuesday	I.	Warm-up + speed training: 10·20 s double poling on roller ski
	II.	Warm up (running) + strides and plyometrics 45 min
Wednesday	I.	Low intensity: 2 h cycling + stabilization training 30 min
Thursday	I.	Warm-up + high intensity: 6·4 min running with poles
	II.	Low intensity: 1 h 30 min roller ski skating incl. 5·10 s sprints
Friday	I.	Warm-up (running) + strength/power training 1 h
	II.	Low/moderate intensity: 1 h 30 min double poling on roller ski
Saturday	I.	Warm-up + very high intensity: 10 ·1 min roller ski skating
	II.	Low intensity: 1 h swimming
Sunday	I.	Low intensity: 3 h running with poles

STUDY I

Is not included due to copyright

STUDY II

Is not included due to copyright

STUDY III

Which physiological and kinematic variables determine gender differences in sprint skiing performance?

Øyvind Sandbakk, Gertjan Ettema, Stig Leirdal, Hans-Christer Holmberg

Running title: Gender differences in sprint skiers

Abstract

The present study examined gender differences in performance, physiological characteristics and kinematics of elite sprint cross-country skiers. Eight men and eight women, matched for performance level, performed a submaximal test, a maximal aerobic capacity (VO_{2max}) test and a maximal treadmill speed (V_{max}) test in the skating G3 technique while treadmill roller skiing. Men reached 17% higher peak speed at both the VO_{2max} and the V_{max} test (both $P<0.05$). Furthermore, men showed 14% and 7% higher VO_{2max} when normalized for total and lean body mass (both $P<0.05$). Gross efficiency did not differ between genders, whereas a higher fractional utilization of VO_{2max} at anaerobic threshold was found in women ($P<0.05$). Men employed 11% longer cycle lengths at lower cycle rates at the same absolute speed, and 21% longer cycle lengths at similar cycle rates at peak speed (all $P<0.05$). The current study demonstrated ~5% greater gender differences in performance than other comparable endurance sports. These gender differences in performance could mainly be explained by VO_{2max} and fat percentage, whereas gross efficiency did not differ between genders. Furthermore, the current study provides novel information on gender differences in kinematics in elite skiers.

Keywords: cross-country skiing, efficiency, men, physiology, skating, women

Introduction

Over recent decades, scientists have examined the characteristics of successful endurance athletes (Joyner and Coyle 2008; Saltin and Astrand 1967). Gender differences in endurance performance are shown to be 10-15% in elite runners, track cyclists, speed skaters and swimmers (Coast et al. 2004; Joyner 1993; Maldonado-Martin et al. 2004; Schumacher et al. 2001; Seiler et al. 2007).

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In order to explain these differences, performance have been attributed to a multitude of physiological factors, such as maximal oxygen uptake (VO_{2max}), anaerobic threshold and efficiency (Joyner and Coyle 2008). Some studies suggest that variables should be normalized for lean rather than total body mass when comparing men and women (Calbet and Joyner 2010; Mayhew and Salm 1990). When normalized for lean body mass, strength and power in throwing has been shown similar in men and women (van den Tillaar and Ettema 2004), whereas the differences in VO_{2max} and endurance performance are reduced, but still significant (Astrand 1956; Joyner 1993).

Cross-country skiing is a physiologically and biomechanically demanding sport (Holmberg 2009; Smith 1992). Both male and female cross-country skiers have shown some of the highest VO_{2max} values reported in the literature (Ingjer 1991; Saltin and Åstrand 1967). In addition, specially trained cross-country skiers of both genders are well trained both in their upper and lower extremities (Holmberg 2009; Terzis et al. 2006). The sprint event in cross-country skiing is performed as a time-trial qualification race and three subsequent knock-out heats, each 2-4 min (FIS 2009). Male world-class sprint skiers have shown superior peak aerobic capacities, gross efficiency and peak speed compared to national level skiers (2010a; Sandbakk et al. 2010b). Accordingly, highly trained sprint skiers may be relevant subjects for evaluating gender differences when employing whole body exercise through a wide range of physiological capacities.

The purpose of the present study was to compare performance, physiological characteristics and kinematics of male and female sprint cross-country skiers while roller ski skating on a treadmill. Furthermore, we aimed to see whether normalizing for lean body mass would explain these differences between men and women.

Methods

Subjects

Eight male and eight female Norwegian elite sprint cross-country skiers volunteered to participate in the study. The groups were similar as regards the classification of sprint performance level on snow (FIS points) as calculated by the International Ski Federation (FIS 2009) and included skiers with sprint results among the 30 best in the World Cup. The skiers' characteristics are shown in Table 1. All skiers were fully acquainted with the nature of the study before signing a written consent to participate. The study was approved by the Regional Ethics Committee, Trondheim, Norway.

Overall Design

All subjects were tested for performance, physiological response and kinematics using three treadmill roller ski tests employing the G3 skating technique (Andersson et al. 2010): 1) three 5-min submaximal stages, 2) a ~5-min maximal aerobic capacity (VO_{2max}) test, and 3) a ~1-min maximal treadmill speed (V_{max}) test. The standard of sprint skating performance was determined by FIS points (FIS 2009) and their training volume was quantified according to individual training diaries.

Instruments and materials

Respiratory variables were measured by open-circuit indirect calorimetry using an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Before each measurement the VO_2 and VCO_2 gas analyzers were calibrated using a high-precision two-component gas mixture (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & co, Lichtenfels, Germany) and the expiratory flow meter was calibrated with a 3 L volume syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate (HR) was measured with a heart rate monitor (Polar RS800, Polar Electro OY, Kempele, Finland). Blood lactate concentration (BLa) was measured on 5 µL samples taken from the fingertip by a Lactate Pro LT-1710*t* (ArkRay Inc., Kyoto, Japan), validated by Medbø et al. (2000).

Table 1 Anthropometric characteristics, annual training and sprint performance level (FIS points) in eight male and eight female elite sprint cross-country skiers (mean ± SD).

	Men	Women
Age (yr)	25.8 ± 2.2	24.1 ± 2.4
Body height (cm)	183.8 ± 5.1*	168.0 ± 2.8
Body mass (kg)	83.3 ± 7.2*	60.1 ± 4.7
Body mass index ($kg \cdot m^{-2}$)	24.6 ± 0.6*	21.3 ± 1.4
Body fat (%)	8.5 ± 2.3*	14.5 ± 2.0
Lean body mass (kg)	76.1 ± 6.0*	51.3 ± 3.2
Training (h)	673 ± 96	686 ± 65
FIS points	49.9 ± 12.0	49.0 ± 14.3

* Significant group differences, $P < 0.001$

Body mass was measured on a Kistler force plate (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland) and body height on a calibrated stadiometer (Holtain Ltd., Crosswell, UK). Body fat percentage was estimated using skinfold calipers on a four-site skinfold measurement (Holtain Skinfold caliper PE025, Holtain Ltd., Crosswell, UK), according to the calculations of Durnin and Womersley (1973) for men and women.

Treadmill tests were performed on a 6 × 3 m motor-driven treadmill (Bonte Technology, Zwolle, the Netherlands). Inclination and speed were calibrated using the Qualisys Pro Reflex system and the Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The treadmill belt consisted of a non-slip rubber surface that allowed skiers to use their own poles (pole length: 90 ± 1% of body height for both genders) with special carbide tips. A safety harness secured the skiers during the treadmill testing. To minimize variations in rolling resistance, the skiers used the same pair of skating roller skis with standard wheels (Swenor Roller skis, Troesken, Norway). The roller skis were pre-warmed before each test with 20 min of roller skiing on the treadmill. They were also tested for rolling friction force (P_f) using a towing test, previously described by Sandbakk et al. (2010a). The friction coefficient (μ) was determined by dividing P_f by the normal force (N) ($\mu = P_f \cdot N^{-1}$) and the μ-value was incorporated in the work rate calculations. Two synchronized 50-Hz Sony video cameras were fixed to the front and side of the treadmill (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) and recorded kinematics for analysis by DartFish Pro 4.5 (DartFish Ltd., Fribourg, Switzerland).

Test protocols and measurements

Submaximal test

Submaximal physiological responses were tested during three 5-min stages at a 5% inclination with 1 min separating them and a 0.3 $m \cdot s^{-1}$ increase in speed for every stage. The starting speeds were 3.9 $m \cdot s^{-1}$ and 3.6 $m \cdot s^{-1}$ for men and women respectively. The genders were compared in two conditions: 1) at the same absolute speed (3.9 $m \cdot s^{-1}$) and 2) at the onset of blood lactate accumulation (OBLA), defined at 4 $mmol \cdot L^{-1}$ BLa calculated by linear interpolation (Sjodin et al. 1982). Pulmonary VO_2 and VCO_2 production were determined by the average of the last minute. BLa was measured immediately after the test. Gross efficiency was calculated as the work rate divided by the metabolic rate during steady-state conditions, according to Sandbakk et al. (2010a). Work rate was calculated as the sum of power against gravity (P_g) and friction (P_f). Aerobic metabolic rate was determined from VO_2 and VCO_2 by using the associated measurements of RER and standard conversion tables (Peronnet and Massicotte 1991). Anaerobic metabolic rate was determined from the obtained BLa measured directly after the test and calculated according to di Prampero and Ferretti (1999). An increase of 1 $mmol \cdot L^{-1}$

BLa was regarded as equivalent to 3 $mL \cdot kg^{-1}$ of oxygen consumed with an RER = 1.0.

