The importance of body-mass exponent optimization for evaluation of performance capability in cross-country skiing

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Abstract

Introduction Performance in cross-country skiing is influenced by the skier's ability to continuously produce propelling forces and force magnitude in relation to the net external forces. A surrogate indicator of the "power supply" in cross-country skiing would be a physiological variable that reflects an important performance-related capability, whereas the body mass itself is an indicator of the "power demand" experienced by the skier. To adequately evaluate an elite skier's performance capability, it is essential to establish the optimal ratio between the physiological variable and body mass. The overall aim of this doctoral thesis was to investigate the importance of body-mass exponent optimization for the evaluation of performance capability in cross-country skiing.

Methods In total, 83 elite cross-country skiers (56 men and 27 women) volunteered to participate in the four studies. The physiological variables of maximal oxygen uptake ($\dot{V}O_2max$) and oxygen uptake corresponding to a blood-lactate concentration of 4 mmol·l^{-1} ($\dot{V}O_2obla$) were determined while treadmill roller skiing using the diagonal-stride technique; mean oxygen uptake ($\dot{V}O_2dp$) and upper-body power output ($\dot{W}$) were determined during double-poling tests using a ski-ergometer. Competitive performance data for elite male skiers were collected from two 15-km classical-technique skiing competitions and a 1.25-km sprint prologue; additionally, a 2-km double-poling roller-skiing time trial using the double-poling technique was used as an indicator of upper-body performance capability among elite male and female junior skiers. Power-function modelling was used to explain the race and time-trial speeds based on the physiological variables and body mass.

Results The optimal $\dot{V}O_2max$-to-mass ratios to explain 15-km race speed were $\dot{V}O_2max$ divided by body mass raised to the 0.48 and 0.53 power, and these models explained 68% and 69% of the variance in mean skiing speed, respectively; moreover, the 95% confidence intervals (CI) for the body-mass exponents did not include either 0 or 1. For the modelling of race speed in the sprint prologue, body mass failed to contribute to the models based on $\dot{V}O_2max$, $\dot{V}O_2obla$, and $\dot{V}O_2dp$. The upper-body power output-to-body mass ratio that optimally explained time-trial speed was $\dot{W} \cdot m^{-0.57}$ and the model explained 63% of the variance in speed.

Conclusions The results in this thesis suggest that $\dot{V}O_2max$ divided by the square root of body mass should be used as an indicator of performance in 15-km classical-technique races among elite male skiers rather than the absolute or simple ratio-standard scaled expression. To optimally explain an elite male skier's performance capability in sprint prologues, power-function models based on oxygen-uptake variables expressed absolutely are recommended. Moreover, to evaluate elite junior skiers' performance capabilities in 2-km double-poling roller-skiing time trials, it is recommended that $\dot{W}$ divided by the square root of body mass should be used rather than absolute or simple ratio-standard scaled expression of power output.

Abbreviations

ANOVA	Analysis of variance
ATP	Adenosine triphosphate
CI	Confidence interval
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
r	Pearson's correlation coefficient
R^2	Coefficient of determination
SD	Standard deviation
$\dot{V}O_2dp$	Mean upper-body oxygen uptake
$\dot{V}O_2max$	Maximal oxygen uptake
$\dot{V}O_2obla$	Oxygen uptake at the relative work intensity corresponding to a blood-lactate concentration of 4 mmol·l^{-1}.
$\dot{V}O_2peak$	Peak oxygen uptake
$\dot{V}O_2var$	Variables of oxygen uptake
$\dot{W}$	Mean upper-body power output

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 T, Carlsson M, Felleki M, Hammarström D, Heil D, Malm C, Tonkonogi M. Scaling maximal oxygen uptake to predict performance in elite-standard men cross-country skiers. J Sports Sci. 2013;31(16):1753-60.

II   Carlsson T, Carlsson M, Hammarström D, Rønnestad B, Malm C, Tonkonogi M. Optimal $\dot{V}O_2$max-to-mass ratio for predicting 15-km performance among elite male cross-country skiers. *Submitted*

III   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(12):2587-95.

IV   Carlsson T, Carlsson M, Hammarström D, Malm C, Tonkonogi M. Scaling of upper-body power output to predict time-trial roller skiing performance. J Sports Sci. 2013;31(6):582-8.

The studies within this thesis are reprinted with permisson from the original publisher.

Introduction

Cross-country skiing

History of cross-country skiing

The first skis have been dated to approximately 5,200 years ago, and for the majority of this period, skis were used as a means of transportation to facilitate gathering, hunting, and visiting [1], most likely because it is more energy efficient to move on surfaces covered by snow and ice using skis compared to walking or using snowshoes [2]. Approximately 150 years ago, the transformation of cross-country skiing from being just a mean of transportation to become a sport and a recreational activity begun [1]. In the year 1924, cross-country skiing was a part of the Olympic Winter Games in Chamonix and the year after, the first World Championships was held. The competitive distances during these events were 18 km and 50 km performed in classic technique (i.e. skiers are only allowed using double-poling, double poling with kick, diagonal-stride, or herringbone technique) and only men competed. Skiing for women was included in the Olympic program in 1952, and two years later, they competed in the World Championships [1]. In 1987, competitions in freestyle technique (i.e. skating with skis) were included in the World-Championships program and have been part of the Olympic and World-Championships program ever since [3]. Until 2000, only distance races (5 – 30 km for women and 15 – 50 km for men) were performed in these two recurrent international events, but in the World Championships in 2001, sprint competitions (0.8 – 1.6 km for women and 1.0 – 1.8 km for men) were introduced [1].

Physics of cross-country skiing

Independent of competitive distance, performance is determined by the time the skier needs to complete the actual race distance. During the strive to reach the finish line in the shortest time possible, the skier has to overcome a number of counteracting forces that are all related to forward movement; hence, the counteracting forces together with the movement of body mass or body segments entails a power demand the skier has to exceed by the produced power output. Total power demand is related to six fundamental counteracting forces/power demands.

When the skis glide upon the snow *frictional forces* between the skis and the snow-covered surface arises. The forces related to friction are parallel to the movement direction of the skis but directed in the opposite direction. The frictional force of a ski is dependent on the force applied to the ski that is perpendicular to the surface multiplied by the coefficient of friction. The power demand that originates from friction increases, theoretically, linearly with skiing speed; therefore, if speed doubles, the power demand increases twofold. Another force that the skier has to overcome that is also associated with skiing speed is *air resistance*. Air resistance is dependent on the frontal area of the body that is perpendicular to the movement

direction and the accompanying power demand increases with skiing speed raised to the 3rd power (i.e. if speed doubles, the air resistance increases eightfold). In uphill sections, the skier has to lift the body mass against the force of gravity, which results in a *net increase in potential energy*. The power demand related to the work against gravity is the product of the force of gravity due to body mass and vertical velocity. Similarly, an elevation of the centre of mass causes an *increased potential energy during the stride cycle*, and power demand is a function of mean elevation of body mass and stride frequency. Moreover, there is a reduction in speed during the stride cycle, from one muscle-force transfer to the next, which is related to a reduction in kinetic energy. The power demand associated with the *translational kinetic energy during the stride cycle* is body mass multiplied by the squared speed difference and stride frequency. During the stride cycle, a number of body segments rotate in relation to their joints. The *rotational kinetic energy during the stride cycle* is linked to these rotational movements, and power demand is related to each segment's moment of inertia and the square of its angular velocity [4].

Based on the dimensional analysis, these counteracting forces are related to body mass although in different proportions [4]; hence, an evaluation of the performance of cross-country skiers must acknowledge the influence of body mass [4,5]. Body mass of the skier could therefore be considered an indicator of the net external forces or "power demand" [6]. The power output produced by the muscles has to overcome the power demand to create a forward motion, and the greater the ratio between power-output production and power demand, the faster the skiing speed that is achieved. For endurance performances, such as cross-country skiing competitions, it is important from a performance perspective to have high power output–to–power demand ratio when the entire race is analysed; therefore, a skier's performance capability could be considered the ability to sustain a high mean skiing speed for the total race distance. From a physical perspective, a higher mean skiing speed is related to a higher energy expenditure compared to that of a lower mean skiing speed due to the counteracting forces, which are greater, being a function of the skier's speed.

Physiology of cross-country skiing
To continuously produce power for forward motion by the skeletal muscles, the contractile proteins in the force-generating muscles have to be supplied with adenosine triphosphate (ATP); otherwise no force would be produced [7]. Because of limited ATP storage in the muscles [7], the re-synthesis of ATP in the skier's force-generating muscles is necessary for generating propelling forces throughout a cross-country skiing competition. This ATP re-synthesis is promoted in two different ways that are fundamentally different from a physiological point of view; the aerobic energy-supply system requires oxygen for the re-synthesis of ATP, whereas the anaerobic energy-supply system regenerates ATP without the presence of oxygen [8]. The anaerobic energy-supply system has a higher maximal ATP-re-

synthesis rate compared to that of the aerobic energy-supply system; however, the aerobic energy-supply system is superior if the total ATP-re-synthesis capacity of both systems are compared [7]. In this context, it is important to note that a high utilization rate of the anaerobic energy-supply system will, eventually, lead to fatigue due to the accumulation of fatigue-related metabolites and a disturbance of the homeostasis in the working muscles; factors such as acidosis as well as changes in concentrations of phosphocreatine, inorganic phosphate and potassium most likely influence the appearance of fatigue [8-10]. Therefore, the skier has to use the anaerobic energy-supply system wisely by continuously controlling the work intensity based on the remaining distance and profile of the course.

Consequently, each energy-supply system's contribution to ATP supply for the generation of propelling forces in cross-country skiing depends, in particular, on the work intensity and duration of the race. For the shortest individual race distances in distance cross-country skiing in the World Championships or Olympic Games, which currently are 10 km for women and 15 km for men, the completion times range from 25 to 45 min (depending on the course profile, snow and track conditions), corresponding to an energy contribution of approximately 95% from the aerobic energy-supply system [8,11]. An equal contribution of aerobic and anaerobic energetic resources to power output for maximal exercises was reported to occur between 100 and 120 s [8,12]. Therefore, for sprint races with a competitive duration of approximately two to four minutes, a slight predominance of the aerobic energy-supply system would be expected [8], which has been supported by mathematical modelling [13]. Accordingly, the ratio between the aerobic and anaerobic energy contribution was approximately 3:1 during a 600-m uphill roller-skiing time trial, with a mean completion time of approximately 3 min [14,15]. Hence, independent of race distance in elite cross-country skiing, there is an interaction between the aerobic and anaerobic energy-supply systems. Because of the intimate relationship between force-generating capability and the capability of the energy-supply systems in terms of ATP resynthesis it is reasonable to assume that a high ATP-turnover rate is important for skiing performance. Therefore, the performance capability of cross-country skiers could be evaluated on an *energy-supply level*.

In a test situation, anaerobic capacity (i.e. the capacity of the anaerobic energy-supply system) can be investigated by analysing the maximal accumulated oxygen deficit. Based on the extrapolation from a linear relationship between exercise intensity and oxygen uptake, the maximal accumulated oxygen deficit is considered the difference between the energy expenditure at a supra-maximal intensity and actual oxygen consumed during the test [16]. However, as a consequence of the high ratio between aerobic and anaerobic energy supply in competitive cross-country skiing, the capability of the aerobic-energy system is more frequently evaluated than the anaerobic capacity. The upper limit of the aerobic energy-supply rate is termed the maximal oxygen uptake ($\dot{V}O_2max$), which is defined as the highest rate at which

oxygen can be taken up and utilized by the body during severe exercise [17]. There is a sequence of events in the transport of oxygen from the atmosphere to the mitochondria wherein cardiac output, which can be considered an indicator of the transportation capacity of oxygenated blood, is suggested to be the primary limiting factor for $\dot{V}O_2$max in exercising humans [17]. The $\dot{V}O_2$max of cross-country skiers is, in general, achieved using the diagonal-stride technique [11] which is a whole-body exercise with the involvement of large muscle masses; the large oxygen requirements of the working muscles at high work intensities means that the cardiorespiratory system is fully stressed. For the double-poling technique and the sub-techniques included in the freestyle technique, an oxygen uptake equivalent to $\dot{V}O_2$max is generally not attained due to a lower muscle-mass involvement; therefore, the upper limit in these sub-techniques is termed peak oxygen uptake ($\dot{V}O_2$peak). Elite skiers achieve approximately 86 to 92% of their $\dot{V}O_2$max while double poling [18-22], whereas the corresponding interval for the freestyle sub-techniques remains to be investigated even though oxygen uptake during exercise at maximal intensity appears to be lower than $\dot{V}O_2$max [11,23].

