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Physiological demands of competitive elite cross-country skiing

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Abstract

Introduction Researchers have, for decades, contributed to an increased collective understanding of the physiological demands in cross-country skiing; however, almost all of these studies have used either non-elite subjects and/or performances that emulate cross-country skiing. To establish the physiological demands of cross-country skiing, it is important to relate the investigated physiological variables to the competitive performance of elite skiers. The overall aim of this doctoral thesis was, therefore, to investigate the external validity of physiological test variables to determine the physiological demands in competitive elite cross-country skiing.

Methods The subjects in Study I – IV were elite male (I – III) and female (III – IV) cross-country skiers. In all studies, the relationship between test variables (general and ski-specific) and competitive performances (i.e. the results from competitions or the overall ski-ranking points of the International Ski Federation (FIS) for sprint (FISsprint) and distance (FISdist) races) were analysed. Test variables reflecting the subject's general strength, upper-body and whole-body oxygen uptake, oxygen uptake and work intensity at the lactate threshold, mean upper-body power, lean mass, and maximal double-poling speed were investigated.

Results The ability to maintain a high work rate without accumulating lactate is an indicator of distance performance, independent of sex (I, IV). Independent of sex, high oxygen uptake in whole-body and upper-body exercise was important for both sprint (II, IV) and distance (I, IV) performance. The maximal double-poling speed and 60-s double-poling mean power output were indicators of sprint (IV) and distance performance (I), respectively. Lean mass was correlated with distance performance for women (III), whereas correlations were found between lean mass and sprint performance among both male and female skiers (III). Moreover, no correlations between distance performance and test variables were derived from tests of knee-extension peak torque, vertical jumps, or double poling on a ski-ergometer with 20-s and 360-s durations (I), whereas gross efficiency while treadmill roller skiing showed no correlation with either distance or sprint performance in cross-country skiing (IV).

Conclusion The results in this thesis show that, depending on discipline and sex, maximal and peak oxygen uptake, work intensity at the lactate threshold, lean mass, double-poling mean power output, and double-poling maximal speed are all externally valid physiological test variables for evaluation of performance capability among elite cross-country skiers; however, to optimally indicate performance capability different test-variable expressions should be used; in general, the absolute expression appears to be a better indicator of competitive sprint performance whereas the influence of body mass should be considered when evaluating competitive distance performance capability of elite cross-country skiers.

Abbreviations

ATP	Adenosine triphosphate
CI	Confidence interval
CMJ	Counter-movement jump
CMJA	Counter-movement jump with an arm swing
DP20Fpeak	Peak force during 20 s double poling
DP60Pmen	Mean power during 60 s double poling
DP60$\dot{V}O_2$mean	Mean oxygen uptake during 60 s double poling (equivalent to $\dot{V}O_2$dp)
DP360Pmean	Mean power during 360 s double poling
DP360$\dot{V}O_2$mean	Mean oxygen uptake during 360 s double poling
DXA	Dual-emission x-ray absorptiometry
FIS	International Ski Federation
FISdist	International Ski Federation’s ski-ranking points for distance races
FISsprint	International Ski Federation’s ski-ranking points for sprint races
GE	Gross efficiency
LM	Lean mass
LMLB	Lean mass lower body
LMUB	Lean mass upper body
LMWB	Lean mass whole body
OBLA4mmol	Relative work intensity at a blood-lactate concentration of 4 $mmol·l^{-1}$
PT60	Mean isokinetic knee extension peak torque with angular velocity $60°·s^{-1}$
PT180	Mean isokinetic knee extension peak torque with angular velocity $180°·s^{-1}$
PT300	Mean isokinetic knee extension peak torque with angular velocity $300°·s^{-1}$
r	Correlation coefficient
RER1.0	Relative work intensity where respiratory-exchange ratio reached 1.0
Rise1mmol	Relative work intensity where blood-lactate concentration had increased 1 $mmol·l^{-1}$ above the lowest measured concentration
SD	Standard deviation
SNC15	Performance at the 15 km race at the Swedish National Championships
SNC30	Performance at the 30 km race at the Swedish National Championships
SQJ	Squat jump
TTEX	Time to exhaustion

VAS	Visual analogue scale
Vmax	Maximal speed
$\dot{V}O_2dp$	Mean oxygen uptake during 60 s of double poling (equivalent to DP60$\dot{V}O_2$mean)
$\dot{V}O_2max$	Maximal oxygen uptake
$\dot{V}O_2obla$	Oxygen uptake related to a blood-lactate concentration of 4 $mmol \cdot l^{-1}$
$\dot{V}O_2peak$	Peak oxygen uptake

List of publications

This doctoral thesis is based on the following original studies and they will hereafter be referred to by their roman numerals.

I Carlsson M, Carlsson T, Hammarström D, Tiivel T, Malm C, Tonkonogi M. Validation of physiological tests in relation to competitive performances in elite male distance cross-country skiing. J Strength Cond Res. 2012;26:1496-504.

II Carlsson M, Carlsson T, Knutsson M, Malm C, Tonkonogi M. Oxygen uptake at different intensities and sub-techniques predicts sprint performance in elite male cross-country skiers. Eur J Appl Physiol. 2014;114:2587-95.

III Carlsson M, Carlsson T, Hammarström D, Malm C, Tonkonogi M. Prediction of race performance of elite cross-country skiers by lean mass. Int J Sports Physiol Perform. 2014;9:1040-5.

IV Carlsson M, Carlsson T, Wedholm L, Nilsson M, Malm C, Tonkonogi M. The physiological demands of competitive sprint and distance performance in elite female cross-country skiing. *Submitted*

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Introduction

Cross-country skiing

History of cross-country skiing

Knowledge, creativity, ingenuity, and, occasionally, serendipity are some of the underlying qualities that give rise to solutions to problems. To move more effectively in different environments, humans have invented tools, e.g. fins, boats, and wheels, to help compensate for the limitations of the human body [1]. To be able to move through snow-covered terrain as swiftly and effortless as possible was most likely important for the survival of inhabitants in places with long, freezing winters [2]. Faced with this problem, a long time ago, someone acquired the knowledge that it was easier to move through the snow-covered terrain by placing themselves on an object that distributes the body weight over a larger surface area than the feet, thereby reducing the risk of sinking down into the snow. This knowledge gave rise to the invention of snowshoes and skies, and the oldest preserved skis are approximately 5200 years old [3]. In the 50’s, it was scientifically shown that it is far more efficient in terms of movement economy to use skies than to use snowshoes or to walk [4]. During the Viking Age (AD 700 to 1100), cross-country skiing was strongly associated with the Asa God Ull, who was considered to be the best skier and archer of all of the Asa Gods [3]. Throughout the millennia, cross-country skiing has evolved from being equated as a means of transportation of Gods and an important mode of transportation while hunting to a demanding endurance sport, where the hunt for wildlife has been replaced with a hunt for seconds.

History of competitive cross-country skiing

The first known cross-country skiing race was held in Oslo, Norway, in the year 1767, with soldiers as participants [5]. The first documented race that was open to the public was held in 1848 in Tromsø, Norway [5,6]. In Sweden, the first public race was held in 1879 in Stockholm; however, the first race that attracted much attention from both the media and the public was the Nordensiöld race in 1884, which had a race distance of 220 km and a substantial cash prize for the winner [5]. The race was launched by the famous arctic explorer to prove to nonbelievers the veracity of the reported information concerning the skiing distance covered in a short time, as was performed by two of the skiers in the expedition, during their second Greenlandic exploration in 1883 [5]. Fifteen men entered the competition, and the winner’s time was 21 hours and 22 minutes, proving that the reported information was not exaggerated [5]. In the year 1882, the association for the promotion of cross-country skiing was founded, which resulted in organized skiing competitions [5]. Although there was newfound popularity among the public, a great distrust of this new sport also developed because children's parents felt that this sport was harmful to practice [7]. To scientifically clarify if this sport was harmful or beneficial to health, Dr. Henschen conducted a series of investigations on skiers before and after competitions and concluded in his thesis in 1897 that skiers with the enlarged hearts were more successful than skiers with smaller hearts, therefore stating that "big hearts win races!" He also concluded that cross-country skiing should be encouraged as a form of exercise that is beneficial to health [7]. Along with an increased interest in participating in cross-country skiing, the number of ski clubs also increased. On December 11th 1908, the Swedish Ski Association became a member of the Swedish Sports Confederation. Moreover, the International Ski Federation (FIS) was founded on the 18th of February in 1910. Cross-country skiing has, since the first Games in 1924 in Chamonix, France, been a part of the Winter Olympics. Twenty-eight years later (1952), the first cross-country skiing event for women was included in the Winter Olympic program.

Recent changes in competitive cross-country skiing

The 50 km race at the Olympic Games in 1924 was held in the French Alps and had an "up and down" course profile, where the start was at 1100 m above sea level and the highest point at 1800 m; this resulted in very demanding uphill skiing at first as well as a terrifying descent during the last part of the race [5]. Today, certified FIS courses are, for example, homologated (e.g. distribution of approximately 1/3 each of uphill, downhill, and undulating terrain) and have a minimum prepared course width of 3 – 12 m, depending on the discipline [8]. Traditional cross-country skiing was performed using a classical style comprising herringbone, double-poling, kick double-poling, and diagonal-stride techniques [9]. However, in the 80's, the freestyle was developed to increase skiing speed and was accepted as a new style by the FIS in 1986 [10]. The freestyle has five predominant sub-techniques, which are known as gears (G1-5) in the Swedish nomenclature [11], and is faster compared with classical style [12]. In the 90's, the sprint discipline, with a race distance of 0.8 to 1.8 km, was introduced. Currently, cross-country skiing comprises different distances (0.8 to 50 km), styles (classical and free), and starting methods (interval and mass starts). In addition, double pursuit with a mandatory ski change adds to the complexity of the sport. Along with improved track preparation and technological advances in ski equipment, there has been an increased usage of the double-poling technique in classical races [13,14]. In recent years, several skiers have used the double-poling technique exclusively throughout World Cup sprints and competitions included in the FIS Marathon Cup. Consistent with this change, cross-country skiing research has suggested that a greater proportion of a skier's training should focus on developing upper-body strength and power output [15-21].