Maximal aerobic capacity test
Maximal aerobic capacity was tested in an incremental test at a 5% inclination with starting speeds at 4.5 and 3.9 $m \cdot s^{-1}$ for men and women respectively. The speed was increased by 0.6 $m \cdot s^{-1}$ after 1 and 2 min, and thereafter increased by 0.3 $m \cdot s^{-1}$ every min until exhaustion. The tests were considered to be a maximal effort if two of the following three criteria were met: 1) a VO_2 plateau with increasing exercise intensity, 2) RER above 1.10, and 3) BLa exceeding 8 $mmol \cdot L^{-1}$. VO_2 was measured continuously, and the average of the three highest 10-s consecutive measurements determined VO_{2max} in both tests. The highest HR value during the test was defined as peak HR. BLa was measured 1, 3, 6 and 10 min after finishing the test and the highest value determined peak BLa. The skiers skied at 2 $m \cdot s^{-1}$ between the BLa measurements. Blood lactate clearance was calculated as peak BLa minus the BLa 10 min after finishing the test.

Maximal treadmill speed
Maximal treadmill speed was tested in an incremental test at an 8% inclination, initiated with 30 s of medium intensity (3.9 $m \cdot s^{-1}$), before the treadmill speed was increased to the starting speed of 4.4 $m \cdot s^{-1}$, that was similar for men and women. Speed was thereafter increased every 10 s by 0.3 $m \cdot s^{-1}$ until exhaustion.

Time to exhaustion in the VO_{2max} and V_{max} tests was recorded at the time the subject failed to keep the roller skis' front wheels ahead of a marker placed 4 m from the front of the treadmill. Peak speed in the same tests was calculated as $v = V_f + [(t \cdot T^{-1}) \cdot V_d]$, where V_f is the speed of the last completed workload, t is the duration of the last workload, T is the standard duration of each workload and V_d is the speed difference between the last two workloads (Holmberg et al. 2005). Peak speed was used to assess peak work rate in the VO_{2max} and V_{max} test.

Kinematical analyses
Cycle time was determined as the average time between two pole plants during six consecutive cycles. Cycle length was calculated as the speed multiplied by the cycle time and the cycle rate was the reciprocal of cycle time. In this regard, kinematics was measured during the last minute of an absolute submaximal speed (3.9 $m \cdot s^{-1}$) and during the subject's final 30-s workload at the VO_{2max} test.

Statistical Analysis
All data were checked for normality with a Shapiro-Wilks test and presented as mean and standard deviation (mean ± SD). Comparisons between groups were analyzed using the independent *t*-test procedure with Bonferroni adjusted alpha levels. Relationships between variables were analyzed by linear regression. When both groups showed significant linear regression lines, their slopes and intercepts were compared according to Crowder and Hand (1990). When only one of the groups showed a significant regression line, a dependent *t*-test was used to test whether the non-significant group showed actual values different from the predicted values (based on the significant regression line). Statistical significance was set at $\alpha < 0.05$. All statistical tests were processed using SPSS 11.0 Software for Windows (SPSS Inc., Chicago, IL, USA).

Results
Submaximal test
Same absolute speed (3.9 $m \cdot s^{-1}$)
Table 2 shows physiological and kinematic responses at the same absolute speed in male and female sprint skiers. At this speed, men showed 36% higher absolute VO_2, employing 39% higher work rates (both $P < 0.05$). The genders did not differ in VO_2 or metabolic rate when normalized for total body mass (i.e., work economy). Men utilized 8% lower VO_2 when normalized for lean body mass and worked at 12% lower percentages of VO_{2max} at 3.9 $m \cdot s^{-1}$ (both $P < 0.05$). Furthermore, men showed 9% lower HR and lower BLa (both $P < 0.05$). The genders did not differ in gross efficiency. Men and women showed almost identical regression lines and did not differ in slopes or intercepts when metabolic rate was plotted against work rate (Figure 1A).

Table 2 Physiological response and kinematics in eight male and eight female international level sprint cross-country skiers in a 5-min submaximal stage at 3.9 m·s^{-1} at 5% inclination in the G3 technique in treadmill roller skiing (mean and SD).

Variables	Men	Women
Work rate (W)	234 ± 20**	169 ± 13
VO_2 (L·min^{-1})	4.32 ± 0.38**	3.18 ± 0.27
VO_2 (mL·min^{-1}·kg^{-1})^{TBM}	52.0 ± 1.7	52.9 ± 2.9
VO_2 (mL·min^{-1}·kg^{-1})^{LBM}	56.8 ± 2.5**	60.9 ± 3.6
VO_2 in % of VO_{2max}	74.9 ± 4.3**	87.1 ± 3.7
HR (bpm)	165 ± 11**	182 ± 5
HR in % of peak HR	85.7 ± 4.2**	92.9 ± 3.6
BLa (mmol·L^{-1})	3.2 ± 0.5**	4.2 ± 1.1
RER	0.94 ± 0.02	0.95 ± 0.02
Gross efficiency (%)	14.9 ± 0.4	14.6 ± 0.9
Cycle length (m)	7.6 ± 0.4**	6.9 ± 0.5
Cycle rate (Hz)	0.51 ± 0.03**	0.57 ± 0.04

BLa = blood lactate concentration; HR = heart rate; ^{TBM} = normalized for total body mass, ^{LBM} = normalized for lean body mass. Significantly different from females, * $P < 0.05$ and ** $P < 0.01$.

Onset of blood lactate accumulation (4 mmol·L^{-1} BLa)
At OBLA, men showed higher speed (4.3 ± 0.2 vs 3.9 ± 0.3 m·s^{-1}, $P < 0.05$), whereas the percentage of peak speed, at the VO_{2max} test, did not differ between men and women (71.0 ± 2.8% vs 74.7 ± 3.9%). VO_2 normalized for total body mass was higher in men at OBLA (56.5 ± 3.3 vs 53.3 ± 3.2 mL·kg^{-1}·min^{-1}, $P < 0.05$), whereas women showed a higher percentage of VO_{2max} (87.6 ± 2.6% vs 81.3 ± 3.9%, $P < 0.05$). VO_2 and work rate at OBLA did not differ between men and women when normalized for lean body mass (61.7 ± 3.5 vs 62.3 ± 3.5 mL·kg^{-1}·min^{-1} and 3.4 ± 0.1 vs 3.3 ± 0.2 W·kg^{-1}).

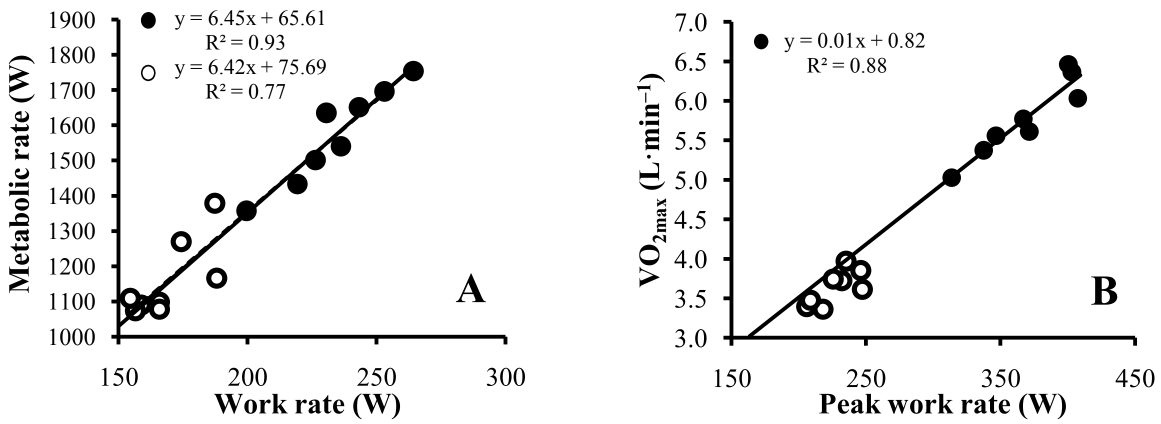

Figure 1A-B A) Submaximal metabolic rate plotted against work rate for the same absolute speed (3.9 m·s^{-1}) and B) VO_{2max} plotted against peak work rate on VO_{2max} test in male and female elite sprint cross-country skiers while treadmill roller-ski skating. Individual data and significant trend lines, based on linear regression, are shown for men (filled circles and straight line) and women (open circles and dashed line).

Maximal aerobic capacity test
Performance and physiological characteristics from the VO_{2max} test are shown in Table 3. Men showed 17% higher peak speed at a 62% higher peak work rate (both $P < 0.05$). The gender differences in peak work rates were 17% and 9% when normalized for total and lean body mass respectively (both $P < 0.05$). Figures 2A-B show peak work rate plotted against total and lean body mass. The comparisons of regression lines reveal gender differences in intercepts ($P < 0.05$), but not in slopes. Men employed 59% higher absolute VO_{2max}, whereas when normalized for total and lean body mass the gender differences in VO_{2max} were 14% and 7% respectively (all $P < 0.05$). Figures 2C-D show VO_{2max} plotted against total and lean body mass ($P < 0.05$). When VO_{2max} was plotted against peak work rate, women showed a VO_{2max} significantly below the men's regression line (Figure 1B, $P < 0.05$). No differences in peak BLa, peak HR, peak RER or blood lactate clearance were found between genders in the VO_{2max} test.

