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Physiological determinants of performance in modern elite cross-country skiing

Acknowledgements

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1 ABSTRACT

This thesis consists of four studies with additional unpublished results, in which the main objective was to examine factors that determine performance in modern elite cross-country (XC) skiing. Thirty-two elite male XC skiers volunteered to participate, with some subjects participating in several studies. Maximal aerobic power, maximal anaerobic capacity, O_2-cost and performance was measured during rollerski skating on a treadmill to investigate differences between techniques (V1 and V2), differences between skiers, and changes in these variables during an annual training season. In addition, a novel approach involving PET/MRI scanning was used to investigate muscle use at low- and high-intensity exercise in double poling (DP). The studies together demonstrate that performance in elite male distance skiing (> 15 km) is highly related to VO_{2max}, exemplified by the findings that the best skiers reached values of 83 ± 3 mL·kg^{-1}·min^{-1}. Sprint skiing (< 1.8 km) performance has somewhat different physical and physiological demands, as sprint skiers have a larger body-mass index and a significantly higher anaerobic capacity compared to distance skiers. With systematic testing of elite skiers during an annual training year VO_{2max} was unchanged and the increased performance was related to enhanced O_2-cost and anaerobic capacity. The observed constant VO_{2max} across the yearly training cycle, and the finding that VO_{2max} is not related to increased performance during an annual training season, seems contradictory to results obtained during the 1980s and is likely related to changes in training habits of elite skiers in recent decades. With respect to propulsion technique, there were no differences between V1 and V2 in O_2-cost or performance, but individual differences occurred and therefore, choice of skiing technique is likely important for the individual skier. The present results further suggest that with increasing intensity during DP, the legs contribute significantly to the total increased energy turnover. Hence, specific training is not only related to exercise modes but also to the intensity of exercise performed by the skier.

2 LIST OF PAPERS

This thesis is based on the following studies, but unpublished results related to the studies will also be presented. The studies are referred to by their Roman numerals in the text. The articles are reprinted with the permission from the publisher.

I **Losnegard T**, Myklebust H, & Hallén J (2012). No differences in O_2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *Journal of Strength and Conditioning Research* 26(5):1340-7.

II **Losnegard T**, Myklebust H, & Hallén J (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Medicine & Science in Sports & Exercise* 44(4):673-681.

III **Losnegard T**, Myklebust H, Spencer M, & Hallén J. Seasonal variations in VO_{2max}, O_2-cost, O_2-deficit and performance in elite cross-country skiers. *Journal of Strength and Conditioning Research* (Accepted).

IV Bojsen-Møller J, **Losnegard T**, Kemppainen J, Viljanen T, Kalliokoski KK, & Hallen J (2010). Muscle use during double poling evaluated by positron emission tomography. *Journal of Applied Physiology* 109:1895-1903.

3   ABBREVIATIONS AND ACRONYMS

CL	Cycle length
CR	Cycle rate
DP	Double poling
HIT	High intensity training
HR	Heart rate
La^-	Blood lactate concentration
LIT	Low intensity training
MIT	Medium intensity training
MRI	Magnetic resonance imaging
O_2	Oxygen
OBLA	Onset of blood lactate accumulation
PET	Positron emission tomography
RPE	Rate of perceived exhaustion
SD	Standard deviation
VE	Ventilation
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen uptake
XC	Cross-country
ΣO_2-deficit	Accumulated oxygen-deficit
ΣO_2-demand	Accumulated oxygen-demand
ΣO_2-uptake	Accumulated oxygen-uptake

4 INTRODUCTION

Remarkable changes have occurred in cross-country (XC) skiing over the last decades. Introduction of new types of races such as the sprint event and mass start, as well as better track preparation, improved skiing equipment and changes in course profiles have contributed to this development (Holmberg et al. 2005, Stöggl et al. 2008). As an example, the race velocity in distance skiing (≥ 10-15 km, women and men respectively) has increased ~ 5-8% in World Cup races during the last two decades (Figure 1) and during sprint skiing (competition distance < 1.8 km), a ~ 20% higher average velocity is reached compared to distance skiing (Fis-ski.com). In line with this, considerable development has occurred in ski skating technique, as demonstrated by the development of numerous different propulsion techniques and sub-techniques used in competition (Anderson et al. 2010, Stöggl et al. 2008; 2010). Also, the classic style has developed substantially, exemplified by the introduction of "modern DP" (Holmberg et al. 2005) and is today a main technique used during competition. These changes may have impacted the physiological and technical demands and therefore training methods in XC skiing. Therefore, this thesis was planned and conducted with the purpose of elucidating factors that govern performance in "modern" elite XC skiing.
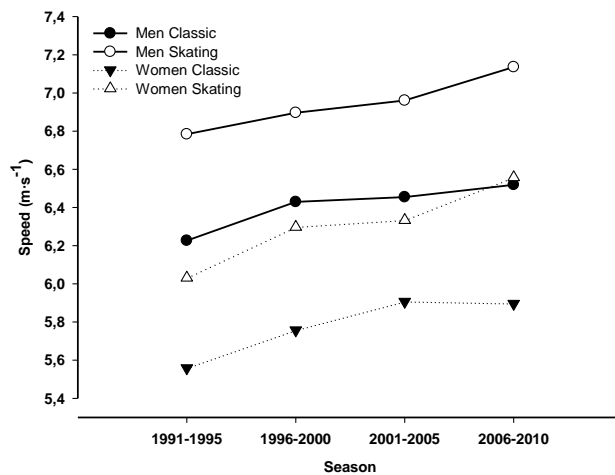
Figure 1*. Development of average race speed during women's 10 km classic races (races = 52) and skate races (races = 37) and men's 15 km classic races (races = 50) and skate races (races = 41) with individual starts in World Cup from 1991-2010. Average of top 3 finishes in all races included. Season refers to winter, eg., races from October - December in 2000 are in "season 2001" (Fis-ski.com).*

4.1 Performance in endurance sports

The average speed (m·s^{-1}) for a required distance is mainly determined by energy turnover (J·s^{-1}) balanced by work economy (J·m^{-1}) (di Prampero et al. 1986, di Prampero 2003).

$$\text{Speed } (m \cdot s^{-1}) = \frac{\text{Energy turnover } (J \cdot s^{-1})}{\text{Work economy } (J \cdot m^{-1})}$$

Accordingly, a greater energy turnover and/or an improved work economy will increase speed and thus improve performance. During traditional lab testing, speed or performance is specifically determined by the energy turnover and work economy described in terms of oxygen equivalents (mL·kg^{-1}·min^{-1} or L·min^{-1}) and O$_2$-cost (mL·meter^{-1}). The specific variables can therefore be presented as shown below, where the fractional utilization is the percentage of the VO$_{2max}$ that on average can be utilized and the anaerobic power is the average power during the race/test:

$$\text{Performance (speed)} = \frac{\text{VO}_{2max} \cdot \text{fractional utilization of VO}_{2max} + \text{anaerobic power}}{\text{O}_2\text{-cost}}$$

Regardless of race distance, XC skiing is an endurance sport that demands a very high energy turnover and high movement efficiency (Ingjer 1991, Norman et al. 1989, Sandbakk et al. 2010, Mahood et al. 2001, Millet et al. 2003, Millet et al. 2002, Ainegren et al. 2012). However, since modern XC skiing includes race durations ranging from ~ 2-3 min to several hours, the contributions from aerobic and anaerobic energy sources will vary with race distance. Therefore, the following chapters will identify how the respective factors determine performance in elite XC skiing.

4.2 The significance of energy turnover and O$_2$-cost in XC skiing

Total energy turnover is determined in general by the VO$_{2max}$, the fractional utilization of VO$_{2max}$ (% VO$_{2max}$) and the anaerobic energy turnover during the race (di Prampero et al. 1986, di Prampero 2003, Basset & Howley 2000). Previous studies have demonstrated that male world-class skiers are among the endurance athletes with the highest VO$_{2max}$, and

accordingly, world-class performance has been associated with values above 80 mL·kg^{-1}·min^{-1} or 6.0 L·min^{-1} (Ingjer 1991, Rusko 2003, Holmberg et al. 2007, Sandbakk et al. 2011[a]). Clearly, VO_{2max} is one of the most important factors for performance, both in distance- and in sprint skiing (Ingjer 1991, Sandbakk et al. 2011[a], Vesterinen et al. 2009). However, the introduction of sprint races and mass start events has yielded new appraisals of the performance-limiting factors in elite XC skiing. Race velocities in running show that mean velocity decreases with increasing duration or distance (Figure 2A), while for XC-skiing a significant difference in race-velocity is found between sprint and 5/10 km with no further decrease with increasing distances (Figure 2B).
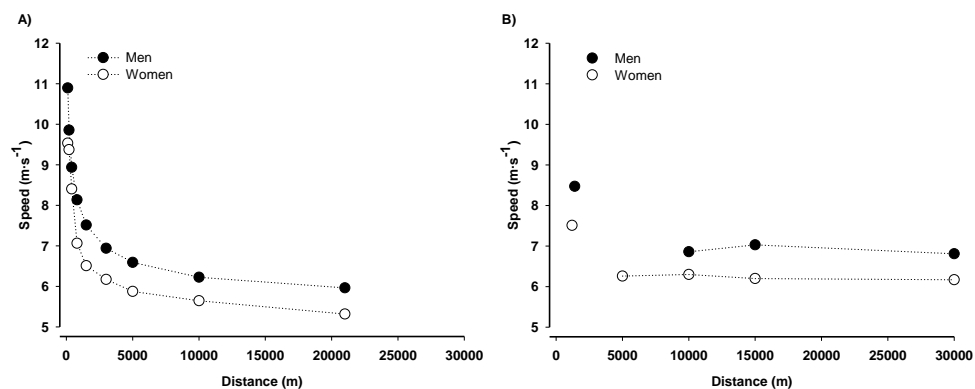
Figure 2. A) Mean speed in running (world records) at 800, 1500, 5000, 10000 m and half-marathon (21095 m) with a logarithmic trend line for both genders. B) Mean speed in World Cup, World Championship and Olympic games in Sprint freestyle technique (in average 1.2 km for women and 1.4 km for men), 5, 10, 15 and 30 km freestyle technique (Fis-ski.com). Velocity is the average of the top three rankings in each race from the year 2001-2010. Races included; 162 (men = 82, women = 80). Mean speed in sprint refers to the prologue (time trial).

Accordingly, since the speed is ~ 20% higher in sprint (~ 2-3 min) compared to distance skiing (~ 15-120 min) (Figure 2B) the performance-limiting factors will likely be different. Further, due to the short duration, a significant anaerobic energy contribution is expected in sprint skiing. Anaerobic energy production during supramaximal exercise has been estimated in different sports from the ΣO_2-deficit, but to date, not in XC skiing.

A considerable number of studies have examined the O_2-cost in XC skiing (Hoffman et al. 1990, Mahood et al. 2001, Millet et al. 2002, Millet et al. 2003, Kvamme et al. 2005, Mikkola et al. 2007, Losnegard et al. 2011, Rønnestad et al. 2012[b]). In general, these studies indicate

that the level of the skier and the skiing technique affects O_2-cost. The importance of O_2-cost is emphasized by a close relationship between O_2-cost and performance observed in a heterogeneous group of trained- to highly-trained skiers (Mahood et al. 2001, Millet et al. 2002, Millet et al. 2003).

Studies in cycling and running demonstrate that cadence or step frequency influences energy cost and performance (Foss & Hallén 2004; 2005[a], Cavanagh et al. 1986). A unique aspect in XC skiing is the different techniques, or "gears", that skiers choose based on speed, terrain, snow conditions and work capacity. This empirical choice of technique has been validated by research on O_2-cost or performance, and it has been shown that V1 (one pole plant for two ski pushes) is superior compared to V2 (two pole plants for two ski pushes) on steep inclines (Boulay et al. 1995, Kvamme et al. 2005). However, elite XC skiers may benefit from using different ski skating techniques in the uphills, compared to the well-trained athletes or junior skiers who have so far served as subjects (Boulay et al. 1995, Kvamme et al. 2005, Millet et al. 2003). Recently, in a simulated sprint event, faster skiers used the V2 more extensively in uphill terrain compared to lower-ranked skiers (Anderson et al. 2010). In addition, a sub-technique of V2 (called "double push") seems to rate equally with V1 ("jumping V1") in short uphill terrain (Stöggl et al. 2010). Hence, a study investigating the physiological response in elite skiers to different techniques on moderate to steep inclines is warranted.

4.2.1 Seasonal changes in the energy turnover and O_2-cost

The training for XC skiers must be based on a detailed analysis of the determinants of performance. A fundamental question in training and testing for elite skiers is which sport-specific variables change with time and training and to what extent? To date, no studies have systematically investigated the seasonal variation in energy turnover, O_2-cost and performance in elite skiers. Ingjer (1991) showed that elite skiers reached a significantly higher VO_{2max} (5-10%) during the competition period than in the early preparation phase. This finding was further supported by the study of Gaskill et al. (1999). Hence, a close link between increased VO_{2max} and increased performance was suggested. However, since these studies were performed during running or ski walking the findings may not be directly transferable to performance in a ski-specific exercise. In addition, not only the VO_{2max} is expected to change due to a large amount of endurance training, but also the fractional

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utilization of VO_{2max}, anaerobic capacity and the O_2-cost of the skier. Recent studies have demonstrated that systematic heavy strength training (and subsequent strength gains) reduce O_2-cost during DP on ergometers or rollerskis in highly trained skiers (Hoff et al. 1999; 2002, Østerås et al. 2002, Mikkola et al. 2007) albeit not all studies have confirmed such a mechanism during rollerski skating (Losnegard et al. 2011, Rønnestad et al. 2012[b]). However, to date limited information exists on longitudinal changes (i.e., > 12 weeks) and effects of training on O_2-cost during skiing.

The extent to which economy or efficiency in other sports such as cycling and running can be improved with training has been of long-standing interest (eg. Sassi et al. 2008, Lucia et al. 2000, Coyle 2005, Jones 1998). Sassi et al. (2008) suggested that changes in economy are less evident in elite compared to non-elite cyclists. In contrast to cycling, XC skiing is a highly technically demanding exercise and technical improvements through the season are likely to affect the energy cost. Since repeated assessments of O_2-cost serve as a basis for both routine testing and intervention studies, measurements of changes in this parameter with "normal" training in elite XC skiers are warranted.

4.3   Muscle use at low and high intensity

Elite skiers are reported to train using a "polarized" endurance training model with a high volume of low-intensity, and a low volume of high-intensity training (Seiler & Kjerland 2006, Seiler 2010, Gaskill et al. 1999, Sandbakk et al. 2011[a], Verges et al. 2006). It has been proposed that high volume of low-intensity training (< 80% of HR_{max}) has the advantage of stimulating peripheral adaptations (Esteve-Lanao et al. 2007, Seiler & Kjerland 2006). Hence, to justify the large fraction of low-intensity training reported (~ 70-80% of total training) it may be necessary that muscle use during low-intensity resemble, to a reasonable extent, those of high-intensity - which is the actual intensity in a competition (Norman et al. 1989, Welde et al. 2003). Moreover, a unique aspect of XC skiing is the use of both upper body and legs to a different extent between techniques, inclines and intensities. In the DP-technique, which has traditionally been linked to upper-body use, recent biomechanical and physiological studies show that elite skiers increasingly involve muscles of the lower body at high intensity (Holmberg et al. 2005, Lindinger et al. 2009[b], Calbet et al. 2004; 2005, Rud et al. 2011). Therefore, muscle activation and the respective muscle energy turnover from upper-body and leg muscles might change with increased intensity in DP, as suggested by

kinetic and kinematic analyses (Lindinger et al. 2009[a,b], Rud et al. 2011). Finally, the arm and shoulder muscles seem to level off in aerobe energy output at submaximal levels during DP, and that increase in workload towards high intensity is mainly covered by muscles in the lower part of the body (Calbet et al. 2004; 2005, Rud et al. 2011). Taken together the above studies suggest that leg muscles contribute more to an increase in total energy turnover than other muscles, which in turn resembles a change in technique or at least activation pattern. Therefore, specific training may not only be related to choice of exercise, but also the work intensity performed by the skier. Recent gains in three-dimensional imaging techniques such as Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) have enabled acquisition of more detailed information with respect to muscle use. This method has been applied in running and cycling (Fujimoto et al. 2003, Tai et al. 2010), but it seems that such an approach could also contribute to the understanding of muscle use in sports where both the upper and lower body contributes to propulsion, such as XC skiing.

4.4 Aim of the dissertation

In light of the recent changes in XC skiing, this study examined modern XC skiing from a performance perspective. Given the paucity of data mentioned in the introduction, elite skiers served as subjects to investigate how different techniques influence performance and how the anaerobic capacity differentiates performance between skiers during sprint skiing. Further, elite skiers were examined with respect to longitudinal changes in physiological response and performance. Finally, a novel approach (PET) for estimating muscle use during increasing intensity in DP was used. The specific aims were to:

1. Determine how the energy turnover and O_2-cost reflect performance in modern distance and sprint XC skiing (*Studies I-III*).
2. Investigate performance, energy turnover and O_2-cost in different ski skating techniques (V1 and V2) in moderate to steep inclines (*Studies I-II*).
3. Study how the physiological response and performance change during a full sport season (*Study III*).
4. Investigate muscle use during DP, and understand how exercise intensity affects muscle use (*Study IV*).

5 METHODS

5.1 Subjects

In total, thirty-two male XC skiers volunteered, with some subjects participating in several studies. The characteristics of the subjects are summarized in Table 1. *Studies I-III* included national or international elite level senior male XC skiers. Ten skiers had top 30 rankings including 6 skiers with top 15 ranking in FIS World Cup races and 3 skiers with several top 10 finishes in FIS Marathon cup races. All skiers had top 30 rankings, including 9 skiers with top 5 ranking, in the Norwegian national championships (NCh). *Study IV* comprised of subjects who were present ($n = 1$) or previous ($n = 7$) national elite-level XC skiers. The studies were approved by the Regional Ethics Committee of Southern Norway (*Studies I-III*) or the Ethics Committee of the Intermunicipal Hospital District of Southwest Finland (*Study IV*) and the subjects (including subjects in unpublished results) gave their written informed consent before study participation.

Table 1. Subject characteristics in Studies I-IV.

Study	n	Age (yr)	Height (cm)	Body-mass (kg)	VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	VO_{2max} ($L \cdot min^{-1}$)
I	14	24 ± 3	184 ± 5	79 ± 7	71.5 ± 3.3	5.7 ± 0.5
		(20 - 30)	(172 - 194)	(67 - 90)	(64.9 - 76.7)	(4.7 - 6.8)
II	12	24 ± 3	183 ± 5	79 ± 7	72.4 ± 3.2	5.7 ± 0.5
		(20 - 30)	(172 - 190)	(67 - 90)	(64.9 - 76.7)	(4.7 - 6.8)
III	13	23 ± 2	182 ± 6	76 ± 8	79.3 ± 4.4	6.0 ± 0.5
		(21 - 27)	(172 - 188)	(68 - 90)	(72.2 - 85.5)	(5.3 - 7.3)
IV	8	23 ± 2	182 ± 5	78 ± 4	68.0 ± 5.3	5.3 ± 0.6
		(20 - 27)	(174 - 191)	(73 - 86)	(60.4 - 75.8)	(4.7 - 6.3)

Note; *Studies I-III;* during V2 rollerski skating. *Study IV*; during running. Data are mean ± SD and (range).

5.2 Experimental Approach

5.2.1 Familiarization

Prior to the experiments, the subjects had been familiarized with treadmill skiing through regular testing over 1-4 years. In addition, in *Study II*, subjects completed two training sessions for the high intensity performance test (described below) in order to determine pacing strategy. In *Study IV,* subjects had two training sessions on separate days on the DP ergometer before the main testing sessions.

5.2.2 Study design

In *Studies I-II* a within-subject repeated measures design was used in order to determine whether V1 and V2 differ in VO_{2max}, O_2-cost, ΣO_2-deficit and performance at moderate to steep inclines. *Study IV* used the same design to investigate muscle use at low and high intensity. In these studies, testing was counterbalanced for type of technique or intensity, to eliminate potential influence of testing order. In *Study III,* each subject was tested 4-5 times during the year, early in the preparation phase (June; T_1), in the middle of the preparation phase (August; T_2), at the end of the preparation phase (October; T_3) and in the competition phase (January – February; T_4). Seven of the subjects also completed testing the following June (T_5). Specific study designs are given below. *Studies I-III* were conducted in the laboratories of the Norwegian School of Sport Sciences while the main part of *Study IV* was conducted at Turku PET Centre, University of Turku, Turku, Finland.

Study I: To investigate physiological and kinematic differences between VI and V2 at moderate to steep inclines, fourteen elite skiers performed three submaximal trials (4, 5 and 6°, 3 m·s^{-1}) and one maximal trial in both V1 and V2 to measure the VO_{2max} (8°, $\geq$ 3 m·s^{-1}) (Figure 3A). During submaximal trials, O_2-cost, heart rate (HR), blood lactate concentration (La$^-$), rate of perceived exhaustion 6-20 (RPE) and kinematic variables (CR and CL) were evaluated. All testing was done on a rollerski treadmill.

Study II: This study investigated physiological and kinematic differences between the ski skating techniques V1 and V2 during a performance test. Twelve elite skiers (the same skiers

as in *Study I*) completed a performance test ($7°$, > 3 m·s^{-1}, 600 m) in both in the V1 and V2 ski skating techniques on a rollerski treadmill (Figure 3B), in addition to the submaximal and maximal protocol in *Study I* (Figure 3A). Here, supramaximal energy demand was estimated by extrapolating the linear relationship between external load and the steady-state O_2-cost measured during submaximal intensities ($< 90\%$ of VO_{2max}), modified after Medbø et al. (1988). The ΣO_2-deficit was estimated from the differences between the ΣO_2-demand and ΣO_2-uptake during the performance test.
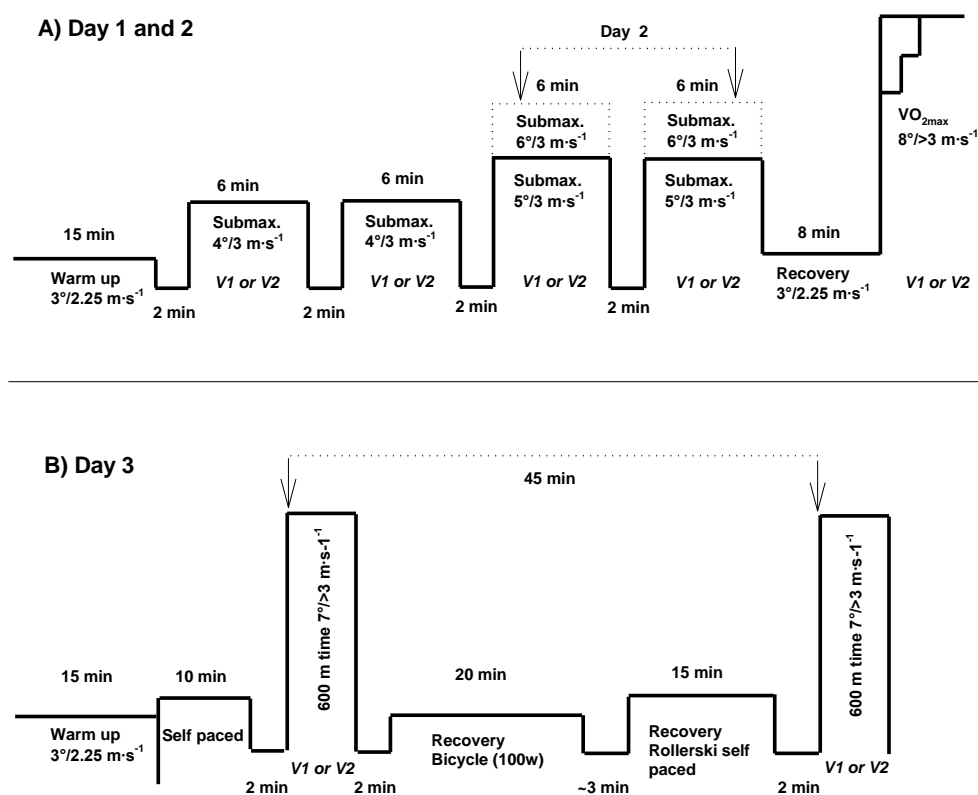
Figure 3. *Test protocol for the submaximal workloads and the VO_{2max} tests on day 1 and 2 (A) (Study I-II) and the 600 m tests on day 3 (B) (Study II). On day 1 the subjects completed two workloads at $4°$ (both V1 and V2) before performing two workloads at $5°$ and finally one VO_{2max} test. On day 2, two trials at $4°$ and $6°$ were conducted before performing a VO_{2max} test and the order of the techniques was reversed during the submaximal efforts.*

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Study III: Seasonal variations in VO_{2max}, O_2-cost, ΣO_2-deficit and performance were evaluated in thirteen elite skiers during an annual training season. O_2-cost during submaximal efforts (3.5-6°, 3 m·s^{-1}) and VO_{2max}, ΣO_2-deficit and performance during a 1000m test (6°, > 3.25 m·s^{-1}) were determined in the V2 technique on a rollerski treadmill (Figure 4). In addition, detailed training logs for the annual training season were collected.
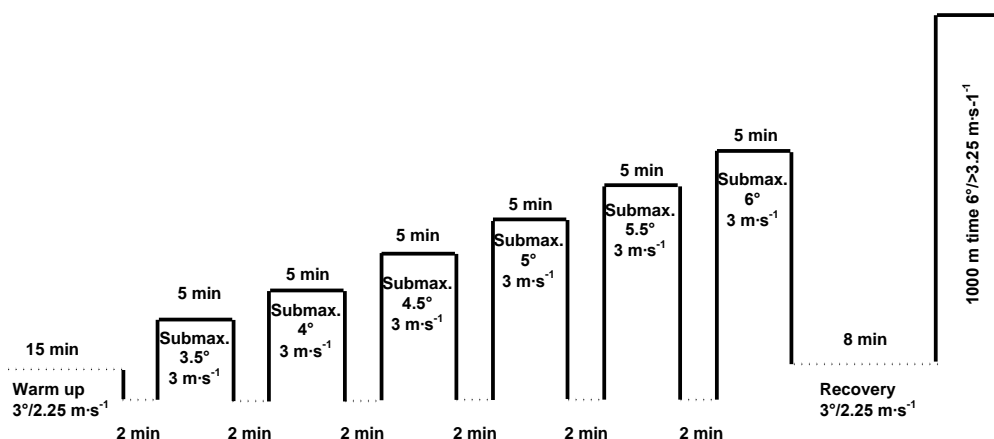
Figure 4. Schematic protocol, Study III. Steady state VO_2, HR and La$^-$ were measured at all submaximal trials. During the 1000 m test, HR and VO_2 were measured continuously and La$^-$ was obtained immediately after the test

Study IV: Muscle use at low and high intensity during DP was investigated using PET/MRI imaging. Eight highly-trained skiers underwent testing on seven separate experimental days. Days 1-4 included ergometer familiarization and assessment of O_2-uptake at different exercise intensities (O_2-cost and VO_{2max}). On days 5 and 6, the subjects performed one 20-min bout of ergometer DP at low ("distance training"; ~ 74% of HR_{max}) and high ("high-intensity training"; ~ 88% of HR_{max}) intensities respectively, with a tracer fluorodeoxy-glucose ([18F]FDG) infused, and subsequently the subjects underwent a full-body PET scan (Figure 5). At day seven, a full-body MRI scan was performed to serve as anatomic reference to the PET images.
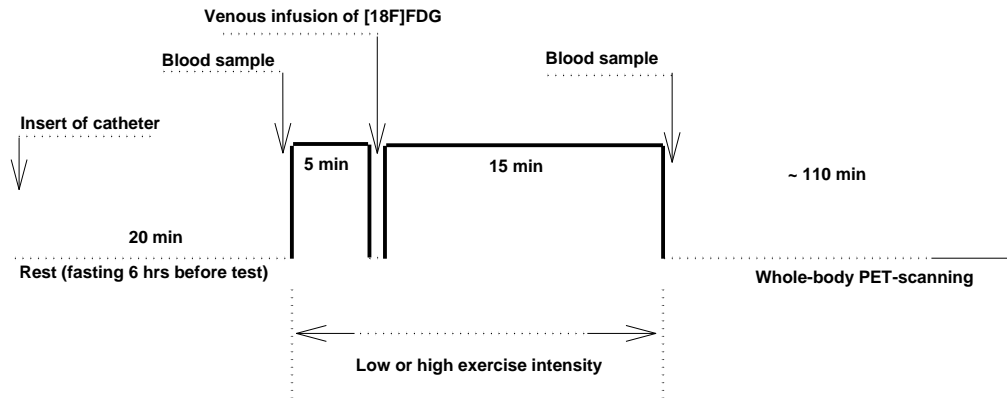
Figure 5. Schematic protocol, Study IV.