In addition to maximal-intensity tests, there are submaximal tests that could be considered for investigating the interaction between the aerobic and anaerobic energy-supply systems such as lactate-threshold or anaerobic-threshold tests, which are used to determine the power output or oxygen uptake for a specific blood-lactate level or predetermined blood-lactate increase [24]. This power output/oxygen uptake is supposed to indicate a work intensity that could be held for a prolonged duration. For example, the commonly used blood-lactate reference value of 4 mmol·l^{-1} is suggested to represent the intensity at which the aerobic-anaerobic transition occurs [25]. The evaluation of the energy-supply systems is intended to reflect the ability of ATP re-synthesis at different work intensities, which is proposed to be an indirect measure of the skier's capability to produce propelling forces. However, skiers are also frequently evaluated at a *force-generating level* at which force production or power output for specific muscles or ski-specific motions are measured. For example, double-poling using a ski ergometer has been shown to be a reliable and valid measure of a skier's power output [26].

A skier with a large muscle mass will, in general, be able to have a higher power output expressed absolutely compared to a skier with less muscle mass; moreover, there is a strong relationship between body size and the absolute expression of $\dot{V}O_2$max [27]. However, these advantages for large skiers do not automatically entail a superior performance capability because of the influence of body mass on performance. Therefore, to optimally indicate performance capability, indicators of both power production and power demand need to be considered.

Scaling

Previously, it has been established that performance and physiological characteristics are influenced by the size of the body [28]; therefore, differences in body size have to be considered when performance and/or physiological characteristics of athletes are investigated. Body-size differences can be adjusted by using an appropriate allometric-scaling approach (*allometric* from the Greek words *alloios*, which means to change, and *metry*, which means to measure), and the suggested approach for these adjustments is non-linear allometric modelling [28,29]. The non-linear allometric modelling can be divided into two fundamental different modelling approaches to determine either *physiological capability* or *performance capability* of individuals or groups.

Physiological capability

Therefore, to investigate the influence of an anthropometric variable (e.g. body mass) on a physiological characteristic (or sometimes on a sport performance), modelling is often based on the following model:

$$y = a \cdot x^b, \tag{1}$$

where y is the physiological variable (or performance); a is a constant; x is the anthropometric variable; and b is the scaling exponent. To scale appropriately, the scaling exponent for the anthropometric variable should be identified from log-log transformations. Log-transformation of Model (1) enables the use of linear regression to determine a and b in accordance with the following model:

$$\log_e y = \log_e a + b \cdot \log_e x. \tag{2}$$

This approach can be considered to determine the *physiological capability* of individuals or groups based on a specific physiological characteristics by normalising the influence of body mass. The described approach has previously been used in sport science for physiological variables, such as oxygen-uptake variables [29-34] and variables of power output [35-40]. Moreover, the influence of body mass on various sport performances has also been investigated using allometric scaling in accordance with Models (1) and (2) [41-44].

Performance capability

A different model was suggested to optimally combine a physiological variable and an anthropometric variable to explain a performance [29], and the arrangement of the power-function model was:

$$z = a \cdot y^c \cdot x^b \tag{3}$$

where z is the performance variable; a is a constant; y is the physiological variable; x is the anthropometric variable; and b and c are the scaling exponents. Log-transformation of Model (3) to determine the constant and scaling exponents gives:

$$\log_e z = \log_e a + c \cdot \log_e y + b \cdot \log_e x. \tag{4}$$

This modelling approach can be considered to determine the *performance capability* of individuals or groups, and it has been applied to explain performance in different sports based on physiological variables and body mass. For example, oxygen-uptake variables have been used to explain distance running [29,45,46] and time-trial cycling [47,48] performance; power-output variables have been used to explain sprint running [29], time-trial cycling [47,49], and rowing [50-52] performance. This modelling approach has also been used to describe of rowing performance based on a subject's age and stature [53]. Consistent with the results of these studies, it has been suggested that power-function modelling is appropriate for exploring the relationship between physiological variables and performance [54].

Scaling in cross-country skiing

In cross-country skiing research, the influence of body size on physiological characteristics of elite skiers, by using the allometric-scaling approach to determine *physiological capability*, has not yet been thoroughly investigated. In a previous study, an attempt has been made to find the body-mass exponent for $\dot{V}O_2max$ that normalizes the influence of body mass by compiling unpublished results and an exponent derived from an investigation of a 60-km skiing competition; the researchers found that the mean value was 2/3, and it was therefore suggested that the use of the unit "$ml \cdot min^{-1} \cdot kg^{-0.67}$" is, compared to the simple ratio-standard scaled expression ($ml \cdot min^{-1} \cdot kg^{-1}$), more appropriate if the objective is to equalize for differences in body mass [5]. However, the simple ratio-standard scaled expression of an oxygen-uptake variable (such as $\dot{V}O_2max$ or $\dot{V}O_2peak$) is still commonly used to express physiological characteristics of skiers [55-60], to investigate physiological differences between groups of skiers [61-66], and to evaluate its relationship to different types of skiing performances (i.e. competitive, ranking, time trials, and roller skiing) related to both sprint [67,68] and distance [69-74] cross-country skiing. The simple ratio-standard scaled expression of anaerobic capacity ($ml \cdot kg^{-1}$) has also been used to investigate 0.6-km uphill roller-skiing performance

[14,15] and the differences between groups of skiers [75]. On a force-generating level, correlation analyses to investigate the relationship between the simple ratio-standard expressed power output ($W \cdot kg^{-1}$), especially double-poling tests, and different types of skiing performances have been conducted [26,74,76-79]. However, no previous study has used power-function modelling to investigate performance capability among elite skiers based on their double-poling power output and body mass; therefore, it is important to establish the optimal body-mass exponent for power output to enable appropriate evaluations of elite skiers' performance capabilities.

For $\dot{V}O_2max$ (and $\dot{V}O_2peak$), the previously proposed physiological-capability expression "$ml \cdot min^{-1} \cdot kg^{-0.67}$", which is suggested to better reflect performance-capability differences among elite skiers compared to the simple ratio-standard scaled expression [62], has been adopted for the evaluation of skiers' performance [4,70,71,74,80,81], differences between groups of skiers [4,62,75,82,83], and longitudinal oxygen-uptake development data [62,84,85] and to describe physiological characteristics of skiers [86,87]. However, when the 0.67 body-mass exponent for $\dot{V}O_2max$ is used for evaluating performance in cross-country skiing, it is assumed that qualitative differences in the aerobic energy-supply system directly reflect performance-capability differences. It has been proposed that there is a tendency that skiing speed in distance races is positively related to body mass [5]. This notion was supported by results in a recent study that showed that race speed in distance competitions was related to body mass raised to the power of 0.26 [88]. Consequently, to explain performance, both the influence of $\dot{V}O_2max$ and body mass needs to be considered, which can be addressed by using the above described allometric-scaling approach in Model (3) and (4).

The body-mass exponent for $\dot{V}O_2max$ has also been proposed to vary with course-profile differences as suggested by exponents lower and higher than 0.67 for level and uphill skiing, respectively [5]. This is consistent with the finding that the counteracting forces are scaled differently to body mass, where the power demand related to changes in potential-energy increases in proportion to body mass, whereas the other four fundamental counteracting forces increase less than body mass [4,5]. However, the influence of course inclination on the body-mass exponent for $\dot{V}O_2max$ remains to be investigated for elite skiers in a cross-country skiing competition. Moreover, it has previously been demonstrated that skiers' race speed generally decreases throughout a race [67,70,89] and that this speed reduction is reflected by a reduced speed in ascents [67]. Hence, if a larger proportion of the time is spent uphill skiing, it can be reasonable to assume that the body-mass exponent is influenced by the distance covered of the race.

To the best of our knowledge, no previous study has used power-function modelling in accordance with Model (3) and (4) to explain performance in cross-country skiing. As suggested by the results from studies in other endurance sports, this allometric-scaling approach can provide more comprehensive information about

how different physiological characteristics should be expressed, in relation to body mass, to optimally reflect performance capability among elite cross-country skiers.

Aims

The aim of this doctoral thesis was to investigate the importance of body-mass exponent optimization for evaluation of performance capability in cross-country skiing.

The specific aims were:

I   To establish the optimal body-mass exponent for $\dot{V}O_2max$ to indicate 15-km performance in elite-standard men cross-country skiers and to evaluate the influence of course inclination on the body-mass exponent.

II   To validate the 0.5 body-mass exponent for $\dot{V}O_2max$ as the optimal predictor of performance in 15-km classical-technique skiing competitions among elite male cross-country skiers and to evaluate the influence of distance covered on the body-mass exponent for $\dot{V}O_2max$ among elite male skiers.

III To investigate the relationship between sprint-prologue performance (using the classical technique) and the oxygen uptake at the work intensity corresponding to a blood-lactate concentration of 4 $mmol \cdot l^{-1}$ ($\dot{V}O_2obla$), $\dot{V}O_2max$, and mean upper-body oxygen uptake ($\dot{V}O_2dp$).

IV   To establish the most appropriate allometric model to predict mean skiing speed during a double-poling roller-skiing time trial using scaling of upper-body power output ($\dot{W}$).

Methods

Overall design

In Study I – IV, the overall design was to reliably collect physiological variables and performance data for elite skiers, which subsequently were used in scaling analyses to determine the optimal body-mass exponent for the physiological variable of interest to optimally explain skiing performance.

Subjects

The four studies included in this doctoral thesis were performed separately and the subjects were elite cross-country skiers. In total, 83 subjects volunteered to participate where four of them participated in two studies and one subject participated in three studies. The sex, number, stature, body mass, and age of the subjects in each study are displayed in Table 1.

Table 1. The characteristics of the subjects included in Study I – IV

Study	Sex	n	Stature	Body mass	Age
I	♂	12	183.9 ± 5.5	76.2 ± 5.8	23.9 ± 4.2
II	♂	24	180.4 ± 6.0	75.5 ± 6.3	21.4 ± 3.3
III	♂	8	183.5 ± 5.3	77.0 ± 4.5	24.8 ± 4.9
IV	♂+♀	45	176.1 ± 9.3	69.3 ± 8.0	18.2 ± 1.3
IV	♂	27	181.0 ± 7.4	73.2 ± 7.3	18.5 ± 1.2
IV	♀	18	168.9 ± 6.9	63.6 ± 4.9	17.9 ± 1.3

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

Test equipment

Test data were collected during treadmill roller-skiing tests (I – III) and ski-ergometer tests (III – IV) by using equipment for oxygen uptake, blood-lactate concentration, force and displacement measurements.

Measurements of oxygen uptake

During the oxygen-uptake tests, variables of expired air were continuously analysed using a metabolic cart in mixing-chamber mode (Jaeger Oxycon Pro, Erich Jaeger Gmbh, Hoechberg, Germany) for determination of oxygen uptake. Before each test, the equipment was calibrated according to the specifications of the manufacturer. The equipment has previously been shown to be an accurate system for measuring oxygen uptake (CV: 1.2% and $P < 0.05$ at oxygen uptakes between 0.5 and 6.0 $l \cdot min^{-1}$) [90].

Measurements of blood-lactate concentration

During and after the roller-skiing tests, capillary-blood samples were collected. They were subsequently analysed to determine the subject's blood-lactate concentrations (Biosen 5140, EKF-diagnostic Gmbh, Barleben, Germany). The equipment was calibrated according to the specifications of the manufacturer and it has previously been reported to be a valid and reliable [91].

Roller-skiing tests

The tests of $\dot{V}O_2obla$ and $\dot{V}O_2max$ were commenced roller-skiing on a motor-driven treadmill (OJK-2, Telineyhtymä, Kotka, Finland (I – III); RL 3500, Rodby Innovation AB, Vänge, Sweden (II)) using the diagonal-stride technique. The subjects used roller skis (Pro-Ski C2, Sterner Specialfabrik AB, Dala-Järna, Sweden), provided by the sport-science laboratory, and their own poles with rubber-ski-pole tips (Biomekanikk A/S, Oslo, Norway).

Ski-ergometer test

For the measurements of upper-body power output in Study IV, a modified [26] air-braked Nordic ski ergometer (Concept II, Concept Inc., Morrisville, VT, USA) was used, which previously showed both high test-retest reliability (CV: 3.0% at power outputs between approximately 95 and 295 W) and high validity (i.e. power output in a 6-min double-poling test was correlated with a 3-km double-poling performance, $r = 0.86$ and $P < 0.05$) [26]. The measurement of the horizontal double-poling force was conducted by using a load cell (546QDT, DS Europe, Milan, Italy), whereas the horizontal double-poling speed was registered by using a potentiometric displacement sensor (Burster 8718, Burster Praezisionsmesstechnik GmbH, Gernsbach, Germany). Before each new test, the load cell and displacement sensor was calibrated for zero load and 1-m displacement, respectively.