Maximal treadmill speed test
In the maximal treadmill speed test, the V_{max} was 6.6 ± 0.2 $m \cdot s^{-1}$ in men and 5.6 ± 0.1 $m \cdot s^{-1}$ in women, representing 17% higher V_{max} and 35 s longer time to exhaustion in men (both $P < 0.05$). This leads to 63%, 17% and 10% higher work rates in men when expressed in absolute values (557 ± 47 vs 342 ± 27 W), normalized for total body mass (6.7 ± 0.2 vs 5.7 ± 0.1 $W \cdot kg^{-1}$) and lean body mass (7.3 ± 0.3 vs 6.7 ± 0.2 $W \cdot kg^{-1}$), respectively (all $P < 0.05$).

Kinematics
At the same absolute submaximal speed, men employed 11% longer cycle lengths at 11% lower cycle rates (Table 2, both $P < 0.05$). Men employed 21% longer cycle lengths at similar cycle rates compeared to women at peak speed during the VO_{2max} test (Table 3, both $P < 0.05$). Cycle length and cycle rate were not related to any measures of body size (i.e., total body mass, lean body mass or body height).

Table 3. Physiological characteristics, performance and kinematics in eight male and eight female international level sprint cross-country skiers performing an incremental test in the skating G3 technique while treadmill roller skiing (mean and SD).

Variables	Men	Women
TTE (s)#	299 ± 71	232 ± 35
Peak speed ($m \cdot s^{-1}$)	6.1 ± 0.3**	5.2 ± 0.2
Work rate (W)	368 ± 34**	227 ± 16
Work rate ($W \cdot kg^{-1}$) TBM	4.4 ± 0.2**	3.8 ± 0.1
Work rate ($W \cdot kg^{-1}$) LBM	4.8 ± 0.2*	4.4 ± 0.2
VO_{2max} ($L \cdot min^{-1}$)	5.77 ± 0.49**	3.64 ± 0.43
VO_{2max} ($mL \cdot min^{-1} \cdot kg^{-1}$) TBM	69.5 ± 3.7**	60.8 ± 3.8
VO_{2max} ($mL \cdot min^{-1} \cdot kg^{-1}$) LBM	76.0 ± 4.1*	71.1 ± 4.3
Peak HR (bpm)	193 ± 6	196 ± 7
Peak RER	1.12 ± 0.03	1.11 ± 0.02
Peak BLa ($mmol \cdot L^{-1}$)	13.3 ± 1.5	12.0 ± 1.9
ΔBLa_{rec} ($mmol \cdot L^{-1}$)	4.9 ± 0.9	4.8 ± 1.0
Peak cycle length (m)	9.9 ± 0.9**	8.2 ± 0.7
Peak cycle rate (Hz)	0.63 ± 0.04	0.64 ± 0.03

ΔBLa_{rec} = blood lactate recovery; BLa = blood lactate concentration; HR = heart rate; TTE, time to exhaustion. # = different protocols, TBM = normalized for total body mass, LBM = normalized for lean body mass. Significant group differences, * $P < 0.05$ and ** $P < 0.01$.

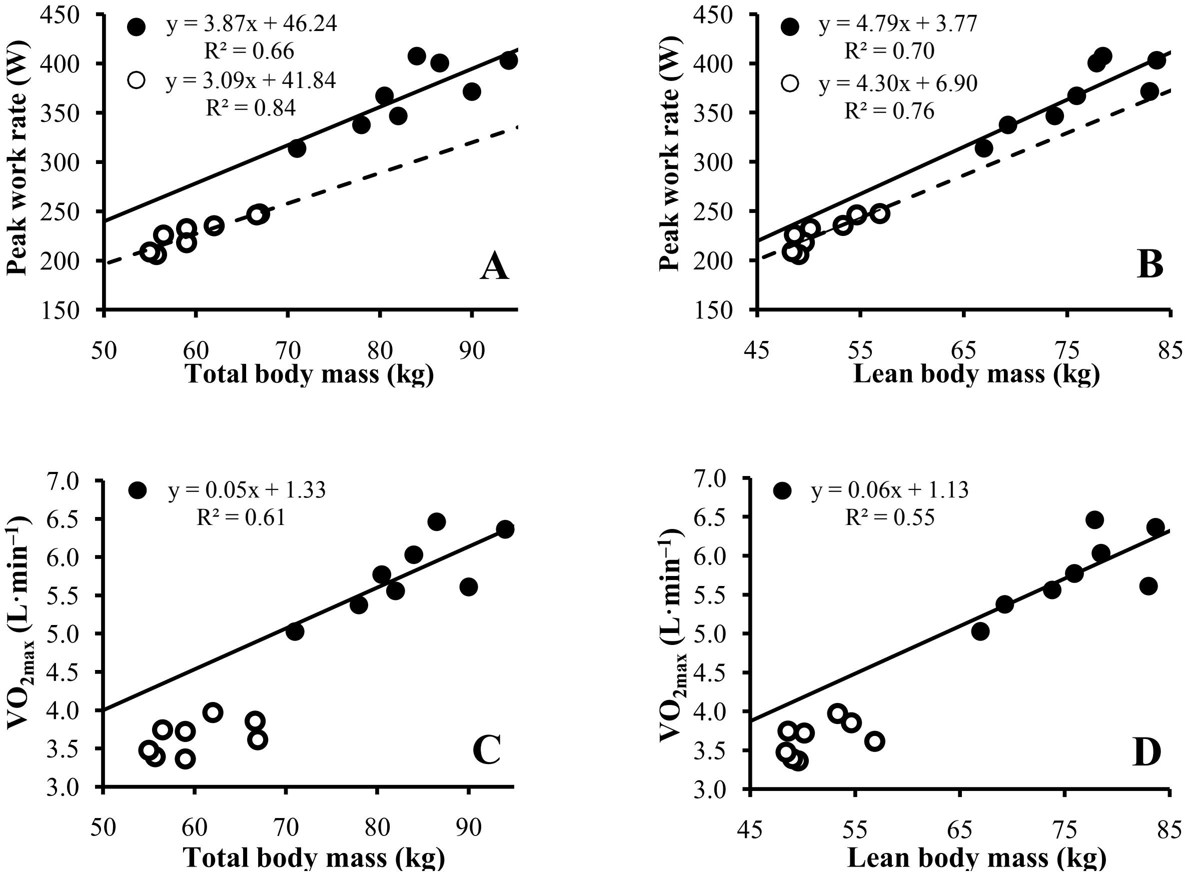

Fig. 2A-D Peak work rate and VO_{2max} plotted against total and lean body mass in male and female elite sprint cross-country skiers while treadmill roller-ski skating. Individual data and significant trend lines based on linear regression are shown for men (filled circles and straight line) and women (open circles and dashed line).

Discussion

The current study compared male and female elite sprint cross-country skiers for performance, physiological characteristics and kinematics in the G3 skating technique. The main findings were as follows: 1) men reached 17% higher peak speed than women in both the ~5 min VO_{2max} and the ~1 min V_{max} incremental tests, 2) when normalized for lean body mass, the gender differences in peak work rate in both tests were reduced by 50% compared to when they were normalized for total body mass, but remained significant, 3) VO_{2max} was 14% and 7% higher in males when normalized for total and lean body mass, 4) women utilized a higher fraction of VO_{2max} at OBLA, 5) gross efficiency and work economy at submaximal speed did not differ between genders, and 6) male skiers employed 11% longer cycle lengths at lower cycle rates at the same absolute submaximal speed, and 21% longer cycle length at similar cycle rates at peak speed.

Performance

The gender differences in peak speed were ~5% greater than performance differences observed in other endurance sports, such as running, cycling, speed skating and swimming (Coast et al. 2004; Maldonado-Martin et al. 2004; Schumacher et al. 2001; Seiler et al. 2007). One possible limitation of the performance tests in the current study was the use of peak speed on incremental protocols, which differed from the other endurance sport studies, which utilized time during a race to assess performance. These comparisons with studies on other endurance sports are nonetheless regarded valid because the tests used in the present study strongly correlated to sprint time-trial performance in an earlier investigation (Sandbakk et al. 2010b). Furthermore, the gender differences in the current study are equivalent with differences in mean speed between men and women during

World Cup sprint time-trials during the two previous seasons (FIS 2009).

One possible explanation for these greater performance differences between male and female skiers might be the significant involvement of the upper body while skiing (Holmberg et al. 2005; Smith 1992). Several studies have highlighted the importance of high upper body strength and endurance capacity, as well as sufficient muscle mass in the upper body for skiing performance (Hoff et al. 1999; Larsson and Henriksson-Larsén 2008; Nilsson et al. 2004; Stöggl et al. 2010; Terzis et al. 2006). Whether male skiers are better trained or have body composition advantages in the upper body over female skiers is an important question for further examination.

In accordance with Batterham et al. (1999), a mass exponent of one fitted our data reasonably when work rate and VO_2 variables were plotted against total and lean body mass. Thus, normalizing for body mass rather than applying allometric principles seems appropriate. After normalizing for lean body mass, the gender differences in peak work rate in both performance tests were reduced by 50% compared to when they were normalized for total body mass, but were still significant. This indicates that other factors than body mass and fat percentage were also of importance to the performance differences between male and female cross-country skiers. In this connection, differences in 1) VO_{2max}, 2) fractional utilization of VO_{2max}, 3) gross efficiency and 4) anaerobic capacity have been suggested as potential explanatory physiologically factors for performance differences among sprint skiers (Sandbakk et al. 2010a; 2010b).