5.3 Procedures and calculations

5.3.1 Technique description

Double poling is a classic style high-speed propulsion technique that contains a synchronized pole push as the skis are gliding forward. This technique has previously been considered to be mainly upper-body work, but with the introduction of the so-called "modern DP-technique", the leg muscles also seem to contribute significantly (Holmberg et al. 2005; 2006). In skating, competitive skiers use different techniques according to terrain, speed, snow conditions and their work capacity. The primary ski skating technique used in flat terrain and moderate uphill terrain is V2 (also called "gear 3" or "double dance"), whereas V1 (also called "gear 2" or "paddling") is traditionally used on steeper inclines (Kvamme et al. 2005). In V1, skiers use their poles on every second leg push-off (left or right) in contrast to the V2 technique, where the poles are used on every leg push-off.

5.3.2 Submaximal oxygen uptake (*Studies I-IV*)

Prior to the test, subjects warmed up for 15 min at ~ 60-75% of HR_{max}. Submaximal trials of 6 min duration (5 min in *Study III*) separated by 2 min breaks between trials were performed.

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O_2-cost was defined as the mean oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$) between 3.5 and 5.5 min for each trial/workload (2.5 and 4.5 min in *Study III*). Heart rate was measured during the same time intervals, while La^- was measured < 30 s into the breaks.

5.3.3 Maximal oxygen uptake (*Studies I-IV*)

During running (*Studies III-IV*), subjects exercised at a constant 6° incline, while the speed was increased incrementally each minute until exhaustion. Subjects ran at 9-16 $km \cdot h^{-1}$ with individual adjustments, which is a protocol that has been used for decades by XC skiers in our lab. During the incremental protocol in rollerski skating on the treadmill (*Studies I-II*), the starting incline and speed of the test was 6° and 3 $m \cdot s^{-1}$. The initial speed was kept constant and the incline was subsequently increased by one degree every minute until it reached 8°. Thereafter, speed was increased by 0.25 $m \cdot s^{-1}$ every minute. During *Studies II* and *III*, VO_{2max} was also measured during a 600 m or 1000 m test as presented above. In all maximal exercises during roller skiing a safety harness was put on the subjects in case of a fall. In the VO_{2max} test in DP ergometer, work load (W) was set to "high intensity" (~ 88% of HR_{max}: individually from the submaximal loads) for 1 min and thereafter increased by 15 W. After 2 min the subject was asked to increase the intensity with the goal of reaching complete exhaustion between 4 and 6 min. In all tests, exhaustion and a plateau in VO_2 were used as criteria to indicate that VO_{2max} was obtained. The VO_{2max} was also evaluated during the 600 or 1000 m test (*Studies II-III*) as described below. For all tests, VO_2 was measured continuously and the highest mean values over one minute were taken as VO_{2max}, except in *Study II*, where VO_{2max} during the 600 m test was calculated over 30 s, due to the short duration of the test.

5.3.4 600 - 1000 m test (*Studies II-III*)

Subjects skied as fast as possible over 600 or 1000 m (named "600 m test" or "1000 m test") on a rollerski treadmill. The incline was 7° (*Study II*) and 6° (*Study III*). The speed in *Study II* was fixed at 3 $m \cdot s^{-1}$ for the first 100 m (< 36 s) and in *Study III* at 3.25 $m \cdot s^{-1}$ for the first 100 m and 3.5 $m \cdot s^{-1}$ for 100-200 m, to avoid over-pacing. Thereafter, the subjects controlled the speed by adjusting their position on the treadmill relative to laser beams situated in front of and behind the skier. Each contact with the front wheels with the front or rear laser induced

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an increase or reduction in speed by 0.25 m·s^{-1} respectively (Figure 6). The speed changes were manually adjusted by the test leader. Visual feedback with respect to distance travelled was provided to the subjects. A separate monitor allowed the test leader to follow the subject's motion. When the subjects completed the test, the treadmill was automatically stopped and all data including speed changes and time were saved on the computer using a custom-built program (Labview, National Instruments, Texas, USA).
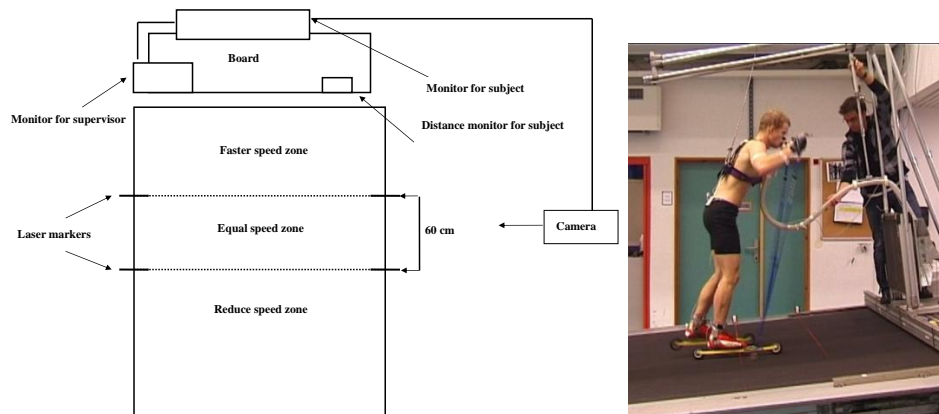
Figure 6. Instrumental settings for the treadmill 600-1000 m test (left) and a subject performing a 600 m test with VO$_2$ measurement (right).

5.3.5   **Validity of the performance tests and calculation of FIS points (*Studies II-III*)**

In order to evaluate how the performance tests predict on-snow performance a regression analysis was performed between 1000 m time and FIS points. The average of FIS-points (Fis-ski.com) for each subject that was collected during free-technique starts in FIS international competitions during the season were used (*Study III*). However, results including subjects from all studies (*Studies I-III* and unpublished results), the overall FIS distance points were used. This was done because some skiers completed < 3 ski skating races during the specific season they were tested in, and none of the subjects used in this specific part were classic style specialists. Also, in this group there was a close relationship between FIS distance points and FIS distance skate points (r = 0.95, $P < 0.05$, $n = 14$). According to FIS (2011), a skier's rank is relative to a 0-point standard established by the top-ranked skier in the world. A skier's total points for a given race are determined by adding race points (from comparing

the individual skier's time with the winner's time) and race penalties based on the five best competitors' FIS points in the specific competition.

5.3.6 Training history survey (*Study III*)

Annual training history (12 months; May to May), was recorded based on the skiers' training diaries. Training was categorized into intensity zones according to the session goal method (Seiler & Kjerland 2006). Endurance training- and competition intensity was monitored by HR, and categorized into three intensity zones: (1) low intensity training (LIT: HR < 81% of HR_{max}), (2) moderate intensity training (MIT; 82–87% of HR_{max}), and (3) high intensity training (HIT; > 88% of HR_{max}).

5.3.7 Biomechanical analyses (*Studies I-IV*)

In *Studies I-II*, cycle rate (CR) and cycle length (CL) were calculated using video analysis. The motion of the skiers was recorded with a stationary 50 Hz video camera (Sony DCR-TRV900E, Sony, Tokyo, Japan) positioned 5 m from the skiers and perpendicular to the skiing direction. One cycle was defined as the time between consecutive right pole plants for V1, and the time between every other right pole plant for V2. Cycle length was calculated as average treadmill velocity divided by CR. In *Study IV*, the elbow and hip joint angle amplitude (ROM) (°), CR (Hz), duration of the cycle time (s) including the poling time (s) and recovery time (s), as defined by Holmberg et al. (2005), were determined based on the goniometer and contact-switch signals (Noraxon MyoResearch XP1.04 Scottsdale, Arizona, USA).

In *Studies I-III,* power was calculated as the sum of the power against gravity (Pg) and the power against rolling friction (Pf), in a coordinate system moving with the treadmill belt at a constant speed. Power against gravity was calculated as the increase in potential energy per time ($Pg = m \cdot g \cdot \sin(\alpha) \cdot v$) and the power against friction was calculated as the work against Coulomb frictional forces at a given tangential speed ($Pf = \mu \cdot m \cdot g \cdot \cos(\alpha) \cdot v$), where μ is the coefficient of friction, m is the total mass of the skier and equipment, g is gravitational acceleration, v is the belt speed and α the incline in degrees (°). The rolling μ of the skis was tested before, during and after the studies using a towing test, previously described by

Hoffman et al. (1990). All tests were performed after warming up with 15 min of treadmill rollerskiing which had a μ of 0.018-0.020.

5.3.8 ΣO_2-deficit

Accumulated O_2-demand was estimated by extrapolation from the individual linear relationships between the work rate (watts) and steady state O_2-cost from the 3.5-6° gradient treadmill bouts, modified after Medbø et al. (1988) and demonstrated in Figure 7. The ΣO_2-deficit was calculated as ΣO_2-demand minus ΣO_2-uptake (Figure 7). After onset of exercise, the stored O_2 in the venous blood is reduced from typically 160 mL per litre blood at rest to ~ 20 mL per litre blood during maximal exercise in elite XC skiers (Calbet et al. 2005). This is an aerobic contribution to the total energy release that in these studies formed part of the ΣO_2-deficit. The reduction in stored O_2 was calculated based on these values and the calculation of Medbø et al. (1988). Hemoglobin mass (*Studies II-III*) was measured by the optimized CO-rebreathing method as described in Schmidt & Prommer (2005).
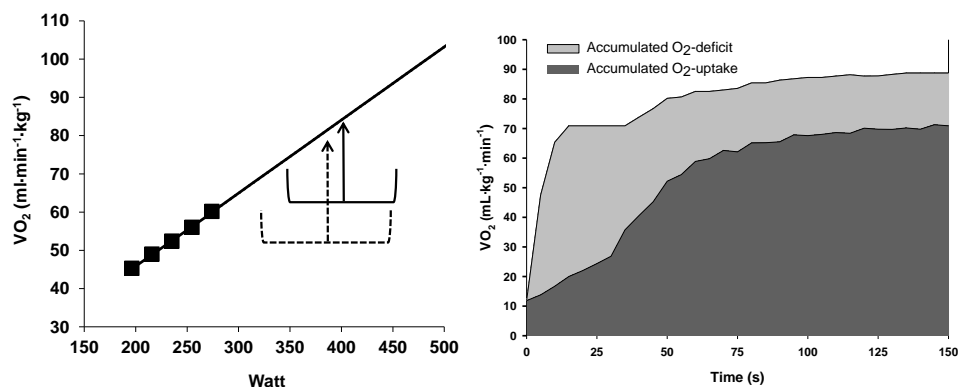
Figure 7*. Left: The method for extrapolation the individual linear relation between the work rate (watt) and O_2-cost from the 3.5-6° gradient treadmill bouts (black squares) to supramaximal loads. The solid line and arrow illustrates the mean and range of workload at the 600 m time (Study II), and the dotted line and arrow for the 1000 m time (Study III). Right: Illustration of the ΣO_2-uptake and ΣO_2-deficit during the first 150 s of the 600 m time.*

5.4 **Apparatus and materials**

All rollerskiing tests in *Studies I-III* were performed while skating on a motor-driven treadmill with belt dimensions of 3 x 4.5 m (Rodby, Södertalje, Sweden). Swix CT1 poles (Swix, Lillehammer, Norway) with a tip customized for treadmill rollerskiing were used. Two different pairs of Swenor Skate rollerskis (Swenor, Sarpsborg, Norway) with wheel type 1 were used, depending on the binding system the skiers normally used (NNN, Rottefella, Klokkarstua, Norway or SNS, Salomon, Annecy, France). In *Study IV*, all ergometer exercise was performed on a commercially available DP ergometer (ThoraxTrainer Elite, Kokkedal, Denmark). VO_{2max} running in *Studies III-IV* were measured during treadmill running (Woodway GmbG, Weil am Rein, Germany). In all studies, oxygen consumption (VO_2) was measured by an automatic system (Oxycon Pro Jaeger Instrument, Hoechberg, Germany), evaluated against the Douglas bag system by Foss & Hallén (2005[b]). Heart rate was measured with a Polar S610i™ monitor (Polar Electro OY, Kempele, Finland) and blood lactate concentration was measured in unhaemolysed blood, from capillary fingertip samples. One exception was *Study IV*, where blood lactate concentration was measured in haemolysed whole blood. Blood was collected in a heparinized capillary tube, and 25 µl was injected with a pipette into the mixing chamber of the lactate analyser (YSI 1500 Sport, Yellow Springs Instruments, Yellow Springs, OH, USA). The lactate analyser and Oxycon Pro Jaeger Instrument were calibrated according to the instruction manual and described in detail by Losnegard et al. (2011). The subject's body-mass was measured before each treadmill test (Seca, model 708 Seca, Hamburg, Germany).

The PET scanner was a Siemens ECAT HR (Siemens Medical Systems, Knoxville, TN) and the PET imaging was performed either using GE Advance (General Electric Medical Systems, Milwaukee, WI) or CTI ECAT HR (Siemens Medical Systems, Knoxville, TN), which both operated in two-dimensional (2D) mode. Three dimensional volume-rendered images of the whole body were constructed by use of MRIcro 1.4 software (Chris Rorden, Georgia Institute of Technology, Atlanta, GA). A full-body MRI scanning was performed with a Philips Intera 1.5 T scanner (Philips Medical Systems, Best, The Netherlands) for anatomical reference. During analysis, PET and MRI images were placed in isometry on the same computer screen by use of the Vinci v.3. software (Max-Planck-Institute for Neurological Research, Köln, Germany), and regions of interest (ROIs) were defined based on the MRI images.

5.5   Statistics

In *Studies I-II* and *IV*, paired t-tests were used for detecting significant differences in O_2-cost at each incline during submaximal testing, VO_{2max} between V1 and V2 techniques, or between glucose uptakes at different intensities. In *Studies I* and *III*, a one-way repeated-measure ANOVA was calculated to analyse changes in CR over the three different inclines or changes in submaximal and maximal parameters during the season. When global significance over time was observed, Bonferroni *post hoc* (*Study II*) or Tukey *post hoc* (*Study III*) analysis was used to determine changes over inclines. Pearson's Product Moment Correlation Analysis was used in all studies. The following criteria were adopted for interpreting the strength of correlation (*r*) between the measures: < 0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; and 0.9-1.0, almost perfect (Hopkins 2004). Multiple linear regression analysis was used to determine which of the variables was the best predictor of performance time in *Studies II-III*. A *P* - value ≤ 0.05 was considered statistically significant. Data are presented as mean ± standard deviation (SD), unless otherwise stated.

Precision of estimation and magnitude-based inferences were also conducted in *Studies I-III*. Confidence limits for the true mean values for effects were estimated (Hopkins 2004). Each subjects change score was presented as a percentage via the analyses of log-transformed values. The spreadsheet provides a precision of the estimates as 90% confidence limits. The magnitudes of differences between exercise modes were expressed as standardized mean differences (Cohen`s *d* effect size). The criteria to interpret the magnitude of the effects sizes were: 0.0-0.2 trivial; 0.2-0.6 small; 0.6-1.2 moderate; 1.2-2.0 large; and >2.0 very large (Hopkins 2000). Statistical calculations were performed with Microsoft Excel, SPSS 18.0 and SigmaPlot 11 software.

6 RESULTS

6.1 Differences between V1 and V2 (*Studies I-II*)

No differences were found between V1 and V2 skating in the physiological responses at submaximal intensities at moderate to steep inclines (Table 2; *Study I*). In addition, there were no differences in physiological responses or performance between the techniques at maximal workload. Here, both an incremental VO_{2max} test (*Study I*) and a 600 m test at steep incline (Table 2; *Study II*) were conducted.

Table 2. Performance (600 m time) and physiological responses during submaximal and maximal tests in V1 and V2 and the magnitude of differences between techniques (Studies I-II) (n = 11-14).

Variable	V1	V2	Differences in %	Magnitude of differences
	Mean ± SD	Mean ± SD	Effect ± 90% CL	Cohans`*d* ES
600 m time (s)	171.8 ± 8.4	172.1 ± 9.9	0.1 ± 1.9	0.03
O_2-cost ($mL \cdot kg^{-1} \cdot min^{-1}$)	55.1 ± 1.8	55.4 ± 2.2	0.5 ± 0.6	0.14
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	71.1 ± 2.9	71.4 ± 2.3	0.6 ± 1.1	0.15
ΣO_2-deficit ($mL \cdot kg^{-1}$)	62.2 ± 16.8	60.2 ± 15.0	-3.8 ± 11.4	0.13
%VO_{2max}	82.5 ± 3.3	82.7 ± 2.7	0.0 ± 0.7	0.01

Note; CL confidence limits; *ES* effect size: < 0.2 (trivial); 0.2-0.6 (small); 0-6-1.2 (moderate); 1.2-2.0 (large); > 2.0 (very large). O_2-cost is the average from 4-6°, 3 m·s⁻¹. %VO_{2max} is the fractional utilization of VO_{2max}

6.1.1 Kinematic differences between V1 and V2 (*Studies I-II*)

Cycle rate was highest and CL shortest in V1 compared to V2 for all submaximal inclines (4-6°), during the 600 m test (7°) and VO_{2max} test (8°) (all data taken from 3 m·s^{-1}, all $P < 0.05$, Figure 8). At constant speed of 3 m·s^{-1}, CR increased linearly with increasing incline for both V1 and V2 (both, r = 0.99, $P < 0.05$, Figure 8). V2 600 m time was negatively correlated with CL (r = 0.86, $P < 0.05$), while V1 600 m time tended to correlate negatively with both longer CL and higher CR (r = 0.59 and 0.57, both $P = 0.06$) (Figure 9).
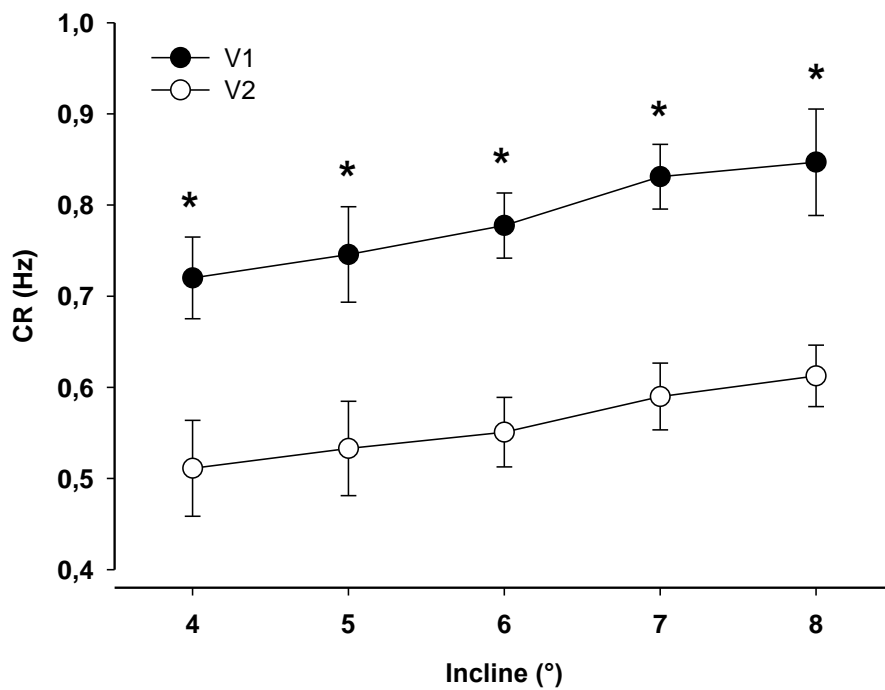
Figure 8. *Differences in cycle rate (CR) between V1 and V2 with increasing incline at constant speed of 3 m·s^{-1}. Data are mean ± SD, n = 12-14. * Significantly different to V2.*
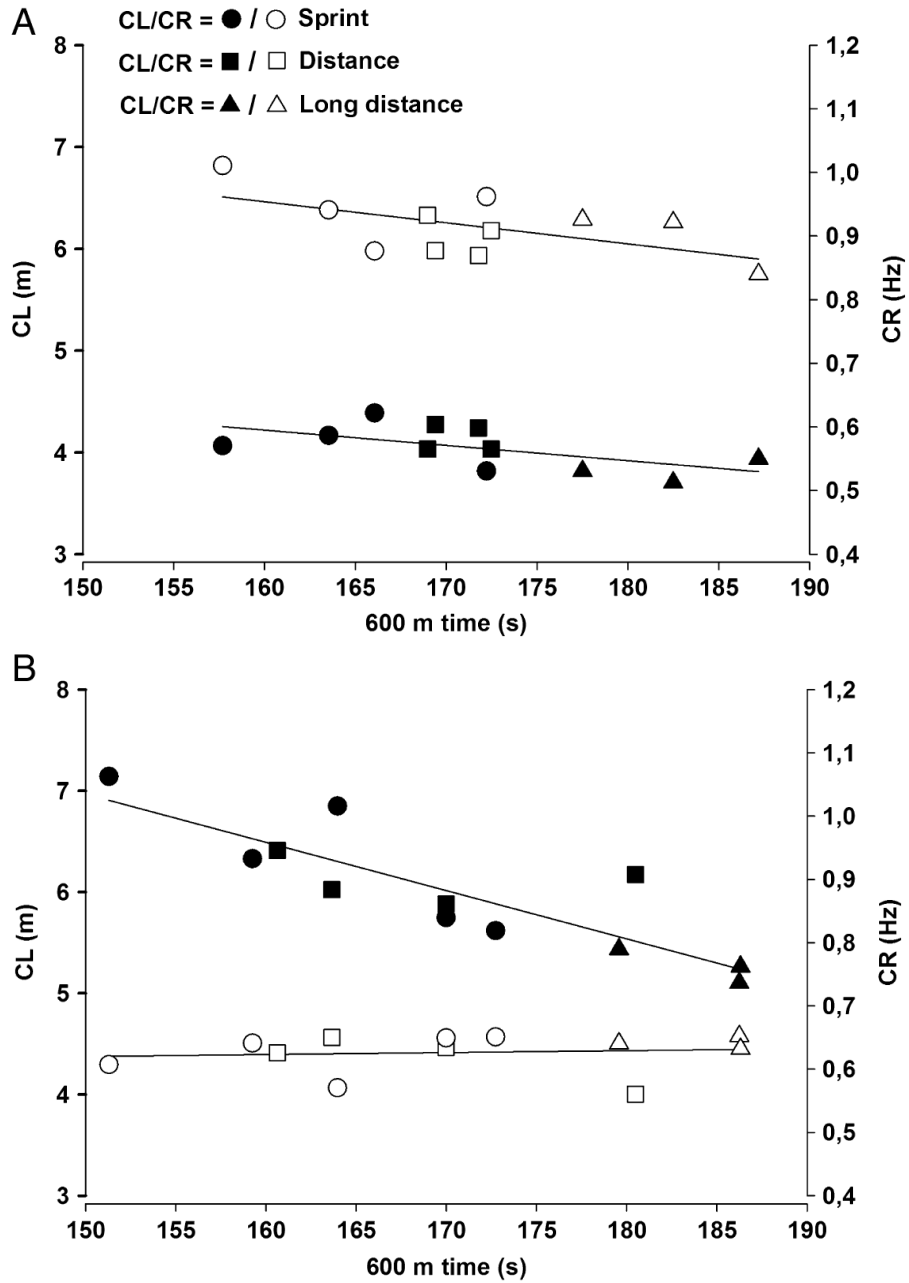
Figure 9. Mean cycle rate (CR) and cycle length (CL) for each of the subjects from 100-600 m (freely chosen speed) from the 600 m tests in A) V1 (n = 11) and B) V2 (n = 12). Open symbols are CR and filled symbols are CL. Different symbol types (circles, squares and triangles) explain the different type of skiers. Sprint skiers: n = 4 in V1, n = 5 in V2, Distance skiers: n = 4, Long distance skiers: n = 3.

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6.2 **Anaerobic capacity as a determinant of performanc*e* (*Study II*)**

The 600 m test in *Study II* lasted ~ 170 s, similar to the duration of a sprint competition. The ΣO_2-demand over the 600 m time was 232.5 ± 6.9 and 228.8 ± 12.0 mL·kg^{-1}, the ΣO_2-uptake was 170.3 ± 12.6 and 168.6 ± 12.6 mL·kg^{-1}, and thus, the ΣO_2-deficit was 62.2 ± 16.8 and 60.2 ± 15.0 mL·kg^{-1}, for V1 and V2, respectively. Hence, the ΣO_2-deficit accounted for ~ 26% of the ΣO_2-demand.
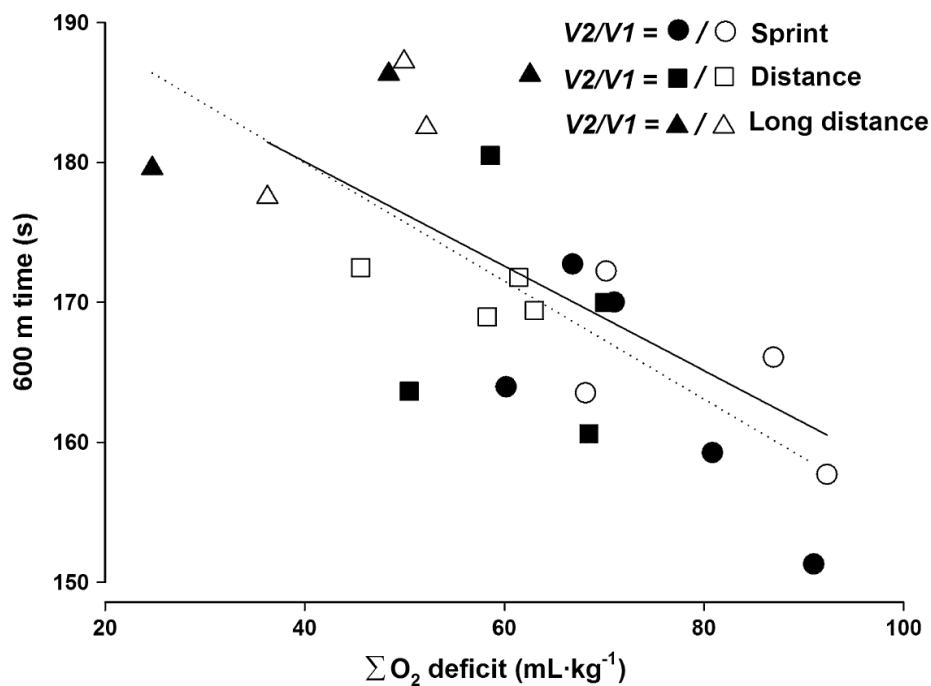
Figure 10. *Relationship between ΣO_2-deficit and 600 m time using V1 (n = 11) and V2 (n = 12). Open symbols are V1 and filled symbols are V2. Different symbol types (circles, squares and triangles) explain the different type of skiers. Sprint skiers: n = 4 in V1, n = 5 in V2; Distance skiers: n = 4; Long distance skiers: n = 3. Solid trend line is V1, dotted trend line is V2.*

Low to moderate correlations were found between 600 m time and VO_{2max}, O_2-cost (5°), and fractional utilization of VO_{2max} (measured as the ΣO_2-uptake divided by time and VO_{2max}), whereas a moderate to strong correlation was found between 600 m time and ΣO_2-deficit (*Study II*, Table 3, Figure 10). ΣO_2-deficit alone explained ~ 50% of the total variance in 600 m time in this group of skiers when using the SPSS stepwise analyses.