Measurements of physiological characteristics

The scaling analyses in Study I – III are based on different variables of oxygen uptake; Study I and II focuses on $\dot{V}O_2max$ whereas the analyses in Study III are based on $\dot{V}O_2obla$, $\dot{V}O_2max$, and $\dot{V}O_2dp$. In Study IV, the scaling analysis is based on $\dot{W}$. For detailed information about test procedures and protocols, see the studies.

Submaximal oxygen uptake

The roller-skiing test to determine $\dot{V}O_2obla$ was a five-stage graded protocol where the work intensity was increased every four minutes by increasing treadmill speed and/or inclination. A capillary-blood sample was collected between stages and during the last minute of each stage mean oxygen uptake was established. Based on the relationships between (a) relative work intensity ($W \cdot kg^{-1}$) and blood-lactate concentration and (b) relative work intensity and oxygen uptake, the $\dot{V}O_2obla$ was determined.

Maximal oxygen uptake

During the $\dot{V}O_2$max test the work intensity was increased each minute, by regulating either the inclination or speed of the treadmill, until volitional exhaustion. Two and five minutes after the time of volitional exhaustion, capillary-blood samples were collected. In Study I, the $\dot{V}O_2$max was defined as the highest mean oxygen uptake during a 60-s period with a plateau (change in $\dot{V}O_2$ less than 2.1 ml·min^{-1}·kg^{-1} between successive stages) in oxygen uptake; additionally, at least one of two secondary criteria (a respiratory exchange ratio $\geq$ 1.15 or a blood-lactate concentration > 8 mmol·l^{-1}) had to be fulfilled [92]. In Study II and III, the $\dot{V}O_2$max was defined as the highest mean oxygen uptake during a period of 60 s when meeting the criterion of an oxygen-uptake plateau proposed by Poole et al. [93].

Upper-body oxygen uptake

The 60-s double-poling test on a ski ergometer was used to determine $\dot{V}O_2$dp, which was defined as mean oxygen uptake during the test duration.

Upper-body power output

The 120-s upper-body power-output test was used to determine mean propulsive power output from 5 to 120 s during double poling on a ski ergometer ($\dot{W}$).

Timing system

Performance data in Study I − III were collected with time-base stations (EMIT eLine Base station, EMIT AS, Oslo, Norway), which communicate with the skiers' individual timing chip with a built-in radio transceiver (emiTag, EMIT AS, Oslo, Norway). This timing system was used to collect section-split times (I), lap-split times (II), and completion times (I − III) during the cross-country skiing competitions. During the 2-km time trial in Study IV, the time to complete the double-poling roller-skiing time trial was registered by using a stop watch and rounded to the nearest second.

Collection of performance data

In Study I − III, results from competitions in cross-country skiing are used as dependent variables in the scaling analyses, whereas, results in the 2-km double-poling roller-skiing time trial were used as performance data in Study IV.

The competitive distance that is most common for distance races in World Cup competitions is 15 km among elite male skiers (e.g. during the season 2014 − 2015 approximately 85% of the World-Cup races, excluding races in the tours and World Championships, had a competitive distance of 15 km [see: fis-ski.com]), and performance data was therefore collected from 15-km classical-technique skiing competitions in Study I and II. The cross-country skiing performance that differ greatest from 15-km races in an energy-supply perspective is sprint competitions; therefore, to investigate the importance of body-mass exponent optimization in a

broader perspective, performance data was collected from a 1.25 km classical-technique sprint prologue for elite male skiers in Study III. The competitions in Study I – III were performed on homologated courses (i.e. specific norms for height differences and an equal proportion of uphill, downhill and undulating terrain sections). In Study IV, power-function modelling was used to investigate how upper-body power-output should be scaled in relation to body mass to optimally explain performance during which the skiers used the same movement pattern as in the test; therefore, a 2-km double-poling roller-skiing time trial was used as performance data.

Competitive performance
In Study I, the competitive-performance data were collected from a 15-km classical-technique skiing competition which comprised three laps on a 5.4-km course (i.e. a total race distance of 16.2 km). The course characteristics were: a total climbing of 161 m, an altitude difference of 84 m, and a maximum continuous climbing section of 68 m (Figure 1a). The timing system was used to collect completion time and section-split times were registered by using time-base stations (A – K) which were positioned throughout the course. In Study II, performance in a 15-km classical-technique skiing competition was evaluated. Time-base stations were positioned at start (A), lap split (B), and finish (C) (Figure 1b), which resulted in lap distances of 5.22 km (lap 1), 5.25 km (lap 2), and 5.00 km (lap 3). Each lap comprised a total climbing of 162 m, an altitude difference of 48 m, and a maximal continuous climbing section of 44 m.
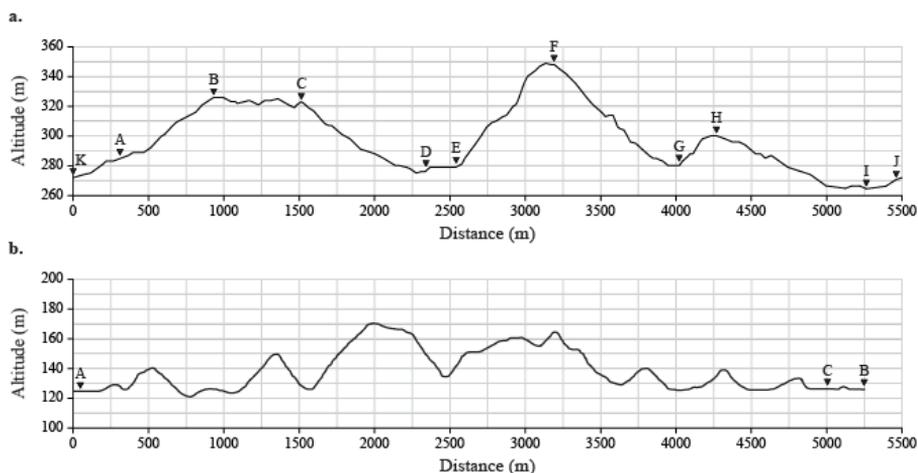
Figure 1. Course profile of the 5-km lap in the 15-km competition in (a) Study I and (b) Study II, where triangles (▼) represent placement of time-base stations

In Study III, the competitive-performance data were collected from a 1.25 km classical-technique sprint prologue, which comprised a total climbing of 42 m, an maximal altitude difference of 22 m, and a maximum continuous climbing section of 17 m.

Time-trial performance

The 2-km double-poling roller-skiing time trial was performed along an asphalt road and no drafting or double poling with kick was allowed. The inclination of the road was equable throughout the 2-km course and comprised 40.5 m of total climbing (i.e. a mean inclination of 1.2°). The roller skis the subjects used during the time trial (Pro-Ski C2, Sterner Specialfabrik AB, Dala-Järna, Sweden) were provided by the sport-science laboratory.

Ski-ranking points

To investigate the generalisability of the performance data (i.e. competition and time-trial results), the International Ski Federation's ski-ranking points for distance races (FISdist) and sprint races (FISsprint) were compiled from the actual FIS Cross-Country Lists at the time of the performance. The FIS-point system is constructed to indicate the performance capability of the skiers based on an average of the skier's best five FIS-point results from the last twelve month. The FIS-point value a skier obtains in a competition is related to the ratio between the winner's completion time and the skier's completion time, characteristics of the competition (sprint or distance race, individual or mass-start), and the performance capability of the three best skiers who finished among top five.

Statistical analyses

To investigate the importance of body-mass exponent optimization for evaluation of performance capability in cross-country skiing, the optimal body-mass exponent was determined for different oxygen-uptake variables and upper-body power output to evaluate performance in distance races (I – II), a sprint race (III), and a 2-km time trial (IV). The performance evaluation was based on finding the optimal ratio between the physiological variable and body mass in accordance with a previously described allometric-scaling approach in Model (3) and (4) [29]. In addition to the studies included in this thesis, this allometric-scaling approach has previously been used to evaluate performance in other endurance sports, such as cycling [47-49], running [29,45,46], and rowing [50-53].

Evaluation of competitive performance

Previously, it was suggested that the average speed of a performance was more symmetric, normally distributed and linearly related to other variables (such as $\dot{V}O_2max$) compared to the completion time [29,48,50]; therefore, the subjects'

completion times were converted to race speeds, which were used as a race-performance measure for subsequent scaling analyses.

In Study I – III, the aim was to establish the most appropriate scaling of oxygen-uptake variables ($\dot{V}O_2var$), i.e. $\dot{V}O_2obla$, $\dot{V}O_2max$ or $\dot{V}O_2dp$, to optimally reflect race speed in cross-country skiing competitions (15-km or sprint-prologue race speed). The following power-function model was used to explore the optimal relationship between race speed, $\dot{V}O_2var$, and body mass:

$$\text{race speed} = \beta_0 \cdot \dot{V}O_2var^{\beta_1} \cdot m^{\beta_2} \cdot \varepsilon, \tag{5}$$

where race speed is the mean skiing speed for the actual race ($m \cdot s^{-1}$); β_0 is a constant; $\dot{V}O_2var$ is the oxygen-uptake variable of interest ($l \cdot min^{-1}$); m is the body mass (kg); ε is the multiplicative error ratio; and β_1 and β_2 are the scaling exponents. Log-transformation of Model (5) yielded:

$$\log_e \text{race speed} = \log_e \beta_0 + \beta_1 \cdot \log_e \dot{V}O_2var + \beta_2 \cdot \log_e m + \log_e \varepsilon. \tag{6}$$

Linearization of the model allowed linear regression to be used to estimate the constant β_0 and the scaling exponents β_1 to β_2.

Evaluation of time-trial performance

In Study IV, the subjects' completion times were converted to mean skiing speeds of the 2-km time-trial performance. In accordance with the allometric-scaling approach used for the competitive-performance data, the following power-function model was applied to evaluate how the subjects' $\dot{W}$ and body mass influenced the time-trial speed, where sex and age were included as potential covariates in the model:

$$\text{time-trial speed} = \beta_0 \cdot \dot{W}^{\beta_1} \cdot m^{\beta_2} \cdot e^{\beta_3 \cdot sex + \beta_4 \cdot age} \cdot \varepsilon, \tag{7}$$

where time-trial speed is the mean roller-skiing speed for the 2-km double-poling roller-skiing time trial ($m \cdot s^{-1}$); β_0 is a constant; $\dot{W}$ is the upper-body power output (W), i.e. the rate at which external mechanical work is performed double poling on the ski ergometer; m is the body mass (kg); e, base of the exponential function; sex is coded 0 for the women and 1 for the men; age is the subjects age (years); ε is the multiplicative error ratio; and β_1 to β_4 are the scaling exponents. To estimate β_0 to β_4, the Model (7) was linearized and the log-transformation yielded:

$$\log_e \text{time-trial speed} = \log_e \beta_0 + \beta_1 \cdot \log_e \dot{W} + \beta_2 \cdot \log_e m + \beta_3 \cdot sex + \beta_4 \cdot age + \log_e \varepsilon. \tag{8}$$

Model (8) enabled linear regression to be used to estimate the constant β_0 and the scaling exponents β_1 to β_4.

Evaluation of performance in different sections

In Study I, a secondary aim was to evaluate the influence of course inclination on the body-mass exponent for $\dot{V}O_2$max; hence, the following power-function model was applied to the section speeds (i.e. the inverse transformation of section-split times) to describe the effect of $\dot{V}O_2$max, body mass, and course-profile characteristics on the section speeds:

$$\text{section speed} = b_0 \cdot \dot{V}O_2\text{max}^{b_1} \cdot m^{(b_2 + b_3 \cdot \alpha)} \cdot e^{b_4 \cdot \Delta + (1|\text{Id})} \cdot \varepsilon, \tag{9}$$

where section speed is mean skiing speed for the course section (m·s^{-1}); b_0 is a constant; $\dot{V}O_2$max is maximal oxygen uptake (l·min^{-1}); m is body mass (kg); α is the mean inclination of the course section (°); e, base of the exponential function; Δ is the altitude difference of the previous course section (m); (1|Id) is a random effect to account for within-participants variation [94], where Id is the identity number of the participants from 1 to 12; ε is the multiplicative error ratio; b_1, b_2, b_3, and b_4 are the scaling exponents used for the evaluation of mean skiing speed for the course sections based on the predictor variables: $\dot{V}O_2$max, m, α, and Δ. Log-transformation of the Model (9) gives the following equation:

$$\log_e \text{section speed} = \log_e b_0 + b_1 \cdot \log_e \dot{V}O_2\text{max} + (b_2 + b_3 \cdot \alpha) \cdot \log_e m + b_4 \cdot \Delta$$
$$+ (1|\text{Id}) + \log_e \varepsilon. \tag{10}$$

Linearization of the model allowed linear regression to be used to estimate the constant b_0 and the scaling exponents b_1 to b_4.