Physics of cross-country skiing

In cross-country skiing, the goal of the skier is to create the largest possible imbalance between propulsive and counteractive forces throughout the race; in general, greater imbalance leads to higher speed and a faster finishing time. There are several counteracting forces that the skier must overcome to create forward motion, as follows: work against gravity in ascents and during the stride cycle, air resistance, ski friction, and translational and rotational kinetic-energy changes during the stride cycle. Previously, it has been suggested that the counteracting forces affecting the skier during skiing are all related to body mass. Therefore, a skier with larger body mass must generate higher propulsive forces compared with a lighter skier to have the same skiing speed in level and uphill terrain; conversely, a large body mass is advantageous when potential energy is transformed to kinetic energy in descents [22]. Skeletal muscle forces are transferred through the skis and poles to the snow for propulsion, and the force-generating potential is related to the skeletal muscle cross-sectional area [23-27]. However, the proportion of the generated muscle forces that contributes to the propulsive forces depends on the efficiency of the skier’s movement pattern in the specific sub-technique.

Energy supply during cross-country skiing

A prerequisite for power production by the muscles is the availability of adenosine triphosphate (ATP); to continuously generate high propulsive forces, rapid synthesis of ATP in exercising muscles is necessary. This is emphasized by the potential 400-fold increase in the ATP turnover rate for exercising compared with resting skeletal muscles [28].

ATP can be synthesized through both aerobic and anaerobic pathways. During aerobic ATP synthesis, oxidative phosphorylation occurs in the mitochondria, which is an effective but relatively slow process. The aerobic processes are dependent on the availability of oxygen in the exercising muscles, and the aerobic energy supply system is limited by the ability of the cardiorespiratory system to deliver oxygen to the exercising muscles [29]. The available anaerobic pathways involve the usage of stored ATP as well as the synthesis of ATP by phosphocreatine splitting and adenosine diphosphate fusion and the anaerobic catabolism of carbohydrates to lactic acid. Together, these anaerobic pathways allow the muscles to generate force when the oxygen supply is limited. The processes are rapid but have a limited capacity compared with the aerobic system. If the oxygen supply does not meet the increased oxygen demand in the exercising muscles, a larger proportion of the required ATP will come from the anaerobic catabolism of carbohydrates, which will result in a more rapid depletion of intracellular glycogen stores and an increased production of fatigue-related metabolites [30]. The anaerobic capacity has previously been related to the muscle volume [31,32] which, to some extent, could be explained by the proportional increase in available energy stores with an increase in volume [31]. This is consistent with the the results where the anaerobic energy production during intense exercise was shown to be related to the muscle mass involved [33]. The proportion of the required ATP that comes from aerobic and anaerobic pathways, respectively, depends mainly on the duration of the race [34].

In cross-country skiing, sprint races generally last from 2 to 4 minutes, indicating that the proportion of energy derived from aerobic processes ranges from 50-70% (i.e. 50-30% anaerobic energy contribution); whereas the corresponding value for distance races (5-50 km), with a skiing time from 13 min to more than 2 hours, ranges from 90-99% [34,35]. This difference in the aerobic energy contribution indicates that there is a potential difference in the physiological demands between sprint and distance disciplines.

To evaluate the capability of a skier's aerobic processes, oxygen uptake is analysed at different intensities and with different sub-techniques. For elite skiers, the maximal oxygen uptake ($\dot{V}O_2max$) is reached using the diagonal-stride technique [35], whereas the oxygen uptake at maximal work intensity for the other sub-techniques is less than the $\dot{V}O_2max$ [15,35-38] and is generally reported as the peak oxygen uptake ($\dot{V}O_2peak$). In this thesis, the different oxygen uptake variables are therefore referred to accordingly.

Recent investigations of the physiological demands in cross-country skiing

With the various recent changes (e.g. the inclusion of sprint, freestyle, and mass-start races, improved track preparation and ski equipment), it can be assumed that the physiological demands have changed to meet the new prerequisites. Generally, studies on sport performance need to be externally valid; hence, the dependent variable need to be a competitive performance with athletes that belong to the targeted population to whom the result is intended to be generalizable to [39,40]. Therefore, to determine the physiological demands in modern elite cross-country skiing, research should be based on the relationship between competitive performance (i.e. the results of skiing competitions or FIS overall ski-ranking points for sprint (FISsprint) and distance (FISdist) races) and the physiological characteristics of elite skiers competing at the senior level. It is important that all of these criteria are met to obtain accurate information concerning the physiological demands of competitive elite cross-country skiing.

When reviewing previous research from the 80's (when the major changes in cross-country skiing began) to the time when the research plan for this thesis was written in 2010, a limited number of studies were identified as having investigated correlations between test variables and performance (Table 1).

Table 1. Studies (1980-2010) which has investigated correlations between test variables and performances

Study		Sex	AC	PL	PC	Performance	Test variable	*P*
Alsobrook	[41]	♂	S+J	Rec	C	10 km mass-start classic	Ppeak DP abs.	*
							Ppeak DP rel.	*
							Pmean DP abs.	*
							Pmean DP rel.	
							$\dot{V}O_2$peak abs.	*
							$\dot{V}O_2$peak rel.	
		♀	S+J	Rec	C	10 km mass-start classic	Ppeak DP abs.	
							Ppeak DP rel.	*
							Pmean DP abs.	
							Pmean DP rel.	*
							$\dot{V}O_2$peak abs.	
							$\dot{V}O_2$peak rel.	
Andersson	[42]	♂	S	E	Em	TT 1425 m skate	Vmax skate	
							Vpeak DP	*
							$\dot{V}O_2$max abs.	
							LMWB	
					FIS	FISsprint	Vmax skate	*
							Vpeak DP	
							$\dot{V}O_2$max abs.	*
							LMWB	
Bortolan	[43]	♂	S+J	E/Sub	Em	TT sprint vel. last 180 m	Pmean DP abs.	*
							Pmean DP rel.	*
Fabre	[44]	♀	S	E	R	National FISI distance	$\dot{V}O_2$peak DP abs.	**
							$\dot{V}O_2$LT DP	*
							$\dot{V}O_2$LT DS	*
Holmberg	[45]	♂	S	E	Em	3 km TT DP	Pmean DP abs.	*
							Pmean DP rel.	*
Mahood	[46]	♂	S	Sub	Em	10 km TT RS skate	$\dot{V}O_2$peak DP rel.	*
							$\dot{V}O_2$peak rel.	*
							Rise1mmol	*
							GE	*
					R	Subject rank-ordered	$\dot{V}O_2$peak DP rel.	*
							$\dot{V}O_2$peak rel.	*
							Rise1mmol	*
							GE	*
Mikkola	[18]	♂	S	E	Em	Sim. sprint RS skate	LT 3mmol	*
							LT 5mmol	**
							LT 7mmol	**
Mygind	[47]	♂	S	Sub	R	Rank-ordered 10 races	$\dot{V}O_2$peak DP abs.	*
Ng	[48]	♂	S	Rec	C	Mean race time 4 x 10 km	$\dot{V}O_2$peak abs.	*
							$\dot{V}O_2$peak rel.	*
							UBS abs.	*
							UBS rel.	*

Table 1. *Continue.*

Study		Sex	AC	PL	PC	Performance	Test variable	*P*
Staib	[20]	♂	S+J	Sub	R	National FIS distance	$\dot{V}O_2$peak abs.	*
							$\dot{V}O_2$peak 0.67	
							$\dot{V}O_2$peak rel.	
							$\dot{V}O_2$peak DP abs.	*
							$\dot{V}O_2$peak DP 0.67	*
							$\dot{V}O_2$peak DP rel.	*
							Ppeak DP abs.	*
							Ppeak DP rel.	*
Stöggl	[49]	♂♀	S	E/Sub	Em	1 km TT RS DP	Vmax DP	***
Stöggl	[50]	♂	S	E/Sub	Em	Sim. sprint TRS classic	Vmax DP	***
							Vmax DS	***
							$\dot{V}O_2$max 0.67	
							$\dot{V}O_2$max rel.	
Stöggl	[21]	♂♀	S	E	Em	1 km TRS DP	Ppeak DP	***

Subjects sex, ♂, men; ♀, women; AC, age category; S, senior; J, junior; PL, performance level of the subjects, E, elite; Sub, sub-elite; Rec, recreational; PC, performance category, Em, performance emulating cross-country skiing; C, cross-country skiing competition; R, different type of ranking; FIS, International Ski Federation's ski-ranking points for sprint (FISsprint) and distance (FISdist); FISI, Italian Ski Federation's ski-ranking points; TT, time trial; RS, roller skiing; TRS, treadmill roller skiing; DP, double-poling technique; Ppeak, peak power output; $\dot{V}O_2$peak, peak oxygen uptake; Pmean, mean power output; $\dot{V}O_2$LT, oxygen uptake at the anaerobic threshold; $\dot{V}O_2$max, maximal oxygen uptake using the diagonal-stride technique; Vmax; maximal speed; Vpeak, peak speed; LMWB, lean mas for the whole body; Rise1mmol, relative work intensity where blood lactate had increased 1 $mmol \cdot l^{-1}$ above the lowest measured concentration; GE, gross efficiency; LT, lactate threshold; UBS, isokinetic upper-body strength; abs, absolute expression; rel, relative expression; reported alpha levels of significance for the included studies are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$.

When summarizing the results of the included studies in Table 1, two studies met all of the aforementioned criteria [42,44]; no study has investigated the relationship between distance performance and the $\dot{V}O_2$max or variables of lean mass. Several of the other variables, included in Table 1, have only been investigated on one occasion. Moreover, merely two studies have investigated the relationship between test variables and distance performance among elite female skiers, and no study has used women's sprint performance as a dependent variable.

Because of this limited research and the wide variety of new elements affecting cross-country skiing performance, it is essential that further investigations be performed to increase the knowledge regarding the physiological demands in competitive elite male and female cross-country skiing.

Aims

The overall aim of this doctoral thesis was to investigate the external validity of physiological test variables to determine the physiological demands in competitive elite cross-country skiing. The specific aims of the original studies included in this thesis were:

I To establish which physiological test parameters reflects the distance performances in the Swedish National Championships in cross-country skiing (SNC) and the International Ski Federation's (FIS) ranking points for distance performances (FISdist). The present study also aimed to create multiple regression models to describe skiing performance for the SNC distance races and FIS ranking.

II To investigate the relationship between sprint-prologue performance (using the classical technique) and the $\dot{V}O_2obla$, $\dot{V}O_2max$, and $\dot{V}O_2dp$.

III To investigate the relationship between race performance and LM variables, as well as to examine sex differences in body composition in elite cross-country skiers.