Table 3. Summary of Pearson's product-moment correlation coefficients between 600 m time (dependent variable) and physiological variables measured during submaximal loads as well as during maximal loads (the 600 m test) in V1 and V2. * = P < 0.10 # = P < 0.05. O₂-cost is from 5°, 3 m·s⁻¹. % VO₂max is the fractional utilization of VO₂max.

Variable	V1 (*n* = 11)	V2 (*n* = 12)
O_2-cost (mL·kg^{-1}·min^{-1})	0.30	0.31
VO_{2max} (mL·kg^{-1}·min^{-1})	-0.15	-0.51*
% VO_{2max}	0.12	0.09
ΣO_2-deficit (mL·kg^{-1})	-0.75#	-0.64#
ΣO_2-deficit (%)	-0.77#	-0.69#

6.3 Seasonal variations (*Study III*)

In *Study II*, multiple linear regression analysis using the 600 m time as the dependent variable and VO_{2max}, O_2-cost (5°, 3 m·s^{-1}) and ΣO_2-deficit as the independent variables produced the best model summary with $r^2 = 0.66$ (V1) and $r^2 = 0.75$ (V2). Hence, in these groups of skiers, ~ 70% of the variation in performance was explained by these variables. Therefore, the VO_{2max}, O_2-cost and ΣO_2-deficit were used as the main variables in the analysis of seasonal variations (*Study III*). In this study, a 1000 m test was used to evaluate changes in performance. On average, the 1000 m time improved significantly from June to January (-7.4 ± 1.9%, ES = 1.37, large). So did O_2-cost (-3.0 ± 1.2%, ES = 0.63, moderate) and ΣO_2-deficit (24.8 ± 20.9%, ES = 0.94, moderate) (all $P < 0.05$), while no significant changes were observed in VO_{2max} (1.3 ± 2.4%, ES = 0.17, trivial, $P > 0.05$) (Figure 12). Multiple linear regression analysis using the 1000 m time as the dependent variable and VO_{2max}, O_2-cost (5°) and ΣO_2-deficit as the independent variables produced the best model summary with $r^2 = 0.81$ (June), $r^2 = 0.78$ (August), $r^2 = 0.88$ (October) and $r^2 = 0.58$ (January). In terms of training, the subjects had a total annual volume of 675 ± 103 hrs (range 469 – 833 hrs). The relative training distribution over 12 months is shown in Table 4 and the total training in the respective endurance training zones are shown in Figure 11.

Table 4. *Distribution of the different training modalities (in % of total training) during different parts of the season. Data are mean ± SD, n = 11.*

	May-Jun	Jul-Aug	Sep-Oct	Nov-Dec	Jan-Feb	Mar-Apr
Endurance LIT (< 81% of HR$_{max}$)	82 ± 7	82 ± 4	79 ± 6	81 ± 6	79 ±6	72 ± 10
Endurance MIT (82–87% of HR$_{max}$)	4 ± 3	5 ± 2	5 ± 3	4 ± 2	4 ± 3	5 ± 3
Endurance HIT (> 88% of HR$_{max}$)	4 ± 2	4 ± 1	5 ± 2	7 ± 2	9 ± 3	12 ± 9
Strength	7 ± 4	6 ± 2	8 ± 2	6 ± 4	6 ± 3	9 ± 7
Speed	2 ± 2	2 ± 2	2 ± 2	1 ± 1	1 ± 1	1 ± 1
Other	1 ± 1	1 ± 2	1 ± 1	1 ± 1	1 ± 2	1 ± 2
Total	100	100	100	100	100	100

Figure 11. *Total training (hours) in the respective training zones from May-March. A) LIT;*
low intensity training (< 81% of HR_{max}), B) MIT; moderate intensity training (82-87% of
HR_{max}) and C) HIT; High intensity training (> 88% of HR_{max}). Solid lines indicate the best
fitting curve for the respective months vs. training volume. Data are mean ± SD, n = 11.

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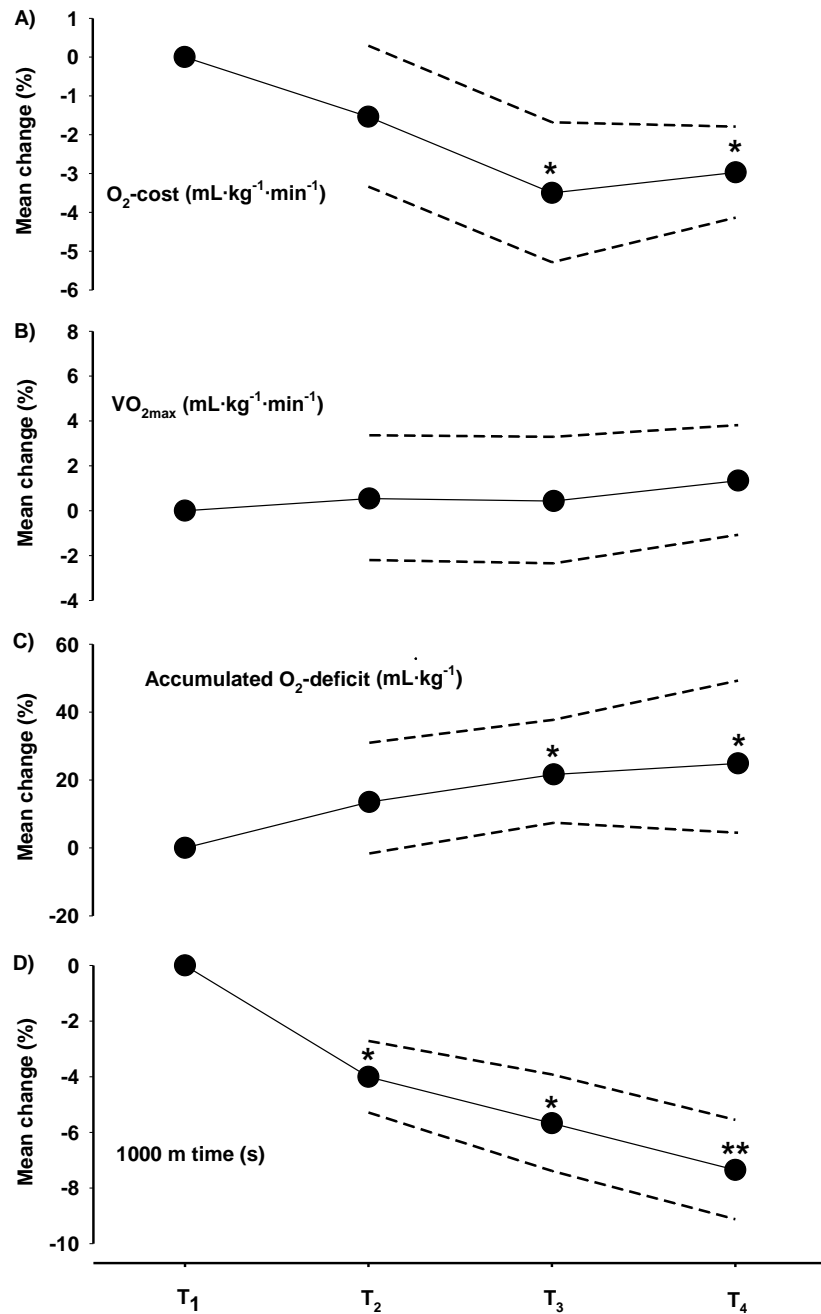
Figure 12. *Log-transformed data for true mean changes in A) O_2-cost (5°, 3 $m \cdot s^{-1}$), B) VO_{2max}, C) ΣO_2-deficit and D) 1000 m time. T_1 refers to testing conducted in June, T_2: August, T_3: October and T_4: January/February. Dotted lines are upper and lower 90 % confidence limits. * Significantly different to T_1, ** significantly different to T_2 (P < 0.05), n = 11.*

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6.4 **Muscle use at low and high intensity during double poling (*Study IV*).**

Cross-country skiing is a biomechanically complex sport where both the arms and the legs are responsible for the propulsive forces. Testing cardiopulmonary responses does not take this complexity into account. To investigate the distribution of workload between upper and lower body, complex biomechanical as well as invasive physiological studies have been performed (e.g., Smith et al. 2009, Holmberg et al. 2005, Calbet et al. 2004, Rud et al. 2011). This study used PET to evaluate glucose uptake in different upper- and lower-body muscles during DP at two different intensities.

The O_2-cost during low- and high-intensity exercise was $53 \pm 5\%$ and $74 \pm 7\%$ of DP VO_{2max} and the HR was ~ 74% and ~ 88% of DP HR_{max}. The highest (average of low- and high-intensity) glucose uptake index (GUI) was seen in the triceps brachii followed by the latissimus dorci, the teres major, the pectoralis major and the posterior part of the deltoid muscle. When increasing the intensity from low to high, no significant increase in GUI was seen in the upper body muscles. In fact, a tendency to decreased GUI was observed in the triceps brachii ($P < 0.1$). However, in the lower body muscles around the knee and hip an increase in GUI was observed (Figure 13).

In terms of kinematic changes, CR and elbow ROM (°) increased significantly while poling time and recovery times were significantly reduced from low- to high intensity ($P < 0.05$, Table 5). However, there were no significant differences in poling- and recovery times in terms of % of cycle time or hip ROM (°) between intensities (Table 5).
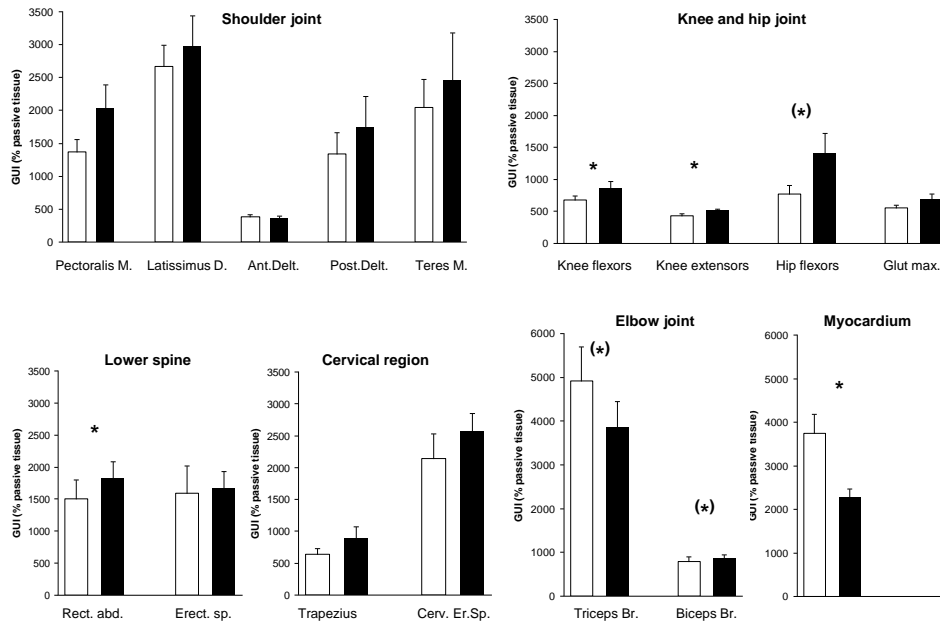
Figure 13. *Muscle glucose uptake index (GUI) for relevant muscles and muscle groups. Open bars denote GUI on the low-intensity day, while filled bars represent uptake on the high-intensity day. * P < 0.05 from day to day. (*) P < 0.1. Note individual y-axis scaling for the elbow joint and myocardium plots.*

Table 5. *Work load and biomechanical data acquired during low- and high-intensity in DP.*

	Low	High
Variable	**Mean ± SD**	**Mean ± SD**
Workload (W)	68 ± 14	106 ± 18*
Cycle rate (Hz)	0.74 ± 0.11	0.83 ± 0.11*
Cycle time (s)	1.38 ± 0.25	1.23 ± 0.19*
Poling time (s)	0.91 ± 0.22	0.80 ± 0.19*
Poling time (% of cycle time)	65 ± 8	66 ± 10
Recovery time (s)	0.47 ± 0.11	0.43 ± 0.12*
Recovery time (% of cycle time)	35 ± 8	34 ± 10
Elbow ROM (°)	75 ± 17	80 ± 13*
Hip ROM (°)	64 ± 19	65 ± 13

Data are mean ± SD, * significant to Low ($P < 0.05$).

6.5 Prediction of on-snow competition performance (*Studies I-III* and *UR*)

For more details about the average group responses the reader is referred to the original articles appended to the thesis. The collected data showed large individual variations in both O_2-cost of skiing and maximal energy turnover measured as accumulated and maximal VO_2 and oxygen deficit. Even though all the subjects in *Studies I-III* were elite skiers, they differed in terms of race distances preferences as well as performance level. In the following part of the result section, the subjects are grouped to explore the relationships between the physiological variables and different types of skiers as well as performance levels. This grouping may differ from that presented in the articles, and in some analyses unpublished results (*UR*) are included.

6.5.1 Relationship between VO_{2max}, O_2-cost, ΣO_2-deficit and performance

To investigate how VO_{2max}, O_2-cost or ΣO_2-deficit affect performance in XC skiing on snow, the relationship between these variables and FIS points was examined (Figure 14). Multiple linear regression analysis using the FIS distance points as the dependent variable and VO_{2max}, O_2-cost ($5°$, 3 m·s^{-1}) and ΣO_2-deficit as the independent variables produced the best model summary with $r^2 = 0.63$ ($P < 0.05$, $n = 26$). Using the same independent variables and FIS sprint points as the dependent variable produced a model where r^2 was 0.46 ($P < 0.05$, $n = 24$). However, using absolute values of VO_{2max} (L·min^{-1}), produced the best model summary ($r^2 = 0.58$, $P < 0.05$, $n = 24$).

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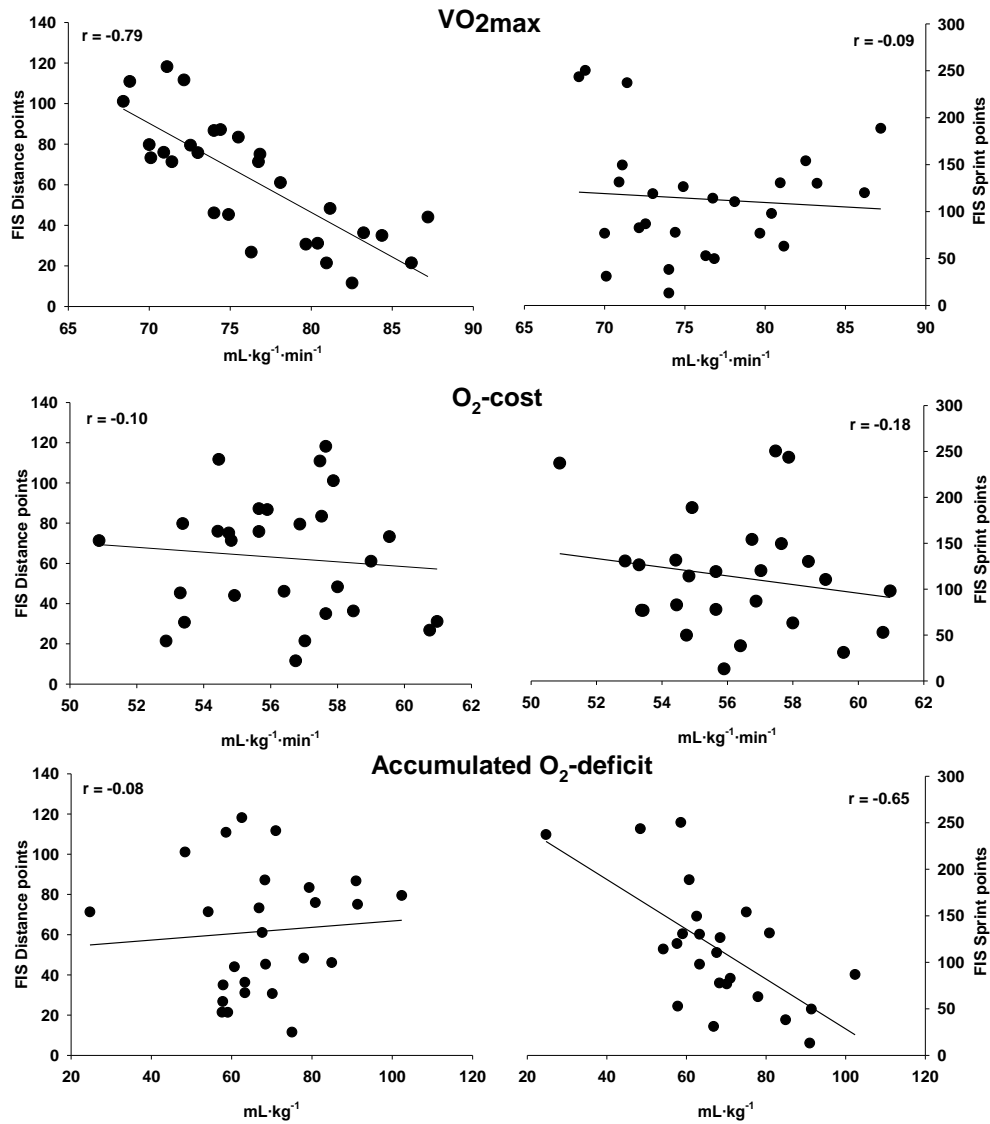
Figure 14. *Relationship between VO$_{2max}$, O$_2$-cost (5°, 3 m·s^{-1}), ΣO$_2$-deficit and FIS distance points or FIS sprint points (n = 26-28, subjects from Study II: n =11, III: n =11 and UR: n = 6). All data collected in the V2 technique during rollerski treadmill testing from October - February.*

6.5.2 The physiology of international- and national-level skiers

In the single correlation analysis presented above, skiers with a wide range of preferred race types were analysed. In addition, group comparisons of several physical and physiological variables between international and national-level skiers as well as distance and sprint skiers are presented in Tables 6 and 7. Subjects who were in the top 15 in World-Cup races and/or the top 5 in the Norwegian national Championship (NCh) were categorized as international-level skiers. Subjects with no international merits, but in the top 30 in NCh were categorized as national-level skiers.

The international-level distance skiers had a higher VO_{2max} relative to body-mass and a lower body-mass ($P < 0.05$) and tended to have a lower body-height, body-mass index and ΣO_2-deficit compared to national-level distance skiers (all $P < 0.13$, Table 6). The international-level sprint skiers had a higher body-mass, body-mass index and VO_{2max} in absolute terms ($P < 0.05$) and tended to have a higher ΣO_2-deficit ($P = 0.15$) compared to national-level sprint skiers (Table 7). Only small and non-significant differences were found in O_2-cost between levels of skiers in the distance and sprint groups, respectively.

Comparing international-level sprint- with distance skiers showed that the sprint skiers had a significantly greater body-mass, body-height and body-mass index compared to distance skiers. Further, the sprint skiers displayed higher absolute VO_{2max} and a higher ΣO_2-deficit compared to distance skiers. However, the distance skiers showed a significantly higher VO_{2max} relative to body-mass (all $P < 0.05$, Table 6 and 7).

Table 6. *Differences between international- and national-level distance elite skiers. Data from Study III (n =11) and UR (n = 3).*

Variables	Int. skiers (n = 7)	Nat. skiers (n = 7)	Cohen`s d effect size
Height (cm)	179 ± 7 (172-187)	183 ± 3 (180-186)	0.77
Body-mass (kg)	70.9 ± 6.4 (62.5-82.0)	77.7 ± 5.2 (71.2-86.1)*	1.09
Body-mass index (kg·m^2)	22.2 ± 1.1 (21.1-23.6)	23.3 ± 1.4 (21.3-25.2)	0.78
FIS-distance points	28.6 ± 12.0 (11.5-44.0)	74.1 ± 13.9 (48.3-87.1)*	3.35
O_2-cost (mL·kg^{-1}·min^{-1})	55.9 ± 2.2 (52.8-58.5)	56.4 ± 1.3 (54.8-58.0)	0.28
VO_{2max} (mL·kg^{-1}·min^{-1})	83.4 ± 2.7 (79.7-87.2)	76.6 ± 2.8 (72.6-81.2)*	2.32
VO_{2max} (L·min^{-1})	5.9 ± 0.4 (5.2-6.6)	6.0 ± 0.5 (5.2-6.6)	0.08
ΣO_2-deficit (mL·kg^{-1})	63.4 ± 6.7 (57.6-75.0)	76.8 ± 16.5 (54.2-102.4)	0.96

Values are mean ± SD (range). *Significant differences between groups, $P < 0.05$. Effect size: < 0.2 (trivial); 0.2-0.6 (small); 0-6-1.2 (moderate); 1.2-2.0 (large); > 2.0 (very large). O_2-cost data are from 5° and 3 m·s^{-1}. All data collected in the V2 technique during rollerski treadmill testing from October - February.

Table 7. *Differences between international- and national-level sprint elite skiers. Data from Study II (n = 5), III (n = 2) and UR (n = 5).*

Variables	Int. skiers (n = 6)	Nat. skiers (n = 6)	Cohen`s d effect size
Height (cm)	186 ± 5 (181-194)	185 ± 3 (182-190)	0.19
Body-mass (kg)	84.9 ± 6.1 (77.8-92.7)	77.2 ± 5.6 (71.2-86.5)*	1.21
Body-mass index (kg·m^2)	24.5 ± 1.1 (22.8-26.1)	22.5 ± 1.1 (21.3-24.0)*	1.70
FIS-sprint points	39.5 ± 17.9 (9.1-50.5)	77.5 ± 9.8 (60.0-86.7)*	2.37
O_2-cost (mL·kg^{-1}·min^{-1})	56.7 ± 1.8 (54.8-59.6)	57.3 ± 2.7 (53.4-60.6)	0.23
VO_{2max} (mL·kg^{-1}·min^{-1})	76.4 ± 4.0 (71.8-81.4)	74.6 ± 4.2 (67.2-79.7)	0.41
VO_{2max} (L·min^{-1})	6.5 ± 0.5 (5.8-7.3)	5.8 ± 0.3 (5.4-6.0)*	1.57
ΣO_2-deficit (mL·kg^{-1})	80.6 ± 8.0 (68.1-91.0)	74.4 ± 5.6 (68.3-82.2)	0.83

Values are mean ± SD (range). *Significant differences between groups, $P < 0.05$. Effect size: < 0.2 (trivial); 0.2-0.6 (small); 0-6-1.2 (moderate); > 2.0 (very large). O_2-cost data are from 5° and 3 m·s^{-1}. All data collected in the V2 technique during rollerski treadmill testing from October - February.

6.6 Seasonal variation in different level of skiers (*Study III* and *UR*)

To investigate whether different levels of skiers show different seasonal variations in physiological response and performance, the skiers in *Study III* were separated into two groups based on FIS distance points (free technique) collected the respective season. The six best skiers were international-level skiers in the top 15 in World Cup races or in the top 5 in NCh (FIS distance point; 37 ± 7, VO_{2max}; 83.4 ± 3.7 mL·kg^{-1}·min^{-1}). Six other skiers were categorized as national-level skiers (FIS distance point; 96 ± 17, VO_{2max}; 76.5 ± 3.6 mL·kg^{-1}·min^{-1}, both $P < 0.05$ compared to international-level skiers). This analysis is presented in Figure 15. The international-level skiers reduced their 1000 m time significantly from June to January (mean $\pm$ SD; $-8.2 \pm 3.9\%$, $P < 0.05$). The O_2-cost was reduced by $-4.2 \pm 1.5\%$ while ΣO_2-deficit tended to be elevated ($32.2 \pm 37.7\%$, $P = 0.09$). No significant changes were seen in VO_{2max} ($2.5 \pm 4.5\%$ in mL·kg^{-1}·min^{-1} and $0.2 \pm 4.0\%$ L·min^{-1}). The national-level skiers significantly reduced their 1000 m time ($-5.7 \pm 2.4\%$, $P < 0.05$), and tended to reduce their O_2-cost ($-2.2 \pm 2.4\%$, $P = 0.08$), while no significantly different changes in VO_{2max} ($0.4 \pm 4.1\%$ in mL·kg^{-1}·min^{-1} or $-1.0 \pm 5.0\%$ in L·min^{-1}) or ΣO_2-deficit ($26.8 \pm 40.1\%$) were evident during the annual training season. No significant differences in changes between the two groups were observed, although a tendency to a more reduced O_2-cost was seen in the international-level skiers ($P = 0.11$). Five of the skiers tested in *Study III* (VO_{2max}; 81.3 ± 3.6 mL·kg^{-1}·min^{-1}, FIS distance points: 40 ± 20), participated in testing over two annual training seasons (*UR*). These findings are presented as %-changes (mean $\pm$ SD) from June the first year in Figure 15. Over these 17 months, O_2-cost was reduced by 6.7 ± 3.5 % and 1000 m time by $11.1 \pm 4.6\%$ (both $P < 0.05$). VO_{2max} increased $6.8 \pm 4.9\%$ ($P = 0.07$) in mL·kg^{-1}·min^{-1} and $4.7 \pm 4.1\%$ in L·min^{-1} ($P = 0.11$). No changes was seen in ΣO_2-deficit (13.0 ± 24.0 %).
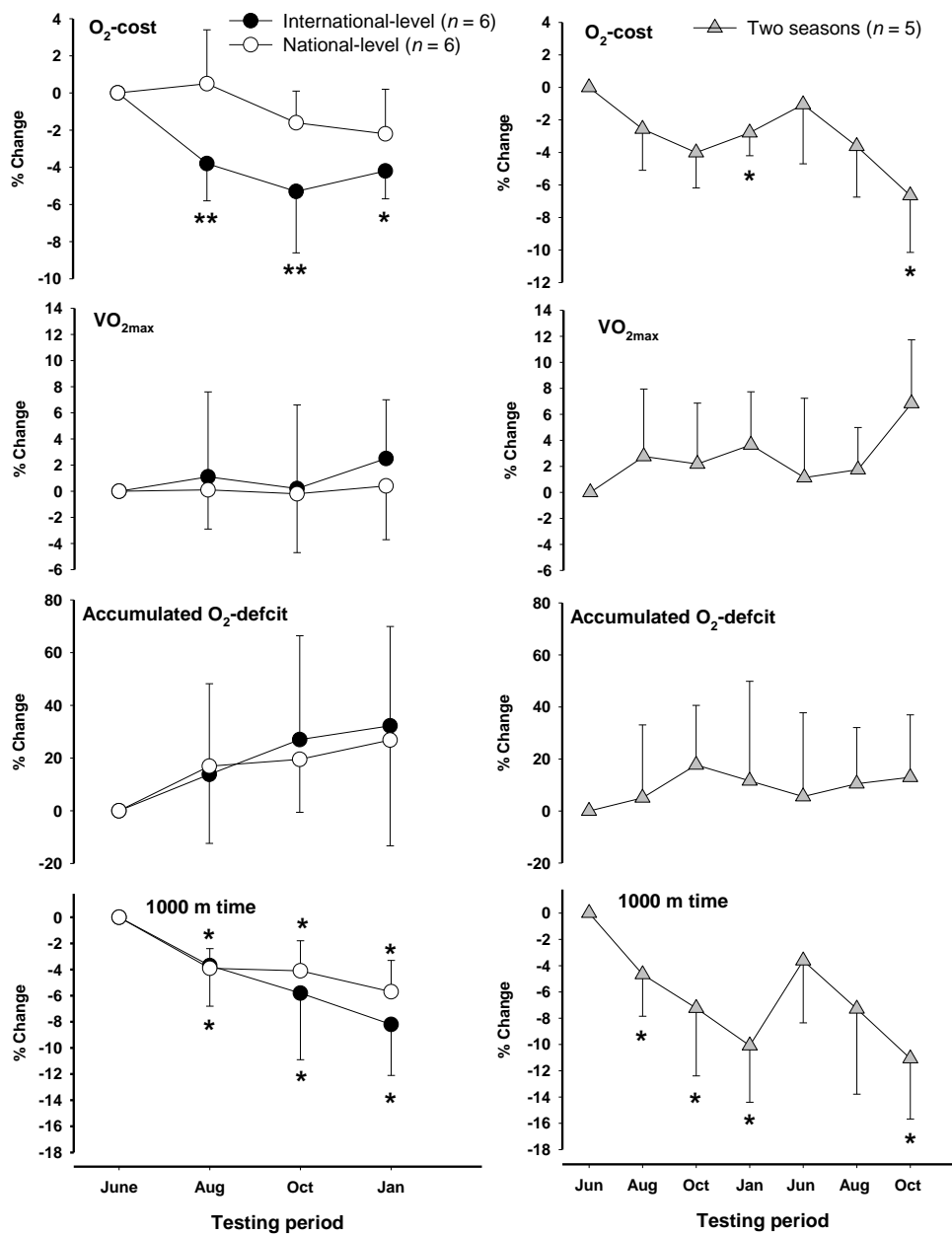
Figure 15. *Seasonal variations in O₂-cost, VO₂max, ΣO₂-deficit and 1000 m time in two different performance groups of skiers (left) and in five elite skiers during 17 months (right). Data are mean ± SD. * significant different from June (first year), ** different from June (first year) and to national-level, P < 0.05. All data collected in the V2 technique during rollerski treadmill testing.*