Evaluation of performance in different laps

In Study II, a secondary aim was to evaluate the influence of distance covered on the body-mass exponent for $\dot{V}O_2$max. The following power-function model was applied to the lap speeds (i.e. inverse transformation of lap-split times) to describe the effect of $\dot{V}O_2$max, body mass, lap number, and age on the lap speeds:

$$\text{lap speed} = b_0 \cdot \dot{V}O_2\text{max}^{b_1} \cdot m^{(b_2 + b_3 \cdot \text{lap})} \cdot e^{b_4 \cdot \text{age} + (1|\text{Id})} \cdot \varepsilon, \tag{11}$$

where lap speed is the mean skiing speed for the actual lap (m·s^{-1}); b_0 is a constant; $\dot{V}O_2$max is the maximal oxygen uptake (l·min^{-1}); m is body mass (kg); lap is the number of the lap coded as lap 1 = 0, lap 2 = 1, and lap 3 = 2; e is the base of the exponential function; age is the age of the subject (years); (1|Id) is a control for random effects to account for potential within-subjects variation [94], where Id is the identity number of the subjects from 1 to 24; ε is the multiplicative error ratio; and b_1, b_2, b_3, and b_4 are the scaling exponents used to explain the lap speed based on the independent variables of $\dot{V}O_2$max, m, lap, and age, respectively. Log-transformation of Model (11) yielded:

$$\log_e \text{ lap speed} = \log_e b_0 + b_1 \cdot \log_e \dot{V}O_2\text{max} + (b_2 + b_3 \cdot \text{lap}) \cdot \log_e m + b_4 \cdot \text{age}$$
$$+ (1|\text{Id}) + \log_e \varepsilon. \tag{12}$$

Model (12) enabled linear regression to be used to estimate the constant b_0 and the scaling exponents b_1 to b_4.

Correlation analyses

Before the power-function modelling and correlation analyses, the normality of each variable's distribution was investigated by using the Shapiro-Wilk test. To evaluate linear relationships between variables, Pearson's product-moment correlation coefficient (r) test was used. In Study I – III, the correlations between competitive performance (i.e. race speed) and oxygen-uptake variables (i.e. $\dot{V}O_2$obla, $\dot{V}O_2$max, and $\dot{V}O_2$dp) expressed both absolutely (l·min^{-1}) and as a simple ratio-standard (ml·min^{-1}·kg^{-1}) were investigated. In Study IV, the relationships between the 2-km time-trial performance (i.e. time-trial speed) and the absolute (W) as well as the simple ratio-standard expression (W·kg^{-1}) of $\dot{W}$ were evaluated. The relationships between performance (i.e. race speed and time-trial speed) and FIS points (i.e. FISsprint and FISdist) were evaluated in Study I, III and IV.

Analysis of lap-speed differences

To investigate lap-speed differences in Study II, a one-way repeated measures analysis of variance (ANOVA) was used with post-hoc tests using Bonferroni's correction.

Level of significance

All of the statistical tests were performed at an alpha of 0.05.

Statistical programs

The statistical analyses were processed using the R statistical data program, version 2.13.2 (R Development Core Team, Auckland, New Zealand) and IBM Statistical Package for the Social Sciences (SPSS) statistics software, version 20 (IBM Corporation, New York, USA).

Ethical considerations

All of the subjects in Study I – IV provided written informed consent to participate. The Ethics Committee at Dalarna University, Falun, Sweden (I) and the Regional Ethical Review Board, Uppsala, Sweden (II – IV) approved the studies. The 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

Physiological measurements

The test results related to the physiological measurements in Study I – IV are displayed in Table 2.

Table 2. The test results in Study I – IV

Study	Sex	Physiological variable (unit)		Test result	Technique
I	♂	$\dot{V}O_2$max	(l·min^{-1})	5.34 ± 0.34	DS
I	♂	$\dot{V}O_2$max	(ml·min^{-1}·kg^{-1})	70.3 ± 4.2	DS
II	♂	$\dot{V}O_2$max	(l·min^{-1})	5.39 ± 0.57	DS
II	♂	$\dot{V}O_2$max	(ml·min^{-1}·kg^{-1})	71.5 ± 6.3	DS
III	♂	$\dot{V}O_2$obla	(l·min^{-1})	4.66 ± 0.38	DS
III	♂	$\dot{V}O_2$obla	(ml·min^{-1}·kg^{-1})	60.5 ± 2.3	DS
III	♂	$\dot{V}O_2$max	(l·min^{-1})	5.57 ± 0.52	DS
III	♂	$\dot{V}O_2$max	(ml·min^{-1}·kg^{-1})	72.2 ± 3.7	DS
III	♂	$\dot{V}O_2$dp	(l·min^{-1})	3.66 ± 0.37	DP
III	♂	$\dot{V}O_2$dp	(ml·min^{-1}·kg^{-1})	47.5 ± 3.9	DP
IV	♂+♀	$\dot{W}$	(W)	187 ± 39	DP
IV	♂+♀	$\dot{W}$	(W·kg^{-1})	2.7 ± 0.4	DP
IV	♂	$\dot{W}$	(W)	210 ± 29	DP
IV	♂	$\dot{W}$	(W·kg^{-1})	2.9 ± 0.3	DP
IV	♀	$\dot{W}$	(W)	152 ± 23	DP
IV	♀	$\dot{W}$	(W·kg^{-1})	2.4 ± 0.3	DP

Study is the number of the study referred to in this thesis; ♂ is men; ♀ is women; $\dot{V}O_2$max is maximal oxygen uptake; $\dot{V}O_2$obla is oxygen uptake related to a blood-lactate concentration of 4 mmol·l^{-1}; $\dot{V}O_2$dp is mean upper-body oxygen uptake; $\dot{W}$ is mean upper-body power output; the test results for each variable are presented as mean ± SD; DS means the test was performed using the diagonal-stride technique; and DP means the test was performed using the double-poling technique.

Performance data

The 15-km race speeds were 5.23 ± 0.32 m·s^{-1} and 5.83 ± 0.41 m·s^{-1} in Study I and II, respectively. In Study III, the 1.25-km race speed in the sprint prologue was 6.33 ± 0.14 m·s^{-1}. In Study IV, time-trial speed in the 2-km double-poling roller-skiing time trial was 5.07 ± 0.32 m·s^{-1}.

In Study I, performance data were collected from eleven different sections and the section speeds are displayed in Table 3.

Table 3. Performance data and course characteristics

Section	Section speed	α	Altitude
K – A	4.36 ± 0.20	2.4	13.0
A – B	3.51 ± 0.34	3.8	41.0
B – C	5.94 ± 0.39	-0.3	-3.0
C – D	11.55 ± 0.67	-3.3	-47.0
D – E	7.64 ± 0.58	0.8	2.9
E – F	3.01 ± 0.28	6.2	69.2
F – G	7.85 ± 0.42	-4.6	-66.8
G – H	3.62 ± 0.33	4.6	20.0
H – I	7.71 ± 0.42	-2.1	-35.7
I – A	3.58 ± 0.30	2.2	20.6
I – J	3.95 ± 0.28	1.8	6.3

Section speed (m·s^{-1}) between time-base stations (Figure 1a) are presented as mean ± SD; α is mean inclination of the actual course section (°); and altitude is altitude difference of the actual course section (m).

In Study II, the lap speeds for the three consecutive laps of the 5-km course were 6.08 ± 0.39 m·s^{-1}, 5.76 ± 0.42 m·s^{-1}, and 5.66 ± 0.43 m·s^{-1}. The one-way repeated measures ANOVA displayed a significant effect of lap number on the pacing-induced lap speeds ($F_{2,46}$ = 221.32, $P < 0.001$, partial η^2 = 0.906). Post-hoc tests, using Bonferroni's correction, revealed a consecutive reduction in lap speed for each new lap (lap 1 vs. lap 2, $P < 0.001$; lap 2 vs. lap 3, $P < 0.001$).

Ski-ranking points according to FIS-point system were: FISdist = 121.7 ± 58.1 points (I); FISsprint = 95.5 ± 26.5 points (III); FISdist (♂) = 171.4 ± 79.9 points and FISdist (♀) = 156.2 ± 93.7 points (IV).

Correlations

The performance-related correlations in Study I – IV are presented in Table 4.

Table 4. Performance-related correlations in Study I – IV

Study	Variable A (unit)		Variable B (unit)		r
	Competitive performance vs. oxygen uptake variables				
I	15-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2max$	$(l \cdot min^{-1})$	0.70 *
I	15-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2max$	$(ml \cdot min^{-1} \cdot kg^{-1})$	0.62 *
II	15-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2max$	$(l \cdot min^{-1})$	0.76 ***
II	15-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2max$	$(ml \cdot min^{-1} \cdot kg^{-1})$	0.76 ***
III	1.25-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2obla$	$(l \cdot min^{-1})$	0.79 *
III	1.25-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2obla$	$(ml \cdot min^{-1} \cdot kg^{-1})$	0.60
III	1.25-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2max$	$(l \cdot min^{-1})$	0.86 **
III	1.25-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2max$	$(ml \cdot min^{-1} \cdot kg^{-1})$	0.72 *
III	1.25-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2dp$	$(l \cdot min^{-1})$	0.94 ***
III	1.25-km race speed	$(m \cdot s^{-1})$	$\dot{V}O_2dp$	$(ml \cdot min^{-1} \cdot kg^{-1})$	0.64
	Time-trial performance vs. upper-body power output				
IV	2-km time-trial speed	$(m \cdot s^{-1})$	$\dot{W}$	(W)	0.72 ***
IV	2-km time-trial speed	$(m \cdot s^{-1})$	$\dot{W}$	$(W \cdot kg^{-1})$	0.73 ***
	Performance vs. ski-ranking points				
I	15-km race speed	$(m \cdot s^{-1})$	FISdist	(points)	-0.94 *** [a]
III	1.25-km race speed	$(m \cdot s^{-1})$	FISsprint	(points)	-0.78 * [a]
IV	2-km time-trial speed	$(m \cdot s^{-1})$	FISdist (♂)	(points)	-0.83 *** [a]
IV	2-km time-trial speed	$(m \cdot s^{-1})$	FISdist (♀)	(points)	-0.76 ** [a]

Study is the number of the study referred to in this thesis. Relationships between performance and test variables as well as between performance and ski-ranking points are presented as Pearson's product-moment correlation coefficients (r). Alpha levels of significance are: * for $P < 0.05$; ** for $P < 0.01$; and *** for $P < 0.001$. $\dot{V}O_2max$ is maximal oxygen uptake; $\dot{V}O_2obla$ is oxygen uptake related to a blood-lactate concentration of 4 mmol$\cdot$l^{-1}; $\dot{V}O_2dp$ is mean upper-body oxygen uptake; $\dot{W}$ is mean upper-body power output; FISdist is International Ski Federation's ski-ranking points for distance races; FISsprint is International Ski Federation's ski-ranking points for sprint races; ♂ is men; and ♀ is women.

Power-function modelling

Results of the power-function modelling for evaluation of the performance-related variables in Study I – IV are presented below.

Modelling of competitive performance

Statistical modelling to evaluate competitive performance were based on log-transformed Model (6) and the subsequent retransformation of the model yielded the following model to optimally explain race speed for the 15-km races in Study I – II:

15-km race speed (I)

$$race\ speed = 7.86 \cdot \dot{V}O_2max \cdot m^{-0.48} \tag{13}$$

Model (13) explained 68% of the variance in race speed in the 15-km classic technique skiing competition ($P < 0.001$), and all variables contributed to the model (all $P < 0.01$) (Figure 2a).

15-km race speed (II)

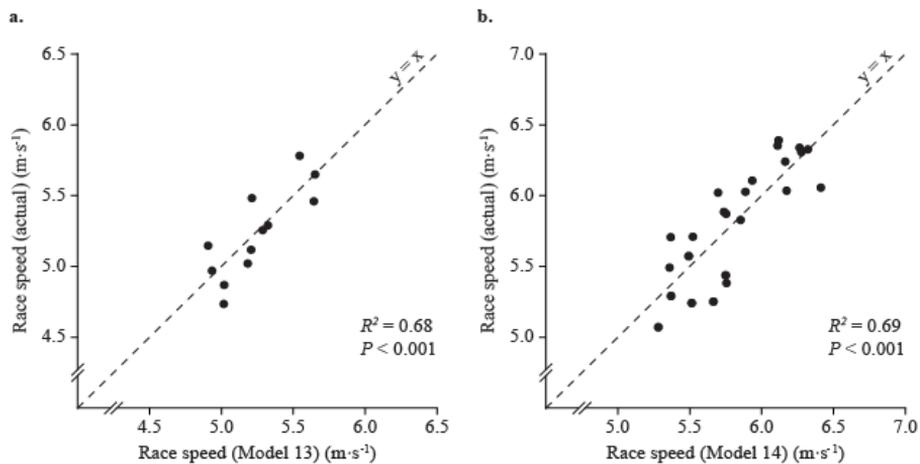$$\text{race speed} = 8.83 \cdot (\dot{V}O_2\text{max} \cdot m^{-0.53})^{0.66} \tag{14}$$

Model (14) explained 69% of the variance in race speed in the 15-km classic technique skiing competition ($P < 0.001$), and all variables contributed to the model (all $P < 0.05$) (Figure 2b).