Physiological characteristics

Men employed 59% higher absolute VO_{2max}, whereas the gender differences were reduced to 14% when normalized for total body mass. These gender differences in VO_{2max} are in agreement with historic investigations on elite cross-country skiers over traditional distances (5-50 km) throughout the decades (Ingjer 1991; Saltin and Åstrand 1967). The gender differences in VO_{2max} among cross-country skiers thus seems higher than the ~10% difference found in elite endurance athletes in other sports (Joyner and Coyle 2008; Pate et al. 1987). Most studies explain gender differences in VO_{2max} through a higher body fat percentage and lower hemoglobin levels in women (Astrand 1956; Calbet and Joyner 2010). When normalizing for lean body mass in the current study, the gender differences in VO_{2max} were reduced to 7%. Furthermore, the women's hemoglobin levels were around 10% lower than the men's (13.5 vs 15.0 $g \cdot dL^{-1}$, based on unpublished data for these groups), which may explain the majority of the remaining differences in VO_{2max}. However, the cardiac output was not measured in the current study, and the exact impact of the differences in hemoglobin levels on VO_{2max} still remains uncertain.

Women showed a higher fractional utilization of VO_{2max} at OBLA in the present study, which is regarded as being of paramount importance to performance in endurance sports (Joyner and Coyle 2008; Saltin 1997). This finding is supported by earlier investigations, suggesting that women partly compensate for a lower VO_{2max} with a higher fraction of VO_{2max} at anaerobic threshold (Maldonado-Martin et al. 2004). One possible explanation for this may be differences in substrate oxidization between genders (Jeukendrup and Wallis 2005).

Gross efficiency and work economy were similar in men and women in the current study. The relationship between metabolic rate and work rate was strongly linear within both genders, and there were no significant gender differences between slopes or intercepts (Figure 1A). In fact, these regression lines were close to identical. A linear metabolic-work rate relationship was also found by Sandbakk et al. (2010a) when investigating male world-class and national level sprint skiers. However, higher gross efficiency was found in the world-class skiers. This may indicate that gross efficiency differs between performance levels, but not between men and women at equivalent performance levels.

Anaerobic capacity may be responsible for the remaining differences between genders. This is supported by the similarity in gender differences between the two performance tests, where the influence of anaerobic energy is clearly higher in the shorter V_{max} test

(Sandbakk et al. 2010b). However, in order to understand how anaerobic capacity differentiates between skiers, a better method of measuring anaerobic metabolic rate is needed (Bangsbo 1998).

Kinematics

At the same absolute speed, men employed 11% longer cycle lengths at lower cycle rates compared to women. The gender differences in cycle lengths increased twofold, up to 21%, at peak speed, whereas the cycle rates were similar (~0.65 Hz). Explosive strength and efficiency have recently been suggested as explanatory factors for differences in cycle lengths in the skating technique (Sandbakk et al. 2010a; Stöggl and Muller 2009). Because gross efficiency did not differ between genders in the current study, the differences in cycle length are probably linked to the differences in physical capacities between men and women. This is supported by earlier studies examining cycle lengths in skating between skiers of different physical capacities (Bilodeau et al. 1996; Sandbakk et al. 2010a; Stöggl et al. 2007).

Conclusions

The current study showed gender differences in performance and VO_{2max} slightly larger than in other endurance sports and provides novel data on differences in kinematics between elite male and female sprint skiers. The gender differences in performance were mainly explained by a higher VO_{2max} and a lower fat percentage in men. Efficiency did not differ between genders, whereas our results indicate that women have a higher fractional utilization of VO_{2max} at the anaerobic threshold.

Acknowledgements

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STUDY IV

Analysis of a sprint ski race and associated laboratory determinants of world-class performance

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Running title: Determinants of Sprint Skiing Performance

Abstract

This investigation was designed to analyze the time-trial (STT) in an international sprint skating competition in cross-country skiing for 1) overall STT performance and relative contributions of time spent in different sections of terrain, 2) work rate and kinematics on uphill terrain and 3) relationships to physiological and kinematic parameters while treadmill roller ski skating. Total time and times in nine different sections of terrain by 12 world-class male sprint skiers were determined, along with work rate and kinematics for one specific uphill section. In addition, peak oxygen uptake (VO_{2peak}), gross efficiency (GE), peak speed (V_{peak}), and kinematics in skating were measured. Times on the last two uphill and two final flat sections were correlated to overall STT performance (all r=~-0.80, P<0.001). For the selected uphill section, speed was correlated to cycle length (r=-0.75, P<0.01) and the estimated work rate was approximately 160% of peak aerobic power. VO_{2peak}, GE, V_{peak} and peak cycle length were all correlated to STT performance (all r=~-0.85, P<0.001). More specifically, VO_{2peak} and GE were correlated to the last two uphill and two final flat section times, whereas V_{peak} and peak cycle length were correlated to times in all uphill, flat and curved sections except for the initial section (all r=~-0.80, P<0.01). Performances on both uphill and flat terrain are strong determinants of overall STT performance. Peak oxygen uptake, efficiency, peak speed and peak cycle length are strongly correlated to overall STT performance, as well as to performance in different sections of the race.

Keywords: aerobic power; anaerobic power; cycle length; efficiency; speed; work rate

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Introduction

The endurance sport of cross-country skiing on varying terrain and at widely varying speeds is both physically and technically demanding (Andersson et al. 2010; Saltin 1997; Smith 1992). During competitions the skier must constantly alter rate of work and technique to suit the terrain (Bergh and Forsberg 1992; Norman and Komi 1987; Smith 1992).

Sprint cross-country skiing begins with a time-trial qualification, followed by three knock-out heats. Although analyses of simulated sprint skiing have recently been performed employing roller skiing (Mikkola et al. 2010; Stöggl et al. 2007; Vesterinen et al. 2009) and while skiing on snow (Andersson et al. 2010; Zory et al. 2006; Zory et al. 2009), an actual sprint competition has not yet been examined. In distance races, approximately 50% of total skiing time involves moving uphill and this is generally regarded as the major determinant of performance (Bergh and Forsberg 2000). This finding was supported by Andersson and coworkers (2010), who investigated sprint skating on snow. Uphill work rates have been estimated to be 10-30% above what can be produced aerobically in distance cross-country skiing, and approximately 50% higher than corresponding work rates on level terrain (Norman and Komi 1987; Norman et al. 1989). Thus, uphill work rates in sprint skiing may be hypothesized to be as high as 150% of peak aerobic power.

Today's world-class sprint skiers achieve higher peak oxygen uptake, efficiency and maximal speed and skate with a longer cycle length than elite sprint skiers at the national level (Sandbakk et al. 2010a; Sandbakk et al. 2010b). Vesterinen and coworkers (2009) found that anaerobic capacity was closely related to performance in the first heats of a simulated sprint race, whereas aerobic capacity became more important during consecutive heats. Furthermore, Andersson and coworkers (2010) found that the velocity decrease in the uphills from the first to the second half of a sprint time-trial was correlated with VO_{2max}. In the case of cycling, the best uphill riders demonstrate higher maximal oxygen uptake, whereas the best riders on flat terrain have higher maximal power and speed (Sallet et al. 2006). The specific influence of physiological characteristics on different terrains within the sprint heats should be examined more extensively.

The present study was designed to investigate 1) sprint time-trial (STT) performance in relationship to the amount of time spent on different terrains, 2) work rate and kinematics in uphill terrain and 3) the relationships of these parameters to physiological and kinematic characteristics utilizing roller ski skating in the laboratory. Three hypotheses were tested: 1) average speed on uphill terrain is the major determinant of STT performance; 2) skiers perform at work >150% of peak aerobic power on uphill terrain; and 3) peak oxygen uptake and efficiency on uphills, and maximal speed on flat terrain are of particular importance to overall STT performance.

Methods

Subjects

Twelve elite male sprint cross-country skiers, including three World Champions, volunteered to participate in this study and their background characteristics and sprint performance levels (classified according to the system proposed by the International Ski Federation (FIS) (2009)), are shown in Table 1. This study was pre-approved by the Norwegian Regional Ethics Committee, Norway and all subjects were fully informed of its nature before providing their written consent to participate.

Overall design of the study

Initially, a time-trial for an international FIS sprint skating competition in cross-country skiing was investigated with respect to overall performance and time spent in nine different sections of terrain, as well as kinematics and estimated work rates for one representative uphill section of terrain. The kinematics were examined by analyzing video and work rates estimated on the basis of work against gravity, friction on snow and air resistance. One week later, the subjects performed treadmill roller ski skating in the laboratory and were assessed for 1) gross efficiency (GE) in a submaximal test; 2) peak oxygen uptake (VO_{2peak}), treadmill performance and kinematics in a ~5-min incremental test and 3) peak treadmill speed (V_{peak}) in a ~1-min incremental test.

Table 1 Anthropometric, physiological and performance characteristics of the 12 elite male sprint cross-country skiers involved in this study.