IV To investigate the relationship between elite females' competitive performance capability in sprint and distance cross-country skiing and the variables of gross efficiency (GE), work rate at the onset of blood-lactate accumulation (OBLA4mmol), maximal oxygen uptake ($\dot{V}O_2max$), maximal speed (Vmax), and peak upper-body oxygen uptake ($\dot{V}O_2peak$).

Methods

Overall design

The overall design of this thesis was to investigate external validity of physiological test variables by correlating the test variables with competitive performance from the targeted population of elite male and female skiers.

Subjects

In total, 50 subjects (29 men and 21women) elite cross-country skiers, including 26 with World Championships and/or World Cup experience (14 men and 12 women), volunteered to participate in the studies included in this thesis. Some of the subjects volunteered to more than one study, more precisely, five men and five women took part in two studies, while two men took part in three studies. The characteristics of the subjects for each study are presented in Table 2.

Table 2. The characteristics of the subjects included in Study I – IV

Study	Sex	n	Age	Body mass	Stature
I	♂	12	23.9 ± 4.2	76.2 ± 5.8	183.9 ± 5.5
II	♂	8	24.8 ± 4.9	77.0 ± 4.5	183.5 ± 5.3
III	♂	18	24.9 ± 3.6	78.1 ± 5.7	183.9 ± 6.1
III	♀	16	23.0 ± 3.1	60.3 ± 5.2	169.5 ± 6.1
IV	♀	10	24.5 ± 2.8	64.4 ± 5.4	169.5 ± 5.9

The values representing the subjects' age, body mass, and stature are presented as mean ± SD; ♂, men; ♀, women; n, the number of subjects in the specific study; Age, the age of the subjects (years); Body mass, the body mass of the subjects (kg); Stature, the height of the subjects (cm).

Measuring equipment

Brief descriptions of the equipment used to measure physiological capabilities of the subjects in Study I – IV are presented below. For more detailed description of the measuring equipment, see the studies.

Oxygen-uptake measurements

Throughout the oxygen-uptake tests, parameters of expired air were continuously analysed using a stationary metabolic cart in mixing chamber mode (Jaeger Oxycon Pro, Erich Jaeger Gmbh, Hoechberg, Germany) (I, II, IV) and a mobile metabolic unit (Jaeger Oxycon Mobile, Erich Jaeger Gmbh, Germany) (I). Both equipment have previously been shown to be accurate systems for measuring oxygen uptake [51,52]. Prior to each new test, the equipment were calibrated according to the specifications of the manufacturer.

Ski-ergometer measurements

An air-braked Nordic ski-ergometer (Concept II, Concept Inc., Morrisville, VT, USA) was used to measure the subject's poling force and velocity during the double-poling cycles (I). The ski-ergometer has previously been shown to be both reliable and valid [45]. To measure the horizontal force and velocity for the double-poling cycles, a load cell (Load Cell, model 333A, Ergotest Technology AS, Norway) and a linear encoder (Linear encoder, Ergotest Technology AS, Norway) were attached to the ski-ergometer. Prior to each new subject, the load cell was checked for zero load and with a 10-kg precision weight, whereas the linear encoder was controlled for a known length.

Vertical-jump measurements

The maximal jump height was determined with an infra-red mat based IVAR-system (IVAR Jump & Speed Anayzer, LN Sport Konsult HB, Sweden), which calculates the vertical jump height based on the subject's flight time. The system have previously shown to be reliable and valid [53].

Isokinetic measurements

The isokinetic peak torque measurements at different angular velocities were performed using a Biodex muli-joint dynamometer 2 (Biodex Medical Systems Inc., NY, USA). At the start of each new test day, the equipment was calibrated according to the specifications of the manufacturer. It has previously been reported the Biodex is reliable equipment for measuring isokinetic strength [54], and it is considered to be the golden standard for measuring the knee-extension peak torque [55].

Blood-lactate measurements

The capillary-blood samples, collected during and after the roller-skiing tests were analysed to determine the subject's blood-lactate concentrations (Biosen 5140, EKF-diagnostic Gmbh, Barleben, Germany). The equipment was calibrated according to the manufacturer's specifications and the equipment has shown to be both a reliable and valid blood-lactate analyser [56].

Body-composition measurements

The body composition of the subjects was measured using dual-emission X-ray absorptiometry (DXA) (GE Healthcare Lunar, Madison, USA), and were analysed by the DXA software (enCORE, Version 13.6, General Electric Company, Madison, USA). The equipment was calibrated each day, according to the manufacturer's instructions, by using a standardized phantom. When an appropriate protocol designed to minimize the influence of the potential confounding factors is applied, DXA provides a useful method for prediction of skeletal muscle mass [57-59].

Physiological measurements

The analyses in Study I – IV are based on physiological variables collected from both general and ski-specific tests. A schematic overview of the study designs (I – IV) is presented in Figure 1. Brief descriptions of test procedures and test variables are presented below. For more detailed information of the test procedures and variables, see the studies. The roller-skiing tests in the studies were performed on two motor-driven treadmills (OJK-2; Telineyhtymä, Kotka, Finland (I, II); Saturn 450/300rs, h/p/cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany (IV)).

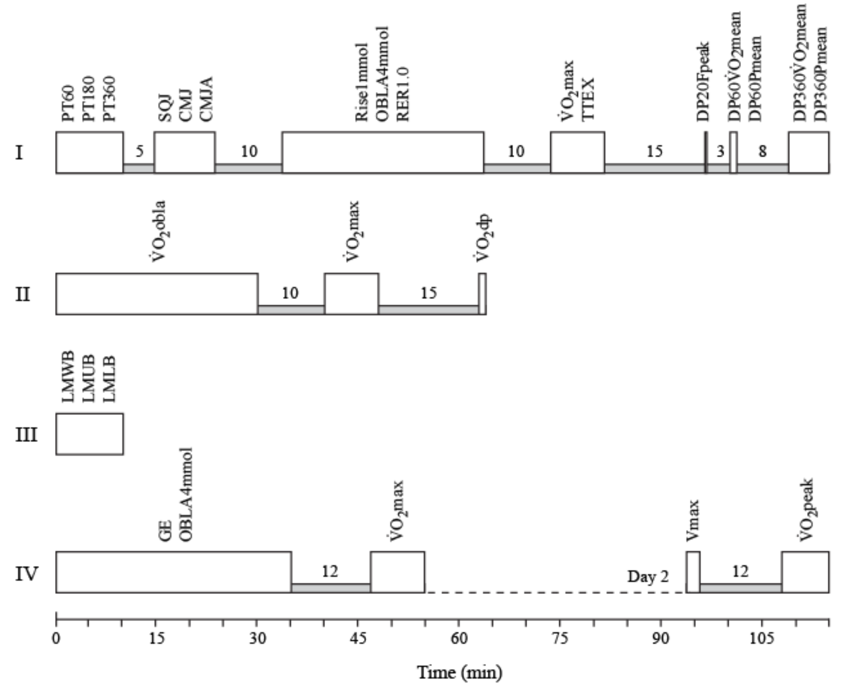

Figure 1. Schematic overview of the study designs (I – IV), where the white blocks represents the physiological tests and the associated test variables whereas the gray blocks represents the rest between tests.

Variables obtained during the lactate-threshold tests

The lactate-threshold test was performed treadmill roller skiing using the diagonal-stride technique. The test protocols had an incremental exercise test design, where the duration of each work intensity was 3.5 min (I, II) or 4 min (IV). Directly after each stage, a capillary-blood sample was collected; thereafter, the work intensity was increased by increasing treadmill speed and/or inclination (for test protocols, see the studies). Based on the relationship between blood-lactate concentration and work intensity, the relative work intensity ($W \cdot kg^{-1}$) where blood-lactate concentration had increased 1 $mmol \cdot l^{-1}$ above the lowest measured concentration (Rise1mmol) (I), and the relative work intensity at blood lactate concentration of 4 $mmol \cdot l^{-1}$ (OBLA4mmol) (I, IV) were determined (Figure 2a).

During the last minute of each stage, volume of both oxygen uptake and produced carbon dioxide were determined. For each subject, the linear relationship between relative work intensity and oxygen uptake was established and based on this relationship, the oxygen uptake at the relative work intensity corresponding to a blood-lactate concentration of 4 $mmol \cdot l^{-1}$ ($\dot{V}O_2$obla) was calculated (II) (Figure 2b).

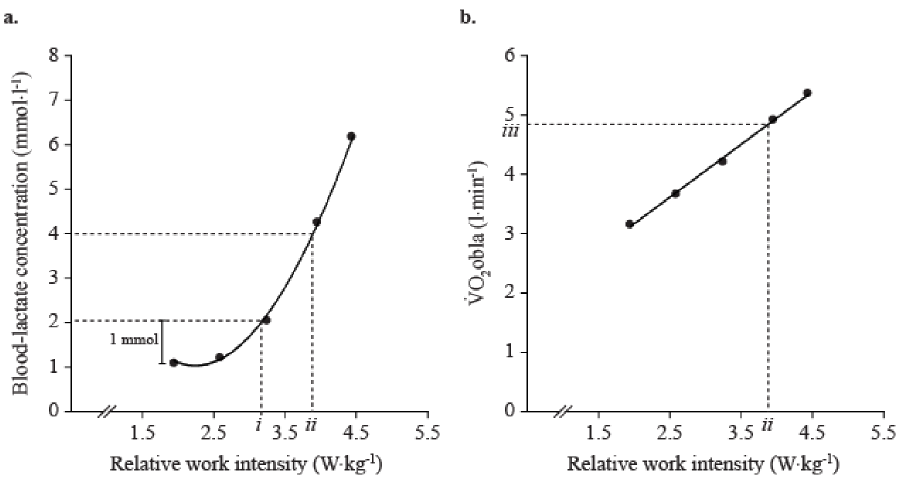

Figure 2. Determination of test variables related to the lactate-threshold test, where *i*, the relative work intensity where blood-lactate concentration have increased 1 $mmol \cdot l^{-1}$ above the lowest measured concentration; *ii*, the relative work intensity at a blood-lactate concentration of 4 $mmol \cdot l^{-1}$; *iii*, the oxygen uptake related to the relative work intensity (*ii*) at the onset of the blood-lactate concentration of 4 $mmol \cdot l^{-1}$.

Based on the relationship between $\dot{V}CO_2/\dot{V}O_2$-ratio and work rate, the relative work intensity where the respiratory-exchange ratio reached 1.0 (RER1.0) (I) was established. In Study IV, the subject's gross efficiency (GE) was determined for a treadmill speed/inclination of 9.5 $km \cdot h^{-1}$/5.0°, and was calculated as the ratio between the work rate (WR) and metabolic rate (MR) during the last minute of the specified intensity, i.e. GE = WR / MR (for more information about the calculations regarding GE, see Study IV).