Figure 2. Relationships between actual and model race speeds in the 15-km classical-technique skiing competition according to (a) Model (13) in Study I, and (b) Model (14) in Study II.

1.25-km race speed (III)
Power-function modelling based on Model (6), for the oxygen-uptake variables $\dot{V}O_2\text{obla}$, $\dot{V}O_2\text{max}$, and $\dot{V}O_2\text{dp}$, revealed that the body mass failed to contribute significantly to each of the models; however, the oxygen-uptake variable of interest contributed to the specific model.

$$\text{race speed} = 1.09 \cdot \dot{V}O_2\text{obla}^{0.21} \tag{15}$$

Model (15) explained 60% of the variance in the race speed in the 1.25-km classic technique race ($P = 0.024$) (Figure 3a).

$$\text{race speed} = 1.05 \cdot \dot{V}O_2max^{0.21} \tag{16}$$

Model (16) explained 73% of the variance in the race speed in the 1.25-km classic technique race ($P = 0.0073$) (Figure 3b).

$$\text{race speed} = 1.19 \cdot \dot{V}O_2dp^{0.20} \tag{17}$$

Model (17) explained 87% of the variance in the race speed in the 1.25-km classic technique race ($P < 0.001$) (Figure 3c).
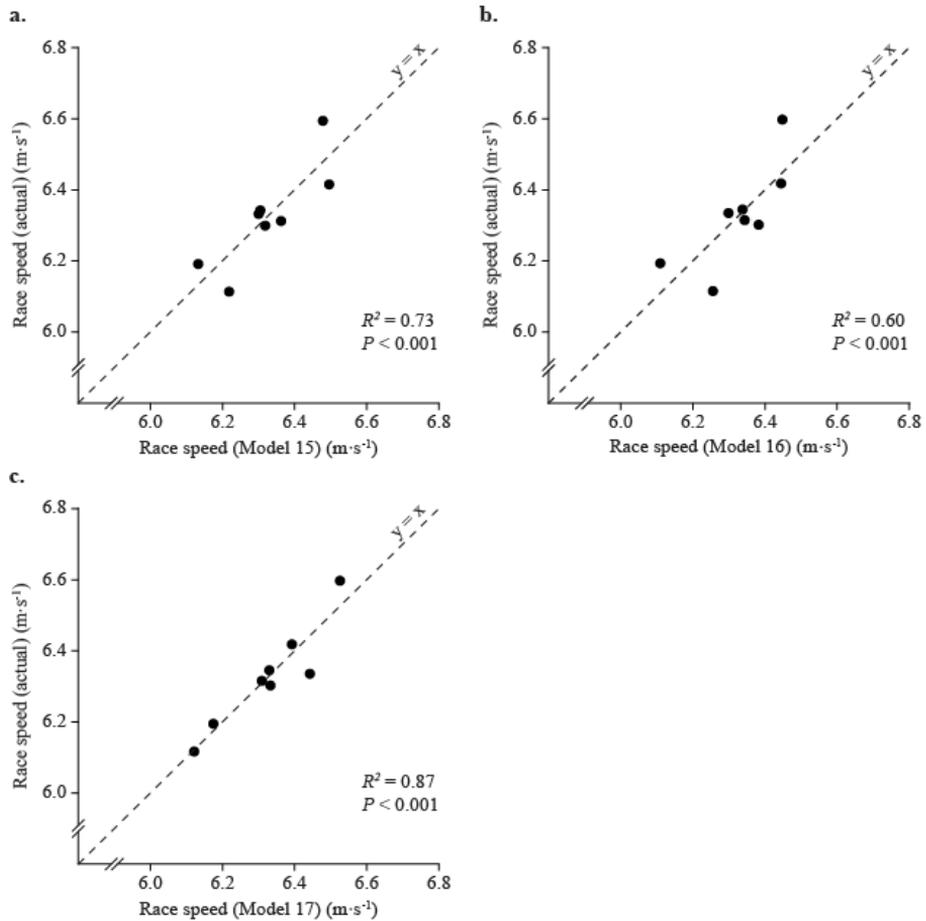
Figure 3. Relationships between actual and model race speeds in the 1.25-km classical-technique sprint prologue according to (a) Model (15), (b) Model (16) and (c) Model (17) in Study III.

Optimal body-mass exponents for $\dot{V}O_2max$

To investigate the importance of body-mass exponent optimization for evaluating competitive performance capability in cross-country skiing, the CIs for the body-mass exponents were calculated. The optimal body-mass exponents (β_2) for $\dot{V}O_2max$ to explain competitive performance among elite male cross-country skiers are presented in Table 5.

Table 5. The optimal body-mass exponents (β_2) for $\dot{V}O_2max$ to explain competitive performance among elite cross-country skiers

Study	Model	Variable	Performance	β_2	CI
I	(13)	$\dot{V}O_2max$	15-km race speed	0.48	(0.19 − 0.77)
II	(14)	$\dot{V}O_2max$	15-km race speed	0.53	(0.12 − 0.94)
III	(16)	$\dot{V}O_2max$	1.25-km race speed	N/A	

Study is the number of the study referred to in this thesis; model is the number of the model where equation for optimal model to explain performance is presented; variable is the test variable the modelling is based on; performance is the performance-related variable; β_2, the body-mass exponent for $\dot{V}O_2max$ that optimally explains performance in accordance with the model: race speed = $\beta_0 \cdot \dot{V}O_2max^{\beta_1} \cdot m^{\beta_2} \cdot \varepsilon$, where race speed is the mean skiing speed for the actual performance (m·s^{-1}); β_0 is a constant; $\dot{V}O_2max$ is the maximal oxygen uptake (l·min^{-1}); m is the body mass (kg); ε is the multiplicative error ratio; and β_1 and β_2 are the scaling exponents used to explain race speed; CI is 95% confidence interval for β_2; N/A, not applicable because m did not contribute to the model (i.e. β_2 can not be expected to be different from 0)

If the body-mass exponent's CI for a specific variable/performance-combination in Table 5 does not include 0, the absolute expression of the physiological variable should not be recommended for evaluating performance capability of elite male skiers; conversely, if 1 is not included in the CI, the simple ratio-standard scaled expression of the variable should not be recommended for performance-capability evaluation.

Modelling of time-trial performance

Power-function modelling to evaluate performance in the 2-km time-trial roller skiing using the double-poling technique were based on the log-transformed Model (8) and the subsequent retransformation demonstrated the following model to optimally explain time-trial speed in Study IV:

$$\text{time-trial speed} = 1.06 \cdot (\dot{W} \cdot m^{-0.57})^{0.56} \qquad (18)$$

Model (18) explained 59% of the variance in the time-trial speed in the 2-km double-poling roller-skiing time-trial (P < 0.001), and all variables contributed to the model (all *P* < 0.05) (Figure 4).
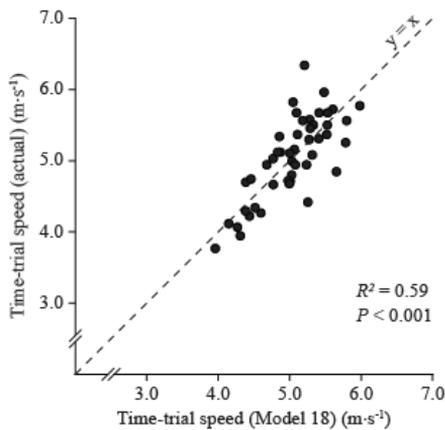
Figure 4. Relationships between actual and model time-trial speeds in the 2-km double-poling roller-skiing time trial according to Model (18) in Study IV.

Modelling of performance in different sections

In Study I, statistical modelling to evaluate section speeds during the 15-km classic technique skiing competition was based on Model (10) and the subsequent retransformation of the model yielded:

$$\text{section speed} = 5.96 \cdot \dot{V}O_2\text{max} \cdot m^{-(0.38 + 0.03 \cdot \alpha)} \cdot e^{-0.003 \cdot \Delta} \tag{19}$$

Model (19) explained 84% of the variance in section speed ($P < 0.001$) and all variable contributed to the model (all $P < 0.01$) (Figure 5a).

Modelling to explain performance in different laps

In Study II, power-function modelling was used to evaluate the influence of distance covered on the body-mass exponent for $\dot{V}O_2\text{max}$. The modelling was based on Model (12) and the subsequent retransformation of the model yielded:

$$\text{lap speed} = 5.89 \cdot (\dot{V}O_2\text{max} \cdot m^{-(0.49 + 0.019 \cdot \text{lap})})^{0.43} \cdot e^{0.010 \cdot \text{age}}, \tag{20}$$

Model (20) explained 81% of the variance in lap speed ($P < 0.001$) and all variable contributed to the model (all $P < 0.05$) (Figure 5b).
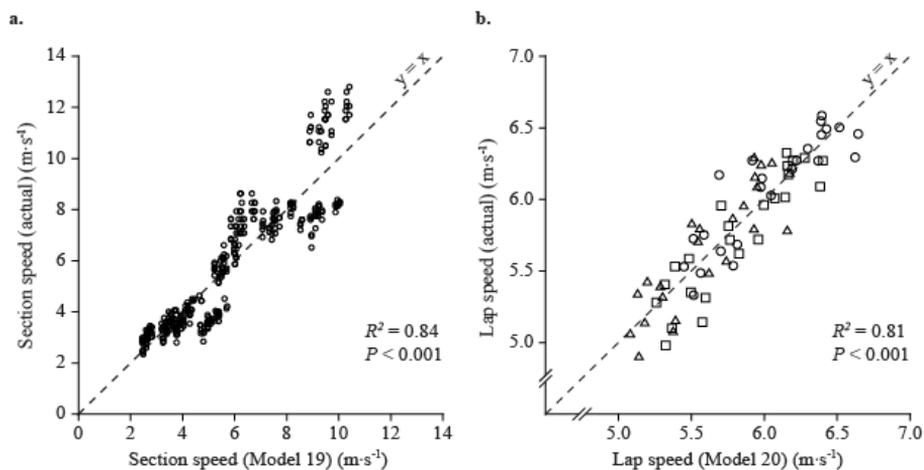
Figure 5. Relationships between (a) actual and Model (19) section speeds in the 15-km classical-technique skiing competition in Study I, and (b) actual and Model (20) lap speeds in the 15-km classical-technique skiing competition in Study II, where lap 1 is represented by circles; lap 2, squares; and lap 3, trian

Discussion

Principal findings

The aim of this doctoral thesis was to investigate the importance of body-mass exponent optimization for the evaluation of performance capability in cross-country skiing; therefore, different skiing performances were used in the power-function models as dependent variables whereas the anthropometric variable (i.e. body mass) and the physiological characteristic (i.e. $\dot{V}O_2max$ or $\dot{W}$) were independent variables that were supposed to explain performance. The power-function modelling demonstrated that the optimal $\dot{V}O_2max$-to-mass ratios to explain 15-km race speed were $\dot{V}O_2max$ divided by body mass raised to the 0.48 and 0.53 power in Study I and II, respectively. Therefore, it may be recommend that $\dot{V}O_2max$ divided by the square root of body mass ($ml·min^{-1}·kg^{-0.5}$) should be used when elite male skier's performance in 15-km classical-technique skiing competitions is evaluated. The confidence intervals for the derived body-mass exponents included neither 0 nor 1; this indicates that to accurately explain 15-km performance among elite male skiers both the absolute and simple ratio-standard scaled expressions should be avoided. This claim appears also to be valid for evaluating performance in a 2-km double-poling roller-skiing time trial based on the skiers' $\dot{W}$ and body mass as a consequence of the confidence interval for the optimal body-mass exponent of 0.57 not including either 0 or 1. Hence, evaluation of performance in classical-technique sprint prologues among elite male skiers should be based on oxygen-uptake variables expressed absolutely, because the simple ratio-standard scaled expression entails a risk of misinterpreting skier's performance capability.

In Study I, the influence of course inclination on the body-mass exponent for $\dot{V}O_2max$ was investigated, and it was revealed that an increased inclination is related to a contemporary increase in the body-mass exponent. Moreover, the power-function modelling in Study II indicated that the body-mass exponent for $\dot{V}O_2max$ is also influenced by the distance covered of the 15-km classical-technique skiing competition and the exponent increased for each new lap on the 5-km course.

Theoretical perspectives

Results from Study I and II indicate that a 0.5 body-mass exponent for $\dot{V}O_2max$ optimally explains performance in 15-km classical-technique skiing competitions among elite male skiers; however, is this exponent supported theoretically?