Seasonal variation in VO_{2max} in a more heterogeneous group of national-level elite skiers according to VO_{2max} values, was also measured (range: women 53-63 mL·kg^{-1}·min^{-1}, $n = 15$, men 61-78 mL·kg^{-1}·min^{-1}, $n = 22$, values from May, *UR*). Skiers were divided into two groups (under and above median, women and men separate) based on their VO_{2max} values in May. The skiers with the lowest VO_{2max} values in May (named "Medium") (women: ~ 55 mL·kg^{-1}·min^{-1}, men: ~ 65 mL·kg^{-1}·min^{-1}) showed a significant increase in both running (4.6 ± 3.9%, $P < 0.05$) and V1 skating VO_{2max} (5.3 ± 4.9%, $P < 0.05$) from May to September testing. However, the skiers with the highest VO_{2max} values in May (named "High") (women: ~ 60 mL·kg^{-1}·min^{-1}, men: ~ 74 mL·kg^{-1}·min^{-1}) showed no significant changes in VO_{2max} during V1 or running (Figure 16). Hence, a significant difference in the development of VO_{2max} was found between the two groups ($P < 0.05$).
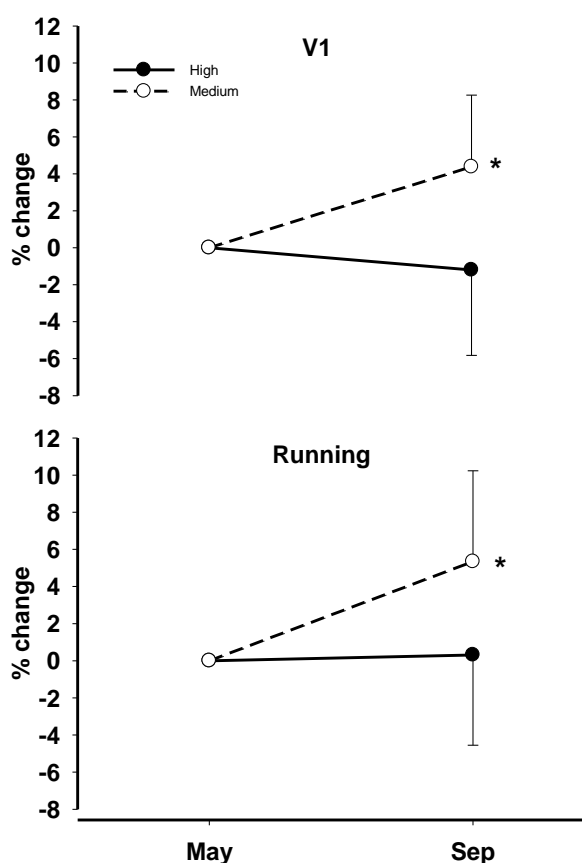
*Figure 16. Changes in VO_{2max} V1 and running between May and September in two groups of skiers. Medium (n = 18) refers to subjects with the lowest values (under median) at May test and High (n = 19) with the highest values at May test (Total subjects = 37; Women = 15, men = 22). * Significant increase compared to May and "High" subjects (P < 0.05).*

6.7 Validity and reliability

The 600 m time (~ 170 s) correlated significantly with the subjects` sprint points (r = 0.58 -
0.66, $P < 0.05$, n = 12, Figure 17, *Study II*), but not to distance points (0.30 - 0.43 $P > 0.05$, *n*
= 12). In contrast, the 1000 m time (~ 250 s) tested in January was significantly correlated
with the subjects` FIS distance points (r = 0.75, $P < 0.05$, n = 13, Figure 17, *Study III*), but
not sprint points collected during the season (r = -0.43, $P > 0.05$, n = 13). A reliability study
of ten subjects tested over two days was conducted and these results are presented in Table 8.
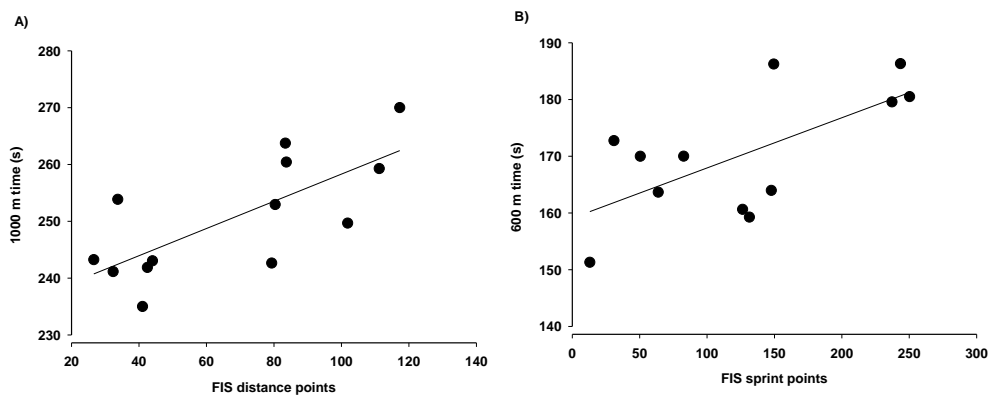
Figure 17. *A) Validity of the 1000 m test conducted in January and FIS sprint points (r =
0.75, n = 13). B) Validity of the 600 m test conducted in October and FIS distance skating
points (r = 0.66, n = 12). FIS distance points collected in skating during the respective
season.*

Table 8. *Reliability of the main variables tested on two different days with one rest day in between in ten elite male skiers. Performance was measured as a 800 m test.*

Subject	Performance (s)			VO$_{2max}$ (mL·kg^{-1}·min^{-1})			O$_2$-cost (mL·kg^{-1}·min^{-1})			ΣO$_2$-deficit (mL·kg^{-1})		
	Day 1	Day 2	*Diff.*	Day 1	Day 2	*Diff.*	Day 1	Day 2	*Diff.*	Day 1	Day 2	*Diff.*
1	207.6	206.9	*-0.7*	67.3	66.6	*-0.8*	50.2	50.5	*0.3*	82.1	88.0	*5.9*
2	199.8	197.6	*-2.2*	69.3	72.4	*3.1*	46.6	46.0	*-0.6*	97.3	91.7	*-5.6*
3	206.2	209.2	*3.0*	68.3	68.8	*0.4*	48.9	48.6	*-0.3*	120.5	121.1	*0.6*
4	219.8	214.0	*-5.9*	76.4	73.8	*-2.6*	47.0	47.0	*0.0*	73.1	81.5	*-8.4*
5	201.3	213.9	*12.5*	72.9	73.6	*0.7*	49.0	47.2	*-1.7*	84.4	70.1	*14.3*
6	219.5	207.3	*-12.2*	75.2	75.1	*-0.1*	45.0	45.6	*0.6*	95.2	83.9	*-11.3*
7	211.2	204.2	*-7.0*	72.4	68.4	*-4.0*	47.5	48.2	*0.7*	93.7	107.8	*14.0*
8	205.9	197.5	*-8.4*	76.0	73.2	*-2.8*	47.7	50.1	*2.4*	100.5	93.6	*-6.9*
9	195.3	190.5	*-4.8*	74.7	79.4	*4.6*	48.1	48.3	*0.2*	99.9	98.5	*-1.4*
10	198.7	207.3	*8.6*	72.5	71.6	*-0.9*	51.8	50.3	*-1.5*	72.5	71.4	*-1.1*
MEAN	**206.5**	**204.8**	*-1.7*	**72.5**	**72.3**	*-0.2*	**48.2**	**48.2**	*0.0*	**91.3**	**91.3**	*0.0*
SD	**8.4**	**7.5**	*7.8*	**3.2**	**3.7**	*2.6*	**1.9**	**1.8**	*1.2*	**15.1**	**15.1**	*8.9*
CV %			*3.8*			*3.6*			*2.4*			*9.8*

Note: ΣO$_2$-demand for both days is calculated based the same submaximal loads (day 1). All tests conducted using the V2 technique. CV = coefficient of variation (SD/mean). For the individual skiers, all tests conducted < 7 days.

7   DISCUSSION

The aerobic and anaerobic energy turnover balanced by the energy cost could be taken as an expression for the main determinants of performance in endurance sports (di Prampero et al. 1986, di Prampero 2003). This thesis provides new information on how aerobic power and anaerobic capacity, together with the O_2-cost of skiing, collectively or independently affect performance in elite XC skiers.

A novel approach in this thesis was the adoption of the accumulated oxygen deficit method to evaluate anaerobic capacity in XC skiing. Another important aspect is that every evaluation of the physiological variables was followed by an evaluation of performance, in which the physiological variables were measured during the performance test. Furthermore, only elite skiers at top national and international-level participated as subjects. This is important since the relationship between physiological capacities and performance is influenced heavily by the heterogeneity of the subjects. To acknowledge that XC skiing is a complex sport where both the arms and the legs are responsible for propulsion and that whole body cardio-pulmonary responses do not take this complexity in to account, this thesis used PET/MRI to evaluate muscle use during different intensities of skiing.

The studies together demonstrate that distance XC skiing is highly related to maximal aerobic power even in a homogeneous group of skiers, while sprint skiing furthermore demands a high anaerobic capacity. Nonetheless, the changes in performance during an annual training season were related to changes in anaerobic capacity and O_2-cost of skiing. In addition, the present data suggest that choice of technique (V1 or V2) in uphill terrain does not influence the energy turnover, O_2-cost or performance. Finally, as the intensity increases during DP, glucose uptake increases in the legs while no significant changes occur in the arms. Hence, sport-specific training might not only be related to exercise mode, but also to the work intensity accomplished by the skier.

In the multiple linear regression analysis, VO_{2max}, O_2-cost and ΣO_2-deficit explained 58-88% of the 600-1000 m time and ~ 55-65% of the FIS distance or sprint points collected by the skier during the respective season (*Studies II-III*). Therefore, these variables can be used as a framework to detect physiological differences between skiers, techniques and training-induced changes during an annual training season.

7.1 VO$_{2max}$ as a determinant of performance (*Studies I-III*)

The highest VO$_{2max}$ does not necessarily equate to the best performance, but it seems that the best performances in endurance sports consistently demands very high VO$_{2max}$ values (Saltin & Åstrand 1967, Bassett & Howley 2000). In XC skiing, previous studies have demonstrated that better skiers obtain higher VO$_{2max}$ values compared to lower-level skiers (Ingjer 1991, Rusko 2003, Saltin 1997, Sandbakk et al. 2011[a]). Data from the current studies support these findings, as a strong linear relationship was found between VO$_{2max}$ (mL·kg^{-1}·min^{-1}) and performance (FIS distance points or 1000 m time) in elite skiers with different race specialties (sprint, distance or long distance). Comparing skiers with the same preferred race type, but with different race merits, underscored this finding. Independent of the changes that have occurred in XC skiing in recent decades, values above 80 mL·kg^{-1}·min^{-1} are probably a prerequisite for international success in distance XC skiing (Table 9).

Table 9. *Maximal oxygen uptake expressed in different units and body-mass for international-level male distance XC skiers as a time-line from 1960-2010. From [a]Rusko (2003), [b]Saltin (1997), [c]Ingjer (1991), [d]Holmberg et al. (2007), [e]Studies II-III and UR.*

	1960s[ab]	1970s[ab]	1980s[c]	1990s[b]	2000s[d]	2010s[e]
n	5	8	6	6	7	7
L·min^{-1}	5.7 (-)	6.1 (-)	6.4 (5.8-6.6)	6.3 (-)	6.0 (5.6-6.7)	6.1 (5.8-7.3)
mL·kg^{-1}·min^{-1}	82 (80-85)	84 (82-87)	86 (84-88)	87 (83-90)	76 (-)	85 (80-91)
mL·kg$^{-2/3}$·min^{-1}	337 (-)	351 (-)	355 (352-359)	360 (-)	338 (-)	353 (341-386)
Body-mass (kg)	70 (-)	73 (-)	75 (66-78)	72 (-)	80 (-)	72 (64-82)

Note: Data are mean and (range) where available. All data origin from running tests.

In the present study, body-mass was on average 20% (14 kg) higher in the international-level sprint skiers than the international-level distance skiers (Table 6 and 7). Interestingly, these sprint skiers had a significantly higher absolute VO$_{2max}$ (L·min^{-1}) compared to the distance skiers, but a significantly lower VO$_{2max}$ relative to body-mass. They also had a significantly higher absolute VO$_{2max}$ than national-level sprint skiers. Importantly, body-mass, body-height and body-mass index in these international-level sprint skiers were almost identical to the only study that has explicitly used international-level sprint skiers (Sandbakk et al. 2011[a]) (Table 10). Hence, it can be assumed that body composition is a significant variable for different types of skiers. It has previously been shown that heavier skiers appear to have an advantage in flat terrain, but not on steep inclines (Bergh & Forsberg 1992). Therefore, the different body-mass between sprint and distance skiers might be a consequence of different

competition format, race terrain and speed. Several authors have recommended that VO_{2max} should be expressed in terms of $mL \cdot kg^{-2/3} \cdot min^{-1}$ to better predict performance in elite skiing (Bergh 1987, Bergh & Forsberg 1992, Ingjer 1991). The terms $L \cdot min^{-1}$, $mL \cdot kg^{-1} \cdot min^{-1}$ and $mL \cdot kg^{-2/3} \cdot min^{-1}$ were all correlated with performance in the present study (600-1000 m time and FIS points), but absolute values (sprint) and $mL \cdot kg^{-1} \cdot min^{-1}$ (distance) predicted performance best (data not shown).

The VO_{2max} values (both absolute and relative to body-mass) in the present international-level sprint skiers were significantly greater than those previously reported in studies where "elite skiers" had participated (Table 10). One reason for the different VO_{2max} values is likely the level of the skiers, as the term "elite" might not refer to a specific level (national- or international-level). In addition, testing mode (speed, incline, resistance) might explain why some studies only find moderate VO_{2max} values even in international-level skiers (eg., Sandbakk et al. 2011[a]). Nevertheless, even if only a trivial correlation was found between VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$) and performance, the prerequisite VO_{2max} (both $L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$) in sprint skiing might be higher than previously assumed and similar to that reported in international-level rowers (Fiskerstrand & Seiler 2004). The present data suggest that a VO_{2max} of above 6 $L \cdot min^{-1}$ is probably a prerequisite for international success in sprint skiing. Such data are important for coaches and scientists when predicting physiological demands in the respective sport.

Table 10. Summary of maximal aerobic power and anthropometrical data from studies that have investigated "elite" male sprint skiers. Data are mean ± SD.

| | *n* | VO_{2max} | | Body-mass | Body-height | Body-mass index |
		$L \cdot min^{-1}$	$mL \cdot kg^{-1} \cdot min^{-1}$	(kg)	(cm)	(kg/m^2)
Study II, III and *UR*	6	6.5 ± 0.5	76.4 ± 4.0	84.9 ± 6.1	186 ± 5	24.5 ± 1.1
Anderson et al. (2010)*	9	5.5 ± 0.6	73.4 ± 5.8	74.5 ± 6.2	181 ± 5	22.7 ± -
Sandbakk et al. (2011[a])	8	5.9 ± 0.4	70.6 ± 3.2	83.3 ± 6.4	185 ± 6	24.4 ± 0.6
Stöggl et al. (2007)*	12	4.9 ± 0.6	64.6 ± 0.6	76.0 ± 4.0	182 ± 5	22.9 ± -
Stöggl et al. (2010)	14	5.2 ± 0.5	68.6 ± -	75.8 ± 4.9	180 ± 5	23.4 ± -
Stöggl et al. (2011)	16	5.2 ± 0.5	67.6 ± 5.4	76.1 ± 5.2	180 ± 5	23.5 ± -
Vesterinen et al. (2009)	16	5.1 ± -	66.9 ± 3.6	76.0 ± 5.0	181 ± 5	23.2 ± -
Zory et al. (2006; 2009)	8	5.2 ± -	67.1 ± 1.7	77.8 ± 6.5	176 ± 5	25.1 ± -
Zory et al. (2011)	8	5.2 ± -	66.4 ± 1.6	78.1 ± 6.3	176 ± 5	25.2 ± -

Note: *Not recorded how many of the skiers were sprint skiers. −: not reported.

7.1.1 The fractional utilization of VO_{2max}

The fractional utilization of VO_{2max} is closely correlated to performance in numerous endurance sports such as running, on-road- and off-road cycling (Costill et al. 1973, Impellizzeri et al. 2005, Basset & Howley 2000). It has also been suggested that the fractional utilization of VO_{2max} is of great importance in both sprint and distance XC skiing, although limited amounts of data are available (Eisenman et al. 1989, Saltin 1997, Mahood et al. 2001, Sandbakk et al. 2011[a]). In sprint XC, Sandbakk et al. (2011[a]) speculated that the fractional utilization of VO_{2max} might differentiate international- and national-level sprint skiers, as the best skiers were able to ski for a longer time on supramaximal workloads. However, in *Study II* we found no significant correlation between performance (600 m time) and fractional utilization of VO_{2max}, suggesting that other variables are of more importance for sprint skiing performance.

Direct measurement of the fractional utilization of VO_{2max} during races is difficult, and therefore, indirect measurements such as the VO_2 at the onset of blood lactate accumulation (OBLA) is one method used in XC to characterise the ability of the endurance athlete to perform for long periods (Eisenman et al. 1989, Welde et al. 2003). Successful distance skiers compared to less successful counterparts with similar VO_{2max}, seem to have a higher VO_2 at OBLA and correspondingly a higher fractional utilization of VO_{2max} (Eisenman et al. 1989, Mahood et al. 2001). However, accurate assessment of the VO_2 at OBLA was difficult in the present study where relatively few trials of submaximal workloads were recorded (eg., 3 trials in *Studies I-II*).

7.1.2 Seasonal variations in VO_{2max}, training and performance (*Study III*)

Long term endurance training will ideally lead to improved performance as well as physiological indices for performance (eg., VO_{2max}, O_2-cost or fractional utilization of VO_{2max}). However, few studies have systematically documented seasonal changes in VO_{2max} together with changes in performance in elite athletes (Table 11). We found no-significant changes in VO_{2max} from summer to winter, in either the international- or national-level skiers despite a significantly improved performance. This is in contrast to the findings by Ingjer (1991) who collected data from international-level skiers during the 1980s. He reported that

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elite skiers showed a significantly higher VO_{2max} (5-10%) during the competition period than in the early preparation phase. Such improvements were also found in young XC skiers, elite cyclists and elite runners (Gaskill et al. 1999, Sassi et al. 2008, Svedenhag & Sjodin 1985, Zapico et al. 2007), whereas other studies report no significant changes in VO_{2max} (Evertsen et al. 1999, Lucia et al. 2000, Legaz Arrese et al. 2005) (Table 11).

Table 11. *Summary of changes in VO_{2max} and performance in elite senior (>20 years) XC skiers, cyclists and runners with minimum 6 months training. - = not reported.*

	Periode	Changes in VO_{2max}	Performance
XC skiers			
Ingjer (1991)	Summer-Winter	↑ (77.6 → 85.6)	-
Gaskill et al. (1999)	July-February	↑ (66.1 → 70.0)	↑ (Race points)
Evertsen et al. (1999)	May-October	↔ (73.4→ -)	↑ (3%, running)
Study III	June-January	↔ (76.0 → 76.9)	↑ (8%, ski skating)
Runners and cyclist			
Svedenhag & Sjodin (1985)	Winter - summer	↑ (72.4 → 77.4)	-
Sassi et al. (2008)	December - June	↑ (69.4 → 76.7)	↑ (Predicted TE)
Lucia et al. (2000)	November - May	↔ (72.6 → 75.2)	-
Zapico et al. (2007)	November - June	↑ (73.1 → 81.5)	-
Legaz Arrese et al. (2005)	3 years	↔ (76.6 → 76.8)	↑ (2%)

To investigate whether similar adaptations occur in lower level skiers, an additional study was conducted on a group of skiers with rather heterogeneous VO_{2max} values. Thirty-seven skiers (22 male, 15 females) were examined during both running and ski skating in May and September (*UR*). The subjects with the highest VO_{2max} and comparable to subjects in *Study III*, showed no change in both running and ski skating VO_{2max}. However, subjects with significantly lower VO_{2max} in May (~ 65 mL·kg^{-1}·min^{-1}), showed a significant increase in both running and ski skating (~ 5%) from May to September (Figure 16). Why these differences occur is not known, but obviously skiers with low training volume and intensity in the "off season" will also reduce their VO_{2max}. This is underscored by an example of one international-level skier from *Study III* who showed a large seasonal variation in VO_{2max} and performance (Figure 18). This subject had a significant drop in training volume in April and May (< 10 hrs per month) for both seasons. These training differences between skiers could also reflect differences between most of today's top-elite and skiers who competed during the 1980s. Fiskerstrand & Seiler (2004) quantified training, performance markers and ability

among Norwegian international-level rowers from 1970-2001. They found a 12% higher VO_{2max} and a 10% higher performance ability during the 1990s compared to the 1970s. During this time-line, the total amount of training was increased due to more LIT training. Most of this increase in LIT was achieved during the preparation phase, but unfortunately, no seasonal variation in VO_{2max} was reported. Although speculative, the improved VO_{2max} (measured in the preparation phase) from the 1970s to the 1990s could be related to less seasonal variation as these rowers had the opportunity to take time off from work or studies during important training periods. A similar pattern is recognized in Norwegian elite XC-skiers from the 1980s to the 2010s (F. Ingjer, personal communications).
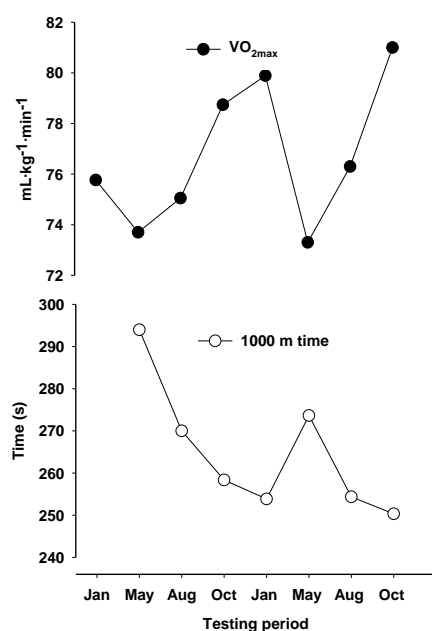
Figure 18. Seasonal changes in VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$) and 1000 m time in one international-level skier that differ from the mean results. Data from Study III and UR.

Notably, the skiers in *Study III* performed 30-40% of their total endurance training in the skating technique, and several of the skiers were ski skating specialists. Therefore, it is unlikely that non-specific training is the reason for the unchanged VO_{2max} during the period. This is supported by the finding that in average, no significant change in VO_{2max} occurred from January/February to the following June. Also, the five skiers who were followed over 17 months displayed no significant changes in VO_{2max}, although a tendency was seen in an

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overall increased VO_{2max} relative to body weight during these 17 months (Figure 15). Thus, it can be concluded that training-induced changes in VO_{2max} in this high-level group of skiers take several years to develop and that changes will not be reflected during one season.

In terms of training, there are three variables that together set the training load with the explicit goal of maximizing performance; *Training load = training intensity · duration · frequency* (Seiler 2010). The skiers in *Study III* undertook a training program that consisted of a high-volume of LIT in the preparation phase complemented by more HIT nearer to the competitive season, which is a well-known training strategy for endurance athletes (Laursen & Jenkins 2002, Seiler 2010). Laursen & Jenkins (2002) suggested that for well-trained athletes, an additional increase in submaximal training (eg., *duration*) does not lead to improved performance or performance markers (eg., VO_{2max}). Further, they stated that only HIT can elicit further improvements in performance in highly trained athletes. Interestingly, the international-level skiers showed a significantly higher amount of LIT training than the national-level skiers (83 vs. 77% of total training, $P < 0.05$, *Study III*), tended to have a lower MIT (4 vs. 6%, $P = 0.10$) but similar HIT (6 vs 6 %) during the annual training year. Although no significant differences were found between groups in terms of improved 1000 m time (~ 8 vs. 6%, $P = 0.20$), it is logical to assume that the best skiers also trained best.

In summary, there is no question of the importance of VO_{2max} for performance in modern XC skiing, as VO_{2max} correlated significantly with FIS distance points. As it has been suggested that only HIT improves VO_{2max} in highly trained athletes (Laursen & Jenkins 2000), this is often used as a justification by coaches and athletes for the increased frequency of HIT sessions performed close to the competition period. However, the subsequent increase in volume of high intensity training during the annual training season seen in *Study III* did not increase VO_{2max}. For coaches, athletes and testing staff these findings can contribute to a better understanding of which variables are expected to change during different parts of the training year for elite XC skiers. For many athletes and coaches, changes in VO_{2max} are synonymous with changes in performance. *Study III* shows that this is not the case and illustrates the importance of a performance test in addition to physiological testing in elite skiers.