Variables obtained during the maximal and peak oxygen-uptake tests

The test to determine the subject's $\dot{V}O_2max$ was an incremental treadmill roller-skiing test using the diagonal-stride technique, where the work intensity increased every 30 s (IV) or 60 s (I, II) depending on which test protocol that was used (for detailed descriptions of the test protocols, see the studies). During the $\dot{V}O_2max$ test, the subject's oxygen uptake was continuously analysed and the $\dot{V}O_2max$ was defined as the highest mean oxygen uptake during a 60-s period when meeting specific criterion(s). The criterions in Study I was: (a) plateau in oxygen uptake i.e. less than 2.1 $ml \cdot min^{-1} \cdot kg^{-1}$ in $\dot{V}O_2$ between successive stages; (b) at least one of two secondary criteria, a respiratory exchange ratio $\geq$ 1.15 or a blood-lactate concentration > 8 $mmol \cdot l^{-1}$, had to be fulfilled [60]. In Study II and IV, the criterion was the recognition of data points that fell outside (and below) the extrapolated CI for the $\dot{V}O_2$ – work-intensity relationship (established for a period of 3 min immediately preceding the levelling-off behaviour) (Figure 3) [61]. This criterion for a plateau in oxygen uptake was also used in Study IV to determine the subject's highest mean oxygen uptake during a 60-s period ($\dot{V}O_2peak$). The $\dot{V}O_2peak$ test was commenced roller skiing on a treadmill using double-poling technique and the work intensity was increased every 30 s. In addition to the $\dot{V}O_2max$, the time to exhaustion (TTEX) was used as a test variable in Study I.

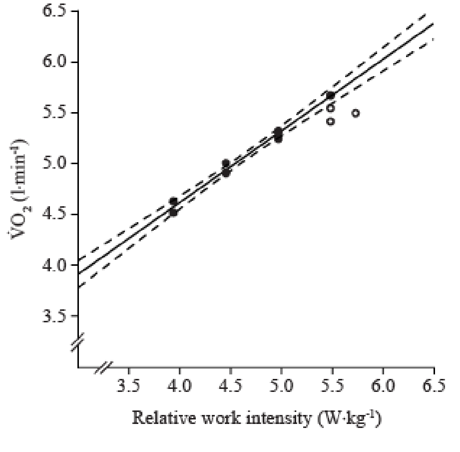

Figure 3. The recognition of a plateau in oxygen uptake during the $\dot{V}O_2max$ test (II, IV)

Variables obtained during the mean oxygen-uptake tests

During the ski-ergometer double-poling tests with test duration of 60 s (I, II) and 360 s (I), the oxygen uptake was continuously analysed for the whole test duration. Based on the oxygen-uptake measurements during the tests, the subject's mean oxygen uptake for the 60-s (DP60$\dot{V}O_2$mean (I) and $\dot{V}O_2$dp (II)) and 360-s (DP360$\dot{V}O_2$mean) double-poling tests was determined.

Variables obtained during the double-poling tests

Simultaneously with the oxygen-uptake measurements during the double-poling tests, the subject's mean double-poling power output for the 60-s (DP60Pmean) and 360-s (DP360Pmean) was determined by using the force and displacement measurements during the test. In addition to the power-output measurements in Study I, a 20-s double-poling test was used to determine the peak force produced during a single double-poling cycle (DP20Fpeak). In Study IV, the subject's maximal roller-skiing speed using the double-poling technique (Vmax) was determined by using speed increments of 1 km·h^{-1} every 4 s while maintaining a constant treadmill inclination. The subject's Vmax was determined as the treadmill speed of the last completed 4-s stage.

Variables obtained during the body-composition test

The body composition of the subject was analysed using DXA and the subject's lean mass, fat mass, and bone-mineral content for whole body and body segments (head and neck, arms, trunk, and legs) was determined. The test variables used in the correlation analyses were lean mass in the whole body (LMWB), upper body (arms + trunk) (LMUB), and lower body (legs) (LMLB).

Variables obtained during the knee-extension and vertical-jumps tests

The isokinetic knee-extension peak torque was determined, with a 90° range of motion, for three different angular velocities: 60°·s^{-1}, 180°·s^{-1}, and 300°·s^{-1} using a Biodex dynamometer. The peak-torque value for the right and left leg were used to calculate a mean-peak torque value for each of the tested velocities and the test variables derived from the peak-torque test were PT60, PT180, and PT300 (I).

In Study I, three different vertical-jump tests were performed. The highest jump height for squat jump (SQJ), counter-movement jump (CMJ) and counter-movement jump with an arm swing (CMJA) were used as test variables.

Competitive performances

The investigated variables in Study I – IV are related to elite male and female competitive cross-country skiing performances, i.e. the results of skiing competitions, FISsprint or FISdist. Descriptions of the performances included in the studies are presented below.

Cross-country skiing competitions

All cross-country skiing competitions were performed on homologated courses that met the criteria of international competition courses [62], and the track and waxing conditions were stable during the competitions. In Study I, performance data were collected from competitions at the Swedish National Championships (SNC). Completion times from the men's 15-km competition in classical style with interval start (SNC15c) and the men's 30-km double-pursuit competition in mass start (SNC30) were used as performance variables. In Study II, performance data was collected from a 1.25-km sprint prologue in classical technique for men. In Study III, completion times in the SNC from the women's 10-km free-style competition (SNC10) and 1.55-km sprint prologue as well as the men's 15-km free-style competition (SNC15f) and 1.76-km sprint prologue were used as performance variables. For more detailed information concerning the competitions, see the studies.

International Ski Federation's ski-ranking points

The FISsprint (II, IV) and FISdist (I, IV) were used as indicators of competitive cross-country skiing performance. To determine the participants' performance capability in sprint and distance races, ski ranking points were obtained from the FIS Cross-Country List which was the most recent published for each study. The FIS-point system is intended to rank the skiers and a lower FIS-point value indicates better performance ability. A participant's FISdist and FISsprint are based on an average of the skier's best five FIS-point results from the last twelve months in distance and sprint competitions, respectively.

For a specific skiing competition, the skier receives a FIS-point value which is the sum of the race points and the race penalty, i.e. FIS-points = Race points + Race penalty. Calculation of a skier's race points is based on the formula: Race points = $([T_x \cdot T_o^{-1}] - 1) \cdot RF$, where: T_x = the skier's race time (s), T_o = the winner's race time (s), RF = the race factor (800 for distance competitions with interval start, 1200 for sprint races, and 1400 for competitions with mass-start and skiathlon races). For example, for distance competitions with interval start the skier receives 8 race points for each percent in race time behind the winner. The race penalty is calculated as the sum of the three best FIS-points values of the competitors who finished among top five of the race divided by 3.75. If the calculated race penalty is lower than the minimum penalty of the specific race, the minimum penalty is applied to the race. The minimum penalty for FIS competitions is 15. For races included in the World Cup, World Championships, and Olympic Winter Games no race penalty is added to the FIS-point value (i.e. race penalty is fixed to 0).

Statistics

The investigations to establish the physiological demands of competitive elite cross-country skiing were mainly based on correlation analyses between physiological variables and competitive performance in cross-country skiing. If two or more physiological variables were correlated with a specific performance variable, the possibility to create a multiple regression model was evaluated. All of the tests performed at an alpha of 0.05.

Correlation analyses

Prior to the correlation analyses, the potential occurrence of outliers was analysed and the variables agreement with a normal distribution were investigated by using the Kolmogorov-Smirnov test (I, III) and the Shapiro-Wilk test (II, IV). All of the test and performance variables included in the correlation analyses fulfilled the assumptions of level of measurement (interval or ratio scale), related pairs (each subject has a score on both the physiological and performance variable), independence of observations (all test and performance data are independent of one another), linear relationship between variables, homoscedasticity (similar variability for all scores of the performance variable). The correlation analyses were performed by using Pearson's product-moment correlation coefficient test and the relationships between physiological and performance variables are reported as correlation coefficients (r).

Multiple regression analyses

The multiple regression analyses were used investigate how much of the variance in performance that could be explained by two (or more) physiological variables derived from different tests. The rules set to determine a valid model were (a) each of the test variables should display significant correlation with the performance variable, (b) the test parameters were not allowed to be intercorrelated (i.e. $r < 0.7$), (c) each test parameter should significantly contribute to the model (i.e. $P < 0.05$), and (d) to avoid multicolinearity, the variance-inflation factor should be less than 2 and the tolerance value should be higher than 0.3.

Presentation of data

The characteristics of the subjects, test results, and performance data are presented as the means and standard deviations (SD). In addition, ranges (minimum value–maximum value) were presented in Study I.

Statistical programs

The statistical analyses in Study I – IV were processed using the IBM Statistical Package for the Social Sciences (SPSS) statistics software, version 20 (IBM Corporation, New York, USA).

Ethical considerations

Before participation in Study I – IV, all of the subjects provided written informed consent to participate. Approvals for the studies were given by the Ethics Committee at Dalarna University, Falun, Sweden (I) and the Regional Ethical Review Board, Uppsala, Sweden (II – IV). All test procedures in the studies were performed in accordance with the World Medical Association Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects 2008.

Results

Correlations

The relationships between the investigated test variables and competitive cross-country skiing performances in Study I – IV are presented, depending on which test each variable is linked to, in Table 3-7.

Lactate-threshold tests

The relationships between test variables related to the lactate-threshold test and competitive distance and sprint performances are presented in Table 3.