Parameter	Mean ± SD (range)
Age (yr)	25 ± 3 (20-34)
Body height (cm)	185 ± 6 (174-194)
Body mass (kg)	82.6 ± 6.6 (71.0-94.0)
Body mass index (kg·m^{-2})	24.2 ± 0.8 (22.6-25.3)
Body fat (%)	9.0 ± 2.3 (5.7-12.0)
VO_{2peak} (L·min^{-1})	5.74 ± 0.52 (5.03-6.46)
VO_{2peak} (mL·min^{-1}·kg^{-1})	70.0 ± 2.7 (65.5-74.7)
TTE[a] in the VO_{2peak}-test (s)	258 ± 86 (185-395)
Gross efficiency (%)	14.7 ± 0.8 (12.9-15.7)
Peak treadmill speed (m·s^{-1})	8.7 ± 0.4 (7.9-9.0)
Peak BLa[b] (mmol·L^{-1})	11.9 ± 1.7 (8.8-14.1)
Peak cycle length (m)	10.0 ± 1.3 (8.1-12.2)
Sprint FIS points	44.1 ± 40.0 (11.1-118.6)
Training (hours·year^{-1})	702 ± 113 (600-850)

[a] = time to exhaustion; [b] = blood lactate concentration.

Analysis of the sprint competition

The STT was performed on a track 1820 m in length, with equal portions of uphill, flat and downhill terrain and a total climb of 35 m and maximal difference in elevation of 24 m. Each lap consisted of 9 different sections of terrain (S1-S9), with different properties (Figure 1 and Table 2). The three uphill sections (S3, S4 and S7), had mean inclines of 5.5%, 6% and 8%; the two downhill sections (S2 and S6) mean inclines of 5% and 6%; and the three flat sections (S1, S8 and S9) mean inclines < ±1%. There was also one curved section (S5) with an initial 3% incline and a 180° turn.

All of the subjects warmed-up according to their own individual programs and used their own racing poles (90 ± 1% of body height in length) and skis (105 ± 2% of body height). The weather was stable with no wind, air and snow temperatures of -4°C, and relative air humidity of 75%. To minimize the influence of different gliding properties, all of the skis had a similar stone-grind and were waxed by a professional ski technician with the same fluorine wax.

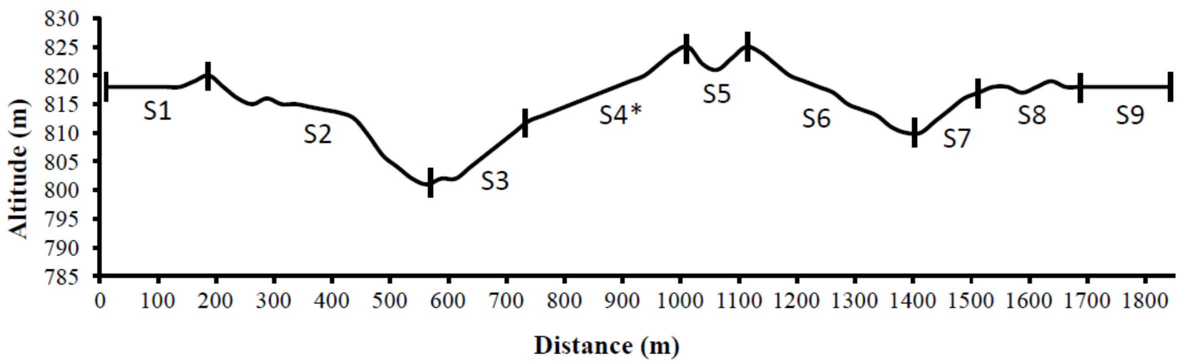

Figure 1 The lengths and inclines of the entire track and sections thereof (S1-9) in the sprint competition. *Kinematics and work rate were analyzed in section S4.

The friction coefficient on snow (μ_s) was calculated on the basis of measurements of deceleration performed three times 30 min prior to the start of the STT. For this, one of the subjects (weighing 80 kg) glided passively down a 5% downhill incline onto a 20-m flat zone, sitting in a tucked-down position and with an initial speed of 3 $m \cdot s^{-1}$. Two pairs of photocells (Speedtrap II Timing System, Brower Timing Systems, Draper, UT), placed 20 cm above the ground and with 50 cm between the members of each pair, were employed to determine the initial and final speeds. The loss of speed was used to calculate the force-balance (deceleration) and subsequently, the friction coefficient ($\mu_s = a \cdot g^{-1} = \sim 0.04$), ignoring the force of air drag which was minimal at this slow speed. The friction coefficient obtained was similar to that reported earlier for similar conditions (Buhl et al. 2001).

The mean drag force on one subject (an elite skier) whose height and mass were approximately the same as the mean for the entire group was measured in a wind tunnel. This subject simulated the skating technique used in uphill terrain on a sliding board mounted on two Kistler force plates (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland), as described by Leirdal and coworkers (2006). The wind was propelled by a 220 kW centrifugal fan and the test area was 12.5 m long, with a width of 2.7 m and a height of 1.8 m.

The time spent in each section of the STT and the total time were measured with ten synchronized 50-Hz video cameras (DCR-TRV900E, Sony Inc., Tokyo, Japan), placed 20 m away from and perpendicular to the track. The times captured when skier's hip passed the reference poles between the different sections were analyzed in DartFish Pro 4.5 (DartFish Ltd., Fribourg, Switzerland). Our measurements of total times differed by 0.12 ± 0.03 s from the official total times. A panning 50-Hz Sony video camera (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) monitored the skiers for 6 consecutive cycles during the mid-part of one uphill section (S4) to allow determination of cycle length and cycle rate.

Laboratory testing

Procedures and measurements

All treadmill tests were performed using the G3 technique with an incline of 5% on a 6 × 3 m motor-driven treadmill (Bonte Technology, Zwolle, The Netherlands). This skating technique was the one employed the most in the STT and the chosen incline corresponded to the analyzed uphill section of terrain. This allowed us to compare work rates and kinematics between skiing on snow and while treadmill roller skiing. The inclination and speed were calibrated by using the Qualisys Pro Reflex system and Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden).

The non-slip rubber surface of the treadmill belt allowed the subjects to use their own poles equipped with special carbide tips. A safety harness secured the subjects during the testing. To minimize variations in rolling resistance, all subjects used the same pair of Swenor roller skating skis with standard wheels (Swenor Roller skis, Troesken, Norway). The rolling friction force (F_f) of these skis was assessed prior to testing using a towing procedure described previously (Sandbakk et al. 2010a). The rolling friction coefficient (μ_r) was determined by dividing F_f by the normal force (N) ($\mu_r = F_f \times N^{-1}$), and the μ_r value (0.024) obtained was incorporated into the calculations of work rate. Two synchronized 50-Hz Sony video cameras fixed to the front and side of the treadmill (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) recorded kinematics for analysis by DartFish Pro 4.5.

Respiratory variables were measured employing open-circuit indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Prior to each measurement, the VO_2 and VCO_2 analyzers were calibrated using a highly precise mixture of gases (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & co, Lichtenfels, Germany) and the expiratory flow meter was calibrated with a 3-L syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate (HR) was assessed with a heart rate monitor (Polar RS800, Polar Electro OY, Kempele, Finland) and the blood lactate concentration (BLa) of 5 μL-samples were taken from the fingertip with the Lactate Pro LT-1710*t* kit (ArkRay Inc, Kyoto, Japan), as validated by Medbø and coworkers (2000).

Test protocols

GE was determined in a sub-maximal 5-min test at a skiing speed of 3.9 $m \cdot s^{-1}$. VO_2, VCO_2 and HR were monitored continuously and the average value for the last minute is presented. BLa was measured immediately after completion of the test.

Thereafter, VO_{2peak} and treadmill performance (time to voluntary exhaustion; TTE) were assessed with an incremental treadmill test. The initial speed of 4.4 $m \cdot s^{-1}$ was increased by 0.6 $m \cdot s^{-1}$ after one and two minutes and thereafter by 0.3 $m \cdot s^{-1}$ every minute until exhaustion was reached. Gas exchange and HR were measured continuously. The average of the three highest consecutive 10-s measurements of VO_2 was designated as VO_{2peak} and used in the calculation of peak aerobic metabolic rate and peak aerobic power. BLa was measured 1, 3 and 5 min after completion of the test and the highest of these values designated as peak BLa. The test was considered to have been performed at a maximal level of effort if the following three criteria were met: 1) a plateau in VO_2 despite increased exercise intensity, 2) RER >1.10, and 3) peak BLa >8 $mmol \cdot L^{-1}$. The VO_2 plateau was defined as the time VO_2 was within 150 mL of the identified VO_{2peak} (Brink-Elfegoun et al. 2007). TTE was the time at which the subject was no longer able to maintain the front wheels of the roller skis' in front of a marker 4 m from the forward edge of the treadmill. Kinematics were analyzed during the final 30-s work load completed.

Assessment of peak treadmill speed (V_{peak}) involved an initial 30-s period at medium intensity (4.4 $m \cdot s^{-1}$), followed by an increase to the starting speed of 5.0 $m \cdot s^{-1}$, and subsequent incremental increases of 0.3 $m \cdot s^{-1}$ every 10 s until exhaustion was reached. The criterion for exhaustion was the same as that used in the VO_{2peak} test. V_{peak} was calculated as $v = V_f + [(t \cdot T^{-1}) \cdot V_d]$, where V_f was the speed of the final work load completed, t the duration of the last work load, T was the duration of each work load and V_d the difference in speed between the last two workloads (Holmberg et al. 2005).