7.2 Anaerobic capacity as a determinant of performance (*Studies II-III*)

Due to the nature of XC competitions with repeated high intensity periods, the O_2-demand exceeds VO_{2max} during parts of the competition (Norman & Komi 1987, Norman et al. 1989, Sandbakk et al. 2011[b], *Study II*). This will influence the energy system contribution during a race, and further, anaerobic capacity might be an important determinant of XC skiing performance that to date has been poorly described. The studies in this thesis are the first to estimate anaerobic capacity in XC skiing, with the use of the ΣO_2-deficit method. The anaerobic contribution in typical sprint duration (170 s) was estimated to be ~ 26%, and in slightly longer durations (250-270 s) to be ~ 16-21%. These data seem to fit well with observations from other sports of similar duration (Gastin 2001). The aerobic/anaerobic contributions to total estimated energy turnover in *Studies II-III* and *UR (800 m, ~ 206 s)* are plotted against other studies, exercise modes and durations in Figure 19. Thus, the present studies support the notion that the energy system contribution in XC skiing is similar to what is found in running, bicycling, kayaking, and swimming, at least with the current duration of maximal exercises.
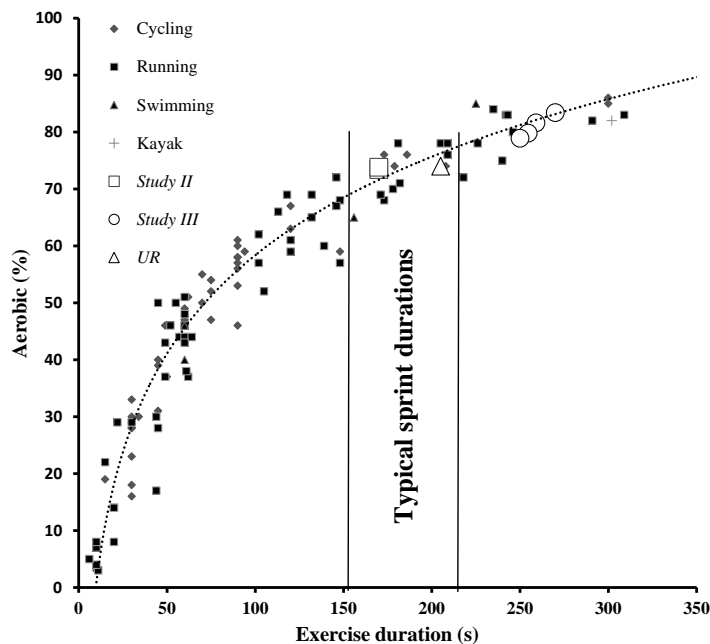
Figure 19. *Aerobic contribution (%) during the time trials in Studies II (600 m), III (1000 m) and UR (800 m, n = 10), together with the findings from other sports (modified from Gastin 2001). Best fitting trend line is shown as a dotted line ($r^2 = 0.94$). The range of typical XC sprint skiing duration is shown as vertical bars (FIS-ski.com).*

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In contrast to distance skiing, the anaerobic capacity seems to be important in sprint skiing, as indicated in the correlation analyses of FIS sprint points and 600 m time (*Study II*) and in group comparisons between levels of sprint skiers (Table 6 and 7). The ΣO_2-deficit correlated significantly with 600 m time, in both V1 and V2, and was the major contributor in explaining the variation in 600 m time between subjects with a large variation in preferred race types. The sprint skiers had a larger ΣO_2-deficit than the distance skiers and the long distance skiers (*Study II*). Furthermore, international-level sprint skiers had a significantly higher ΣO_2-deficit than the international-level distance skiers (~ 81 vs. 63 mL·kg^{-1}, $P < 0.05$, ES = 2.00; Table 6 and 7), and tended to have a higher ΣO_2-deficit than national-level sprint skiers (~ 81 vs. 74 mL·kg^{-1}, $P = 0.14$, ES = 0.83; Table 7). Together, these findings underline the importance of anaerobic capacity as a determinant of performance in sprint skiing.

The higher body-mass and body-mass index in the sprint skiers may partially explain why the sprint skiers seem to have a higher ΣO_2-deficit than the distance skiers. Previous studies have shown that ΣO_2-deficit is related to the muscle mass involved in the exercise (Bangsbo et al. 1990; 1993). Long term heavy strength training will induce increases in muscle cross-sectional area (CSA), and thus, muscle mass in XC skiers (Losnegard et al. 2011). The total volume of strength- and speed training in international-level sprint skiers seems to be significantly higher compared to international-level distance skiers (~ 12% vs 7% of total training time) in the preparation phase (6 months before season), but similar with respect to total time of training (*Study III*, Sandbakk et al. 2011[a]). However, the sprint skiers included less LIT relative to total training than the distance skiers (~ 76 vs 83%) (*Study III*, Sandbakk et al. 2011[a]), which in turn could reduce the negative impairments of combined strength or speed and endurance training for muscle strength adaptations (Rønnestad et al. 2012[a], Losnegard et al. 2011). Thus, it can be suggested that some of the differences in ΣO_2-deficit between skiers (and body-mass) are related to differences in training focus regarding maximal strength, speed and endurance training.

7.2.1 Seasonal variations in ΣO_2-deficit (*Study III*)

The ΣO_2-deficit was significantly increased from May to January. The training logs showed a substantial amount of strength and speed training (8-10 % of total training). This could result in a higher lean body-mass without affecting total body-mass (Losnegard et al. 2011) and

thus, increase ΣO_2-deficit. However, it is not likely that ~ 1-2 % increase in lean body-mass seen after a period of heavy strength training (Losnegard et al. 2011) will result in such large increases (~ 25%) in ΣO_2-deficit (*Study III*). Medbø & Burgers (1990) and Tabata et al. (1996) investigated the effect of 6 weeks of exhaustive intermittent training (20 s to 2 min x 3-8) in sedentary and trained men and found a significant increase (~ 16-28%) in ΣO_2-deficit. The skiers in *Study III* included ~ 6% of HIT together with ~ 10% of speed and strength training which collectively induced a significant anaerobic energy turnover during exercise, and thus, may partially explain some of the changes seen in ΣO_2-deficit. Finally, the increased ΣO_2-deficit might be related to the ability to maintain an effective technique at maximal workloads. The O_2-cost during submaximal loads was significantly reduced from June-October, which in turn might be related to technique improvement. However, this does not take into account the technique improvement in a state of fatigue. Such improvement in technique could reduce 1000 m time without affecting VO_{2max} or O_2-cost at submaximal loads, and to some extent explain the increased ΣO_2-deficit. In terms of fatigability, Joyner & Coyle (2008) described studies where elite cyclists appeared to "rotate" power production through the use of additional muscle mass, thus reducing the stress on any given muscle fibre. They stated that this "power sharing" would reduce the stress on the muscles due to more total mitochondrial sharing for a given rate of aerobic metabolism. Hence, performance could be improved due to a more effective muscle use without affecting VO_{2max} at high intensity.

7.2.2 Reliability of the ΣO_2-deficit (*Studies II-III*)

Notably, there seems to be a relatively large intra-individual variation in ΣO_2-deficit (CV = 9.8%, Table 8, *UR*). ΣO_2-deficit is the result of ΣO_2-demand - ΣO_2-uptake, and the variation in ΣO_2-deficit must rely on one or both of these variables. The ΣO_2-demand should be equal for each subject (Table 8), since the O_2-cost ($ml \cdot watt^{-1}$) ratio was equal in the specific example (based on the same submaximal VO_2 data). However, a small variation was seen in ΣO_2-demand between day 1 and day 2 (CV% = 0.9), and this could be due to the use of 5 s data-saving epochs that were used in order to reduce the amount of data. The ΣO_2-uptake showed a relatively large CV (5.4%), and the intra-class coefficient between delta ΣO_2-uptake (day 1 – day 2) and delta ΣO_2-deficit (day 1 – day 2) was almost perfect (r = 0.98, *P* < 0.05). Therefore, it can be assumed that most of the present variations in ΣO_2-deficit are due to variations in ΣO_2-uptake during the time trial. Why these differences occur is not known,

but it may be related to measurement error (eg., 5 s data epochs), individual day-to-day variation and pacing strategy.

7.3 O$_2$-cost as a determinant of performance (*Studies I-III*)

The importance of O$_2$-cost is emphasized by the finding of a close relationship to performance in groups of heterogeneous XC skiers (Ainegren et al. 2012, Millet et al. 2002, Millet et al. 2003, Mahood et al. 2000). In the present study, no significant relationship was found between O$_2$-cost and performance, and this could be related to the homogeneous group of skiers. Previously, in such groups it has been indicated an "inverse relationship" between O$_2$-cost and VO$_{2max}$, and that the athletes with a relatively low VO$_{2max}$ must compensate with low energy cost and vice versa (Lucia et al. 2002). However, no such relationship exists in the present studies (r = 0.14, *n* = 28). Therefore, to see if O$_2$-cost differentiates skiers with a large range of performance levels, this study investigated O$_2$-cost differences between seven international-level elite skiers (~ 84 mL$\cdot$kg^{-1}$\cdot$min^{-1}) and six non-elite, but highly trained skiers (~ 70 mL$\cdot$kg^{-1}$\cdot$min^{-1}) (data not shown). The elite skiers had a significantly lower O$_2$-cost at submaximal loads (~ 7%, ES = 1.86, *P* < 0.05), underlining O$_2$-cost as an important variable in XC-skiing, at least for a more heterogeneous group of skiers.

Previous studies have investigated the energy cost of skiing using the terms efficiency, economy or O$_2$-cost, which all represent different methodologies. Niinimaa et al. (1978), Hoffman et al. (1995) and Ainegren et al. (2012) used thermal equivalents of O$_2$ and converted this into internal power (J$\cdot$s^{-1}). Further, they divided the external power by the internal power and calculated the efficiency. Sandbakk et al. (2010; 2011[a,b]), and Lindinger & Holmberg (2011) calculated gross efficiency based on total metabolic rate as a function of aerobic and anaerobic metabolism. Here, the anaerobic metabolic rate was calculated based on La$^-$ taken after the submaximal trial. Others have used the O$_2$-cost during submaximal skiing (eg., Mahood et al. 2001, Millet et al. 2003, Kvamme et al. 2005, Losnegard et al. 2011) which was also the term used in this thesis. The latter method could be criticized for not taking the total energy expenditure into account, as the oxygen calorimetric value changes with increasing intensity. Furthermore, La$^-$, as an indication of the anaerobic energy contribution, will influence the total energy expenditure. However, the accuracy of determining anaerobic energy expenditure from La$^-$ values seems uncertain (see Ainegren et al. 2012 for refs). Using the oxygen calorimetric value based on the RER-values and further calculating gross

efficiency had only minor impact on the results in *Studies I-III* (Foss & Hallén 2005). When correlating the gross efficiency (5°, 3 m·s^{-1}) with FIS distance points, only a relation of limited strength was found (r = -0.34, $P > 0.05$, $n = 26$). Here, the external power was 244 ± 21, the internal power 1461 ± 121 W, and thus, gross efficiency was 16.7 ± 0.8%. Hence, gross efficiency in the present study is similar to what has been found in other studies investigating roller ski skating (Sandbakk et al. 2011[a,b]), but this alternative method for determining energy cost did not have a major influence on the conclusions drawn in the present thesis.

7.3.1 Seasonal variations in O$_2$-cost (*Study III*)

The O$_2$-cost at constant workload was significantly reduced during the preparation period from May to October in the eleven skiers who participated in *Study III*. Technical ability (as noted in *Study I*) is likely to affect the O$_2$-cost, and thus, technical improvements could explain some of the changes found in the present study. Importantly, even though no significant correlations were found between O$_2$-cost and performance (600-1000 m time or FIS points), this variable shows a distinct reduction during the annual training seasons. In the five skiers tested over 18 months, O$_2$-cost was reduced by ~ 3% both years, similar to other findings in elite endurance athletes (Jones 1998, Coyle 2005). Thus, it seems obvious that this parameter is of importance for XC-skiing performance despite the non-significant relationship between O$_2$-cost and performance shown above.

To investigate which variables are important for performance, the timing of the testing in relation to the season is important. This is demonstrated by fact that the correlation between the independent variables VO$_{2max}$, O$_2$-cost and ΣO$_2$-deficit and the dependent variable FIS *distance* points (collected in the free technique during the respective season) was insignificant in June (r^2 = 0.37, $P > 0.05$), but was stable and significant in August – January/February testing (r^2 = 0.70, $P < 0.05$). This is also consistent with the inter-individual variations in performance, VO$_{2max}$, O$_2$-cost and ΣO$_2$-deficit, that all showed the highest CV in June. This might be related to the fact that some skiers have a greater seasonal variation than others, as presented above. Thus, a physiological comparison between elite skiers at the early preparation phase can be spurious.

7.3.2 Differences in O_2-cost and performance between V1 and V2 (*Studies I-II*)

Approximately 30-50% of the skier's race time is spent in uphill sections. During racing, skiers exhibit a great range of speeds (~ 3-8 m·s^{-1}, Figure 20) that in turn is related to the length of the race and uphill section, level of skiers and snow conditions (Anderson et al. 2010, Sandbakk et al. 2011[b], Bilodeau et al. 1996). Hence, technique choice could affect the skiers performance. Elite XC skiers use both the V1 and V2 techniques in uphill terrain (Anderson et al. 2010) despite that previous studies have suggested that V1 is superior in terms of lower O_2-cost and better performance on moderate to steep inclines (Boulay et al. 1995, Kvamme et al. 2005). In *Studies I-II*, we found that choice of technique does not influence performance, the maximal energy turnover, or O_2-cost on moderate to steep inclines (4-8°) at the current speeds (3-4 m·s^{-1}). In addition, we demonstrated that the O_2-cost ratio and lactate concentration ratio between techniques is not influenced with greater incline. Hence, it can be assumed that speed, level of skiers and ski glide resistance are the most important factors for technique selection as previously indicated (Anderson et al. 2010).

The different skating techniques can be seen as a "gear system" where the skiers choose technique according to snow condition, speed and work capacity. According to the studies of Kvamme et al. (2005) and Boulay et al. (1995), V1 is superior to V2 at low speed (2.25 - 3.5 m·s^{-1}). At higher speeds, no studies have shown any differences between techniques (Figure 20). However, during races, absolute elite skiers use more of the V2 compared to V1 at speeds > 4 m·s^{-1} (Anderson et al. 2010, Sandbakk et al. 2011[b]). Further, as absolute elite skiers are better able to sustain high speed during repeated uphills sections compared to lower ranked skiers (Anderson et al. 2010), the V2 might be the technique choice for high performers.
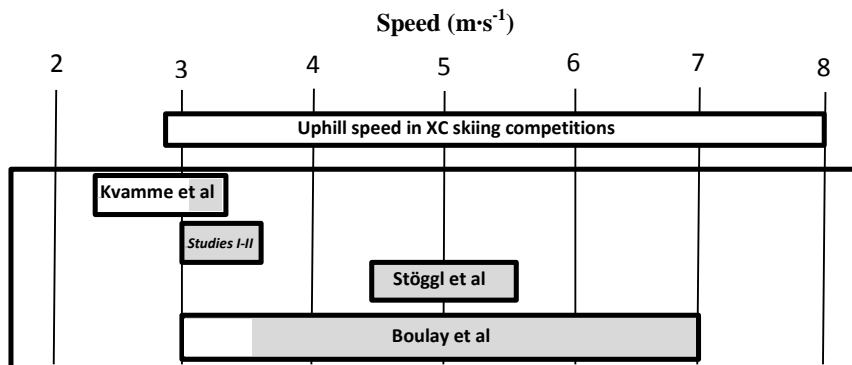
Figure 20. *Speed in uphill terrain during XC-competitions (compiled from Anderson et al. 2010, Sandbakk et al. 2011[b], Bilodeau et al. 1996), and studies that have investigated differences between V1 and V2 (including "jumping V1" or "double push"). Grey bars indicate equal performance or O_2-cost between techniques, while white bars indicate better performance or lower O_2-cost in V1 compared to V2. Data from Kvamme et al. (2005), Stöggl et al. (2010), Boulay et al. (1995) and Studies I-II.*

The reason why we found the same O_2-cost and performance for V1 and V2, even at low speeds (Figure 20), may be related to our subjects' high level. Elite skiers will use more of the "high speed techniques" (e.g., V2) in competitions and training than lower-level skiers, because they have the capacity to use the technique at the speed required. Therefore, elite skiers might adjust the V2 technique according to different speeds and inclines. One of these adjustments may be the ability to preserve a high reliance on leg propulsion even at steep inclines and low speeds. A major upper body contribution to forward propulsion will probably lead to higher lactate production, compared with more use of the legs in ski skating techniques. This notion is based on the findings that the arm muscles have a net release of La^-, while the leg muscles seem to have a net uptake of La^- during whole body exercise (van Hall et al. 2003, Rud et al. 2011). We found a significant correlation between delta La^- and delta O_2-cost, suggesting that skiers with the highest La^- in one specific technique also have a higher O_2-cost (Figure 21). Hence, different use of the arms versus the legs could explain some of the differences between *Study I* and those of Kvamme et al. (2005) (Figure 21).

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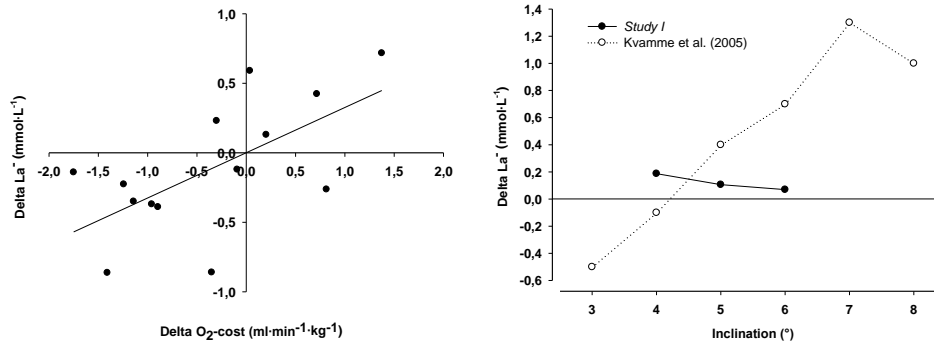
Figure 21. Delta O_2-cost V2-V1 (average 4-6°) compared to delta La⁻ V2-V1 (average 4-6°), $r = 0.64$, $P < 0.05$ (left). Delta La⁻ V2-V1 in Study I and the study by Kvamme et al. (2005). Positive values indicate higher blood lactate concentration during V2 than V1 (right).

In other activities like walking, running and cycling, it has been shown that "gear choice", step frequency or cadence, significantly affects the athlete's work economy and performance (Cavagna & Franzetti 1986, Cavagna et al. 1997, Foss & Hallén 2004; 2005[a]). In addition, the "optimal" step frequency or cadence changes with increasing workloads and, therefore, the choice of cadence may be affected by the performance level of the athletes (Cavagna et al. 1997, Foss & Hallén 2004). This indicates that "optimal" gear choice might also be different between performance levels of athletes in XC skiing. Thus, the similar findings in O_2-cost and performance between techniques might not be true for less skilled skiers.

7.3.3 Individual differences between techniques (*Study I*)

Despite the finding of a close relationship in O_2-cost between the two techniques, there were also consistent individual differences with respect to skiing economy in V1 and V2. This conclusion was based on the fact that most of the subjects ($n = 11$) have been participating in a testing program for 1-3 years using the same testing protocol. For instance, four of these subjects have repeatedly shown the same technique to be the most economical over the last two years during testing. Their most economical technique is also their preferred technique during skiing on snow (personal communications). These four skiers had ~ 2-3% different O_2-cost between techniques (two lowest in V1 and two in V2) and these values are similar to what can be expected to change in O_2-cost during an annual training season (*Study III*). Choice of technique may therefore not be insignificant for the individual skier during racing.

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7.3.4 Kinematic differences between techniques (*Studies I-II*)

Comparison of the techniques from a kinematic view showed that V1 600 m time correlated negatively to greater CR and longer CL, which is in accordance with Smith et al. (1989). Poling rate was ~ 0.90 Hz, which is significantly lower compared to that found at maximal speed (~ 1.30 Hz) at similar inclines (Stöggl et al. 2010). This indicates that the subjects were still able to increase CR to make further improvements in speed, as the CR was far below "maximal CR" in V1. In V2, several authors have associated higher skiing speed with longer CL (e.g., Bilodeau et al. 1996, Sandbakk et al. 2011[b]). This is confirmed in *Study II* where reduced 600 m time was significantly correlated to longer CL. The poling rate in V2 was ~ 1.25 Hz, which is similar to Stöggl et al. (2010) during maximal speed in a steep incline. This indicates that the subjects in the present study work at an upper limit regarding efficient poling rate in V2, and that a further increase in speed must be achieved by increased CL. Altogether, the factors mentioned above could help to explain the different strategies regarding CR and CL in V1 and V2 according to differences in speed between athletes. It is also noteworthy that the correlation between the biomechanical variables from submaximal loads and 600 m time was low and non-significant. Thus, from a practical point of view, technique training might be more appropriate at speeds similar to those used during competition.

Notably, no significant correlation between CR and O_2-cost was found, suggesting that CR alone is not a significant variable with respect to O_2-cost between subjects in ski skating at submaximal loads. This is in line with Leirdal et al. (2011) who investigated high- and low-versus freely chosen frequency in V2 and found that the self-chosen frequency resulted in the best economy.

7.4 Muscle use at low and high intensity (*Study IV*)

Study III revealed that elite XC skiers perform on average 80 ± 4% of their total training at LIT, 5 ± 2% at MIT and 6 ± 2% at HIT during a full sport season. Hence, the majority of the training is conducted at low intensity. In addition, *Study III* also showed that a relatively moderate amount of "specific" training (eg. roller skiing and on snow skiing; ~ 60%) was performed in the pre-competition period compared to sports such as running and cycling (Lucia et al. 2000; 2002, Esteve-Lanao et al. 2007). Because of the nature of XC skiing,

several techniques, with different demands on different muscles, are used and must be included in training. Therefore, skiers have limited amounts of time to execute the respective techniques. Of special interest in XC skiing is the contribution of the upper and lower body to forward propulsion. In the present study, we investigated this phenomenon during DP (*Study IV*). The DP technique serves as an ideal movement for physiological and biomechanical research (Holmberg et al. 2005, Lindinger et al. 2009[b], Calbet et al. 2004).

The PET-scan method was used for the first time to study the contribution of different muscles during whole-body exercise (*Study IV*). We confirmed that DP mainly involves the triceps brachii followed by the latissimus dorci, the teres major, the pectoralis major and the posterior part of the deltoid muscle (Holmberg et al. 2005, Lindinger et al. 2009[a]). More importantly, these muscles show only a limited increase in glucose uptake when exercise intensity increases, while the knee extensors, knee flexors and muscles around the hip to a greater extent increased their glucose uptake. This suggests that the relative contribution from lower-body muscles increases with increasing work intensity. Together with previous studies (Calbet et al. 2004; 2005, Rud et al. 2011), *Study IV* indicates that arm and shoulder muscles reach a plateau in energy output at submaximal levels, and that further increases in whole-body exercise intensity during DP are covered by muscles of the lower part of the body. Calbet et al. (2005) showed that elite XC skiers have similar O_2-extraction in the arms as physically active subjects have in the legs, but still lower than in the leg muscles of well-trained subjects. It has been proposed that this is due to lower mean capillary transit time and lower diffusing area in the arms compared to the legs (Calbet et al. 2005). Further, Rud et al. (2011) tested well-trained XC skiers in DP ($VO_{2max}DP$; ~ 61 mL·kg^{-1}·min^{-1}) on a very similar relative workload (~ 54 and 76% of $VO_{2max}DP$) as that of *Study IV*. They showed that the increased O_2-uptake in the arms (~ 20 %) was due to increased blood flow, while the increased O_2-uptake in the legs (~ 50 %) was related to both increased blood flow and O_2-extraction. Hence, the arms seem to have a lower muscular oxidative capacity than the legs even in well-trained XC skiers. Although a quite different methodology was used by Rud et al. (2011) compared to that of *Study IV*, the results together indicate that well-trained skiers work close to the maximum capacity for arm muscles even at low to medium intensity (~ 53-76% of $VO_{2max}DP$). Therefore, for the present group of skiers (highly trained, but not elite level), the optimal choice of technique during competition may be to involve the legs for propulsive force (double poling with kick or diagonal stride) when exercise intensity is high.

7.4.1 Integrated biomechanical and physiological aspects

To increase the speed and thus performance in DP, elite skiers increase both the CR and CL (Lindinger et al. 2009[b]). The latter is possible due to an increased force production during a brief poling time and due to a more accentuated flexion–extension pattern in the shoulder, elbow and lower body joints (Holmberg et al. 2006, Lindinger et al. 2009[b]). Hence, change in speed or workload leads to changes in kinematics, which in turn will elicit changed physiological response. The latter is demonstrated in *Study IV* which showed that different muscle use distribution in the upper versus the lower body is evident at different workloads. Thus, an increased intensity can only be accomplished by a change in the DP technique towards greater involvement of muscles in the central and lower body, which confirms previous results (Holmberg et al. 2005; 2006, Lindinger et al. 2009[b], Rud et al. 2011). Further, the increased workload must rely on changes in hip, knee and/or ankle joint flexion-extension pattern. In *Study IV*, no data are available for the knee or ankle joints but no changes in hip joint movement were found. However, Rud et al. (2011) showed an increased vertical hip displacement, and thus, changes in knee joint ROM at increased workload during ergometer DP. Hence, these technique adjustments may have occurred also in *Study IV* and will further induce an increase in the energy turnover in the thigh muscles, especially the knee flexors and extensors. This notion is supported by the increased glucose uptake found in *Study IV*. As also noted from the kinematic data in *Study II*, specific training is not only related to choice of exercise, but also the work intensity performed by the skier.

Notably, the subjects in *Study IV* and Rud et al. (2011) were tested on an ergometer and not on rollerskis or snow skis. Hence, differences between testing modes concerning technique and kinematical aspects are likely to occur. During ergometer DP the legs counteract the vertical force (displacement in the hip), but importantly, also horizontal forces to avoid falling forward. The latter could induce an altered activation strategy and an extra metabolic stress on the legs during the pole push compared to that of roller skiing or snow skiing. In addition, a more forward-leaning body position using a so-called "high heel-hip-ankle" strategy is seen during rollerskiing (Holmberg et al. 2005) which cannot be performed during ergometer DP. Hence, it should be kept in mind that testing modes (ergometer vs. ski) could reflect somewhat different biomechanical as well as physiological outputs.

7.4.2 Strength and limitations of the PET method

PET yields detailed information about the whole muscle without catheter-induced stress or any invasive manipulation. Compared to surface electromyography that only enables assessment of superficial muscles, and has some limitations during dynamic contractions, PET enables assessment of muscles that lye deep in the body. For example, the present investigation revealed that the hip-flexors seem to be major contributors to DP propulsion. In addition, individual activation strategies can be identified with PET, as heterogeneous activation of different parts of the same muscle can be investigated (Figure 22). As an example, the method is suitable for investigating whether the same muscle displays heterogeneous activation with different intensity of exercise or technique modifications. However, it should be noted that PET only accounts for muscle glucose uptake, and it is clear that other substrates such as lactate and fat are metabolized in the active muscle cells. Thus, PET is just an indicator of the total energy turnover in the muscles. In addition, PET displays poor time resolution such that if subjects change technique during exercise this is not reflected in the results. Finally, major limitations are the demands of the infrastructure (targetry, radiochemistry and scanning), complexity of modelling and costs.
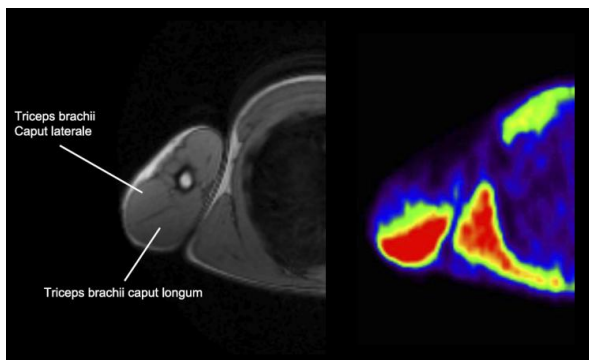
Figure 22. *Example of an individual that displayed an activation strategy in which mainly the medial head of the triceps was activated. This difference would not have been accounted for in a study using surface electromyography if electrodes were only placed on one portion of the muscle as has previously been done. Red color denotes greatest glucose uptake.*

7.5 Practical applications

Elite skiers' technique selections are not determined by degree of incline, but more likely by speed. Some individual skiers prefer V1 and some V2 on moderate to steep inclines, while there are on average no significant differences between techniques according to O_2-cost, the energy turnover, or performance. Selecting the optimal technique for the individual skier seems important as up to 3% differences in O_2-cost was found between techniques for some skiers, equal to the magnitude that O_2-cost can be expected to change during a full sport season. Thus, coaches should be cautious when recommending technique choice for a whole group, given the individual variation between athletes.

Including a time-trial test under controlled conditions allows for comparison of performance and physiological responses between and within athletes. For the athletes, a time trial test is the ultimate evaluation of technique choice or training-induced changes. In addition, such tests allow scientists to investigate several variables, such as the ΣO_2-deficit which was examined for the first time in XC skiing in the present studies. The ΣO_2-deficit differentiates skiers according to a sprint performance, but more surprisingly, showed a significant improvement during the preparation phase in distance and sprint skiers although they did not perform a significant amount of "anaerobic training". At the same time, VO_{2max} was unchanged from summer to winter testing, and could therefore not explain the improved performance. These findings might challenge the traditional assumptions about the type of training that improves specific determinants of performance in elite skiers. However, VO_{2max} is the single most important factor for elite XC skiing, at least for distance skiing performance. Thus, even though new appraisals of performance factors have occurred over recent decades, athletes and coaches must always have this in mind when planning and performing training. Finally, this study demonstrated that technique training as well as training for muscular endurance may be optimal at higher workloads, to simulate specific muscle use or movement patterns.