Table 3. Correlations between test variables related to the lactate-threshold test and competitive performance

Study	Sex	Test variable	(Unit)	Performance	(Unit)	*r*
			Distance performance			
I	♂	Rise1mmol	($W \cdot kg^{-1}$)	FISdist	(points)	-0.69 *
I	♂	Rise1mmol	($W \cdot kg^{-1}$)	SNC15c	(s)	-0.71 **
I	♂	Rise1mmol	($W \cdot kg^{-1}$)	SNC30	(s)	-0.68 *
I	♂	RER1.0	($W \cdot kg^{-1}$)	FISdist	(points)	-0.77 **
I	♂	RER1.0	($W \cdot kg^{-1}$)	SNC15c	(s)	-0.73 **
I	♂	RER1.0	($W \cdot kg^{-1}$)	SNC30	(s)	-0.62
I	♂	OBLA4mmol	($W \cdot kg^{-1}$)	FISdist	(points)	-0.66 *
I	♂	OBLA4mmol	($W \cdot kg^{-1}$)	SNC15c	(s)	-0.66 *
I	♂	OBLA4mmol	($W \cdot kg^{-1}$)	SNC30	(s)	-0.63
IV	♀	OBLA4mmol	($W \cdot kg^{-1}$)	FISdist	(points)	-0.64 *
IV	♀	GE	(%)	FISdist	(points)	-0.48
			Sprint performance			
II	♂	$\dot{V}O_2$obla	($l \cdot min^{-1}$)	Sprint prologue	($m \cdot s^{-1}$)	0.79 *
II	♂	$\dot{V}O_2$obla	($ml \cdot min^{-1} \cdot kg^{-1}$)	Sprint prologue	($m \cdot s^{-1}$)	0.60
IV	♀	OBLA4mmol	($W \cdot kg^{-1}$)	FISsprint	(points)	-0.52
IV	♀	GE	(%)	FISsprint	(points)	-0.46

Relationships are presented as Pearson's product-moment correlation coefficients (*r*) and alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. Rise1mmol, relative work intensity where blood lactate had increased 1 $mmol \cdot l^{-1}$ above the lowest measured concentration during treadmill roller skiing; RER1.0, relative work intensity where the respiratory-exchange ratio ($\dot{V}CO_2$/ $\dot{V}O_2$) reached 1.0 during treadmill roller skiing; OBLA4mmol, relative work intensity at blood-lactate concentration of 4 $mmol \cdot l^{-1}$ during treadmill roller skiing; GE, gross efficiency; $\dot{V}O_2$obla, where the oxygen uptake related to a blood-lactate concentration of 4 $mmol \cdot l^{-1}$ determined during treadmill roller skiing using the diagonal-stride technique; FISdist, International Ski Federation's ski-ranking points for distance races; FISsprint, International Ski Federation's ski-ranking points for sprint races; SNC15c, skiing time for 15 km in classical technique with interval start in Swedish National Championships; SNC30, skiing time for 30 km double pursuit with mass start in Swedish National Championships; Sprint prologue, race speed for the sprint prologue in classical technique; ♂, men; and ♀, women.

Maximal and peak oxygen-uptake tests

The relationships between peak oxygen-uptake variables using different techniques and competitive distance and sprint performances are presented in Table 4.

Table 4. Correlations between oxygen-uptake variables using different techniques and competitive performance

Study	Sex	Test variable	(Unit)	Performance	(Unit)	*r*
			Distance performance			
I	♂	$\dot{V}O_2max$	($l \cdot min^{-1}$)	FISdist	(points)	-0.48
I	♂	$\dot{V}O_2max$	($l \cdot min^{-1}$)	SNC15c	(s)	-0.66 *
I	♂	$\dot{V}O_2max$	($l \cdot min^{-1}$)	SNC30	(s)	-0.37
I	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-0.67}$)	FISdist	(points)	-0.70 **
I	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-0.67}$)	SNC15c	(s)	-0.78 **
I	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-0.67}$)	SNC30	(s)	-0,50
I	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISdist	(points)	-0.63 *
I	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-1}$)	SNC15c	(s)	-0.63 *
I	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-1}$)	SNC30	(s)	-0.43
IV	♀	$\dot{V}O_2max$	($l \cdot min^{-1}$)	FISdist	(points)	-0.74 *
IV	♀	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISdist	(points)	-0.64 *
IV	♀	$\dot{V}O_2peak$	($l \cdot min^{-1}$)	FISdist	(points)	-0.70 *
IV	♀	$\dot{V}O_2peak$	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISdist	(points)	-0.69 *
			Sprint performance			
II	♂	$\dot{V}O_2max$	($l \cdot min^{-1}$)	Sprint prologue	($m \cdot s^{-1}$)	0.86 **
II	♂	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-1}$)	Sprint prologue	($m \cdot s^{-1}$)	0.72 *
IV	♀	$\dot{V}O_2max$	($l \cdot min^{-1}$)	FISsprint	(points)	-0.82 **
IV	♀	$\dot{V}O_2max$	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISsprint	(points)	-0.41
IV	♀	$\dot{V}O_2peak$	($l \cdot min^{-1}$)	FISsprint	(points)	-0.90 ***
IV	♀	$\dot{V}O_2peak$	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISsprint	(points)	-0.67 *

Relationships are presented as Pearson's product-moment correlation coefficients (*r*) and alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. $\dot{V}O_2max$, maximal oxygen uptake during treadmill roller skiing using the diagonal-stride technique; $\dot{V}O_2peak$, peak oxygen uptake during treadmill roller skiing using the double-poling technique; FISdist, International Ski Federation's ski-ranking points for distance races; FISsprint, International Ski Federation's ski-ranking points for sprint races; SNC15c, skiing time for 15 km in classical technique with interval start in Swedish National Championships; SNC30, skiing time for 30 km double pursuit with mass start in Swedish National Championships; Sprint prologue, race speed for the sprint prologue in classical technique; ♂, men; and ♀, women.

In Study I, test variable the TTEX was correlated with the competitive-performance variables FISdist, SNC15c, and SNC30 ($r = -0.79$, $P < 0.01$; $r = -0.86$, $P < 0.001$; $r = -0.81$, $P < 0.01$), respectively.

Mean oxygen-uptake tests

The relationships between mean oxygen-uptake variables using double-poling technique and competitive distance and sprint performances are presented in Table 5.

Table 5. Correlations between mean oxygen-uptake variables using double-poling technique and competitive performance

Study	Sex	Test variable	(Unit)	Performance	(Unit)	*r*
			Distance performance			
I	♂	DP60$\dot{V}O_2$mean	($l \cdot min^{-1}$)	FISdist	(points)	-0.69 *
I	♂	DP60$\dot{V}O_2$mean	($l \cdot min^{-1}$)	SNC15c	(s)	-0.66 *
I	♂	DP60$\dot{V}O_2$mean	($l \cdot min^{-1}$)	SNC30	(s)	-0.75 *
I	♂	DP60$\dot{V}O_2$mean	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISdist	(points)	-0.80 **
I	♂	DP60$\dot{V}O_2$mean	($ml \cdot min^{-1} \cdot kg^{-1}$)	SNC15c	(s)	-0.68 *
I	♂	DP60$\dot{V}O_2$mean	($ml \cdot min^{-1} \cdot kg^{-1}$)	SNC30	(s)	-0.81 **
I	♂	DP360$\dot{V}O_2$mean	($l \cdot min^{-1}$)	FISdist	(points)	-0.33
I	♂	DP360$\dot{V}O_2$mean	($l \cdot min^{-1}$)	SNC15c	(s)	-0.44
I	♂	DP360$\dot{V}O_2$mean	($l \cdot min^{-1}$)	SNC30	(s)	-0.43
I	♂	DP360$\dot{V}O_2$mean	($ml \cdot min^{-1} \cdot kg^{-1}$)	FISdist	(points)	-0.48
I	♂	DP360$\dot{V}O_2$mean	($ml \cdot min^{-1} \cdot kg^{-1}$)	SNC15c	(s)	-0.47
I	♂	DP360$\dot{V}O_2$mean	($ml \cdot min^{-1} \cdot kg^{-1}$)	SNC30	(s)	-0.53
			Sprint performance			
II	♂	$\dot{V}O_2$dp	($l \cdot min^{-1}$)	Sprint prologue	($m \cdot s^{-1}$)	0.94 ***
II	♂	$\dot{V}O_2$dp	($ml \cdot min^{-1} \cdot kg^{-1}$)	Sprint prologue	($m \cdot s^{-1}$)	0.64

Relationships are presented as Pearson's product-moment correlation coefficients (*r*) and alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. DP60$\dot{V}O_2$mean, mean oxygen uptake during the 60-s double poling ski-ergometer test; DP360$\dot{V}O_2$mean, mean oxygen uptake during the 360-s double poling ski ergometer test; $\dot{V}O_2$dp, mean oxygen uptake during double poling on a ski-ergometer; FISdist, International Ski Federation's ski-ranking points for distance races; FISsprint, International Ski Federation's ski-ranking points for sprint races; SNC15c, skiing time for 15 km in classical technique with interval start in Swedish National Championships; SNC30, skiing time for 30 km double pursuit with mass start in Swedish National Championships; Sprint prologue, race speed for the sprint prologue in classical technique; and ♂, men.

Double-poling tests

The relationships between double-poling variables and competitive distance and sprint performances are presented in Table 6.

Table 6. Correlations between double-poling variables and competitive performance

Study	Sex	Test variable	(Unit)	Performance	(Unit)	*r*
			Distance performance			
I	♂	DP60Pmean	$(l \cdot min^{-1})$	FISdist	(points)	-0.82 *
I	♂	DP60Pmean	$(l \cdot min^{-1})$	SNC15c	(s)	-0.80 *
I	♂	DP60Pmean	$(l \cdot min^{-1})$	SNC30	(s)	-0.51
I	♂	DP60Pmean	$(ml \cdot min^{-1} \cdot kg^{-1})$	FISdist	(points)	-0.72 *
I	♂	DP60Pmean	$(ml \cdot min^{-1} \cdot kg^{-1})$	SNC15c	(s)	-0.69
I	♂	DP60Pmean	$(ml \cdot min^{-1} \cdot kg^{-1})$	SNC30	(s)	-0.35
I	♂	DP360Pmean	$(l \cdot min^{-1})$	FISdist	(points)	-0.45
I	♂	DP360Pmean	$(l \cdot min^{-1})$	SNC15c	(s)	-0.50
I	♂	DP360Pmean	$(l \cdot min^{-1})$	SNC30	(s)	-0.49
I	♂	DP360Pmean	$(ml \cdot min^{-1} \cdot kg^{-1})$	FISdist	(points)	-0.61
I	♂	DP360Pmean	$(ml \cdot min^{-1} \cdot kg^{-1})$	SNC15c	(s)	-0.59
I	♂	DP360Pmean	$(ml \cdot min^{-1} \cdot kg^{-1})$	SNC30	(s)	-0.65
IV	♀	Vmax	$(km \cdot h^{-1})$	FISdist	(points)	-0.56
			Sprint performance			
IV	♀	Vmax	$(km \cdot h^{-1})$	FISsprint	(points)	-0.76 *

Relationships are presented as Pearson's product-moment correlation coefficients (*r*) and alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. DP60Pmean, mean power during the 60-s double poling ski-ergometer test; DP360Pmean, mean power during the 360-s double poling ski-ergometer test; Vmax, maximal double-poling speed determined while treadmill roller skiing; FISdist, International Ski Federation's ski-ranking points for distance races; FISsprint, International Ski Federation's ski-ranking points for sprint races; SNC15c, skiing time for 15 km in classical technique with interval start in Swedish National Championships; SNC30, skiing time for 30 km double pursuit with mass start in Swedish National Championships; ♂, men; and ♀, women.