The maximal force (F) a muscle can produce is related to its cross-sectional area [95-98]; hence, muscle force is proportional to length (L) raised to the 2nd power ($F \sim L^2$). Furthermore, work performed (W) is the function of force multiplied with length ($W \sim F · L$); consequently, work performed is proportional to length raised to the 3rd power ($W \sim L^3$) [28].

Work performed is related to energy expenditure whereas $\dot{V}O_2max$ is an expression of energy expenditure per unit of time; therefore, $\dot{V}O_2max$ is proportional

to work performed divided by time ($\dot{V}O_2max \sim W \cdot t^{-1}$). Because time is proportional to length ($t \sim L$), $\dot{V}O_2max$ is proportional to length raised to the 3rd power divided by length raised to the 1st power ($\dot{V}O_2max \sim L^3 \cdot L^{-1}$); hence, $\dot{V}O_2max$ is proportional to length raised to the 2nd power ($\dot{V}O_2max \sim L^2$). Furthermore, mass (m) is proportional to volume (i.e. L^3), which means that length is proportional to mass raised to 1/3 power (i.e. $L \sim m^{1/3}$ and consequently $L^2 \sim m^{2/3}$) [8]. Thus $\dot{V}O_2max$ is proportional to mass raised to the 2/3 power ($\dot{V}O_2max \sim m^{2/3}$).

This theoretically derived relationship between $\dot{V}O_2max$ and body mass has previously been identified for well-trained endurance athletes [8,29,42]. In cross-country skiing, a body-mass exponent for $\dot{V}O_2max$ of 0.7 (i.e. close to 2/3) has been proposed to partitioning out differences in body mass [5,88]. However, race speed in distance races is reported to be proportional to body mass raised to the 0.26 power [88] and can be expressed as follows:

$$\text{race speed} \sim m^{0.26}. \tag{21}$$

Moreover, results from Study I and II suggest that a 0.5 body-mass exponent for $\dot{V}O_2max$ optimally explains performance in 15-km classical-technique skiing competitions among elite male skiers in accordance with the following power-function model:

$$\text{race speed} \sim \dot{V}O_2max \cdot m^{-0.50}. \tag{22}$$

If the relationship for race speed described in Model (22) is substituted with the race speed in Model (21), the combined model will be:

$$\dot{V}O_2max \cdot m^{-0.50} \sim m^{0.26}, \tag{23}$$

and this can be rearranged and expressed as:

$$\dot{V}O_2max \sim m^{0.76}. \tag{24}$$

Model (24) suggests that $\dot{V}O_2max$ divided by body mass raised to the 0.76 power can partitioning out differences in body size among elite male skiers. This 0.76 body-mass exponent differs slightly from the theoretically expected 2/3 (i.e. 0.67) body-mass exponent according to the *surface law*, which emphasises that when body mass and volume increase, there is a disproportionate reduction in surface area [28]. However, the body-mass exponent of 0.76 is close to the previously proposed 0.75 exponent [99,100]. This proposed exponent is derived from the discovery that the metabolism of species, which differ markedly in body mass, is normalized by a 0.75 body-mass exponent; an explanation for this proportionality is the *theory of elasticity* in which it is suggested that the absorption and release of energy from the body's structures (e.g. tendons) can influence the relationship between body mass

and metabolic rate [101]. A body-mass exponent of 0.75 has also been proposed to reflect physiological capabilities such as metabolic rate, cardiac output, and oxygen-consumption rate [102], which are variables that are closely related to $\dot{V}O_2$max. In a more recent study, a body-mass exponent of 0.73 was suggested to eliminate the body-size differences in $\dot{V}O_2$max for a large group of elite athletes from different sports [33]. Another approach to the exponent issue is called the *allometric cascade* and this approach considers the exponent to be the sum of processes (such as ventilation, cardiac work, and circulation) that is necessary to attain the maximal sustainable work rate. This rate is equivalent to maximal sustainable ATP-turnover rate, and a body-mass-exponent interval of 0.82 to 0.92 is suggested [103], which subsequently was supported by the results of another study [104]. In this context, it should be stated that this thesis makes no claim to determine which of the theories is correct; however, it can be concluded that the body-mass exponent of 0.76 in Model (24) is comprised in the interval of proposed exponents from the described theories. If the purpose of the usage of body-mass exponents is to compare the physiological capability of an individual against a standard or to compare groups on the basis of $\dot{V}O_2$max, the 0.67 or 0.75 exponent (i.e. $\dot{V}O_2$max units: $ml \cdot min^{-1} \cdot kg^{-0.67}$ or $ml \cdot min^{-1} \cdot kg^{-0.75}$) appears to be appropriate.

Optimal $\dot{V}O_2$max-to-mass ratios for competitive performances

Both Study I and the subsequent validation in Study II report that the optimal body-mass exponent for $\dot{V}O_2$max is close to 0.5 and if the objective is to evaluate an elite male skier's performance capability in 15-km classical-technique skiing competitions, then $\dot{V}O_2$max divided by the square root of body mass should be used. Because of the strong relationship between 15-km race speed and FISdist ($r = -0.93$) in Study I, it might be assumed that the 0.5 body-mass exponent for $\dot{V}O_2$max is a general indicator of performance in elite male skiers. The use of the 0.5 exponent is supported by a previous study that suggested that $\dot{V}O_2$max expressed as $ml \cdot min^{-1} \cdot kg^{-0.5}$ was a better estimate of performance capability among world-class male skiers than the use of the body-mass exponent 0.67 [4].

The results obtained in Study I and II indicated that neither the absolute nor the simple ratio-standard scaled expression of $\dot{V}O_2$max should be used for the evaluation of performance among elite male skiers. Nonetheless, the simple ratio-standard scaled expression of $\dot{V}O_2$max is most likely the most frequently used expression by sports scientists and coaches to indicate performance and/or physiological capability among elite skiers even though the use of the simple ratio-standard scaled expression of $\dot{V}O_2$max has been criticized in the literature [105-110] because it could result in spurious relationships between oxygen uptake and performance and, hence, be misleading [54,106].

Given a body-mass exponent estimate that is lower than 1, simple ratio-standard scaling tends to underestimate the performance of heavy athletes and overestimate the performance of their lighter counterparts [108,111]. Because the CI:s for the

body-mass exponent in Study I and II do not include 0, a reversed misinterpretation would occur if $\dot{V}O_2$max expressed absolutely was used for evaluating performance in 15-km classical-technique skiing competitions among elite male skiers; hence, the performance of lighter skiers would be overestimated, whereas an underestimation of the heavier skiers' performance would occur. Consequently, the use of absolute or simple ratio-standard scaled expressions of $\dot{V}O_2$max should be avoided if the objective is to adequately evaluate an elite male skier's performance capability in a 15-km classical-technique skiing competition (Figure 6).
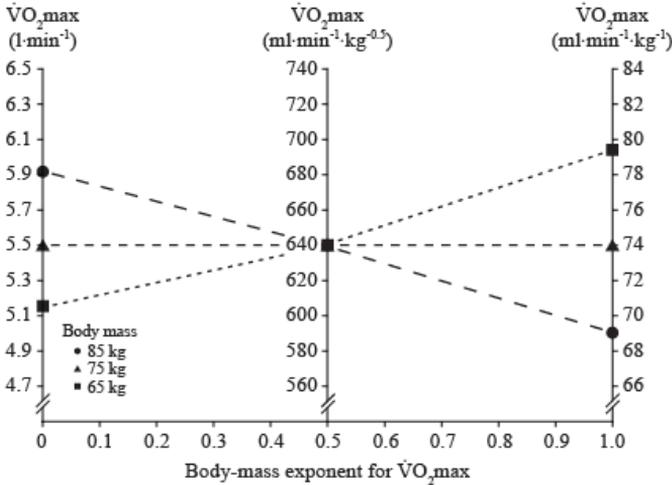
Figure 6. Differences in the estimation of performance in a 15-km classical-technique skiing competition for three elite male skiers with the same performance capability when the 0.5 body-mass exponent for $\dot{V}O_2$max is used; a comparison of the estimations for the exponents: 0 (absolute expression), 0.5 (optimal expression), and 1 (simple ratio-standard scaled expression).

The previously proposed 0.67 exponent, which was reported to be a better indicator of performance capability of elite skiers than the absolute and simple ratio-standard scaled expressions [62], is included in the CI:s derived in Study I and II. Therefore, more studies are needed to clarify which of the exponents, 0.5 or 0.67 (or another), should be used for optimal evaluation of performance capability in distance races. The suggested deviation from the 0.67 exponent, which is used to partitioning out the influence of body mass on $\dot{V}O_2$max (i.e. indicate the physiological capability), could be explained by the positive relationship between body mass and performance [5,88]. Hence, the negative effect of body mass, as a surrogate indicator of counteracting forces, is partly compensated for by the suggested positive relationship that would shift the body-mass exponent for $\dot{V}O_2$max towards 0. This adjustment of the exponent's magnitude is to some extent related to the contribution of the anaerobic energy supply in the force-generating process.

Anaerobic capacity has been shown to correspond to muscle size [112,113], which could be explained by the proportional increase in available anaerobic energy stores with increasing muscle volume [114,115]. Theoretically, anaerobic capacity is directly proportional to body mass [5,116]; consequently, the muscle mass involved in the activity could be considered a surrogate indicator of the skier's physiological power supply from anaerobic processes [117]. When analysing energy supply in the perspective of an entire distance race, less than 5% of the energy supply for the generation of propelling forces is derived from the anaerobic energy-supply system [8,11]. In this context, it should be noted that work intensity varies throughout the race, and the work rate in uphill sections during a distance race reaches an intensity above that of $\dot{V}O_2$max [118]; the skiers thereby incur an appreciable oxygen debt, but this debt is to a great extent balanced by relatively lower work intensity, compared to that of $\dot{V}O_2$max, during downhill skiing.

The same reasoning could be applied for the optimal body-mass exponent for $\dot{V}O_2$max to explain sprint-prologue performance, however, the percent energy supply from anaerobic processes in sprint skiing is considerably higher than the proportion of anaerobic energy supply during distance races. The anaerobic energy contribution in a 3.5-min sprint race would be approximately $30 - 40\%$ [8]. A larger muscle mass and, hence, a higher anaerobic capacity appear to be advantageous in events with relatively short duration, which is supported by a correlation between elite male skiers' maximal oxygen deficit and performance in a 0.6-km uphill roller-skiing time trial [14]. Moreover, it was reported that specialised sprint skiers were heavier than specialised distance skiers [75] and that total lean mass (nearly equivalent to muscle mass) of elite male skiers was positively correlated with sprint-prologue performance [119]. As a consequence of the larger anaerobic energy supply during sprint races, it could be assumed that the optimal body-mass exponent for $\dot{V}O_2$max is lower than the 0.5 exponent suggested for explaining performance in 15-km classical-technique skiing competitions. In fact, a recent study showed that mean speed in a 1-km uphill roller-skiing time trial, with a treadmill inclination of $5°$, was proportional to body mass raised to the 0.43 power [88]; thus, the main counteracting force during this type of exercise is a net increase in potential energy, which scales with body mass raised to the 1st power [4], would penalize skiers with larger body mass. This indicates that the exponent to describe the relationship between actual sprint performance and body mass is higher than the 0.43 exponent for uphill skiing; hence, a body-mass exponent for $\dot{V}O_2$max close to 0 can be expected to optimally explain elite male skiers' performance capabilities in classical-technique sprint prologues.

The power-function modelling to determine the optimal $\dot{V}O_2$max-to-mass ratio for explaining sprint-prologue performance revealed that body mass did not contribute to Model (16); hence, it could not be established statistically that the body-mass exponent for $\dot{V}O_2$max diverges from 0. The results of Study III suggest that the evaluation of elite male skiers' sprint-race performance should be based on

the absolute expression of $\dot{V}O_2$max, whereas the simple ratio-standard scaled expression should be avoided. This finding is supported by a previous study that reported a relationship between elite male skiers' FISsprint and $\dot{V}O_2$max expressed absolutely, whereas no correlation with FISsprint was found for the simple ratio-standard scaled expression [67]. Furthermore, compared with distance skiers, specialised sprint skiers have a higher absolute peak oxygen uptake ($\dot{V}O_2$peak) while using the freestyle technique; however, when the comparison was based on the simple-ratio scaled expression the relationship was reversed [75]. The importance of a high aerobic energy supply for sprint performance is emphasised by the reported difference in qualitatively different skiers where world-class sprint skiers have a higher $\dot{V}O_2$peak, independent of the tested expression, than that of national-level sprint skiers [120]; hence, the aerobic energy contribution is presumably accentuated in the knockout heats (i.e. quarter finals, semi-finals, and final) that follow the sprint prologue because of, for example, the relatively short recovery time between heats (e.g. approximately 15 – 20 min between semi-final and final for men). These findings are consistent with a previous statement that high-level sprint skiing requires both a high anaerobic capacity and a high $\dot{V}O_2$max [11]. Together, this supports the notion that heavier skiers with a high $\dot{V}O_2$max have a performance advantage in sprint races and that the larger anaerobic capacity that follows a larger muscle mass, most likely, exceeds the negative effect of the increase in counteracting forces by the larger body mass.