8 CONCLUSION

In conclusion, the present study demonstrated:

1. Maximal aerobic power, maximal anaerobic capacity and O_2-cost seem to be the most important determinants of performance in modern elite XC skiing. However, while distance skiing performance mainly requires a high VO_{2max} relative to body-weight, sprint skiing performance also requires a high absolute VO_{2max} and anaerobic capacity (*Studies I-III*).

2. Technique choice (V1 or V2) in moderate to steep incline did not influence performance, energy turnover or O_2-cost in elite skiers (*Studies I-II*).

3. Improved performance during an annual training season was related to enhanced ΣO_2-deficit and O_2-cost, while VO_{2max} remained unchanged (*Study III*).

4. During double poling, the muscles of the upper extremity displayed a limited increase in glucose uptake with increasing work intensity compared to that of leg muscles and muscles around the lower spine (*Study IV*).

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10 PAPER I-IV

I   **Losnegard T**, Myklebust H, & Hallén J (2012). No differences in O_2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *Journal of Strength and Conditioning Research* 26(5):1340-7.

II   **Losnegard T**, Myklebust H, & Hallén J (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Medicine & Science in Sports & Exercise* 44(4):673-681.

III   **Losnegard T**, Myklebust H, Spencer M, & Hallén J. Seasonal variations in VO_{2max}, O_2-cost, O_2-deficit and performance in elite cross-country skiers. *Journal of Strength and Conditioning Research* (Accepted).

IV   Bojsen-Møller J, **Losnegard T**, Kemppainen J, Viljanen T, Kalliokoski KK, & Hallen J (2010). Muscle use during double poling evaluated by positron emission tomography. *Journal of Applied Physiology* 109:1895-1903

No differences in O_2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines.

No Differences in O_2-Cost between V1 and V2 Skating Techniques During Treadmill Roller Skiing at Moderate to Steep Inclines

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Abstract

Losnegard, T, Myklebust, H, and Hallén, J. No differences in O_2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *J Strength Cond Res* 26(5): 1340–1347, 2012—Elite crosscountry skiers use both the V1 and V2 techniques on moderate and steep inclines despite previous studies suggesting that the V1 technique is superior in terms of lower O_2-cost and better performance on these inclines. However, this has not been studied in elite athletes, and therefore, the aim of this study was to compare O_2-cost in these 2 main ski skating techniques in a group of 14 elite male crosscountry skiers (age: 24 ± 3 years, height: 184 ± 6 cm, weight: 79 ± 7 kg, V1 $\dot{V}O_2$max: 71.8 ± 3.5 ml·kg^{-1}·min^{-1}). With both techniques, the athletes performed submaximal trials for the determination of O_2-cost on a roller ski treadmill at 4, 5, and 6° (3 m·s^{-1}) and maximal trials at 8° (≥ 3 m·s^{-1}) for the determination of $\dot{V}O_2$max. Video-based kinematic analyses on cycle length and cycle rate (CR) were performed to unravel if there was any relation between these variables and O_2-cost. No significant differences in O_2-cost or $\dot{V}O_2$max between techniques were found. However, large and significant individual variations in physiological response were observed. V2 had a longer cycle length and lower CR than V1 did. No significant correlation was found between CR and O_2-cost. This study shows that both V1 and V2 are appropriate techniques for optimizing O_2-cost on moderate to steep inclines in elite skiers. However, individual variation suggests that ski skating performance on moderate to steep inclines may be determined by technique preferences of the athletes.

Key Words crosscountry skiing, elite skiers, interindividual variations, skiing techniques, $\dot{V}O_2$max, work economy

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Introduction

Since the official appearance of the ski skating technique in the middle of the 1980s, remarkable technique development has occurred. Introduction of new types of races as the sprint event and mass start and better track preparation, improved equipment, and changes in course profiles have contributed to this development (11,29). Ski skating consists of several different techniques that can be considered as a gear system wherein the skiers can freely choose their technique according to the terrain, snow condition, and speed. Their choice will be influenced by their experience, beliefs, and knowledge concerning the optimal technique for performance in that particular situation.

The speed achieved in competition depends on several physiological and mechanical factors. One of these factors is the O_2-cost of locomotion, defined as the amount of energy spent per unit of velocity (6), and there have been reports about a close relation between O_2-cost and performance in several endurance sports (5,21), including crosscountry skiing (16,17,20). According to the rules of the International Ski Federation (FIS), one-third of a crosscountry ski race must be uphill with a gradient between 4.5 and 9° (7), and approximately half of the skier's race time is spent in uphill sections (1). Hence, the O_2-cost of different techniques on uphill terrains will probably influence the skiers' performance.

The primary ski skating technique used on flat terrains and moderate uphill terrains is V2 (also called "gear 3" or "double dance"), whereas V1 (also called "gear 2" or "paddling) is traditionally used on steeper inclines, and this choice has been supported by research showing that on these inclines, V1 is more economical than V2 (14). However, recently, it has been observed that some elite crosscountry skiers use the V2 technique even on steep uphill terrain (1). In the V1 technique, skiers use their poles on every second leg push-off (left or right) in contrast to the V2 technique, where the poles are used on every leg push-off.

It is also evident that the cycle rate (CR) varies substantially among skiers (18), and routine testing has shown a large interindividual variation in O_2-cost. From a kinematic point of view, CR has been shown to influence O_2-cost in different

sports such as bicycling and running (9). However, it is less known if CR relates to some of the differences in O_2-cost between skiers in V1 and V2 ski skating techniques.

Although previous studies have investigated physiological, kinetic, and kinematic differences between V1 and V2 ski skating techniques (2–4,14,17,19,27), there is little updated knowledge on the physiological and kinematical aspects in elite skiers using different ski skating techniques on uphill terrains. The purpose of the study was therefore to compare V1 with V2 with regard to O_2-cost, $\dot{V}O_2$max, and kinematic aspects during treadmill roller skiing at moderate to steep uphill inclines in elite crosscountry skiers. Based on the previous literature, we hypothesize that the O_2-cost will be lower for the V1 compared with the V2 ski skating technique on steep inclines. Second, we hypothesize that the variance in CR would be associated with variance in O_2-cost among subjects.

METHODS

Experimental Approach to the Problem

This study used a within-subject repeated-measures design to determine if V1 and V2 differ in O_2-cost and $\dot{V}O_2$max at moderate to steep inclines. To do this, elite male crosscountry skiers were tested at 3 submaximal loads with V1 and V2 to determine O_2-cost and maximal bouts with both techniques to determine $\dot{V}O_2$max. All testing was conducted over 2 days near the beginning of the season, from mid-September to late November. Day 1 included submaximal tests at 4 and 5° inclines with both techniques and a $\dot{V}O_2$max with one of the techniques. Day 2 was similar, with submaximal tests at 4° (to measure the coefficient of variation) and 6° inclines (instead of 5°), and the skating technique during the $\dot{V}O_2$max test was changed. The 4° submaximal test on day 2 is reported in the final Results section. For 10 of the subjects, there was at least 1 rest day between days 1 and 2. However, for 4 subjects, it was not possible to have a rest day, and they were tested consecutive to day 1. Testing was counterbalanced for the type of ski technique to eliminate the potential influence of testing order, and this order of technique was consistent for each subject between inclines and tests. Each subject was tested at the same time of the day.

Subjects

Fourteen elite senior male crosscountry skiers (age: 24 ± 3 years, height: 184 ± 6 cm, weight: 79 ± 7 kg) volunteered to participate in the study. The subjects had regularly participated in roller ski treadmill testing over the previous 1–3 years and were therefore familiar with the testing. All the skiers competed at the Norwegian national level at a high standard. Among the subjects, there were one World-cup winner, 6 skiers with top 30 results in World-cup races, 3 skiers with several top 10 results in FIS long distance races, and all 14 skiers had top 30 results in the Norwegian championship. The study was approved by the Regional Ethics Committee of Southern Norway, and the subjects gave their written consent before study participation.
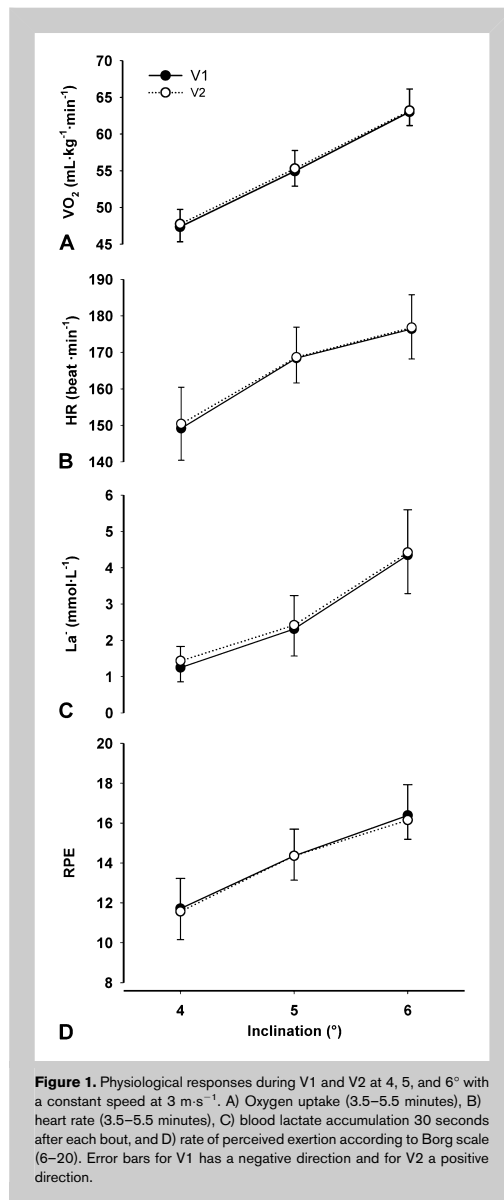
Figure 1. Physiological responses during V1 and V2 at 4, 5, and 6° with a constant speed at 3 m·s^{-1}. A) Oxygen uptake (3.5–5.5 minutes), B) heart rate (3.5–5.5 minutes), C) blood lactate accumulation 30 seconds after each bout, and D) rate of perceived exertion according to Borg scale (6–20). Error bars for V1 has a negative direction and for V2 a positive direction.

Procedures

Submaximal Oxygen Cost. Submaximal tests were all performed at a speed of 3 m·s^{-1}, lasted 6 minutes, and with 2-minute breaks between bouts. The speed was chosen to be high enough to induce a relevant technique at moderate inclines but low enough to obtain a steady state $\dot{V}O_2$

TABLE 1. Physiological responses and time to exhaustion during the $\dot{V}O_2$max tests.

Inclination	Variable	V1 Mean ± SD	V1 Range	V2 Mean ± SD	V2 Range
8°	$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	71.8 ± 3.5	65.1–76.9	71.5 ± 3.3	64.9–76.7
	$\dot{V}O_2$ (L·min^{-1})	5.66 ± 0.4	4.88–6.67	5.65 ± 0.5	4.67–6.80
	HR (b·min^{-1})	189 ± 7	181–202	187 ± 6	181–200
	BF (breath·min^{-1})	56 ± 7	46–68	57 ± 10	43–73
	V_E (L·min^{-1})	189 ± 17	158–223	185 ± 13	150–200
	RER	1.09 ± 0.05	1.00–1.18	1.10 ± 0.05	1.01–1.16
	La$^-$ (mmol·L^{-1})	7.5 ± 0.6	6.5–8.7	7.4 ± 0.7	6.5–8.8
	Time to exhaustion (s)	286 ± 29	240–330	279 ± 31	240–330

$\dot{V}O_2$ = oxygen uptake; HR = heart rate; BF = breath frequency; V_E = ventilation; RER = respiratory exchange ratio; La$^-$ = blood lactate concentration.
Values are mean ± SD and ranges ($x_{min} - x_{max}$).
All physiological variables presented as the average over 60 seconds. One exception is La$^-$, which is taken 1 minute after the test.

(<90% of $\dot{V}O_2$max). Blood plasma lactate concentration was measured 30 seconds into the break after each 6-minute effort. Because of the O_2 measurement apparatus, the subjects were unable to express their rating of perceived exertion (RPE) during the trial. Therefore, at 4 minutes into the trial, they were asked to choose their RPE, which they then reported at the end of the trial. O_2-cost in this study was defined as the average oxygen uptake (milliliters per kilogram per minute) between 3.5 and 5.5 minutes at each submaximal bout. The reliability coefficient (typical error expressed as CV) for the O_2-cost from the 4° (days 1 and 2) was 2.5% (V1) and 2.3% (V2).

Maximal Oxygen Consumption. Eight minutes after the last submaximal effort, the subjects performed the $\dot{V}O_2$max test. The starting incline and speed were 6° and 3 m·s^{-1}. The initial speed was kept constant, and the incline was subsequently increased by 1° every minute until 8°. Thereafter, the speed was increased by 0.25 m·s^{-1} every minute. Skiing to exhaustion and a plateau in $\dot{V}O_2$ were used as criteria to indicate that $\dot{V}O_2$max was reached. Oxygen uptake was measured continuously, and the highest mean values over 1 minute was taken as $\dot{V}O_2$max. A safety harness with autostop (in the case of a fall) secured the subjects during the $\dot{V}O_2$max tests. The reliability coefficient (typical error expressed as CV) for the $\dot{V}O_2$max tests has been shown to be 2.2% (V1) and 2.7% (V2) ($n = 11$; 2 trials) in our laboratory.
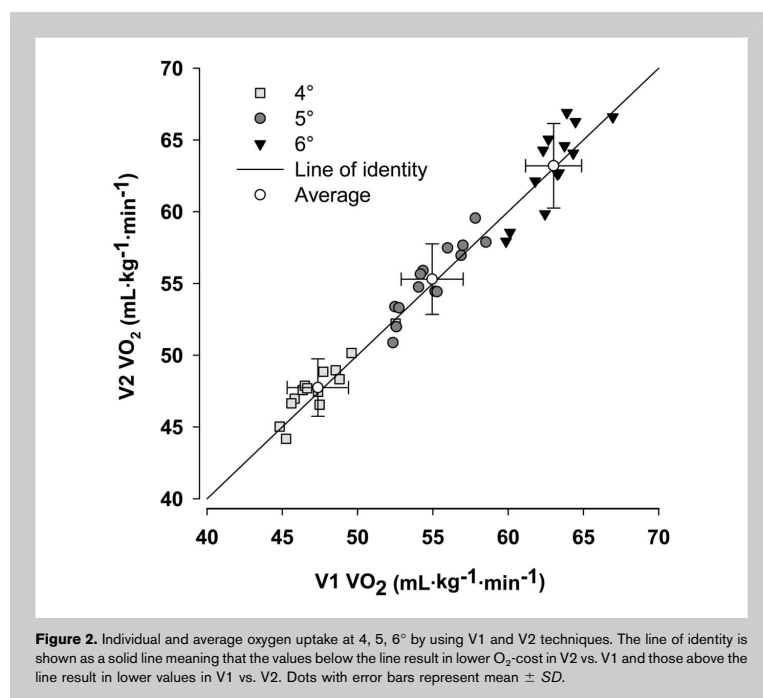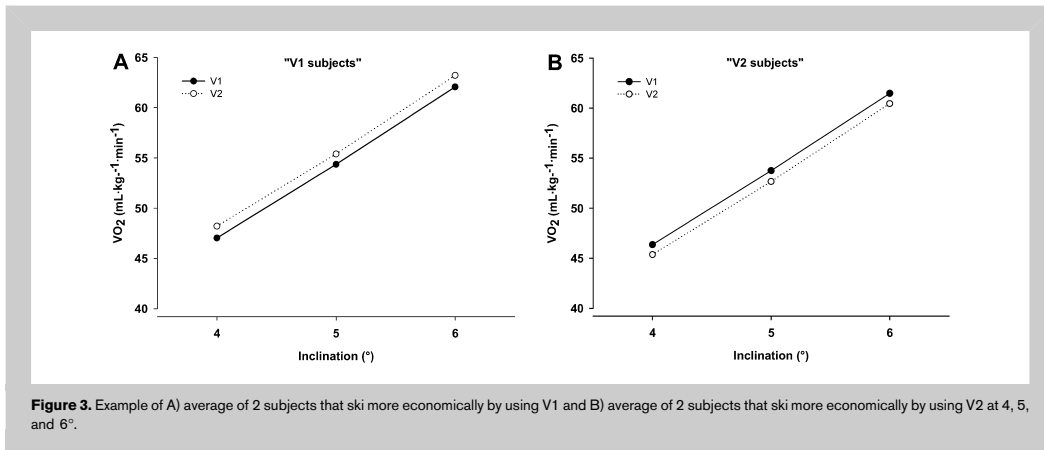

Figure 2. Individual and average oxygen uptake at 4, 5, 6° by using V1 and V2 techniques. The line of identity is shown as a solid line meaning that the values below the line result in lower O_2-cost in V2 vs. V1 and those above the line result in lower values in V1 vs. V2. Dots with error bars represent mean ± SD.

Figure 3. Example of A) average of 2 subjects that ski more economically by using V1 and B) average of 2 subjects that ski more economically by using V2 at 4, 5, and 6°.

Assessment of Individual Variability. Interindividual variation in O_2-cost at a specific workload was calculated as the *SD* of the O_2-cost of the skiers divided by the mean value. Delta economy was measured as the increase in oxygen uptake per degree change in incline. Interindividual coefficient of variance in delta economy was calculated as the *SD* in delta economy divided by the mean value. The intraindividual coefficient of variance in the gross economy between the 2 techniques was calculated as the *SD* of the difference in O_2-cost between techniques, divided by the mean value.

Kinematic Parameters. Cycle rate and CL were calculated using video analysis. One cycle was defined as the time between

consecutive right pole plants for V1, and the time between every other right pole plant for V2 (19). An average of 9 ± 2 consecutive cycles was used for calculating the CR. Mean CL was calculated as treadmill velocity divided by CR.

Apparatus. Oxygen consumption ($\dot{V}O_2$) was measured by an automatic system sampling in 30-second epochs (Oxycon Pro Jaeger Instrument, Hoechberg, Germany) evaluated by Foss and Hallén (9). Heart rate (HR) was measured between 3.5 and 5.5 minutes with a Polar S610i[TM] (Polar electro OY, Kempele, Finland), and blood lactate concentration was measured in unhemolyzed blood, collected from capillary fingertip samples. Blood was collected in a heparinized capillary tube, and 25 μL was injected with a pipette into the mixing chamber of the lactate analyzer (YSI 1500 Sport, Yellow Springs Instruments, Yellow Springs, OH, USA). The lactate analyzer and Oxycon Pro Jaeger Instrument were calibrated according to the instruction manual and described in detail by Losnegard et al. (15). All testing was performed on a roller ski treadmill with belt dimensions of 3×4.5 m (Rodby, Sodertalje, Sweden). Inclines and speed were calibrated before the start of the study and checked during and after the testing period. Swix CT1 poles (Swix, Lillehammer, Norway) with customized treadmill roller skiing tips were used (pole length 167.5 ± 5.5 cm, corresponding to 91% of

Figure 4. Individual cycle rate at 4–6° with a constant speed at 3 m·s⁻¹.

Figure 5. Cycle rate in relation to O$_2$-cost at V1 (A) and V2 (B) at 4, 5, and 6°. Solid lines are trend lines for the respective inclines.

body height). Two different pairs of Swenor Skate skis (Swenor, Sarpsborg, Norway) with wheel type 1 were used depending on the binding system the skiers normally used (NNN, Rottefella, Klokkarstua, Norway or SNS, Salomon, Annecy, France). The rolling friction coefficient (μ) of the skis was tested before, during, and after the project using a towing test, previously described by Hoffman et al. (10). All the tests were performed after warming up with 15 minutes of treadmill roller skiing at a 3° incline at constant individually selected speed (2.25–2.75 m·s^{-1} corresponding to ~60–75% of the HRmax). This served as a warm-up for both the athlete and

the roller skis, which acquired a friction coefficient of 0.018 (NNN) and 0.020 (SNS). The breaks between warm-up, recovery, and tests trial were limited to 2 minutes to maintain stable rolling friction. The subject's body weight was measured before each treadmill test (Seca, model 708 Seca, Hamburg, Germany). The motions of the skiers were filmed with a stationary 50-Hz video camera (Sony DCR-TRV900E, Sony, Tokyo, Japan). The distance between the camera and skiers was 5 m. The camera was positioned perpendicular to the skiing direction and, Dartfish Connect 4.5 (Dartfish Ltd., Fribourg, Switzerland) was used for counting frames in a cycle.

Statistical Analyses

All data were checked for normality with a Shapiro-Wilk test and presented as mean and *SD*. Paired *t*-tests were used for detecting significant differences in O$_2$-cost at each incline during submaximal testing and V̇O$_2$max, between V1 and V2 techniques. A one-way repeated-measure analysis of variance was calculated to analyze the changes in CR over the 3 different inclines. When global significance over time was determined, Bonferroni post hoc analysis was used to determine changes over inclines. Pearson's product moment correlation analysis was used for correlation analyses. The magnitude of differences between techniques was also expressed as standardized mean differences (Cohen's *D* effect size; ES). The

Figure 6. Delta La$^-$ V2–V1 in this study and in the study of Kvamme et al. (14) at different inclines. Positive values indicate higher blood lactate concentrations during V2 than during V1.
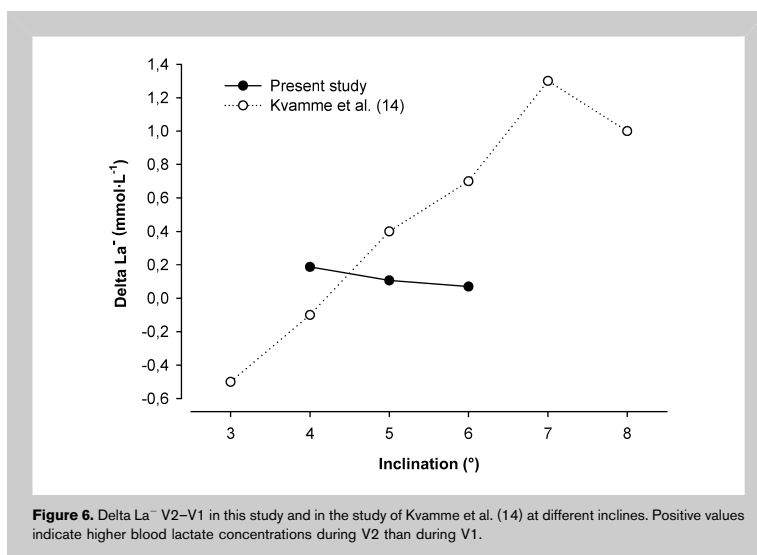
criteria to interpret the magnitude of the ESs were as follows: 0.0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and >2.0 very large (13). Statistical calculations were performed using Microsoft Excel and SigmaPlot 11 software. A p-value ≤0.05 was considered statistically significant.

RESULTS

Submaximal Oxygen Cost and Maximal Oxygen Consumption

The mean O_2-cost at 4, 5, and 6° inclines corresponded to approximately 67, 77, and 87% of $\dot{V}O_2$max values, respectively. The mean HR was 80, 90, and 94% of HRmax as measured during the $\dot{V}O_2$max tests. There were no differences in O_2-cost or HR, La⁻, and RPE during submaximal tests between ski skating techniques at any incline (Figure 1). Time to exhaustion and all the physiological variables during the maximal tests were similar between V1 and V2 (Table 1). The magnitude of the differences in physiological responses between techniques, expressed as standardized mean differences (effects size), was trivial to small. Effect sizes in O_2-cost between V1 and V2 at 4, 5, and 6° were 0.24, 0.08, and 0.05, whereas in $\dot{V}O_2$max the effect size between V1 and V2 was 0.26.

Assessment of Individual Variability

There was a large interindividual variation in the O_2-cost at a specific workload. There were also some consistent intraindividual differences between techniques (Figures 2 and 3) meaning that the same subject had a higher O_2-cost with one of the techniques at all inclines. The absolute difference in the O_2-cost (milliliters per kilogram per minute) at a specific load between the most and the least economical skiers was typically >15% (Figure 2). The interindividual coefficient of variance in O_2-cost was between 3 and 4.7% and decreased with increasing incline in V1 but stayed constant in V2. This is in line with the finding that the interindividual coefficient of variance in delta economy, measured as the increase in oxygen uptake per degree change in incline, was larger in V2 than in V1 (11.5 vs. 7.5%). The intraindividual coefficient of variance in gross economy between the 2 techniques was 1.6%. There was no difference in the average $\dot{V}O_2$max between V1 and V2, but the intraindividual coefficient of variance in $\dot{V}O_2$max between the 2 techniques was 3.4%.

Kinematic Parameters

Cycle rate increased significantly between inclines ($p < 0.05$), and the values at 4–6° were 0.72 ± 0.05, 0.75 ± 0.05, and 0.78 ± 0.04 Hz in V1 and 0.51 ± 0.05, 0.53 ± 0.05, and 0.55 ± 0.04 Hz in V2, respectively. The interindividual coefficient of variance in CR, measured as the average CR at 4, 5, and 6°, was 5.8% (V1) and 8.6% (V2). Despite the large variation in both CR and O_2-cost, there was no significant correlation between the 2 variables (Figures 4 and 5).

DISCUSSION

We found no significant differences between V1 and V2 in the O_2-cost at moderate to steep inclines (4–6°) which is in

contrast to the findings of previous studies (14,17). Millet et al. (17) compared V1 and V2 on snow on different types of terrain and reported a higher O_2-cost in V2 than in V1. However, this study is not directly comparable with our study because of the differences in terrain and level of skiers. Kvamme et al. (14) studied well-trained Nordic combined and biathlon athletes on treadmill inclines and durations that were identical to those of this study. They suggested that V1 has a lower O_2-cost at steeper inclines (>4°) than V2 has. A striking difference between the results of the 2 studies is the blood lactate response. In Kvamme et al. (14), the difference in postexercise lactate between the 2 techniques increased with increasing incline, with the lactate concentration being highest during V2 at inclines >4°. In the present study, there was no difference in the lactate response at any incline (Figure 6). It has previously been shown that in double poling, where most of the total work is achieved from the upper body musculature, the arms have a net release of lactate whereas the legs have a net uptake of lactate (30). Hence, a major upper body contribution to forward propulsion will probably lead to a higher lactate production, compared with a greater use of the legs in ski skating techniques. This may indicate that the balance between leg and upper body contribution to the propulsion shifted more to upper body work as the incline increased for the subjects reported by Kvamme et al. (14). The lack of such a lactate response in this study may indicate that our subjects were able to preserve the high reliance on leg propulsion even at steep inclines. This concurs with the finding that the difference in blood lactate between techniques correlates with the differences in O_2-cost (data not shown). It should be noted that the skiers in the study of Kvamme et al. (14) probably have less ski skating experience, because most of the subjects were well-trained Nordic combined athletes and not elite crosscountry skiers. These factors together could explain some of the different results between studies.

Skiing techniques have evolved with the development of sprint skiing and mass start abilities (28,29). The change in training focus because of the change of competition formats might have led to a more adjustable V2 technique, such as timing in leg push vs. pole push and direction of skis in the set down phase of the skis, as described by Stöggl et al. (29). Optimal timing between arms and legs may have compensated for the possible suboptimal force direction of the V2 technique.

This study was carried out with roller skis on a large treadmill, and it should be noted that there is limited information on how the findings observed in the laboratory could be applied to skiing on snow. Nevertheless, elite crosscountry skiers include high volumes of roller ski training in the precompetition phase and during this training our elite skiers aim to simulate on-snow skating more than achieving an optimal roller skating technique. Also, previous studies on treadmill roller skiing show a strong correlation with on-snow skiing performance (16,25). Interestingly, some skiers prefer either V1 or V2 during on-snow skiing, and we noted that in

some of the most extreme skiers, these preferences concur with the most economical technique during treadmill skiing. Millet et al. (17) compared V1 and V2 on snow on different types of terrains and reported a higher O_2-cost in V2 than in V1 in nonelite crosscountry skiers, the same conclusion as that reached by Kvamme et al. (14) in a similar group of skiers during roller skiing. Hence, we think that the results from roller ski testing are valuable for on-snow skiing, but the results should of course be used with caution.