There were no significant correlations ($P > 0.05$) between DP20Fpeak and the distance competitive performance variables in Study I.

Body-composition test

The relationships between body-composition variables and competitive distance and sprint performances are presented in Table 7.

Table 7. Correlations between body-composition variables and competitive performance

Study	Sex	Test variable	(Unit)	Performance	(Unit)	*r*
			Distance performance			
III	♂	LMWB	(kg)	SNC15f	(s)	-0.08
III	♀	LMWB	(kg)	SNC10	(s)	-0.85 **
III	♂	LMUB	(kg)	SNC15f	(s)	-0.08
III	♀	LMUB	(kg)	SNC10	(s)	-0.86 ***
III	♂	LMLB	(kg)	SNC15f	(s)	-0.12
III	♀	LMLB	(kg)	SNC10	(s)	-0.81 **
			Sprint performance			
III	♂	LMWB	(kg)	Sprint prologue	(s)	-0.69 *
III	♀	LMWB	(kg)	Sprint prologue	(s)	-0.82 ***
III	♂	LMUB	(kg)	Sprint prologue	(s)	-0.66 *
III	♀	LMUB	(kg)	Sprint prologue	(s)	-0.81 ***
III	♂	LMLB	(kg)	Sprint prologue	(s)	-0.69 *
III	♀	LMLB	(kg)	Sprint prologue	(s)	-0.78 **

Relationships are presented as Pearson's product-moment correlation coefficients (*r*) and alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. LM, lean mass; WB, whole body; UB, upper body (arms and trunk); LB, lower body (legs); SNC15f, skiing time for 15 km in free style with interval start in Swedish National Championships; SNC10, skiing time for 10 km in free style with interval start in Swedish National Championships; Sprint prologue, race speed for the sprint prologue in classical technique; ♂, men; and ♀, women.

Knee-extension and vertical-jumps tests

In Study I, there were no significant correlations ($P > 0.05$) between the competitive distance performance variables and test variables derived from the knee extension peak torque (PT60, PT180, PT300) and the vertical jumps test (SQJ, CMJ, CMJA).

Competetive performance

The relationships between FIS points and performance in skiing competitions are presented in Table 8.

Table 8. Correlations between FIS points and performance in skiing competitions

Study	Sex	FIS points	(Unit)	Competition	(Unit)	*r*
			Distance performance			
I	♂	FISdist	(points)	SNC15c	(s)	-0.95 ***
I	♂	FISdist	(points)	SNC30	(s)	-0.91 ***
III	♂	FISdist	(points)	SNC15f	(s)	-0.85 ***
III	♀	FISdist	(points)	SNC10	(s)	-0.71 *
			Sprint performance			
II	♂	FISsprint	(points)	Sprint prologue	(s)	-0.78 *
III	♂	FISsprint	(points)	Sprint prologue	(s)	-0.79 **
III	♀	FISsprint	(points)	Sprint prologue	(s)	-0.84 **

Relationships are presented as Pearson's product-moment correlation coefficients (*r*) and alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. FISdist, International Ski Federation's ski-ranking points for distance races; FISsprint, International Ski Federation's ski-ranking points for sprint races; SNC15c, skiing time for 15 km in classical technique with interval start in Swedish National Championships; SNC15f, skiing time for 15 km in free style with interval start in Swedish National Championships; SNC10, skiing time for 10 km in classical technique with interval start in Swedish National Championships; SNC30, skiing time for 30 km double pursuit with mass start in Swedish National Championships; Sprint prologue, race speed for the sprint prologue in classical technique; ♂, men; and ♀, women.

Multiple regression models

In Study I, the multiple linear regression models, that met the stated criteria for a valid model, which were derived for competitive performance variables are presented in Table 9.

Table 9. Multiple linear regression models for competitive performance variables

Study	Sex	Model	R^2
I	♂	FISdist = 643.9 - 79.2·RER1.0 - 6.6·DP60$\dot{V}O_2$mean/kg	0.814
I	♂	FISdist = 903.2 - 7.5·$\dot{V}O_2$max/kg - 87.3·DP60$\dot{V}O_2$mean	0.764
I	♂	FISdist = 932.8 - 2.06·$\dot{V}O_2$max/kg$^{2/3}$ - 71.7·DP60$\dot{V}O_2$mean	0.716
I	♂	FISdist = 922.6 - 90.9·OBLA4mmol - 6.6·$\dot{V}O_2$max/kg	0.643
I	♂	SNC15c = 6022.5 - 7.94·$\dot{V}O_2$max/kg$^{2/3}$ - 201.9·DP60$\dot{V}O_2$mean	0.780
I	♂	SNC15c = 5617.2 - 24.6·$\dot{V}O_2$max/kg - 269.6·DP60$\dot{V}O_2$mean	0.735
I	♂	SNC15c = 5697.3 - 291.4·OBLA4mmol - 21.6·$\dot{V}O_2$max/kg	0.641

FISdist, International Ski Federation's ski-ranking points for distance races; SNC15c, skiing time for 15 km at classical technique with interval start at Swedish National Championships (s). Test parameters in order of appearance; RER1.0, work intensity where respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$) reached 1.0 during treadmill roller skiing ($W \cdot kg^{-1}$); DP60$\dot{V}O_2$mean/kg, mean relative oxygen uptake during the 60 s double poling ski-ergometer test ($mL \cdot min^{-1} \cdot kg^{-1}$); $\dot{V}O_2$max/kg, maximal relative oxygen uptake during treadmill roller skiing ($ml \cdot min^{-1} \cdot kg^{-1}$); DP60$\dot{V}O_2$mean, mean oxygen uptake during the 60 s double poling ski-ergometer test ($l \cdot min^{-1}$); $\dot{V}O_2$max/kg$^{2/3}$, maximal relative oxygen uptake during treadmill roller skiing ($ml \cdot min^{-1} \cdot kg^{-0.67}$); OBLA4mmol, work intensity at blood-lactate concentration of 4 $mmol \cdot l^{-1}$ during treadmill roller skiing ($W \cdot kg^{-1}$); R^2, to what degree the model explain the variance for the performance parameter; and ♂, men.

Discussion

Principal findings

The results in this thesis provide new insight into the physiological demands, reflected by relevant tests, in competitive elite cross-country skiing. The included studies in this thesis showed that the ability to maintain a high work rate without accumulating lactate is an indicator for distance performance, independent of sex (I, IV). Independent of sex, oxygen uptake in whole-body and upper-body exercise was important for both sprint (II, IV) and distance (I, IV) performance. The maximal double-poling speed and 60-s double-poling mean power output were indicators of sprint (IV) and distance performance (I), respectively. Lean mass was correlated with distance performance for women (III), whereas correlations were found between lean mass and sprint performance among both male and female skiers (III). Moreover, no correlations were found between distance performance and test variables derived from tests of knee-extension peak torque, vertical jumps, and double poling on a ski-ergometer with 20-s and 360-s durations (I), whereas gross efficiency during treadmill roller skiing was not correlated with either distance or sprint performance in cross-country skiing (IV).

Lactate threshold

For each performed sub-maximal stage during lactate-threshold tests, the skier reach a steady state, where the amount of ATP required corresponded to the work rate performed and where the rate of appearance equalled the disappearance of lactate in the blood [30]. The blood-lactate concentration is a reflection of the acidity in the exercising muscles due to the anaerobic catabolism of carbohydrates [34]. To decrease the acidity in the muscles, thereby enabling continued ATP synthesis, the produced lactate is diffused by means of lactate transporters from a higher acidity (lower pH) in the exercising muscles to a lower acidity (higher pH) in the blood. By facilitated diffusion, the lactate in the blood is transported into other tissues, e.g. the liver, where it is transformed to glucose via gluconeogenesis, and to non-exercising muscles, where it is oxidized to pyruvate, which is subsequently used as a substrate, thereby reducing the concentration of lactate in the blood. When the relationship between blood-lactate concentrations and work intensity are plotted, there is generally an exponential rise in the blood lactate concentration with an increase in work intensity [63]. Generally, there are several different types of lactate variables used, which can be divided into three categories: the first rise of the blood-lactate concentration above baseline (e.g. Rise1mmol), a fixed concentration (e.g. OBLA4mmol), and the breakpoint of the curvature [63]. If oxygen uptake is measured during the lactate-threshold test, the oxygen uptake, based on the linear relationship between oxygen uptake and work intensity, could be related to the intensity at different blood-lactate concentrations (e.g. $\dot{V}O_2$obla).

The capability to maintain a high work intensity without accumulating lactate, as reflected by the variables derived from the lactate-threshold test, is an indicator of distance performance, independent of sex (I, IV); hence, this capability entails that a skier with a higher work intensity for a specific lactate-threshold variable will, compared to a skier with a lower work intensity, be able to have a higher mean skiing speed for the investigated performance. These results are consistent with reported data from previous studies, where Rise1mmol was related to a 10-km roller skiing time trial for men [46] and $\dot{V}O_2$obla was related to both a 5.6-km time trial [64] and rankings based on four competitions [65] for male junior skiers. However, no correlation was found between $\dot{V}O_2$obla and ranking for female junior skiers [65]. The work intensity at $\dot{V}O_2$obla was an indicator of male sprint prologue performance (II), whereas OBLA4mmol was not correlated with female sprint performance (IV). Previously, roller-skiing velocities corresponding to blood-lactate concentrations of 3, 5, and 7 $mmol \cdot l^{-1}$ were related to the mean velocity of a four-heat simulated roller-skiing sprint [18]. The somewhat limited research on the relationship between lactate-threshold test variables and competitive skiing performance, especially for women and sprints, warrants further investigations.

Previously, it was reported that 25 different lactate-threshold concepts have been used to assess endurance capacity [63]. For running distances shorter than 16 km, OBLA4mmol appeared to be the best predictor of performance, whereas for longer distances, aerobic thresholds (e.g. Rise1mmol) are better performance indicators [63,66]. For cross-country skiing, the correlation coefficient for the relationship between a simulated sprint performance and velocity at 7 $mmol \cdot l^{-1}$ was higher than for velocities at 3 and 5 $mmol \cdot l^{-1}$ [18]. Moreover, in Study I, the result showed that the performance in the 30-km race was correlated with Rise1mmol but not with OBLA4mmol. This is consistent with previous recommendations that the variable chosen to predict performance capability should reflect the work intensity during the competitive performance [63,66].