In summary, $\dot{V}O_2$max is an important physiological characteristic for distance and sprint performance among elite male skiers and it appears that the optimal body-mass exponent for $\dot{V}O_2$max differs between the two disciplines. Based on the reasoning above, the influence of anaerobic energy supply contributes to this difference. A holistic model, based on an energy-supply level, in which both the aerobic and anaerobic energy-supply systems as well as body mass are included is, therefore, warranted. Such a model would allow for clarification of the importance of each variable for competitive performance in cross-country skiing.

Influencing factors of the body-mass exponent for $\dot{V}O_2$max

The results presented in Study I and II indicate that there are other factors that influence the body-mass exponent for $\dot{V}O_2$max; course inclination (I) as well as race distance covered (II) made a significant contribution on the magnitude of the exponent.

Based on the reported results of a dimensional analysis, the fundamental counteracting forces are scaled in different proportion to body mass [4]. If the distribution of the counteracting forces is altered, the influence of body mass on $\dot{V}O_2$max will be changed accordingly. For example, the counteracting force related to a net increase in potential energy on uphill slopes is directly scaled with body mass (i.e. a body-mass exponent of 1), which is higher than the theoretically expected exponent of 0.67 [5]. Therefore, it could be assumed that the body-mass

exponent for $\dot{V}O_2$max that optimally describes uphill skiing is higher than that for level skiing because the larger proportion of the total resistive force is related to the net increase in potential energy. This assumption is supported by results from scaling analyses in cycling that indicate the dominant counteracting forces experienced in time-trial cycling (e.g. drag for a flat race and gravity for an uphill race) will influence the magnitude of the scaling-derived body-mass exponents [42,49,116]; therefore, uphill cycling, compared with level road cycling, is associated with a higher body-mass exponent for $\dot{V}O_2$max [49,116,121]. Consequently, heavier cyclists are favoured in flat time trials when a small proportion of the resistive force is induced by gravity [42,49,121].

In Study I, the influence of course inclination on the body-mass exponent for $\dot{V}O_2$max during a 15-km classical-technique skiing race was investigated, and this influence was described by the exponent expression $-(0.38 + 0.03 \cdot \alpha)$, where α is the inclination of the section. Hence, the body-mass exponent increases as inclination increases and this relationship is mainly explained by the progressively greater influence of net increase in potential energy on the total resistive force; therefore, lighter skiers have, in general, a performance advantage in steep uphill slopes. However, heavier skiers are favoured in the other parts of a course and this advantage is emphasised when the inclination decreases. This supports a previous statement that heavier skiers appear to be favoured in all types of terrain except the steepest uphill sections [4,5].

Another factor that influenced the body-mass exponent for $\dot{V}O_2$max was the number of the lap in the 15-km classical-technique skiing competition that was performed on a 5-km course and the exponent expression was $-(0.49 + 0.019 \cdot lap)$; this means that the magnitude of the exponent increases for each new lap. This finding indicates that heavier skiers, with a relatively low simple ratio-standard scaled $\dot{V}O_2$max, had a more pronounced positive pacing profile (i.e. race speed gradually decreasing throughout the race) compared with lighter skiers. This pacing-profile dissimilarity can be related to differences regarding muscle mass and force-generating potential when skiers with body-size differences are compared. Elite male skiers' lean mass has been shown to be approximately 83% of total body mass [67,119,122], whereas lean mass could be considered as an indicator of muscle mass [123-125]. Moreover, muscle size, in general, reflects both force-generating potential [95-98] and anaerobic capacity [112,117]; hence, elite male skiers with a large muscle mass can be assumed to have an enhanced capability to generate high skiing speed compared to skiers with less muscle mass. Given the suggested more pronounced positive pacing profile of elite male skiers with a high body mass, it appears that the heavier skiers use their ability to generate a high skiing speed at the beginning of the race. This is consistent with results of a previous study where a relationship between mean speed in the start section of a skiing time trial and total lean mass of the elite male skiers was observed [67]. To generate a high skiing speed, a large proportion of the energy supply comes from anaerobic processes,

which increase the concentration of metabolites related to fatigue. This relationship was supported by a previous study in which a positive pacing profile resulted in a higher rate of perceived exertion and in the accumulation of fatigue-related metabolites [126]. Hence, it appears that skiers with a more pronounced positive pacing profile reduce their race speed toward the end of a race to avoid critical homeostatic disturbances. It has also been shown that a reduced overall skiing speed during the second part of a race, as observed in the current study, is reflected by a reduction in speed on uphill sections [67,89]. Consequently, when the time spent skiing uphill increases, lighter skiers, who are favoured in ascents [4], are progressively more favoured during the latter part of a distance race.

The finding that the body-mass exponent is influenced by both inclination and distance covered of the course needs to be considered when skiers' performance capacity in different events is evaluated. This information might also be used to establish an appropriate pacing strategy for an individual skier on the basis of his $\dot{V}O_2max$ and body mass.

Scaling of upper-body power output

Upper-body power output has previously been correlated with different performance variables such as 10-km competition among male and female recreational skiers [76], 5-km competition among male and female junior skiers [79], 3-km skiing time trial among elite male skiers [26], 180-m spurt in a sprint-skiing time trial among elite male skiers [77], estimation of race velocity from distance races among a mix of male and female junior and sub-elite skiers [78], and ski ranking among elite male skiers [74,80]. All of these studies reported a relationship to performance for both absolute and simple ratio-standard scaled expressions with similar magnitude. These results might indicate that the optimal body-mass exponent for upper-body power output is between 0 and 1.

This indication is to some extent supported theoretically. Power output is work performed divided by time ($\dot{W} \sim W \cdot t^{-1}$), where $W \sim L^3$ and $t \sim L$; hence, power output is proportional to length raised to the 2nd power ($\dot{W} \sim L^2$). Furthermore, length raised to the 2nd power is proportional to mass raised to 2/3 power ($L^2 \sim m^{2/3}$). Power output is, therefore, proportional to mass raised to the 2/3 power ($\dot{W} \sim m^{2/3}$). Hence, from a theoretical perspective, power output divided by body mass raised to the 0.67 power would partitioning out differences in body mass, similar to the theoretically derived exponent for $\dot{V}O_2max$. Furthermore, speed in a 1-km freestyle roller-skiing time trial is reported to be proportional to body mass raised to the 0.43 power [88]. Anaerobic energy supply during the 2-km time trial in Study IV would be expected to lower than that during the 1-km time trial; therefore, a somewhat lower body-mass exponent for the relationship between 2-km time-trial speed and body mass is anticipated. Hence, the optimal body-mass exponent for $\dot{W}$ to explain performance capability in the 2-km time trial is most likely between 0 and 1.

Consistent with the results reported in the previous studies (presented above), both commonly used expressions (i.e. W and W·kg^{-1}) were correlated with performance in the 2-km double-poling roller-skiing time trial in Study IV, as anticipated. However, results of the power-function modelling displayed that the body-mass exponent for $\dot{W}$ that optimally explained time-trial performance was 0.57. Moreover, the modelling revealed that Model (18) is not influenced by the sex of the subjects, which is consistent with results of a previous study where no sex by upper-body power interaction was observed when race speed was evaluated based on upper-body power output [78]. The results presented in Study IV show that there is a correlation between time-trial speed and FISdist for both men and women, respectively. This result is supported by a previous study where performance achieved in a 1-km uphill roller-skiing time trial using the double-poling technique is correlated with ski ranking [71]. Hence, it appears that the model presented herein is appropriate to use when evaluating the performance of elite junior cross-country skiers. However, more research is warranted to establish the optimal body-mass exponents for upper-body power output to explain competitive performance in cross-country among elite skiers of both sexes.

Based on previous research regarding upper-body power production and the results presented in Study IV, it appears that it is important for skiers to be able to contribute to propelling forces by muscle-force generation transferred through the poles. In fact, upper-body muscles contribute to propulsion in almost all sub-techniques and thus, skiers will benefit from increased upper-body power output [127]. Training designed to improve double-poling capacity should focus on upper-body exercises at high intensity and ski-specific movement patterns [78,128,129]. For example, interval training on a double-poling ergometer, where the interval duration was 3 min, increased the upper-body capabilities of cross-country skiers [21]; in addition to an increased power output, the subjects had a reduced blood-lactate concentration at sub-maximal workloads and a higher double-poling $\dot{V}O_2$peak after the 6-week training period. The importance of having a high oxygen uptake while double poling for sprint performance was shown in Study III where $\dot{V}O_2$dp was correlated with sprint-prologue performance. This capability has also been correlated with competitive performance in distance races [80], which together indicate that it is important to have a high aerobic energy contribution in the force-generating musculature to be able to continuously produce high propelling forces.

Power-function modelling of variables on a force-generating level can increase the knowledge about how these variables should be scaled in relation to body mass; however, to find the underlying mechanisms that limit the capability to perform and need to be addressed in training, it is important to direct the physiological testing to focus on potential limiting factors for performance.

Effects of physiological differences on performance

Results from Study I and II suggest that race speed in 15-km classic-technique skiing competitions is related to the skier's $\dot{V}O_2max$ divided by the square root of body mass (i.e. race speed $\sim \dot{V}O_2max \cdot m^{-0.50}$). However, the effect of differences in $\dot{V}O_2max$ and body mass on race performance was different in Study I compared to Study II. In Study I, the optimal power-function model (i.e. Model (13) in this thesis) indicated that skiers with the same $\dot{V}O_2max$ who differ in body mass by 1% will differ in their performance by approximately 0.48% in favour of the lighter skier (for a summary of the performance-related differences in Study I – IV, see Table 6). In Study II, the corresponding difference in performance for skiers with the same $\dot{V}O_2max$, as a consequence of a 1% body-mass difference, was 0.35% in favour of the lighter skier (based on Model (14) calculations). Conversely, skiers with the same body mass whose $\dot{V}O_2max$ differs by 1% will differ in their performance by approximately 1% (I) and 0.66% (II) in favour of the skier with higher aerobic power.

These performance-related differences when the results of the studies are compared are, in particular, related to the 0.66 exponent for the optimal $\dot{V}O_2max$-to-mass ratio in Model (14). This means that performance-related effects of a higher $\dot{V}O_2max$ or a lower body mass is somewhat inhibited in Study II compared to that in Study I. There could be several reasons for this inhibition, and the most likely explanations appear to be related to course-profile and track-condition differences. Although both courses were homologated and the total climbing distance was equal (162 m in Study I and 161 m in Study II), the uphill sections were generally longer for the 5-km course in Study I compared to those in Study II (Figure 1). In a performance perspective, the longer uphill sections and more demanding track conditions (as suggested by the more wet snow conditions during performance-data collection and a lower mean race speed) in Study I will most likely increase the time differences between skiers with "high" and "low" $\dot{V}O_2max$ ($ml \cdot min^{-1} \cdot kg^{-0.50}$). Nonetheless, performance in these two studies was optimally explained by using a similar $\dot{V}O_2max$-to-mass ratio, i.e. $\dot{V}O_2max$ divided by the square root of body mass; hence, $\dot{V}O_2max$ expressed as $ml \cdot min^{-1} \cdot kg^{-0.50}$ appears to be relevant for evaluating elite male skiers' performance capabilities in 15-km classical-technique skiing races. However, it should be noted that the evaluation of race speed, in accordance with each model, is related to the actual competition and its relevance for other skiing competitions is limited.

In Study III, sprint performance was evaluated and skiers with a 1% difference in $\dot{V}O_2max$ and the same body mass will likely differ in their performance by approximately 0.21% in favour of the skier with higher $\dot{V}O_2max$. This performance-related difference appears to be somewhat lower than corresponding differences for the performances in the 15-km classical-technique skiing competitions indicating that $\dot{V}O_2max$ is more important for performance in distance races than in sprint races. This indication is most likely related to the differences in aerobic-energy

supply; the energy supply for the generation of propelling forces that comes from aerobic processes in sprint races is approximately 60%, whereas the aerobic-energy contribution in a 15-km race with a duration of 35 – 45 min would be at least 95% [8].