Definitions of technique and kinematic determination

The different skiing techniques were designated as G2, G3, G4, G5, G6 and G7, according to Andersson and coworkers (2010). G2, a technique for skiing uphill, involves an asymmetrical double pole push in connection with every other leg push. G3, used on moderate inclines and level terrain, involves one double pole push together with every leg push. G4, a symmetrical double pole push in connection with every other leg push is used on level terrain. G5 is downhill skating in a low position with only using the legs. G6, a technique for curves in which leg work is performed with or without poling and G7 downhill skiing in a low stance position without leg or pole push.

In the current study, the G3 technique was used for all kinematic analyses, both on snow and on the treadmill. One cycle contained two pole plants and the cycle time was determined as the average time between two pole plants during 6 cycles. Cycle length was calculated as the speed multiplied by the cycle time and the cycle rate was the reciprocal of cycle time. Skiing speed on the selected uphill section was based on the average speed for that section while peak speed during the VO_{2peak} test was identified as the treadmill speed during the final 30-s work load completed.

Pole and leg push-off times were also analyzed at the final 30-s work load of the VO_{2peak} test. The pole push-off time began when the pole was planted and ended when it lost contact with the ground. The push-off time for the leg began when the pole was planted and ended when the roller ski lost contact with the ground. The recovery times for the legs and poles were calculated as cycle time minus push-off time.

Power calculations

To estimate the contribution of aerobic and anaerobic power during one uphill section of the STT, a modified power balance model was employed (de Koning et al. 2005). Anaerobic power (P_{an}) was calculated as total power/work rate (P_{tot}) minus peak aerobic power (P_{ae}), with P_{ae} being the product of peak aerobic metabolic rate (Q_a, i.e., the energetic equivalent of VO_2 at VO_{2peak}) and GE (Eq. I). Accordingly,

Eq. I

$P_{an} = P_{tot} - P_{ae}$ (Ia)

$P_{an} = P_{tot} - Q_a \cdot GE$ (Ib)

P_{tot} was estimated for the uphill section (S4) that best differentiated performance during a pilot test. This section was straight and GPS data (Polar 800CX, Polar Electro OY, Kempele, Finland) during pilot testing indicated that speed remained relatively constant (< 5% range). P_{tot} was calculated as the sum of power against gravity (P_g), friction (P_f) and air drag (P_d), with v being the average speed, α the angle of incline, μ_s the coefficient of friction, p the density of the air, A the exposed frontal area of the skier and C_d the drag coefficient (Eq II).

Because the skis angled outwards while skating, they are actually moving faster than the average speed forward. Therefore, v_{ski} = v/cos(orientation angle) was incorporated into the calculations of P_f. The ski orientation angles were estimated from 3D analysis of 6 subjects (a representative sample) skating at different speeds on the treadmill at a similar inclination and the resulting mean linear relationship of v_{ski} to speed was used calculating the work rate. Moreover, skiers apply their body mass to the poles while poling, thereby reducing the mean normal force on the skis during a cycle and influencing P_f. Therefore, the work rate calculations were adjusted for body mass according to Millet and coworkers (Millet et al. 1998a; Millet et al. 1998b), revealing that the average poling force (as a percentage of body mass) was stable at approximately 7% for the speeds attained with the G3 technique on a 5% incline.

Eq. II

$P_{tot} = P_g + P_f + P_d$

$P_{tot} = m \cdot g \cdot \sin(\alpha) \cdot v + (1 - 0.05) \cdot m \cdot g \cdot \cos(\alpha) \cdot \mu_s \cdot v_{ski} + 0.5 \cdot p \cdot v^3 \cdot A \cdot C_d$

The wind drag component $A \cdot C_d$ was estimated as 0.35 from wind tunnel testing. GE, determined during the sub-maximal test on the treadmill at an incline similar to that of section S4, was calculated as the work rate divided by the total metabolic rate under steady-state conditions, according to Sandbakk and coworkers (2010a). The work rate was calculated as the sum of P_g and P_f, with incorporation of v_{ski} and adjusted body mass (see above). The aerobic metabolic rate was determined from VO_2 and VCO_2 using the RER value and standard conversion tables (Peronnet and Massicotte 1991). The anaerobic metabolic rate was determined on the basis of the BLa measured immediately after the test as described by di Prampero and Ferretti (1999). An increase in BLa of 1 $mmol \cdot L^{-1}$ was considered equivalent to 3 $mL \cdot kg^{-1}$ of oxygen consumed with an RER value of 1.0.

Statistical analyses

All data were shown to be normally distributed with a Shapiro-Wilks test and are presented as means and standard deviations (SD). Correlations between the various parameters were analyzed using Pearson's product-moment correlation coefficient test and simple linear regression was used to draw trend lines. A *t*-test for dependent correlations was applied to test for differences between section times in relationship to STT performance. The coefficient of variation ($SD \cdot mean^{-1}) \cdot 100$ within each section was also calculated. Stepwise multiple regression was employed to predict STT performance from the physiological and kinematic parameters. Potential interactions and confounders were examined according to Kleinbaum and coworkers (1998). These regression analyses are presented as non-standardized and standardized coefficients. Repeated measurements of the physiological and kinematic parameters on the treadmill demonstrated intraclass correlation coefficients of > 0.90. The corresponding coefficients for repeated determinations of STT performance and the relative contribution of section times during pilot testing were 0.90-0.95. Statistical significance was set at α value of < 0.05. Adjusted Bonferroni alpha levels were used to examine correlations between the entire terrain, specific sections thereof and laboratory parameters versus STT performance. All statistical analyses were processed using the SPSS 11.0 Software for Windows (SPSS Inc., Chicago, IL).

Table 2 The time spent in the 9 different sections of the track during the sprint time-trial (STT), the coefficient of variation (CV) for each section, and the correlation with STT for the 12 elite male cross-country skiers.

Terrain	Track section	Section length (m)	Main gear selection	Time in section (s)	Speed in section		Correlation of the section time to STT
					Mean ($m \cdot s^{-1}$)	CV	
Uphill	S3	160	G3	18.8 ± 0.5	8.5	0.0266	*r* = 0.69
	S4	270	G3	51.4 ± 2.3	5.3	0.0447	*r* = 0.84**
	S7	115	G3 + G2	15.0 ± 0.7	7.6	0.0467	*r* = 0.80**
	Total	545		85.2 ± 3.1	6.0	0.0364	*r* = 0.91**
Flat	S1	170	G2 + G3	19.9 ± 0.4	8.5#	0.0201	*r* = -0.08
	S8	200	G3 + G4	24.9 ± 1.0	8.0	0.0401	*r* = 0.81**
	S9	140	G3	18.9 ± 0.8	7.4	0.0423	*r* = 0.75*
	Total	510		63.8 ± 1.9	8.0	0.0298	*r* = 0.82**
Downhill	S2	375	G4 + G5	41.9 ± 0.6	9.0	0.0145	*r* = 0.16
	S6	270	G3 + G7	30.7 ± 0.7	8.8	0.0228	*r* = 0.72
	Total	645		72.6 ± 1.1	8.9	0.0152	*r* = 0.62
Curve	S5	120	G6	18.4 ± 0.5	6.2$	0.0272	*r* = 0.72

= initial speed of zero, $ = including a 180° curve, * = $P < 0.01$ and ** = $P < 0.001$.

Results

Analysis of the sprint competition

The skiers' mean STT time was 240 ± 5 s (234-248) and their final mean placement in the STT 11 ± 13 (1-46). The periods on the uphill, flat, downhill and curved terrains were approximately 36%, 27%, 30% and 7% of the total racing time, respectively (Table 2). Six different techniques were used in the different sections of the track (Table 2), with G3 being predominant.

Sprint FIS points was strongly correlated to STT performance ($r = 0.96$, $P < 0.001$), as were the times spent on uphill and flat terrain to STT performance (Figure 2, $P < 0.01$ in all cases), with no significant difference between the latter two correlations. In contrast, the time spent on downhill terrain was not significantly correlated with STT performance and the correlation coefficient in this case was significantly lower than the corresponding coefficients for the relationship between STT performance and time on uphill and flat terrain ($P < 0.05$ in both cases). With respect to the time spent in specific sections of terrain, the last two uphill sections (S4 and S7) and the two final flat sections (S7 and S8) exhibited significant relationships to STT performance (Table 2, $P < 0.01$ in all cases), which was not the case for the first three sections (S1-3), the curved section (S5) or the final downhill section (S6). The correlation coefficients between STT performance and S4 and S7-9 were significantly different than the correlations with S1-2 ($P < 0.05$ in all cases). The coefficients of variation within each section showed patterns similar to the correlations themselves, with the highest variation in time spent being associated with the last two uphill sections (S4 and S7), followed by the two final flat sections (S8 and S9; Table 2).

The cycle rate and length in the uphill section examined (S4) were 0.70 ± 0.04 Hz and 7.6 ± 0.7 m, respectively. Cycle length was negative correlated with both the time spent in this section and STT performance ($r = -0.75$ and -0.72, $P < 0.01$ in both cases), whereas cycle rate demonstrated no correlation to these two parameters. The estimated mean work rate in S4 (eq. II) was 476 ± 42 W, which is

Table 3 The correlations (r-values) between physiological and kinematical parameters versus sprint time-trial (STT) performance and time spent in the different sections of terrain for the 12 elite male cross-country skiers.