Skeletal muscles undergo several chronic adaptations with endurance training, e.g. increased capillary numbers, mitochondrial density, oxidative enzyme activity, and type I fibre area; there is also evidence that with endurance training, type II fibres change to have a higher mitochondrial content and thus a higher oxidative capacity [67], resulting in an increased fat oxidation in exercising muscles, which in turn leads to a lower blood-lactate concentration for a given work intensity [68].

It has been proposed that exercising for one hour or more at approximately the lactate threshold produces the greatest adaptation for endurance-trained individuals [35,69]. However, it is important that the training is regular and specific because the adaptations are highly specific to the type, frequency, and duration of the performed training, e.g. the adaptations of increased mitochondrial density and oxidative enzyme activity are specific to the exercising muscles, whereas there is little or no adaptation in untrained muscles [70].

To evaluate the impact of the administered training on the lactate threshold, it is essential to regularly perform the lactate-threshold test. A shift in the curve indicates a change in endurance performance capacity, whereas a right shift of the curve (a lower blood-lactate concentration at a given work intensity) indicates an improved endurance capability [71]. However, it is important that the test procedure is standardized because lactate levels are known to be influenced by factors such as glycogen depletion due to diet or preceding exercise [72,73], resulting in a downward shift of the lactate curve, which could be misinterpreted as an improved endurance capability [74].

Oxygen uptake

During oxygen-uptake tests, oxygen consumption is measured by comparing the amount of oxygen in the volume of inspired air with the oxygen content in the volume of expired air. The inspired oxygen is diffused from the alveoli to the blood, where it predominantly binds to haemoglobin in red blood cells. The oxygen-saturated blood is circulated by the heart to the capillaries in the exercising muscles, where the oxygen is diffused from the blood into the muscle cells. In the cells, the oxygen is transported to the mitochondria, where it is used in the aerobic synthesis of ATP. In endurance events, a large proportion of the required ATP for muscle contractions comes from the aerobic synthesis of ATP, which is limited by the availability of oxygen in the exercising muscles [34]. The $\dot{V}O_2$max is defined as the highest rate at which oxygen can be taken up and utilized by the body during intense exercise [29] and can be expressed as the maximal cardiac output multiplied by the maximal arterial-mixed venous oxygen difference (i.e. Fick equation). This capability is limited by the ability of the cardiorespiratory system to supply the exercising muscles with oxygen [75]. There are, however, exceptions, where other factors could prevent the athlete from reaching the $\dot{V}O_2$max, e.g. exercising with low haemoglobin levels, at high altitude, with a low proportion of total muscle mass (e.g. upper-body exercise) [29]. For elite cross-country skiers, the $\dot{V}O_2$max is reached using the diagonal-stride technique [35], whereas the oxygen uptake at maximal work intensity for other sub-techniques is less than the $\dot{V}O_2$max [15,35,36,76,77] and is therefore reported as the $\dot{V}O_2$peak.

Almost half a century ago, it was reported that cross-country skiers had a higher $\dot{V}O_2$max compared with endurance athletes in other sports [78]. Previously, the $\dot{V}O_2$max or $\dot{V}O_2$peak (e.g. using the skate or double-poling technique) has been correlated with roller skiing time trials [46], cross-country skiing time trials [64], competitions with recreational and sub-elite participants [41,48,79], and different types of ranking systems [20,44,46,47,65]. The results in this thesis show that the $\dot{V}O_2$max is also an indicator of competitive distance performance in both elite male and female cross-country skiing (I, IV). Moreover, a high oxygen uptake while using the double-poling technique is a distance performance indicator for both men (DP60 $\dot{V}O_2$mean) (I) and women ($\dot{V}O_2$peak) (IV).

Correlations between competitive performance and different oxygen uptake variables were found for both the absolute and relative expression (I, IV). This is consistent with results from previous studies [20,48] whereas some studies only found correlations between performance and the $\dot{V}O_2$peak when expressed absolutely [41,44,47,64,65]. Conversely, correlations for a 10-km roller-skiing time trial were reported for relative expression of the $\dot{V}O_2$peak [46]. Previously, it was suggested that the $\dot{V}O_2$max expressed as $ml \cdot min^{-1} \cdot kg^{-0.67}$ should better reflect the performance capability in elite cross-country skiing than its absolute and relative expression [22,80,81]; however, it was recently shown that a body-mass exponent of 0.5 for the $\dot{V}O_2$max optimally predicted competitive distance performance among elite male skiers [82]. Together, this suggests that the influence of body mass should be considered when evaluating competitive distance performance capability of elite cross-country skiers.

For competitive sprint skiing, the $\dot{V}O_2$max is an indicator of performance, independent of sex; in addition, a high oxygen uptake while using the double-poling technique is a sprint performance indicator for both men ($\dot{V}O_2$dp) (II) and women ($\dot{V}O_2$peak) (IV); however, based on the correlation coefficients of the $\dot{V}O_2$ variables, the absolute expression appears to be a better indicator of sprint performance compared with the relative expression; this is supported by the correlation between the FISsprint and $\dot{V}O_2$max expressed absolutely that was found in a previous study [42]. This may in part be due to that the absolute expression of $\dot{V}O_2$ variables reflects not only the skier’s capability to consume oxygen but also the size of the skier to some extent [34]. These results are consistent with results reported on the difference between sprint and distance skiers indicating that sprint skiers had a higher $\dot{V}O_2$peak ($l \cdot min^{-1}$) and were both taller and heavier compared with distance skiers [83]. The reasonably limited research warrants further investigations concerning the relationship between oxygen uptake variables ($\dot{V}O_2$max and $\dot{V}O_2$peak) and competitive skiing performance, especially for women.

In general, the underlying limiting factor of the $\dot{V}O_2$max is suggested to be the stroke volume of the heart, which has been shown to proportionally increase with an increase in the$\dot{V}O_2$max [84]. Thus, a larger stroke volume will improve the ability of the cardiorespiratory system to supply oxygen to exercising muscles. The effect related to an increased stroke volume, as a result of endurance training, is an increased heart volume, with a proportional increase in muscle-wall thickness [34]. In addition, several functional adaptations also contribute to a larger stroke volume, e.g. more rapid and larger ventricular filling, and a higher preload volume, causing more forceful contraction (i.e. Frank-Starling mechanism) [34,85]. It has been recommended that training directed towards improving the $\dot{V}O_2$max should be intensive interval training with intensities at the anaerobic threshold or higher and with an interval duration between 3 to 6 min, followed by a recovery period of an equal (or slightly shorter) duration to the interval [34,35,86]. Moreover, the combined time performed at intensities corresponding to the maximal heart rate or near the maximal heart rate should be at least 15 to 30 min for each training session [35]. Using a whole-body training mode is recommended to activate a large muscle mass and to ensure a high stroke volume, resulting in better adaptation of the blood-circulatory system [34].

In the other sub-technique (e.g. double poling), the peak oxygen uptake is, in general, limited by the total muscle mass involved during exercise. However, along with a more emphasized focus on upper-body training in recent years, the utilization in proportion to the $\dot{V}O_2max$ is approximately 90% [15,36,37,76,77]; this will potentially reach values close to the $\dot{V}O_2max$ in the future. To improve the double-poling $\dot{V}O_2peak$, it has been suggested that a period of upper-body training directed towards hypertrophy should be followed by a period of endurance training that focuses on improving the blood flow and oxidative capacity of the muscles [35].

To obtain a direct evaluation of the $\dot{V}O_2max$ and $\dot{V}O_2peak$, the oxygen uptake is generally measured during an exercise test with an incremental increase in the workload. However, to assess the training effect, especially among elite athletes, exercise specificity is important; therefore, it has been recommended that treadmill roller skiing should be used when evaluating skiers' oxygen uptake [87].

Power output and body composition

Power output (P) could be calculated either as work (*W*) divided by time (t), i.e. $P = W \cdot t^{-1}$ ($Nm \cdot s^{-1} = W$), or as force (F) multiplied by speed (*v*), i.e. $P = F \cdot v$ ($N \cdot m{\cdot}s^{-1} = W$). In cross-country skiing, the power output could be considered as a reflection of the skier's capability to generate propelling forces while skiing. The propelling forces originate from skeletal muscle contractions, which are transferred through the skis and poles to the snow to produce forward motion. The force-generating potential of the muscle is closely related to the cross-sectional area of the muscle [23-27].

During the ski-ergometer double poling test (I), the skier's poling force was measured by a load cell, and the velocity was measured by a linear encoder, enabling calculation of the power output for the performed test duration. The maximal double-poling speed (IV) could be considered as a surrogate indicator of double-poling power production. The skier's body composition was analysed by a DXA scan to determine values of LM, fat mass, and bone-mineral content for different segments as well as for whole-body composition.

For male skiers, the absolute expression of the DP60Pmean was correlated with both the FISdist and the SNC15 (I), and the relative expression was correlated with the FISdist. These results are consistent with previously reported results [41]. No correlations were found between competitive distance performance and the DP360Pmean (I), which contradicts previous results indicating that a 3-km double-poling time trial on a flat ski course was correlated with the DP360Pmean. However, this distance was most likely chosen for its similarity of duration with the 360 s test to validate the double-poling ergometer. One possible explanation for the discrepancy in Study I, concerning the relationships between power output and performance, could be that the mean skiing time for the sections where skiers use the double-poling technique in distance competitions is generally closer to 1 min than 6 min. For women, the ability to reach a high Vmax was correlated with the FISsprint (IV) but not with the FISdist (IV). Previously, Vmax was correlated with a double-poling roller skiing time trial for a combined group of both male and females [21]; for men, a simulated treadmill roller skiing sprint using the diagonal-stride technique were correlated with Vmax [50]. The ability to produce a high Vmax is most likely a product of the skier's force-generating potential and technique-related capabilities [88]. The importance of this ability for competitive sprint performance among elite female skiers is consistent with reported results in a previous study, indicating that the roller-skiing peak speed was related to the sprint-prologue performance among elite male skiers [89]. Moreover, the roller-skiing peak speed has also been related to the LMWB [90]. Together, these results could indicate a relationship between LMWB and sprint performance. This notion was investigated in Study III, where the absolute expression of the LMWB, LMUB, and LMLB was correlated with sprint performance, independent of sex. Moreover, there were correlations between the women's distance performance and the absolute and relative expression of the LMWB, LMUB, and LMLB. However, no correlations were found between LM variables and distance performance in men. Previous studies that have investigated the lean mass of skiers have reported that the LMWB was an indicator of performance in a 5.6-km time trial among male junior skiers [91], whereas no relationship was found between the LMWB and sprint performance for elite male skiers [42]. The results reported in the latter study contradict the result found in Study III. Possible explanation for this discrepancy could be sample size differences, as sample in Study III was larger. The limited research warrants further investigations concerning the relationship between power output, maximal double-poling speed, LM variables and competitive skiing performance in both sprint and distance races.