The coefficient of variance in the O_2-cost between subjects, measured as the average oxygen uptake at 4, 5, and 6° was 3.4% (V1) and 4.2% (V2). The coefficients of variance in O_2-cost (for running) and gross efficiency (for cycling) have been shown to be 1.8–5.0 and 3.0–6.2%, respectively (12,22,23,26). Hence, the individual variations in work economy in crosscountry skiing seem to be similar to cycling and running. This may be somewhat surprising because crosscountry skiing synchronizes both the upper and lower body and may be a more challenging technique than either running or cycling. Another striking finding is the close relationship between the O_2-cost in the 2 techniques. For example, the subjects who were most economical in V1 were also relatively economical in V2 (Figure 2). Because all of our subjects are elite skiers and high performers, this indicates that, in crosscountry skiing, the O_2-cost is partly determined by intrinsic factors.

It has been observed that elite crosscountry skiers and biathlon athletes use different ski skating techniques under similar conditions and have preferences when it comes to choice of technique. Despite the fact that there was a close relationship between O_2-cost of the 2 techniques, there were individual differences, with some athletes being most economical in V1 and some in V2. In general, the coefficient of variance in the difference in O_2-cost between the 2 techniques was 1.6% and not very different from the test-retest reproducibility (4°, day 1 to day 2). However, there are 3 factors that indicate that this is because of individual differences rather than measurement variability. First, we tested the different inclines and techniques over several days in a balanced order, and the differences in these skiers were consistent between days. Second, there was a close relationship between the difference in blood lactate concentration and the difference in O_2-cost. Third, most of the subjects in this study ($n = 11$) have been participating in a testing program during the last 1–3 years using the same testing protocol. For instance, 4 of these subjects have repeatedly tested the same technique as the most economical over the last 2 years (Figure 3). Their most economical technique is also their preferred technique during skiing on snow. Hence, choice of technique may nevertheless not be insignificant for the individual skier.

Cycle rate increased linearly from 4 to 6° with a constant speed at 3 $m \cdot s^{-1}$ (Figure 4). Furthermore, CR was highest and CL shortest during V1, which is in agreement with the findings of previous studies (2,3,17,19,24,27). It is well known that CR (or cadence) influences the O_2-cost in other endurance sports, such as bicycling and running (9) and that this phenomenon has also been observed in crosscountry skiing (18). However, despite the large interindividual variance in CR (V1: 5.8%, V2: 8.6%) and gross economy (V1: 3.4%, V2: 4.2%), no significant correlations between CR and O_2-cost (Figure 5), CR and anthropometric data (weight, height), or CR and pole length data were found in this study. This shows that CR alone is not a significant variable with respect to O_2-cost between subjects in ski skating at submaximal loads.

PRACTICAL APPLICATIONS

This study revealed similar oxygen costs between V1 and V2 ski skating techniques, across multiple inclines. Our results also indicate that elite skiers' technique selections are not determined by degree of incline, because the velocity was constant at all inclines. The differences in O_2-cost between techniques were consistent at all inclines for the individual skier, and consequently, some skiers may prefer V1 and some V2 on moderate to steep inclines. These observations can contribute to optimization and evaluation of training preparation and competition strategies for individual athletes. Thus, coaches should exercise caution when recommending the technique choice for a whole group, because individual variation must always be considered. It is probably essential to take into account a skier's training history and technique focus when selecting a technique for various terrains. In addition, skiers usually shift between techniques even on constant uphill terrain. Therefore, it is important for the athletes to improve their skill and physiological capacity in both techniques, thus improving their weakest technique.

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PAPER II

Anaerobic Capacity as a Determinant of Performance in Sprint Skiing

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ABSTRACT

LOSNEGARD, T., H. MYKLEBUST, and J. HALLÉN. Anaerobic Capacity as a Determinant of Performance in Sprint Skiing. *Med. Sci. Sports Exerc.*, Vol. 44, No. 4, pp. 673–681, 2012. **Purpose**: As cross-country sprint competitions rely on maximal-effort durations of ∼3 min, a significant anaerobic energy contribution is expected. Anaerobic energy production during supramaximal exercise has been estimated in different sports from the accumulated oxygen deficit (ΣO_2 deficit) but, to date, not in cross-country skiing. Therefore, this study investigated the relative contribution of the aerobic and anaerobic energy systems to performance in ski skating sprint time trials using V1 and V2 techniques. **Methods**: Twelve elite senior male cross-country skiers participated in the study (24 ± 3 yr, 183 ± 5 cm, 79 ± 7 kg, $\dot{V}O_{2max}$ = 72 ± 3 mL·kg^{-1}·min^{-1} or 5.7 ± 0.5 L·min^{-1}). Three submaximal trials (4°–6°), one $\dot{V}O_{2max}$ test (8°), and one performance test (7°, 600 m) were performed both in the V1 and in the V2 ski skating technique on a roller ski treadmill. **Results**: ΣO_2 deficit was ∼60 mL·kg^{-1} and contributed to ∼26% of the total energy release during the ∼170-s time trials. Low to moderate correlations (r = 0.09–0.51) were found between O_2 cost of skiing, fractional utilization of $\dot{V}O_{2peak}$, fractional utilization, and 600-m time. However, a moderate to strong correlation was found between ΣO_2 deficit and 600-m time in both the V1 (r = −0.75) and the V2 tests (r = −0.64) (both $P < 0.05$). No significant differences were found between techniques according to 600-m time or physiological responses. **Conclusions**: The contribution from anaerobic energy systems was ∼26% and seemed independent of technique. In a group of elite skiers, the difference in roller ski treadmill sprint performance is more related to differences in anaerobic capacity than maximal aerobic power and O_2 cost. **Key Words**: ACCUMULATED OXYGEN UPTAKE, ACCUMULATED OXYGEN DEFICIT, ANAEROBIC CAPACITY, CROSS-COUNTRY SKIING, SKIING TECHNIQUES, SPRINT SKIING

P erformance in cross-country skiing (XCS), both in sprint and in longer distances, is highly related to the maximal oxygen uptake ($\dot{V}O_{2max}$) [17,26,35] and the O_2 cost of locomotion [20,22]. In addition, with maximal-effort durations of 2.5–3 min, which is typical for an XCS sprint competition, a significant anaerobic contribution is expected. Gastin [12] noted that during maximal exercise of such duration, the distribution of aerobic versus anaerobic energy supply is ∼70%/30%. Anaerobic energy production during supramaximal exercise has been estimated in different sports from the accumulated oxygen deficit (ΣO_2 deficit) method but not as yet in XCS. According to Medbø et al. [21], supramaximal energy production can be estimated by extrapolating the linear relationship between external load and the steady-state O_2 cost at submaximal intensities. The

ΣO_2 deficit method has been widely debated [2,12,23] because of issues regarding the reliability and validity of the O_2 demand estimations, but the method seems to be the best indirect determination of anaerobic energy release [23].

XCS performance is highly related to the skiers' speed in the uphill sections, where up to half of the race time is spent during competition [1,4,5,25]. Choosing an optimal technique according to terrain profile, velocity, and the skier's work capacity is essential for elite skiers. In the V1 technique, skiers use their poles on every second leg push-off (left or right) in contrast to the V2 technique, where the poles are used on every leg push-off. The empirical choice of technique, which has been validated by research on O_2 cost and performance, suggests that the V1 is superior compared with the V2 technique for steep inclines in junior- and "B-level" skiers [6,18]. However, both the V1 and V2 techniques are used by elite cross-country skiers in steep inclines [1]. From a kinematic point of view, higher average speed in V2 has been associated with longer cycle length (CL) (e.g., Bilodeau et al. [5], Sandbakk et al. [25]). However, in the V1, the results are limited and more uncertain. Bilodeau et al. [5] and Smith et al. [29] found a significant relationship between CL and velocity, whereas Smith et al. [30] reported similar correlations between both speed and cycle rate (CR) and speed versus CL. They concluded that elite male skiers could increase speed in V1 by increasing

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CL, CR, or a combination of both. This could indicate that skiers use different strategies to increase speed in V1 and V2.

Given the paucity of data relating energy system contribution, performance, and kinematic aspects during the V1 and V2 skating techniques in elite XCS, the first aim of this study was to examine the contributions of aerobic and anaerobic energy supply in sprint time trials using the V1 and V2 techniques during treadmill skiing. It is well documented that aerobic capacity is a determinant for XCS performance, but the effect of anaerobic capacity is not well described. The second aim was, therefore, to investigate how the variables O_2 cost, $\dot{V}O_{2max}$, and ΣO_2 deficit correlate to sprint performance. To date, no studies have included measurements of both performance and physiological response to maximal uphill bouts of V1 and V2 exercise. The third aim of the study was to compare the V1 and V2 ski skating techniques according to performance, physiological responses, and kinematic variables in a steep uphill sprint test. During exercise times of 2.5–3 min, the main hypotheses of the present study were the following:

1. On the basis of previous literature from other sports, we assumed that ~30% of the total energy release is from the anaerobic system. Further, among a group of skiers with similar maximal aerobic power but with different race specialities, anaerobic capacity would differentiate skiers according to performance.
2. On the basis of observations from elite skiing in steep inclines, we hypothesized that there would be no significant differences in performance between the V1 and V2 techniques. However, the two techniques would significantly differ according to kinematic aspects.

METHODS

Subjects. Twelve elite senior male cross-country skiers (24 ± 3 yr, 183 ± 5 cm, 79 ± 7 kg) volunteered to participate in the study. All skiers competed at an upper Norwegian national level, and some athletes were considered to be international-level skiers in their respective preferred distances (sprint <1.8 km, distance = 15–50 km, or long-distance races >50 km). Among the subjects, there were one sprint International Ski Federation (FIS) World Cup winner, five skiers with top 30 ranking in FIS World Cup races, and three skiers with several top 10 finishes in FIS Marathon Cup races, and all 12 subjects had top 30 results in the Norwegian championship. All subjects had regularly participated in roller ski treadmill testing during the previous 1–3 yr and were, therefore, familiar with this mode of testing. The study was approved by the Regional Ethics Committee of Southern Norway, and the subjects gave their written informed consent before study participation.

Experimental overview. All subjects attended three sessions on three different days at the same time of day. The test protocols are illustrated in Figure 1. During days

1 and 2, steady-state oxygen uptake was measured at three submaximal workloads as well as $\dot{V}O_{2max}$ in V1 and V2. The subjects also performed two familiarization trials each day for the performance test (600-m test). During day 3, two time trial tests over 600 m at 7° were performed with 45 min between the start of the first and the second trial. All tests were conducted on a roller ski treadmill. Before the study, the order of techniques was counterbalanced. The same test leaders conducted all tests.

Submaximal oxygen uptake and $\dot{V}O_{2max}$. Before the start on days 1 and 2, subjects warmed up for 15 min at 3° and 2.25 $m \cdot s^{-1}$ (~60%–75% of HR_{max}). All submaximal tests were performed at 3 $m \cdot s^{-1}$, with 6-min duration and with 2-min breaks between trials. On day 1, the subjects completed two trials at 4° with V1 and V2 before they performed two trials at 5° (V1 and V2). On day 2, two trials at 4° and two trials at 6° were performed with the two techniques but with the order of the techniques reversed compared with day 1. The results from the 4° submaximal test on day 2 were used for subsequent data analyses. The speed was chosen to be high enough to induce a relevant technique at moderate inclines but low enough to obtain a steady-state oxygen consumption ($\dot{V}O_2$) (<90% of $\dot{V}O_{2max}$). O_2 cost in the present study was defined as the mean oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$) between 3.5 and 5.5 min for each trial. O_2 cost at 4°, 5°, and 6° in both V1 and V2 corresponded to 67%, 77%, and 87% of average $\dot{V}O_{2max}$ values, respectively. Eight minutes after the last submaximal effort both days, the subjects performed a $\dot{V}O_{2max}$ test at V1 and V2, respectively. The starting incline and speed of the test were 6° and 3 $m \cdot s^{-1}$. The initial speed was kept constant, and the incline was subsequently increased by 1° every minute until 8°. Thereafter, speed was increased by 0.25 $m \cdot s^{-1}$ every minute. Skiing to exhaustion and a plateau in $\dot{V}O_2$ were used as criteria to indicate that $\dot{V}O_{2max}$ was obtained (17). Oxygen uptake was measured continuously, and the highest mean values during 1 min were taken as $\dot{V}O_{2max}$. Fifteen minutes after the $\dot{V}O_{2max}$ test, the subjects had two training trials for the 600-m test. The first trial was performed at 4°, and the starting speed was at 3 $m \cdot s^{-1}$ to practice the speed changes described later on. The second trial was performed at 7° with a starting speed of 3 $m \cdot s^{-1}$, the same speed as the start of the real 600-m test.

Sprint performance. The subjects skied as fast as possible over 600 m on a roller ski treadmill, and a safety harness was put on the subjects in case of a fall. Before the start, subjects warmed up for 15 min at 3° and 2.25 $m \cdot s^{-1}$ (~60%–75% of HR_{max}) and then 10 min at a self-paced intensity to simulate usual racing routines. After a short break (1 min) to take a blood sample, let the subject drink (<0.1 L of sports drink), and adjust the equipment, they were asked to stand still for 60 s to measure baseline oxygen uptake. In the V1 test, the subjects were allowed to change their "strong side" (the side where the pole plant and ski plant is set simultaneously). The incline was 7°, which is similar to previous studies where both the V1 and the V2 techniques
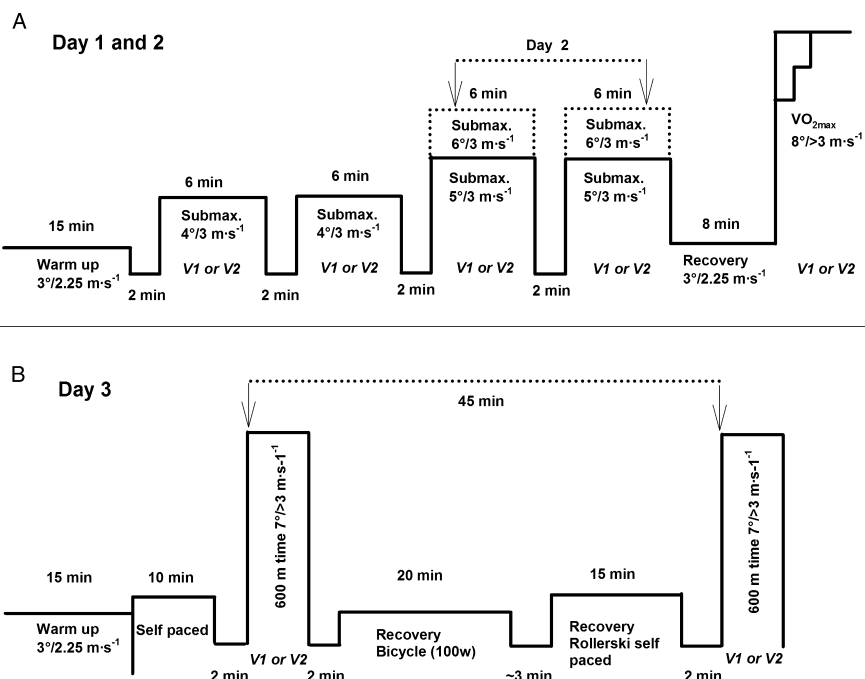
FIGURE 1—Test protocol for the submaximal workloads and the $\dot{V}O_{2max}$ tests on days 1 and 2 (A) and the 600-m tests on day 3 (B). On day 1, the subjects completed two workloads on 4° (both V1 and V2) before performing two workloads at 5° and finally one $\dot{V}O_{2max}$ test. On day 2, two trials at 4° and 6° were conducted before performing a $\dot{V}O_{2max}$ test, and the order of the techniques was reversed during the submaximal efforts.

have been compared (6,34). The speed was fixed at 3 m·s^{-1} for the first 100 m (36 s) to avoid overpacing. Thereafter, the subjects controlled the speed by adjusting their position on the treadmill relative to laser beams situated in front and behind the skier. Each contact with the front wheels with the laser induced either an increase or a reduction in speed by 0.25 m·s^{-1}. The speed changes were conducted manually by the test leader.

Visual feedback with respect to distance traveled was provided to the subjects, and a separate monitor allowed the test leader to follow the subject's motions. When the subjects completed the 600 m, the treadmill was automatically stopped, and all data including speed changes and finish time were automatically saved on the computer. One subject fell at 460 m during the V1 test and was excluded for the comparison between V1 and V2, but the data were included in the V2 correlation analyses. $\dot{V}O_2$ was measured continuously (5-s epochs), and the average over the six highest continuous oxygen values (30 s) was taken as $\dot{V}O_{2peak}$. Blood plasma lactate concentration was measured immediately before and after the test. Approximately 2 min after the first 600-m test, the subjects undertook a recovery exercise for 20 min on a cycle ergometer (100 W, 60 rpm, and ~50%–60% of HR_{max}). The subjects then had a ~3-min break before recommencing exercise on the roller ski treadmill. The subjects skied at 3° and self-paced intensities for 15 min to sta-

bilize the roller ski friction. The second test was identical with the first 600-m test, except that the other skating technique was used.

Calculations of ΣO_2 deficit. Accumulated O_2 demand was estimated by extrapolation of the individual linear relationship between the work rate (W) and steady-state O_2 cost from the 4°–6° gradient treadmill bouts, modified from the model by Medbø et al. (21). The calculations assume that the ratio O_2 cost per watt is constant with increasing speed. The ΣO_2 deficit was calculated as ΣO_2 demand minus ΣO_2 uptake (21). Power was calculated as the sum of the power against gravity (Pg) and the power against rolling friction (Pf), in a coordinated system moving with the treadmill belt at a constant speed. Pg was calculated as the increase in potential energy per time ($Pg = mg\sin(\alpha)v$), and the Pf was calculated as the work against coulomb frictional forces at a given tangential speed ($Pf = \mu mg\cos(\alpha)v$), with v being the belt speed and α the angle of incline.

After onset of exercise, the stored O_2 in the venous blood is reduced from typically 160 mL·L^{-1} blood at rest to ~20 mL·L^{-1} blood during maximal exercise in elite cross-country skiers (7). This is an aerobic contribution to the total energy release that in our measurements will be part of the ΣO_2 deficit. We measured the hemoglobin mass in every subject (average = 1150 ± 139 g) and calculated the reduction in stored O_2 on the basis of these values and the calculation

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of Medbø et al. (21). The total O_2 stores in the blood were estimated to decrease 691 ± 83 mL (range = 543–800 mL) or 8.8 ± 0.6 mL·kg^{-1}. These values are subtracted individually from the ΣO_2 deficit to estimate the anaerobic contribution.

Apparatus. $\dot{V}O_2$ was measured by an automatic system (Oxycon Pro Jaeger Instrument; Hoechberg, Germany), evaluated by Foss and Hallén (11). HR was measured with a Polar S610i™ monitor (Polar Electro Oy, Kempele, Finland), and blood lactate concentration was measured in unhemolyzed blood from capillary fingertip samples. Blood was collected in a heparinized capillary tube, and 25 μL was injected with a pipette into the mixing chamber of the lactate analyzer (YSI 1500 Sport; Yellow Springs Instruments, Yellow Springs, OH). The lactate analyzer and Oxycon Pro Jaeger Instrument were calibrated according to the instruction manual and described in detail by Losnegard et al. (19). All testing was performed on a roller ski treadmill with belt dimensions of 3×4.5 m (Rodby, Sodertalje, Sweden). The treadmill gradients and speed were calibrated before the start of the study and checked during and after the testing period. Swix CT1 poles (Swix, Lillehammer, Norway) with a tip customized for treadmill roller skiing were used (pole length = 167 ± 4 cm, corresponding to 91% of body height). Two different pairs of Swenor Skate roller skis (Swenor, Sarpsborg, Norway) with wheel type 1 were used depending on the binding system the skiers normally used (NNN; Rottefella, Klokkarstua, Norway, or SNS; Salomon, Annecy, France). The rolling friction coefficient (μ) of the skis was tested before, during, and after the project using a towing test, previously described by Hoffman et al. (14). All tests were performed after warming up with 15 min of treadmill roller skiing, which yielded a friction coefficient of 0.018 (NNN) and 0.020 (SNS). The subject's body mass was measured before each treadmill test (Seca model 708; Seca, Hamburg, Germany). CR and CL were calculated using video analysis. The motion of the skiers was recorded with a stationary 50-Hz video camera (Sony DCR-TRV900E; Sony, Tokyo, Japan) positioned 5 m from the skiers and perpendicular to the skiing direction. One cycle was defined as the time between consecutive right pole plants for V1 and the time between every other right pole plant for V2. CL was calculated as average treadmill velocity divided by CR. The mean CR and CL from 100 to 600 m (self-selected speed) are presented in the results. Hemoglobin mass was measured by the optimized CO-rebreathing method as described by Schmidt and Prommer (28).

Statistics. All data were checked for normality with a Shapiro–Wilk test and presented as mean and SD. Paired *t*-tests were used for detecting statistical differences between techniques. The Pearson product–moment correlation analysis was used for correlation analyses. Multiple linear regression analysis was used to determine which of the variables were the best predictors of the 600-m time. The analyses were also conducted with the SPSS stepwise model selection procedure.

Confidence limits for the true mean values for effects were estimated via a spreadsheet described by Hopkins (16). Each subject change score between V1 and V2 was presented as a percentage via the analyses of log-transformed values. The spreadsheet provides a precision of the estimates as 90% confidence limits. The magnitude of differences between exercise modes was expressed as standardized mean differences (Cohen *d* effect size (ES)). The criteria to interpret the magnitude of the ES values were 0.0–0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; and >2.0, very large (15).

Statistical calculations were performed with Microsoft Excel (Redmond, WA), SPSS 18.0 (Chicago, IL), and SigmaPlot 11.0 software (San Jose, CA). An α level of $P \leq 0.05$ was considered significant, and $P \leq 0.10$ was considered a tendency.

RESULTS

The 600-m time was ~170 s and not significantly different between V1 and V2. There were no significant differences between techniques concerning ΣO_2 demand, ΣO_2 uptake, and the ΣO_2 deficit (Table 1) or the time courses of the variables during the 600-m test. Hence, the magnitude of differences in 600-m time and physiological responses between techniques, as expressed as standardized mean differences and the Cohen *d* ES, were trivial to small (Table 1). The

TABLE 1. Performance (time) and physiological responses during the 600-m test in V1 and V2 and the magnitude of differences between techniques (*n* = 11).

Variable	V1 Mean ± SD	V2 Mean ± SD	Differences in Percent Effect ± 90% Confidence Limit	Magnitude of Differences ES
Time (s)	171.8 ± 8.4	172.1 ± 9.9	0.1 ± 1.9	0.03
$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})	71.1 ± 2.9	71.4 ± 2.3	0.6 ± 1.1	0.15
HR$_{peak}$ (beats·min^{-1})	183 ± 5	182 ± 6	−0.5 ± 0.5	0.15
$\dot{V}_{Epeak}$ (L·min^{-1})	191 ± 17	189 ± 19	−1.3 ± 2.9	0.13
BF$_{peak}$ (breaths per minute)	58 ± 8	60 ± 13	3.5 ± 7.6	0.29
La$^-_{peak}$ (mmol·L^{-1})	7.7 ± 1.3	8.1 ± 1.2	5.3 ± 7.1	0.33
ΣO_2 demand (mL·kg^{-1})	232.5 ± 6.9	228.8 ± 12.0	−1.7 ± 2.5	0.52
ΣO_2 uptake (mL·kg^{-1})	170.3 ± 12.6	168.6 ± 12.6	−1.0 ± 1.2	0.12
ΣO_2 deficit (mL·kg^{-1})	62.2 ± 16.8	60.2 ± 15.0	−3.8 ± 11.4	0.13
ΣO_2 deficit (%)	26.6 ± 6.6	26.2 ± 6.1	−2.1 ± 9.1	0.08

ES: <0.2 (trivial), 0.2–0.6 (small), 0.6–1.2 (moderate), 1.2–2.0 (large), >2.0 (very large).
BF$_{peak}$, peak breath frequency;

starting speed (3 m·s^{-1}, first 100 m) corresponded to an O_2 demand of 70.9 ± 1.8 (V1) and 71.0 ± 3.3 $\text{mL·kg}^{-1}\text{·min}^{-1}$ (V2) (Fig. 2A) and were equivalent to 98.3% ± 5.8% and 99.6% ± 6.0% of $\dot{V}O_{2\text{max}}$ reached during the incremental protocol (V1 = 72.4 ± 3.2 and V2 = 71.5 ± 3.5 $\text{mL·kg}^{-1}\text{·min}^{-1}$). $\dot{V}O_{2\text{peak}}$ obtained during the 600-m test (Table 1) was not significantly different from the $\dot{V}O_{2\text{max}}$ reached during the incremental protocol. The mean O_2 demand over the 600-m time was 81.4 ± 5.3 and 80.0 ± 5.6 $\text{mL·kg}^{-1}\text{·min}^{-1}$ and 112% ± 11% (V1) and 113% ± 9% (V2) of $\dot{V}O_{2\text{peak}}$. The O_2 uptake (including the calculated usage of the stored O_2, see "Methods" section) was 59.5 ± 2.4 and 58.8 ± 3.0 $\text{mL·kg}^{-1}\text{·min}^{-1}$, for V1 and V2, respectively. Hence, the average fractional utilization, measured as the accumulated O_2 uptake divided by time and $\dot{V}O_{2\text{peak}}$, for the two techniques was 82.5% ± 3.3% and 82.7% ± 2.7%. Mean external power was estimated to be 214 ± 19, 256 ± 22, and 298 ± 25 W ($n = 12$) at 4°, 5°, and 6°, respectively, in both V1 and V2. The O_2 cost was not significantly dif-

FIGURE 2—A, ΣO_2 deficit and ΣO_2 uptake during the first 150 s of the V1 600-m test ($n = 11$). The *dotted line* is the mean $\dot{V}O_{2\text{peak}}$. **B,** Energy system contribution during the first 150 s in trial 1 ($n = 11$, *dotted lines*) and trial 2 ($n = 11$, *solid lines*), independent of techniques. Values are mean data.

TABLE 2. Summary of Pearson product–moment correlation coefficients between 600-m time (dependent variable) and physiological and biomechanical variables measured during submaximal loads as well as during maximal loads (the 600-m test) in V1 and V2.

	V1 ($n = 11$)	V2 ($n = 12$)
Submaximal loads (5°)		
O_2 cost ($\text{mL·kg}^{-1}\text{·min}^{-1}$)	0.30	0.31
O_2 cost (%$\dot{V}O_{2\text{peak}}$)	0.31	0.53*
HR (%HR_{peak})	−0.26	0.23
RER	−0.02	−0.01
La^- (mmol·L^{-1})	−0.07	0.25
CR (Hz)	−0.13	−0.16
CL (m)	0.13	0.16
Maximal loads (7°)		
$\dot{V}O_{2\text{peak}}$ ($\text{mL·kg}^{-1}\text{·min}^{-1}$)	−0.15	−0.51*
O_2 uptake ($\text{mL·kg}^{-1}\text{·min}^{-1}$)	0.37	−0.11
La^-_{peak} (mmol·L^{-1})	−0.34	−0.43
Fractional utilization (%)	0.12	0.09
ΣO_2 deficit (mL·kg^{-1})	−0.75**	−0.64**
ΣO_2 deficit (%)	−0.77**	−0.69**
CR (Hz)	−0.57*	0.11
CL (m)	−0.59*	−0.86**

* $P < 0.10$.
** $P < 0.05$.

ferent between V1 and V2 at any submaximal workload. There were no significant differences in O_2 cost per watt between inclines (maximal numerical differences <0.5%). Mean external power for the 600-m test was 401 ± 41 and 401 ± 47 W ($n = 11$) in V1 and V2, respectively.