Parameters	STT	Uphill terrain	Flat Terrain	Downhill terrain	Curved section
Gross efficiency (%)	r = -0.83**	r = -0.80**	r = -0.80**	r = -0.65	r = -0.35
VO_{2peak} ($L \cdot min^{-1}$)	r = -0.85**	r = -0.81*	r = -0.81*	r = -0.65	r = -0.60
VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)	r = -0.88**	r = -0.87**	r = -0.87**	r = -0.64	r = -0.55
Peak treadmill speed ($m \cdot s^{-1}$)	r = -0.88**	r = -0.77*	r = -0.78*	r = -0.56	r = -0.78*
Peak BLa[a] ($mmol \cdot L^{-1}$)	r = 0.08	r = 0.03	r = 0.03	r = -0.01	r = 0.03
Peak cycle length (m)	r = -0.88**	r = -0.88**	r = -0.88**	r = -0.49	r = -0.75*

[a] = blood lactate concentration, * = $P < 0.01$ and ** = $P < 0.001$.

approximately 60% greater than the peak aerobic power (i.e., 298 ± 37 W, as assessed by the VO_{2peak} test). Works against gravity, friction and air resistance for this section were estimated to be approximately 54%, 36% and 10%, respectively, of the total work.

Laboratory determinants of sprint performance
Treadmill performance (i.e., TTE in the VO_{2peak} test) was strongly negatively correlated to overall STT performance (r = -0.88, P < 0.001), as well as to the time spent on the uphill and flat sections of the STT (r = -0.85 and -0.80, P < 0.001 in both cases). Regarding the individual sections, strong positive relationships between TTE and time spent were observed for the last two uphill (S4 and S7) and two final flat sections (S8 and S9) (r = ~-0.80, P < 0.01 in all cases), whereas times spent on the three first sections (S1-3), the curved section (S5) and the last downhill section (S6) were not significantly correlated with TTE.

The correlations between physiological parameters versus STT performance and time spent in the different sections of the terrain are documented in Table 3 and Figure 3. VO_{2peak}, GE and V_{peak} (measured in connection with treadmill roller skiing) showed strong negative correlations to overall STT performance and even stronger negative correlations to the time spent in uphill and flat terrain (Table 3, P < 0.05 in all cases), but only moderate negative correlations to S4 (r = ~-0.75, P < 0.05 in both cases). V_{peak} was negatively correlated to the time spent on all uphill and flat sections, except for S1 (r = -0.75 to -0.80, P < 0.05 in all cases), as well as the time spent on the curved section (S5; r = 0.78, P < 0.05). The peak BLa obtained after the VO_{2peak} test and anthropometric parameters exhibited no significant correlation with the time spent in any section of terrain.

The peak cycle length in connection with treadmill roller skiing was strongly negatively correlated to overall STT performance, as well as the time spent on uphill and flat sections (with the exception of S1), and moderately negatively correlated to the time spent in the curved section (Table 3, P < 0.05 in all cases).

Both peak cycle length and rate on the treadmill demonstrated strong positive correlations to the corresponding parameters for the selected uphill section of the STT on snow (r = ~0.90, P < 0.001 in both cases). Moreover, in the laboratory peak cycle length correlated strongly with pole and leg recovery times (r = ~0.80, P < 0.01 in both cases).

Stepwise multiple regression analysis employing overall STT performance as the dependent variable revealed that VO_{2peak}, V_{peak} and peak cycle length in combination provided the best prediction of this (STT_1; R^2 = 0.933, P < 0.001). The second best model was obtained by replacing peak cycle length with GE (STT_2; R^2 = 0.905, P < 0.001). The corresponding linear regression formulas with non-standardized [and standardized] coefficients were as follows:

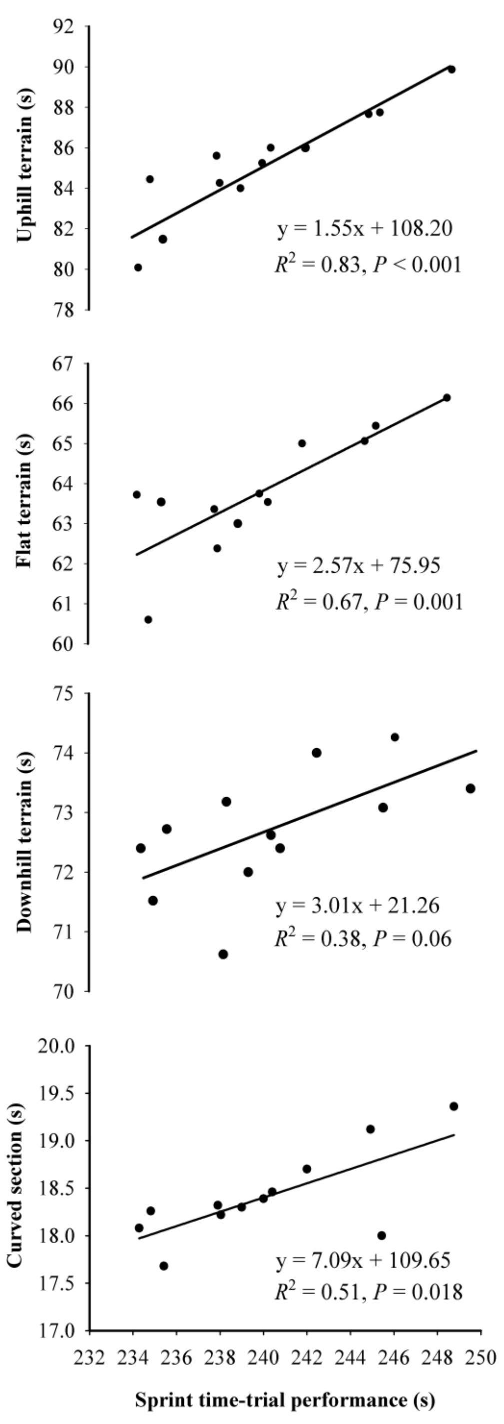

Figure 2 Sprint time-trial performance in relationship to the time spent in different sections of terrain for the 12 elite male sprint cross-country skiers. The data points represent the individual skiers and the lines were obtained by linear regression.

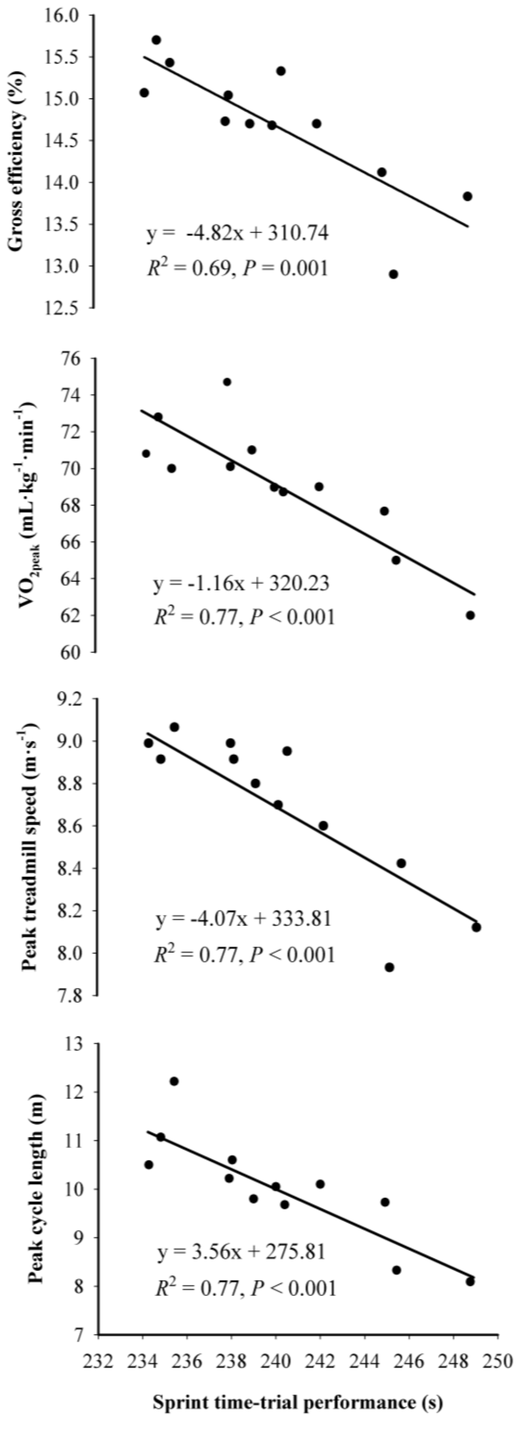

Figure 3 Sprint time-trial performance in relationship to physiological and kinematic variables for the 12 elite male sprint cross-country skiers. The data points represent the individual skiers and the lines were obtained by linear regression.

STT_1 (s) = 324.2 - 0.35 [0.27] · VO_{2peak} (mL·kg^{-1}·min^{-1}) - 1.90 [0.41] · V_{peak} (m·s^{-1}) - 1.57 [0.36] · Peak cycle length (m)

STT_2 (s) = 341.0 - 0.49 [0.26] · VO_{2peak} (mL·kg^{-1}·min^{-1}) - 1.57 [0.41] · V_{peak} (m·s^{-1}) - 1.92 [0.40] · GE (%)

Discussion

The present study investigated the relationships between a time-trial associated with a skating sprint competition in cross-country skiing on snow, regarding 1) the time spent in different sections of terrain (S1-9), 2) kinematics and estimated work rates in one uphill section (S4), and 3) physiological and kinematical parameters in the laboratory. The main findings were as follows: 1) the average speed on uphill and flat terrain were strongly correlated to overall STT performance, with correlations reaching statistical significances in the case of the last two uphill and two final flat sections; 2) cycle length in the uphill section (S4) was positively correlated to the average speed on this section, as well as to overall STT performance; 3) estimation of the work rate in S4 revealed that the skiers performed approximately 160% of their peak aerobic power in this section; 4) performance and kinematics in connection with treadmill roller skiing exhibited a strong positive correlation to these same parameters during the STT on snow; 5) multiple regression analysis demonstrated that peak oxygen uptake, peak treadmill speed and peak cycle length in combination provided the best laboratory prediction of overall STT performance; and 6) peak oxygen uptake and gross efficiency showed strong positive relationships to the average speed on the last two uphill (S4 and S7) and two final flat sections (S8 and S9) of the race, whereas peak treadmill speed and peak cycle length was correlated to the average speed on uphill, flat and curved sections throughout the entire STT.