In cross-country skiing, the goal is to maintain as high a mean skiing speed as possible for the duration of the race. Sprint races are characterized by a high mean race speed and a high absolute exercise intensity, which is determined by the ability of the skeletal muscles to continuously generate high propelling forces throughout the race. The force-generating potential of the muscles is, as previously mentioned, closely related to the cross-sectional area of the muscles [23-27]. To be able to continuously produce propulsive forces, it is essential that ATP synthesis occurs rapidly in exercising muscles. Because of the high absolute exercise intensity in sprint races, there is a relatively high demand on anaerobic energy supply systems [92]. In previous studies, anaerobic capacity was shown to correspond to muscle size [31,32]. One reason for this relationship is the proportional increase in available anaerobic energy stores with increasing muscle volume [31]. As a consequence of the relatively high anaerobic demand during sprint races, it can be assumed that skiers with a larger muscle mass have a higher anaerobic capacity and a higher force-generating potential and therefore have an advantage in sprint competitions. This assumption is supported by a previous study where specialized sprint skiers were both taller and heavier than specialized distance skiers [83]. Thus, it appears that the larger skiers' higher anaerobic capacity and force-generating potential are not counterbalanced by higher contribution of an increased body mass to the counteracting forces. However, according to the square-cube law, first described in 1638 by Galileo Galilei, muscle strength is a function of the cross-sectional area, whereas muscle mass is a function of the volume; thus, the muscle volume grows faster than the muscle cross-sectional area. Therefore, the performance-related increase in the force-generating capability, which is linked to a larger muscle volume, will eventually be neutralized by the concomitant increase in counteracting forces. Consequently, depending on the discipline, there is an optimal muscle mass-to-body mass ratio for each individual skier. The influence of several factors such as the $\dot{V}O_2$max and $\dot{V}O_2$peak in different sub-techniques and technique-related capabilities must be considered when designing training programs for skiers. However, training regimens designed to achieve muscle hypertrophy should be applied with caution to optimally increase muscle mass to improve an individual's performance capability as a sprint and/or distance cross-country skier.

Multiple regression model

A simple regression (correlation) considers the relationship between a single independent variable and the dependent variable, whereas a multiple regression considers the influence of multiple independent variables on a dependent variable, which could increase the degree of explanation in the estimation of performance. However, to be considered a valid model, several stated statistical rules for multiple-regression modelling must be fulfilled (see the statistic section). In Study I, valid regression models were found for both the FISdist and SNC15 (Table 9), whereas no valid model was found for the SNC30. These models emphasize the importance of being able to work at a high intensity without accumulating lactate, of having high oxygen uptake expressed relatively, and of having the ability to quickly adapt to upper-body work in terms of oxygen uptake. The models for both the FISdist and SNC15, which contain OBLA4mmol and the relative expression of the $\dot{V}O_2$max, are consistent with the classical idea that high oxygen uptake and high work intensity at the onset of blood-lactate occurrence are important to success in competitive distance cross-country skiing among elite male skiers. If the mean values for the relative $\dot{V}O_2$max (i.e. 70.3 $ml \cdot min^{-1} \cdot kg^{-1}$) and OBLA4mmol (i.e. 3.69 $W \cdot kg^{-1}$) are inserted into the model for the FISdist (see Table 9), the contribution of both of these physiological variables to the FISdist can be calculated. For the relative $\dot{V}O_2$max, this component is 464.0 points (i.e. $6.6 \cdot 70.3 = 464.0$ points), whereas the corresponding value for the OBLA4mmol is 335.4 points (i.e. $90.9 \cdot 3.69 = 335.4$ points). Moreover, a 1% improvement in the relative $\dot{V}O_2$max and OBLA4mmol will reduce the FISdist by 4.6 points and 3.4 points, respectively. Thus, the effect of a 1% increase in the relative $\dot{V}O_2max$ is approximately 35% higher than for an equal increase in the OBLA4mmol. If this approach is applied for the model describing the SNC15c (see Table 9), the corresponding effect for a 1% improvement is 42% higher for the relative $\dot{V}O_2max$ compared with the OBLA4mmol. This information could be of importance for coaches regarding which physiological capabilities that should be focused on to optimally improve the performance capability of skiers. However, in this context, it is important for the coach to evaluate each skier's improvement potential for each physiological capability before designing the training program. This approach, to evaluate the effect of different independent variables, could also be adapted for the other multiple regression models.

Practical implications

The results provide insights regarding which physiological capabilities cross-country skiers must acquire to reach the level of international elite. Moreover, these insights regarding the physiological demands in different disciplines in cross-country skiing can be used to design long-term training plans and to optimize training. The validated test variables in this thesis, together with the descriptions of how to perform the tests, should be considered as a basis for evaluation of a skier's performance capability and physiological status as well as for identification of the skier's strengths and weaknesses. The results from the physiological tests are useful tools for coaches to evaluate and guide training; however, it is important to keep in mind that an improvement of one underlying system could have a contradicting effect on another, which emphasizes the importance of continuously evaluating the skier's physiological status. Furthermore, knowledge regarding the relationship between physiological variables and body mass and their influence on competitive performance could be used to guide specialization in a specific discipline (i.e. sprint or distance skiing).

Strength and limitations

In Study I – IV, the dependent variables are results from cross-country skiing competitions performed by national or international elite skiers. A high proportion of the research studies within the field of cross-country skiing contain subjects that could be classified as sub-elite or recreational skiers, and the performance variables used are often performances emulating cross-country skiing (such as roller-skiing time trials performed on treadmills, tartan tracks, and asphalts roads). However, to establish the physiological demands in elite cross-country skiing, it is important that the subjects are elite skiers and that the performances are regarded as competitive; the studies in this thesis have investigated the external validity of the included physiological test variables and have therefore significantly contributed to the knowledge about which physiological capabilities must be developed to become an elite skier. In this context, it is advantageous if the time period between the test and performance is not so long that the physiological characteristics reflected by the test variables are relevant on the day of the race. In Study I – III, in which performance in competitions was analysed, there was a close proximity between the test and competition days.

In general, the number of subjects in cross-country skiing research studies is relatively low. This could partly be explained by the limited number of individuals in the population of elite skiers. Furthermore, elite-active athletes are generally very focused on following individual training plans to achieve their performance-related goals, and participation in research studies is often difficult to fit into their plans. From a statistical perspective, a low number of subjects increases the risk of type II errors; thus, it is possible that a “true” correlation will not be detected.

The samples in the studies comprise elite skiers who are considered to belong to top 30-40 in Sweden. The results in the studies should thus be interpreted based on the characteristics of the subjects; therefore, the results provide valuable information of the physiological demands of becoming an international elite skier. However, notably, the established relationships between test variables and competitive performance are not necessarily valid for the differentiation of performance capability of the top ten skiers in championship competitions. If the samples comprised a larger number of international-level elite skiers, the relationship might be curvilinear, indicating that an improvement of the specific physiological capability does not lead to the same absolute performance enhancement for the best skiers in the world.

The variables in Study I – IV are used in terms of their previous usage in other studies. Therefore, slightly different test variables are used, which can be considered as a weakness because it impedes comparisons of the physiological demands between sprint and distance performances as well as between sexes to some extent. In this context, it should be highlighted that only a few studies have studied the influence of anaerobic capacity on skiing performance and that this thesis would have been strengthened if direct measures of anaerobic capacity had been included; however, lean mass, analysed in Study III, is suggested to be a surrogate indicator of anaerobic capacity, because the anaerobic energy contribution is related to the muscle mass involved during intense exercise [33].

In cross-country skiing, a number of elements can potentially affect competitive performance (e.g. waxing, other problems with the equipment, the starting position). To control for the potential influence of waxing (grip and glide) and mishaps during the competitions on the skiing results, the skiers filled out a questionnaire after the race. However, these answers do reflect the skiers’ own experiences of the waxing and thus could not be regarded as a precise measure of their ski waxing compared to that of their competitors. Theoretically, it would be possible to measure the glide of each subject’s skis before the race; however, it would be difficult to administer such glide tests because the skier would be able adjust the waxing until immediately before the start of the race. When the FIS points are used as an indicator of performance capability, only the skier's best five results during the last twelve months are counted. In this case, results from competitions with poor waxing or mishaps are probably not included in the skier's FIS points.

The roller-skiing tests in the studies were performed using the classical style; it would have been beneficial to also include tests using freestyle. Therefore, in future studies, greater focus on the physiological demands in freestyle competitions is warranted.

Future perspectives

Currently, the main research focuses within the field of cross-country skiing research are directed towards biomechanical and technical aspects and acute physiological adaptations related to skiing. During the period from 2011 to the finalization of this thesis, five studies, aside from the studies included in this thesis, have investigated correlations between test variables and performances for male and female skiers. Two of these studies have used performances that emulates cross-country skiing [92,93] and the other three have used competitive performance as dependent variable [82,89,94]. Hence, there is still a lack of knowledge concerning the physiological demands, especially for women, in competitive cross-country skiing; there are several gaps in theory building considering the demands of different competitive distances and skiing styles. Therefore, it is essential that future studies investigate the external validity of physiological variables in cross-country skiing research. Furthermore, in future studies, research should also focus on developing an optimal model that describes the interplay between the skier's aerobic power (i.e. $\dot{V}O_2max$ or $\dot{V}O_2peak$) and anaerobic capacity that can be used to guide training for optimizing performance in different disciplines.

Conclusion

The results in this thesis show that, depending on discipline and sex, maximal and peak oxygen uptake, work intensity at the lactate threshold, lean mass, double-poling mean power output, and double-poling maximal speed are all externally valid physiological test variables for evaluation of performance capability among elite cross-country skiers; however, to optimally indicate performance capability different test-variable expressions should be used; in general, the absolute expression appears to be a better indicator of competitive sprint performance whereas the influence of body mass should be considered when evaluating competitive distance performance capability of elite cross-country skiers.

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