Table 6. The optimal body-mass exponents (β_2) for $\dot{V}O_2$max and $\dot{W}$ for evaluating performance among elite male cross-country skiers

Study	Model	$\dot{V}O_2$max difference	Body-mass difference	Race-speed difference
I	(13)	0 %	+1 %	-0.48 %
I	(13)	+1 %	0 %	+1.00 %
II	(14)	0 %	+1 %	-0.35 %
II	(14)	+1 %	0 %	+0.66 %
III	(16)	0 %	+1 %	N/A
III	(16)	+1 %	0 %	+0.21 %

Study	Model	$\dot{W}$ difference	Body-mass difference	Race-speed difference
IV	(18)	0 %	+1 %	-0.31 %
IV	(18)	+1 %	0 %	+0.55 %

Study is the number of the study referred to in this thesis; Model is the number of the model where equation for optimal model to explain performance is presented; $\dot{V}O_2$max is the maximal oxygen uptake (l·min^{-1}); $\dot{W}$, mean upper-body power output (W). A positive $\dot{V}O_2$max or $\dot{W}$ difference indicate that for skiers with the same body mass, the skier with higher $\dot{V}O_2$max or $\dot{W}$ will have a higher race speed. Conversely, a positive body-mass difference indicate that for skiers with the same $\dot{V}O_2$max or $\dot{W}$, the skier with higher body mass will have a lower race speed.

Practical implications
The results presented herein provide new insights into how $\dot{V}O_2$max should be expressed to optimally indicate performance capability among elite male skiers in sprint and distance races.

Performance capability in 15-km classical-technique skiing competitions
To avoid the risk of misinterpretation of an elite male skier's performance capability in 15-km classical-technique skiing competitions (PC$_{15\ km}$), it is recommended that sport-science laboratories and coaches use the 0.5 body-mass exponent for $\dot{V}O_2$max for evaluating performance capability. This performance-capability measure can easily be calculated by dividing $\dot{V}O_2$max by the square root of body mass according to the formula:

$$PC_{15\ km} = \frac{\dot{V}O_2max}{\sqrt{m}} \tag{25}$$

where PC$_{15\ km}$ is performance capability in 15-km classical-technique skiing competitions among elite male skiers (ml·min^{-1}·kg$^{-0.5}$); $\dot{V}O_2$max is maximal oxygen uptake (ml·min^{-1}); and m is body mass (kg).

Collected test data suggest that the estimated $\dot{V}O_2$max interval for various elite male skiers are as follows: 700 – 650 ml·min^{-1}·kg$^{-0.5}$ for international elite ("top 30 in the world"); 650 – 600 ml·min^{-1}·kg$^{-0.5}$ for national elite I ("top 20 in Sweden"); and 600 – 570 ml·min^{-1}·kg$^{-0.5}$ for national elite II ("top 40 in Sweden"). These classification intervals could be used as guidelines for coaches to evaluate and optimize the training of their athletes (Table 6).

Table 6. Table for classification of an elite male skier's performance capability in 15-km classical-technique skiing competitions (PC$_{15\,km}$)

m (kg)	$\dot{V}O_2$max (l·min^{-1})																		
	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.5
65	583	595	608	620	633	645	657	670	682	695	707	719	732	744	757	769	781	794	806
66	579	591	603	615	628	640	652	665	677	689	702	714	726	739	751	763	775	788	800
67	574	586	599	611	623	635	647	660	672	684	696	709	721	733	745	757	770	782	794
68	570	582	594	606	618	631	643	655	667	679	691	703	715	728	740	752	764	776	788
69	566	578	590	602	614	626	638	650	662	674	686	698	710	722	734	746	758	770	783
70	562	574	586	598	610	622	633	645	657	669	681	693	705	717	729	741	753	765	777
71	558	570	582	593	605	617	629	641	653	665	676	688	700	712	724	736	748	760	771
72	554	566	577	589	601	613	625	636	648	660	672	684	695	707	719	731	742	754	766
73	550	562	574	585	597	609	620	632	644	655	667	679	691	702	714	726	737	749	761
74	546	558	570	581	593	604	616	628	639	651	663	674	686	697	709	721	732	744	756
75	543	554	566	577	589	600	612	624	635	647	658	670	681	693	704	716	727	739	751
76	539	551	562	574	585	596	608	619	631	642	654	665	677	688	700	711	723	734	746
77	536	547	558	570	581	593	604	615	627	638	650	661	672	684	695	707	718	729	741
78	532	543	555	566	577	589	600	611	623	634	645	657	668	679	691	702	713	725	736
79	529	540	551	563	574	585	596	608	619	630	641	653	664	675	686	698	709	720	731
80	525	537	548	559	570	581	593	604	615	626	637	648	660	671	682	693	704	716	727
81	522	533	544	556	567	578	589	600	611	622	633	644	656	667	678	689	700	711	722
82	519	530	541	552	563	574	585	596	607	618	629	641	652	663	674	685	696	707	718
83	516	527	538	549	560	571	582	593	604	615	626	637	648	659	670	681	692	702	713
84	513	524	535	546	556	567	578	589	600	611	622	633	644	655	666	676	687	698	709
85	510	521	531	542	553	564	575	586	597	607	618	629	640	651	662	672	683	694	705

Values in the table represent performance capability in 15-km classical-technique skiing competitions among elite male skiers (PC$_{15\,km}$) (ml·min^{-1}·kg$^{-0.5}$); m is the body mass (kg); $\dot{V}O_2$max is the maximal oxygen uptake (l·min^{-1}). Classification estimates for elite male skiers are as follows: 700 – 650 ml·min^{-1}·kg$^{-0.5}$ for international elite (light-grey cells); 650 – 600 ml·min^{-1}·kg$^{-0.5}$ for national elite I (grey cells); and 600 – 570 ml·min^{-1}·kg$^{-0.5}$ for national elite II (dark-grey cells).

Performance capability in classical-technique sprint prologues
To evaluate performance capability in classical-technique sprint prologues among elite male skiers (PC_{sprint}), the allometric-scaling results indicate that the absolute expression of $\dot{V}O_2max$ should be used.

$$PC_{sprint} = \dot{V}O_2max$$

where PC_{sprint} is performance capability in classical technique sprint prologues among elite male skiers ($l \cdot min^{-1}$); $\dot{V}O_2max$ is maximal oxygen ($l \cdot min^{-1}$).

Collected test data indicate that the following oxygen-uptake intervals differentiate different groups of elite male skiers: $6.4 - 6.1$ $l \cdot min^{-1}$ for international elite; $6.1 - 5.6$ $l \cdot min^{-1}$ for national elite I; and $5.6 - 5.0$ $l \cdot min^{-1}$ for national elite II.

Performance capability in 2-km double-poling roller-skiing time trials
The power-function modelling to establish the optimal body-mass exponent for $\dot{W}$ revealed that the 0.57 exponent optimally explained time-trial performance. To facilitate the evaluation of an elite junior skier's performance capability ($PC_{time\ trial}$), it is recommended that sport-science laboratories and coaches use the following simplified model:

$$PC_{time\ trial} = \frac{\dot{W}}{\sqrt{m}} \qquad\qquad (27)$$

where $PC_{time\ trial}$ is performance capability in 2-km double-poling roller-skiing time trials among elite junior skiers; $\dot{W}$ is mean upper-body power output (W); and m is body mass (kg).

Collected test data suggest that the estimated $\dot{W}$ interval for various elite male junior skiers are as follows: $29 - 25$ $W \cdot kg^{-0.5}$ for national elite I ("top 10 in Sweden"); and $25 - 21$ $ml \cdot min^{-1} \cdot kg^{-0.5}$ for national elite II ("top 40 in Sweden"). Corresponding classification intervals for elite female junior skiers are as follows: $24 - 20$ $W \cdot kg^{-0.5}$ for national elite I ("top 10 in Sweden"); and $20 - 16$ $W \cdot kg^{-0.5}$ for national elite II ("top 40 in Sweden").

Strengths and limitations

Strengths
To investigate the external validity of physiological variables, it is necessary to obtain performance data from competitive performances [130]; therefore, the use of results from cross-country skiing competitions in Study I – III can be considered as a strength.

The subjects in the studies were elite male skiers (I – III) and elite junior skiers (IV); therefore, the derived body-mass exponents in this thesis are appropriate for the evaluation of the performance capability of elite skiers. The samples in the

studies contain skiers with performance capabilities ranging from skiers that can be classified as international elite to skiers that finish at place 40 in the Swedish National Championships, indicating that the results presented herein give valuable information about the physiological demands to attain world-class performance with respect to $\dot{V}O_2$max.

The use of power-function modelling allows for the establishment of potential curvilinear relationships instead of a linear model that would report an unrealistic intercept for zero values. For example, a curvilinear relationship between $\dot{V}O_2$max and skiing performance is somewhat anticipated because when skiing speed increases the accompanied power demand increases more rapidly [131] via, e.g. a progressively larger influence of air resistance.

In general, there is a very small difference in performance that differentiates successful from less successful skiers, and it is therefore important that the skiers obtain appropriate feedback from tests. The use of an optimal body-mass exponent for different physiological variables can provide valuable information for coaches that can be used for, e.g. training optimization and selection of team members in different competitions and relays.

Limitations

From a statistical point of view, it would be beneficial to have larger sample sizes to reduce the confidence intervals of the body-mass exponent estimates. Because of the somewhat limited population of elite skiers and the difficulty to gather a large number of skiers for testing during a short period of time, which is necessary to have the desirable close proximity between test sessions and competitive performance, research studies within the field of cross-country skiing have usually a relatively low number of subjects.

To determine the relationship between a physiological characteristic and the performance capability of elite skiers, it is preferred to use results from cross-country skiing competitions because it is, in fact, competitive-performance capability that is effective for analysis. However, it is the difficult to control all of the factors that may affect performance in a cross-country skiing competitions (e.g. track and weather conditions, glide and grip waxing, start position, drafting behind competitors, intermediate times provided by coaches, etc.), which can be considered to be a limitation in most studies that comprise investigation of competitive performance. In an attempt to investigate the influence of ski grip and glide on performance as well as potential mishaps (e.g. falls and pole breaks), the skiers completed a questionnaire after the competitions in Study I and II.

It would have been a strength if the same allometric approach had been used for elite female skiers because of the body-composition differences between sexes, where males in general have a larger lean body mass [119]. Therefore, the results presented in thesis can not safely be generalizable to be valid for evaluating performance capability among elite female skiers.

Finally, it should be noted that there are several aspects in the chain from the capability of the aerobic energy-supply system to the generation of propelling forces that need to be addressed to create a holistic model of the physiological demands of cross-country skiing. This limitation needs to be considered when coaches use the results presented herein for evaluating and optimizing the training of their skiers.

Future perspectives

The results in Study I and II suggest that a 0.5 body-mass exponent for $\dot{V}O_2max$ optimally explained performance in 15-km classical-technique skiing competitions and that the relationship between 15-km performance and FISdist indicate that this exponent could be used to evaluate distance-performance capability in general. However, this potential generalizability of the 0.5 exponent to indicate performance capability in distance races from $15 - 50$ km needs to be further investigated. Moreover, future work is needed to establish the body-mass exponents for physiological variables such as $\dot{V}O_2peak$ in freestyle and double-poling technique that optimally explain competitive performance for different distances and techniques. In a future perspective, it is important to use power-function modelling to establish the optimal body-mass exponents for validated test variables among elite female skiers to improve the understanding of the physiological demands in elite female cross-country skiing.

To increase the knowledge about the interplay between the aerobic and anaerobic energy-supply systems and their importance for competitive performance in cross-country skiing, both of these energy-supply variables together with body mass have to be included in a power-function model. This holistic approach will hopefully contribute significantly to the clarification of each variable's importance for different competitive performances.

Conclusions

The results in this thesis suggest that $\dot{V}O_2max$ divided by the square root of body mass should be used as indicator of performance in 15-km classical-technique skiing competitions among elite male skiers rather than the absolute or simple ratio-standard scaled expression; the use of the simple ratio-standard scaled expression of $\dot{V}O_2max$ tends to overestimate the performance capability of light skiers, whereas heavier skiers' performance would be underestimated. Conversely, if the absolute expression of $\dot{V}O_2max$ is used for the evaluation of elite male skiers' performance capability in 15-km classical-technique skiing competitions, a reversed misinterpretation would occur. For evaluating elite male skiers' sprint-race performance, power-function models based on oxygen-uptake variables expressed absolutely is recommended, whereas the simple ratio-standard scaled expression should be avoided.

Allometric scaling based on performance in 15-km classical-technique skiing competitions demonstrates that the body-mass exponent for $\dot{V}O_2max$ is influenced

by both course inclination and distance covered; hence, the body-mass exponent increases with increasing inclination and travelled distance. Moreover, to evaluate elite junior skiers' performance capability in 2-km double-poling roller-skiing time trials, it is recommended that $\dot{W}$ divided by the square root of body mass should be used rather than absolute or simple ratio-standard scaled expression of power output. Hence, to accurately explain performance in cross-country skiing, it is important to use a body-mass exponent that is derived from power-function modelling for specific physiological characteristics.

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