Analysis of the sprint competition

Our observation that the times spent on the uphill, flat, downhill and curved sections of terrain accounted for approximately 36%, 27%, 30% and 7%, respectively, of the total racing time differs from the findings by Berg and Forsberg (2000) that more than half of the total time in a distance cross-country skiing race was spent on uphill terrain. The time spent uphill is also slightly lower than that in an earlier study into sprint skiing (Andersson et al. 2010). In the present study, the time spent on uphill and flat terrain was strongly related to overall STT performance, with the correlations and coefficients of variation for the individual sections demonstrating similar patterns, i.e., being greatest for the last two uphill sections (S4 and S7), followed by the two final flat sections (S8-9). The importance of uphill skiing for overall race performance has been observed previously in connection with both distance and sprint skiing (Andersson et al. 2010; Bergh and Forsberg 2000), but the contribution of flat skiing is a novel finding that may be explained by the flatter nature of sprint skiing tracks and the more pronounced significance of skating in flat terrain. The flatter terrain in the end of the race in the current study, compared to the study of Andersson and coworkers (2010), may explain these studies' different results.

It is noteworthy that the time spent on the initial 180-m flat section of the STT was not significantly correlated to performance, showing a lower correlation to overall STT performance than the two flat sections at the end of the race (S8 and S9). This observation indicates that the time required to achieve maximal speed from a standing position may not differ significantly between elite sprint skiers, a conclusion supported by a previous finding of similar performances by world-class and national level sprint skiers in connection with a 30-m acceleration test (Sandbakk et al. 2010b).

The current study, as well as the study of Andersson and coworkers (2010), show that the average speed on downhill sections was not significantly correlated to overall STT performance. It should be noted that the downhill sections involved were relatively straightforward and not technically difficult, so that the skiers were gliding mostly in the deep stance typically used downhill (i.e., the G7 technique) and these sections may thus have been used primarily for recovery. At the same time, since better sprint skiers recover more rapidly (Sandbakk et al. 2010b), the downhill sections may have exerted an indirect impact on performance on the subsequent flat and uphill sections of the race.

To examine in greater detail the relationship between performance on uphill terrain and overall performance, the uphill section S4 was analyzed more closely. Longer cycle lengths were associated with average speed on this section, in agreement with a previous study on skiers using the skating technique during a distance cross-country race (Bilodeau et al. 1996). Thus, cycle length appears to be strongly connected to uphill skiing speed. A previous sprint time-trial study found slightly reduced cycle lengths with maintained cycle rates in the G3 technique from the first to the second lap (Andersson et al. 2010). However, the same study showed an inverse pattern for the G2 technique, with mainly reductions in cycle rate between laps, indicating differences in how skiers adapt to speed and/or fatigue within these two techniques.

Furthermore, the mean work rate in S4 was approximately 60% greater than the skiers' peak aerobic power. Two earlier studies indicated that the uphill sections of 15 km and 30 km races in the classical technique among world-class cross-country skiers were also performed well above peak aerobic power (Norman and Komi 1987; Norman et al. 1989). In other types of endurance sport involving racing times comparable with the STT investigated here (i.e., approximately 4 min), about 20-30% of the total energy requirement during competitions is supplied by anaerobic energy processes (Gastin 2001).

Despite the intense work rate in the uphill section analyzed, the relative anaerobic and aerobic energy contributions during the entire STT might be similar to those in other middle-distance sports, as a consequence of the lower work rates on flat and downhill terrain while skiing. This proposal is supported by the report by Norman and Komi (1987) that work rates on level terrain are approximately 50% lower than on steep uphill terrain. A rough estimation of the work rates on flat terrain in the current investigation, based on the same formula and assumptions as for the uphill terrain (see the methods), indicates rates of work slightly greater than peak aerobic power, i.e., considerably lower than on uphill terrain. Because of the passive nature of the downhill sections of the STT, the metabolic costs on this terrain were probably well below peak aerobic power. Thus, the varying terrain associated with cross-country skiing allows skiers to recover while going downhill, thereby enabling them to generate more pronounced anaerobic power when skiing uphill. Variations in power output on different terrains and under different conditions in connection with cycling has previously been shown to optimize performance (Swain 1997) and this aspect of cross-country skiing clearly merits further examination.

Laboratory determinants of sprint performance
This investigation constitutes the first comparison between performance and kinematics of skiing on a treadmill and on snow. TTE on the treadmill was negatively correlated to the STT performance on snow, with the most pronounced relationships to the average speed on the uphill and flat sections. These findings indicate that treadmill testing is of relevance in evaluating performance in connection with sprint skating on snow.

Furthermore, the current study provides novel information regarding the physiological and kinematic laboratory parameters that are strongly correlated to STT performance. Multiple regression analysis revealed that VO_{2peak}, V_{peak} and peak cycle length in combination provided the best prediction of STT performance with the second best regression model involving VO_{2peak}, V_{peak} and GE. The standardized coefficients in these models were not significantly different and these four independent variables all exhibited relatively similar correlations to STT.

The significance of VO_{2peak} for sprint skiing performance observed here has also been reported previously (Sandbakk et al. 2010a; Sandbakk et al. 2010b) and receives further support from several studies on other middle-distance sports, such as running, rowing and kayaking (Brandon 1995; Michael et al. 2008; Secher 1993). Vesterinen and coworkers (2009) suggested that high aerobic capacity reduces fatigue and improves total performance during four heats of sprint skiing, whereas high anaerobic capacity is associated with better performance in the first two heats. The current investigation reveals a considerable importance of VO_{2peak} to performance in the qualification heat (i.e., a STT) as well. The strong correlations to performance on the uphill and flat terrain during the last part of the race reveal that aerobic capacity influences the ability to maintain speed even during a single sprint time-trial.

The strong negative correlation between V_{peak} and STT performance reported here illustrates the general importance of high-speed ability for sprint time-trial performance, as also demonstrated in previous studies (Andersson et al. 2010; Sandbakk et al. 2010a; Sandbakk et al. 2010b; Stöggl et al. 2006; Stöggl et al. 2007; Vesterinen et al. 2009). V_{peak} was negatively correlated to performance on all uphill, flat and curved sections of the STT, with the exception of the initial flat section. This lack of a significant correlation between V_{peak} and the first section time may indicate that the faster skiers employed a pacing strategy, using a lower percentage of their speed capacity in beginning of the STT to promote their ability to maintain higher speed during the rest of the race. The relationship between V_{peak} and the ability to maintain speed on uphill, flat and curve sections of the STT may also reflect a higher anaerobic capacity in better skiers, as also previously suggested (Sandbakk et al. 2010b; Stöggl et al. 2007).

The negative correlation between GE and STT performance observed here is in agreement with earlier reports that GE is both correlated to treadmill performance and FIS points, and distinguishes world-class from national level skiers (Sandbakk et al. 2010a; Sandbakk et al. 2010b). The technical complexity involved in cross-country skiing, raises the possibility that the efficiency with which muscle power is converted into external power and speed may differ between skiers and, thus, that performance will be influenced by the ratio of work rate to metabolic rate. One limitation of the present investigation is that GE was measured during treadmill roller skiing and not on snow. Accordingly, GE must be further examined on snow, as well as in connection with different skiing techniques.

The peak cycle length on the treadmill exhibited pronounced negative correlations to STT performance as well as to the average speed on flat and uphill terrain, in agreement with other observations that better skiers have longer cycle lengths when skating (Bilodeau et al. 1996; Rundell and McCarthy 1996; Stöggl and Muller 2009). Furthermore, leg and pole recovery times were strongly correlated to peak cycle length here. One explanation for this may be that longer cycle lengths and pole and leg recovery times demonstrated by better skiers are consequences of greater push-off power, as recently shown by Stöggl and coworkers (2010). Other studies have also related cycle length to strength and power (Bilodeau et al. 1996; Stöggl et al. 2007), as well as to technical aspects of skiing (Bilodeau et al. 1996; Sandbakk et al. 2010a; Stöggl and Muller 2009). However, cycle length may also be a function of work rate and speed with longer cycle length as an outcome in faster skiers.

Conclusions

The current findings reveal that the times spent on uphill and flat terrain, especially during the latter part of the race, correlate to STT performance, indicating that the ability to maintain speed is crucial. On a treadmill better sprint skiers demonstrate higher peak oxygen uptake, more efficient technique, and greater speed, as well as longer cycle lengths. VO_{2peak} and GE are important determinants of performance on uphill and flat terrain during the latter part of the race, whereas V_{peak} and peak cycle length are of great significance for performance on flat, uphill and curved terrain throughout the race, with the exception of the initial section (S1). Superior sprint skiing performance is therefore characterized by a greater ability to generate and maintain speed.

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STUDY V

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