Because we found no significant differences in 600-m time or physiological responses between V1 and V2, the effect of the first trial on the second trial was tested. Blood lactate concentration before the two trials was similar (1.4 ± 0.4 and 1.4 ± 0.5 mmol·L^{-1}). There were no significant differences in 600-m time (171.1 ± 9.5 and 172.7 ± 8.7 s), $\dot{V}O_{2\text{peak}}$, ΣO_2 uptake, ΣO_2 demand, or ΣO_2 deficit between the first and the second time trials. Independent of the techniques, the time course of the relative contribution of the aerobic and anaerobic energy systems during test 1 and test 2, estimated from the O_2 uptake and O_2 deficit, was similar (Fig. 2B).

Low to moderate correlations were found between 600-m time and O_2 uptake, $\dot{V}O_{2\text{peak}}$, O_2 cost (5°), and fractional utilization, whereas a moderate to strong correlation was found between 600-m time and ΣO_2 deficit (Table 2, Fig. 3). The correlation between La^-_{peak} and ΣO_2 deficit was $r = 0.38$ ($P > 0.05$) and $r = 0.60$ ($P < 0.05$), for V1 and V2, respectively. Multiple linear regression analysis using the 600-m time as the dependent variable and $\dot{V}O_{2\text{peak}}$, O_2 cost (5°), and ΣO_2 deficit as the independent variables produced the best model summary with an r^2 of 0.66 and 0.75, $P < 0.05$ (V1 and V2, respectively). Hence, in this group of skiers, 66% (V1) and 75% (V2) of the variation in the 600-m time were explained by these variables. When these variables were entered into the SPSS stepwise analysis, ΣO_2 deficit alone explained 58% (V1) and 41% (V2) of the total variance in 600-m time. Excluding the stored O_2 in the correlation analyses did not significantly affect the analyses and showed a correlation coefficient of −0.75 (V1) and −0.63 (V2), both $P < 0.05$, between ΣO_2 deficit and 600-m time.

Figure 4 and Table 2 show that 600-m time in V2 is negatively correlated with CL only ($P < 0.05$), whereas in

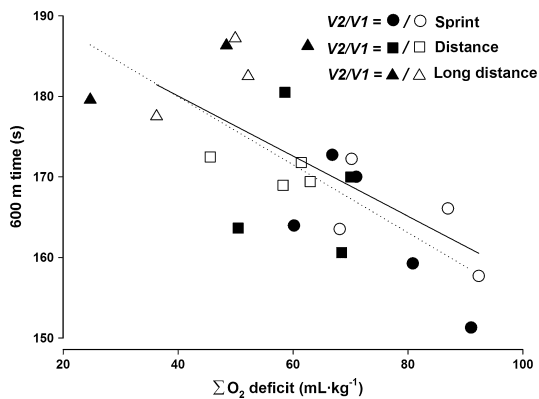FIGURE 3—Relation between ΣO_2 deficit and 600-m time in the V1 ($n = 11$) and V2 ($n = 12$). *Open symbols* are V1, and *filled symbols* are V2. Different symbol types (*circles*, *squares*, and *triangles*) in the figure explain the different types of skiers. Sprint skiers, $n = 4$ in V1 and $n = 5$ in V2; distance skiers, $n = 4$; long-distance skiers, $n = 3$. *Solid trend line* is V1; *dotted trend line* is V2.

V1, 600-m time tended to correlate negatively with both longer CL and higher CR (both $P = 0.06$). Compared with V2, V1 showed higher CR (0.90 ± 0.04 vs 0.63 ± 0.03 Hz) and shorter CL (4.0 ± 0.2 vs 6.0 ± 0.6 m) (all $P < 0.05$). No significant correlation was found between 600-m time and CR or CL at submaximal loads (Table 2).

DISCUSSION

The principal findings were (I) the ΣO_2 deficit during the $\sim$170-s treadmill 600-m tests accounted for $\sim$26% of the total O_2 demand, which is similar to what was found for other sports for the same duration (12); (II) in this group of elite skiers with a relatively large variation of ski sprinting ability, the difference in 600-m time was more related to differences in anaerobic capacity than maximal aerobic power and O_2 cost; (III) there were no significant differences in 600-m time or physiological responses between V1 and V2 ski skating techniques; and (IV) kinematic analyses indicate that faster skiers in the V2 showed longer CL but similar CR as slower skiers, whereas in the V1, the contribution of both CR and CL differentiates skiers with respect to 600-m time.

Energy system contribution. The ΣO_2 deficit corresponded to $\sim$26% of the total energy release in the present study. This fits very well with observations from other sports, where $\sim$27% of the energy comes from anaerobic sources during exhaustive exercise of $\sim$180-s durations (12). Thus, the present study supports that energy system contribution in XCS is similar to running, bicycling, and rowing at least with the current duration of maximal exercise. In terms of exercise intensity, skiers work above their $\dot{V}O_{2peak}$ (on average $\approx$113%, at peak $\approx$128%) during the 600-m test. These O_2 demands are more closely related to 800-m (113%) than

1500-m running (103%) in highly trained athletes (32), although 800-m running has a considerably shorter duration ($\sim$100 s). This is of practical importance because sprint XCS is often related to 1500-m running performance because of the duration of the races. However, exercise intensity is related to not only duration but also muscle use and activation pattern (13,24). This could be of special interest in XCS because speed and terrain vary during a race. In the present study, a constant steep incline was used at a relatively low speed and, therefore, included large muscle mass at a high workload, which is not very technique demanding. However, in contrast to most endurance sports of $\sim$2- to 4-min duration, O_2 demand and exercise intensity change with time in an XCS competition because of the topography of the courses. Therefore, in short uphill sections, skiers are able to work at a higher exercise intensity than in the present study, as supported by the estimates of Sandbakk et al. (25). This could have relevance for training recommendations because the exercise intensity in parts of
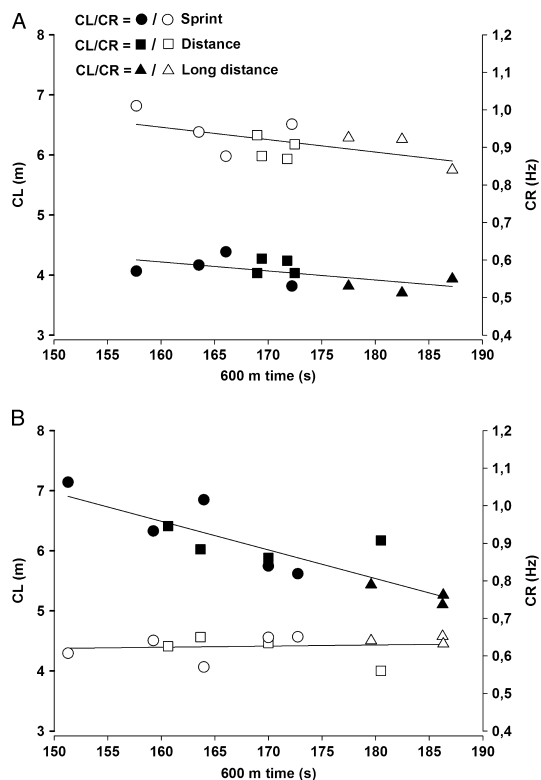
FIGURE 4—Mean CR and CL for each of the subjects from 100 to 600 m (freely chosen speed) from the 600 m tests in V1 ($n = 11$) (A) and V2 ($n = 12$) (B). *Open symbols* are CR, and *filled symbols* are CL. Different symbol types (*circles*, *squares*, and *triangles*) in the figure explain the different types of skiers. Sprint skiers, $n = 4$ in V1 and $n = 5$ in V2; distance skiers, $n = 4$; long-distance skiers, $n = 3$.

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the race in XCS is higher than that in the present study and far above $\dot{V}O_{2max}$.

As presented in Figure 2B, the relative contribution of the aerobic and anaerobic energy systems was equal after ~35 s, independent of techniques and the order of tests. Hence, the aerobic system contributes considerably to the energy demand, and the transition from mainly anaerobic to mainly aerobic energy delivery occurs early in the time trials. If these calculations had been corrected for stored O_2 that was estimated in the present study to ~13% of the ΣO_2 deficit, this energy system transition would have been found earlier because most of the stored O_2 is depleted early in the bout. In addition, the mixing chamber configuration will cause a small delay in the oxygen kinetic, but this delay will of course be independent of technique and not affect our conclusion in comparing techniques. Therefore, the time courses of the relative contributions of the aerobic and anaerobic energy system during test 1 and test 2 were similar (independent of technique). Another important notion is that $\dot{V}O_{2peak}$ was reached twice within 45 min. This ability is probably essential to perform at a high level because a competition in sprint XCS consists of up to four heats, with 17- to 60-min breaks between heats.

Determinants of performance. To date, anaerobic energy release in XCS has not been measured. Vesterinen et al. (35) and Stöggl et al. (33) found a significant relationship between La^-_{peak} and performance. On this basis, they assumed that the anaerobic capacity is important for successful performance in sprint XCS. However, Gastin (12) stated that although lactate in the blood is an indication of the extent of the glycolysis, it does not give a precise estimate of the anaerobic energy release. In the present study, a low nonsignificant correlation was found between La^-_{peak} and 600-m time, whereas a low to moderate correlation was found between La^-_{peak} and ΣO_2 deficit.

The ΣO_2 deficit in the present study correlated significantly with 600-m time, both in V1 and V2, and was the major contributor to explain the differences in 600-m time between subjects. Bangsbo et al. (3) reported a mean ΣO_2 deficit in top-class rowers of ~64 mL·kg^{-1} (range = 58.9–81.2 mL·kg^{-1}), which is comparable to the present study. Bangsbo et al. (3) suggested that a high anaerobic capacity may not be crucial to succeed in rowing because all subjects performed at a high level and that the variation in ΣO_2 deficit between subjects was large. This may be correct in sports such as rowing where all athletes compete during a similar duration of 6–7 min. However, in modern XCS, race times vary between ~2 min and several hours, and this will obviously influence training regimens and draw on the different physical abilities of the skiers. Although all subjects in the present study were elite skiers, they differed considerably in preferred race types. The three slowest skiers in the 600-m test, who were all top-level long-distance skiers, tended to have the lowest anaerobic capacity. It is obvious that anaerobic capacity is not crucial in competition durations of 2–5 h. The three fastest skiers (in V1) were cate-

gorized as typical sprinters according to their racing history. These subjects also showed the highest anaerobic capacity, up to 92 mL·kg^{-1} (adjusted for stored O_2) for one world-class sprinter, which is higher than highly trained (32) and top-class (3) 800- to 1500-m runners who compete over a similar duration and exercise intensities. It is therefore evident that in this group of skiers, high anaerobic capacity is crucial for successful sprint skiing performance. However, this does not necessarily show that anaerobic capacity is a discriminating factor of performance in a more homogeneous group of specialist sprint skiers. Sandbakk et al. (26) showed recently that world-class sprint skiers reached higher $\dot{V}O_{2peak}$ compared with national-level skiers. It is imperative to note that the results in the present study do not suggest that aerobic predictors are unimportant for XCS sprint performance. The nonsignificant correlation between aerobic predictors and 600-m time is likely due to the homogeneous group concerning $\dot{V}O_{2max}$ (coefficient of variation = 3.3%). As seen from Table 1 and Figure 2A, the skiers reached their $\dot{V}O_{2max}$ during the 600-m time tests, and the six fastest skiers in the V2 test ($n = 12$) also showed a significant higher $\dot{V}O_{2peak}$ than the six slowest skiers (data not shown).

V1 versus V2. The different skating techniques can be seen as a "gear system" where the skiers choose technique according to terrain profile, snow condition, speed, and the work capacity. In other activities like walking, running, and cycling, it has been shown that "gear choice," i.e., step frequency or cadence, significantly affects the athletes' work economy and performance (8–10). In addition, the "optimal" cadence changes with increasing workloads, and therefore, the choice of cadence may be effected by the performance level of the athletes (8,10). Compared with cycling and running, the degrees of freedom are larger during skiing and also involve the arms. This use of multiple technique transition has recently been demonstrated in a simulated sprint XCS race and with a large range of velocities (1), showing that some techniques are preferred at low speed and some techniques are used at high speed by elite skiers. Also, higher ranked skiers used a greater proportion of the V2 versus V1 in uphill sections than slower skiers (1). This indicates that "optimal" gear choice might be different between performance levels of athletes also in XCS.

From a kinematic view, V1 600-m time correlated negatively to greater CR and longer CL, which is in accordance with Smith et al. (30). Poling rate was 0.90 ± 0.04 Hz, which is significantly lower compared with maximal speed (~1.30 Hz) at similar inclines (34). This indicates that the subjects were still able to increase CR to make further improvements in speed because the CR was far below their "maximal CR." In V2, several authors have associated higher average speed with longer CL (e.g., Bilodeau et al. [5], Sandbakk et al. [25]). Figure 4 and Table 2 show that reduced 600-m time is only significantly correlated to longer CL. The poling rate in V2 was 1.25 ± 0.06 Hz, which is similar to Stöggl et al. (34) during maximal speed in a steep incline. This indicates that the subjects in the present

study work at an upper limit regarding efficient poling rate in V2 and that a further increase in speed must be achieved by increased CL. Altogether, the factors mentioned above could help to explain the different strategies regarding CR and CL in V1 and V2 according to differences in speed between athletes. It is also noteworthy that the correlation between the biomechanical variables from submaximal loads and 600-m time was low and nonsignificant.

Methodological considerations. In the present study, we assumed that the linear relation between power and O_2 cost established during submaximal loads also applies to supramaximal loads. Importantly, the submaximal loads were at a relative high intensity ($\sim$67%–87% of $\dot{V}O_{2max}$ values), which is recommended for the procedure tested in the present study (21), whereas the load during the 600-m tests was not at the very high range (average $\approx$113% of $\dot{V}O_{2peak}$). Furthermore, the speed was relatively low because of the steep incline (7°) and not very different to speed at submaximal loads (4°–6°). We established the relation between power and O_2 cost by increasing the incline while keeping the speed constant. During the 600-m tests, the incline was constant, and the speed was changed. However, we calculated the ratio between O_2 cost per watt according to increased speed on the basis of the findings from Sandbakk et al. (27), which showed a <0.2% change in this ratio from 3.8 to 5 $m \cdot s^{-1}$ at 2.8°. The treadmill speeds reported by Sandbakk et al. (27) are similar to the speeds in the present study (range = 3–5 $m \cdot s^{-1}$). Taken together, these data with no significant differences in O_2 cost per watt between inclines in the present study indicate that how the workload is changed (angle or speed) does not have a major effect on skiing economy.

Angling of the skis with respect to the forward direction (orientation angle) results in higher speed of the skis than the speed of the treadmill. This might give differences in roller ski friction between V1 and V2 because V1 has a wider ski angle than V2. We therefore calculated the velocity of the skis ($v_{ski} = v_{treadmill}/\cos(\text{orientation angle})$) to compensate for the different angling in V1 and V2 (27). With an angling of the skis at V1 of 18° and V2 of 13° (31), the differences in total friction between techniques is estimated to be 1.5 W or 0.4% of estimated power at 7°. Moreover, during the pole push, the mean normal force on the skis will be reduced and, further, give lower friction from the skis during this part of the cycle. When comparing the two techniques in elite skiers, the poles are in contact with the ground in $\sim$35% in V1 and $\sim$36% in V2 of a full cycle (during 4° at 3 $m \cdot s^{-1}$) (data not shown). Hence, the outward angling would not affect our results significantly, especially when comparing the two techniques.

CONCLUSIONS

Both hypotheses were accepted: (I) during maximal exercise of $\sim$170 s on a roller ski treadmill, the anaerobic energy production contributes $\sim$26% of the total energy production and differentiates elite skiers according to performance; and (II) at long steep inclines, the V1 and V2 ski skating techniques lead to similar racing performance for elite skiers.

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Losnegard T, Myklebust H, Spencer M, & Hallén J.

Seasonal variations in VO_{2max}, O_2-cost, O_2-deficit and performance in elite cross-country skiers.

Title:
Seasonal variations in VO_{2max}, O_2-cost, O_2-deficit and performance in elite cross-country skiers

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Running head:
Training induced changes in elite skiers

ABSTRACT

Long term effects of training are important information for athletes, coaches and scientists when associating changes in physiological indices with changes in performance. Therefore, this study monitored changes in aerobic and anaerobic capacities and performance in a group of elite cross-country skiers during a full sport season. Thirteen male (age; 23 ± 2 yrs, height; 182 ± 6 cm, body-mass; 76 ± 8 kg, V2 roller ski skating VO_{2max}; 79.3 ± 4.4 mL·kg^{-1} min^{-1} or 6.0 ± 0.5 L·min^{-1}) were tested during the early-, middle- and late preparation phase: June (T_1) - August (T_2) - October (T_3), during the competition phase: January/February (T_4) and the following early pre-competition phase: June (T_5). O_2-cost during submaximal efforts and VO_{2peak}, accumulated oxygen deficit (ΣO_2-deficit) and performance during a 1000m test were determined in the V2 ski skating technique on a rollerski treadmill. Subjects performed their training on an individual basis and detailed training logs were categorized into different intensity zones and exercise modes. Total training volume was highest during the summer months (early preseason) and decreased towards and through the winter season, while the volume of high intensity training increased (all $P < 0.05$). There was a significant main effect among testing sessions for 1000 m time, O_2-cost and ΣO_2-deficit (Cohen`s d effect size; ES = 0.63-1.37, moderate - large, all $P < 0.05$). In general, the changes occurred between T_1 and T_3 with minor changes in the competitive season (T_3-T_4). No significant changes were found in VO_{2peak} across the year (ES = 0.17, trivial). In conclusion, the training performed by elite cross-country skiers induced no significant changes in VO_{2peak}, but improved performance, O_2-cost and ΣO_2-deficit.

Key words: ANAEROBIC CAPACITY, ENERGY COST, INDIVIDUAL VARIATIONS, LONGITUDINAL CHANGES, TRAINING.

INTRODUCTION

Long term endurance training will ideally lead to improved performance as well as physiological indices for performance (eg., maximal oxygen uptake: VO_{2max} or O_2-cost). These changes in physiological indices are assessed by scientists and coaches to provide useful diagnostic information about effects of training. However, currently there is limited information on how these physiological indices change in elite endurance athletes during months and years of training, and how these changes relate to changes in performance. This information is important to understand training strategies to improve performance in already extremely well-trained endurance individuals.

Based on a detailed analysis, the most important determinants of performance in cross-country (XC) skiing is VO_{2max} and O_2-cost (7,10,16,18,19,23), while the anaerobic capacity, measured as the accumulated oxygen deficit (ΣO_2-deficit), has been suggested to play a role in sprint XC skiing with duration of ~ 3 min (13). Traditionally, effect of endurance training has most often been evaluate by its effect on VO_{2max} both in senior (4,10) and junior XC skiers (11,22). Rusko (22) and Ingjer (11) documented that up until about the age of 20, there is an increase in running VO_{2max}, whereafter the VO_{2max} seems to plateau with small changes per year. Ingjer (10) concluded that VO_{2max} also varies during a season in elite senior XC skiers and that the best athletes have the greatest yearly variation. The highest VO_{2max} was reached during the competitive season. However, sport specific data on seasonal variation of physiological variables together with performance in XC skiing is not reported.

In terms of training, XC skiers are reported to train after a "polarized" endurance training model with high volume of low-intensity and low- to moderate volume of high-intensity (4,23,27,29). However, limited up to date information is available on how elite skiers train in

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different parts of a full season according to total volume, intensity zones and exercise modes (27,28). This information is important when evaluating changes in physiological capacities and performance.

Hence, the primary aim of this investigation was to detect and associate changes in physiological indices with changes in performance from the preparation phase to the competition phase in elite XC skiers. Also individual changes will be analyzed since coaches and athletes, unlike most scientists, are more interested in the development of the individual rather than the group as a whole (21). In addition, we present a description on how elite XC skiers train with respect to exercise mode and intensity during the annual training cycle. The hypothesis was that improved performance during the preseason would be reflected by augmented sport specific VO_{2max} and lower O_2-cost.

METHODS

Experimental Approach to the Problem

To investigate longitudinal training effect on the physiological responses and performance, the subjects were tested with the same protocol on a roller ski treadmill 4-5 times during an annual training year. The testing sessions were conducted at the early preparation phase (June: T_1), middle preparation phase (August: T_2), late preparation phase (October: T_3) and during the competition phase (January/February: T_4). Testing at T_4 was performed 2 weeks before or 1 week after the Norwegian Championship which was a main goal for most of the subjects. Eleven subjects attended four sessions (T_1-T_4), while five of the subjects also performed a fifth test the following June (T_5). Two more subjects performed T_4 and T_5 and a separate analysis was therefore performed from T_4 to T_5 in these seven subjects. In each testing session, an identical protocol was performed using the V2 ski skating technique. In the

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V2 technique, skiers use their poles on every leg push-off, and this technique has been shown appropriate for the inclines and speeds used in the present study (13). In ten subjects, also one running VO_{2peak} (VO_{2peak}-Run) test was performed on a separate day between T_2 and T_3, and individual values are presented to demonstrate the high maximal aerobic power of these subjects (Table 1).

Subjects

Thirteen male elite senior XC skiers (age; 23 ± 2 yrs, height; 182 ± 6 cm, body-mass; 76 ± 8 kg) were involved in the study and descriptive characteristics of the subjects are presented in Table 1. All skiers competed at upper Norwegian national-level and several athletes were considered to be international-level skiers. During this particular competition season, one subject finished top 5 in the FIS World-Championship, three subjects top 15 in FIS World-cup races, five subjects top 15 in the Norwegian Championship and all subjects were ranked top 30 in the Norwegian Championship, all results from individual races in the free technique. All subjects had regularly participated in rollerski treadmill testing over the previous 2-4 yrs and were, therefore, familiar with rollerski testing on the treadmill. The study was approved by the Regional Ethics Committee of Southern Norway and the subjects gave their written consent before study participation.

<<Table 1 near here>>

<<Figure 1 near here>>

Procedures

Subjects reported to the laboratory at the same time each day (± 2 hrs) and wore the same light clothing for all testing sessions. Each test consisted of 4-6 submaximal loads for

measuring the O_2-cost followed by one 1000 m test for measuring performance, peak oxygen

uptake (VO_{2peak}-V2) and ΣO_2-deficit. Total time including warm-up and cool down was 1 hr.

and 30 min for each test. The schematic protocol is shown in Figure 1 and the detailed

protocol is described below. All testing was conducted at an altitude of 190 m above sea level

and temperature in the laboratory was on average 23 ± 2 °C.

Submaximal loads. Prior to the testing, subjects warmed up for 15 min at 3° and 2.25 m·s^{-1}

(~ 60-75% of heart rate peak: HR_{peak}). Submaximal assessments included measurement of

steady-state oxygen uptake, heart rate (HR) and blood lactate concentration (La$^-$). All

submaximal tests were performed at 3 m·s^{-1}, with 5 min duration and with 2 min breaks

between trials. The speed was set high enough to induce a relevant technique at moderate

inclines, but low enough to ensure a steady state VO_2 (< 90% of VO_{2peak}-V2). Subjects started

at 3.5° and the incline was subsequently increased 4-6 times by 0.5° every trial until the

subjects reached a La$^-$ of $\geq$ 2.5 mmol·L^{-1} or a rate of perceived exertion (RPE; Borg scale 6-

20) of $\geq$ 15. This was done to avoid any possible interference with the 1000 m test, with

regards to a residual fatiguing effect. Only the 5° workload, which was the highest workload

all subjects completed, was used for the subsequent O_2-cost analysis. However, all

submaximal workloads performed by the individual subject were used to determine the O_2-

demand at supramaximal workloads, as described below. O_2-cost was defined as the average

oxygen uptake (mL·kg^{-1}·min^{-1}) between 2.5 and 4.5 min at each trial. Heart rate was

measured in the same 2 min period and blood for evaluation of lactate concentration was

taken 30 s after each bout.

1000 m time, VO$_{2peak}$-V2 and VO$_{2peak}$-Run. The 1000 m test was a modified protocol from

Losnegard et al. (13), suited to test *distance* (> 15 km) XC skiers. The test was conducted

eight minutes after the last submaximal trial. The incline was 6° and the speed was fixed at 3.25 m·s^{-1} for the first 100 m and then 3.5 m·s^{-1} for 100-200 m (55 s) to avoid over-pacing. Thereafter, the subjects controlled the speed (0.25 m·s^{-1} increase or decrease) by adjusting their position on the treadmill relative to laser beams situated in front of and behind the skier. The speed changes were conducted manually by the test leader. Visual feedback with respect to distance travelled was provided to the subjects, and a separate monitor allowed the test leader to follow the subject's motions. All data including speed changes and time were sampled and saved for subsequent analysis. During the 1000 m test, VO_{2peak}-V2, peak ventilation (VE_{peak}), HR_{peak}, peak blood lactate concentration (La^-_{peak}) and the accumulated oxygen demand (ΣO_2-demand), uptake (ΣO_2-uptake) and ΣO_2-deficit were measured. Oxygen uptake and HR was measured continuously (5 s epochs) and the average over the 12 highest continuous VO_2, VE and HR values (60 s) was taken as VO_{2peak}, VE_{peak} and HR_{peak}. Blood lactate concentration was measured immediately after the test. The highest VO_{2peak}-V2 during the season was named VO_{2max}-V2. Oxygen uptake during treadmill running (Woodway GmbG, Weil am Rein, Germany) was measured with the same equipment as during the rollerski treadmill testing. After a standardised 20 min warm up, subjects ran at a constant 6° incline, while speed was increased incrementally each minute until exhaustion. Subjects started at 11 km·h^{-1} and ran to 14.5 – 16 km·h^{-1} depending on their capacity. Oxygen consumption was measured continuously and the highest value averaged over 1 min was considered as VO_{2peak}-Run for that specific test.

Calculations of ΣO_2-deficit. The calculation of the ΣO_2-deficit with adjustments of O_2-stored is described in detail previously (13). Briefly, ΣO_2-demand at the supramaximal speeds was estimated by extrapolation from the individual linear relationship between the work rate (W) and steady state O_2-cost from at least 4 trials between 3.5- 6° for each subject individually,

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modified from Medbø et al. (17). The calculations took into account that the ratio O_2-cost ·

watt^{-1} is constant with increasing speed. The ΣO_2-deficit was calculated as ΣO_2-demand

minus ΣO_2-uptake (17). Power was calculated as the sum of the power against gravity (Pg)

and the power against rolling friction (Pf), in a coordinated system moving with the treadmill

belt at a constant speed. Power against gravity was calculated as the increase in potential

energy per time ($Pg = m · g · \sin(\alpha) · v$) and the power against friction was calculated as the

work against Coulomb frictional forces at a given tangential speed ($Pf = \mu · m · g · \cos(\alpha) · v$),

with μ is the coefficient of friction, m is the total mass of the skier and equipment, g is

gravitational acceleration, v being the belt speed and α the incline in degrees (°).

After onset of exercise, the O_2-stored in the venous blood is reduced and this aerobic

contribution to the total energy release will in our measurements be part of the ΣO_2-deficit.

We measured the haemoglobin mass in every subject and calculated the reduction in O_2-

stored (13). The total O_2-stores in the blood were estimated to decrease 671 ± 87 mL (range;

587-838 mL) or 8.8 ± 0.8 mL·kg^{-1}. These values are subtracted individually from the ΣO_2-

deficit to estimate the anaerobic contribution.

Training history survey. Training history for the annual training cycle (12 months; May to

May), was recorded based on the skiers' training diaries and categorized into intensity zones

according to the session goal method (27). Endurance training- and competition intensity was

monitored by HR, and categorized into three intensity zones: (1) low intensity training (LIT);

< 81% of HR_{max}), (2) moderate intensity training (MIT; 82–87% of HR_{max}), and (3) high

intensity training (HIT; > 88% of HR_{max}). The intensity during continuous workouts was

quantified using the average HR during the whole session. For high intensity interval

training, the average peak HR during the interval bouts was used to determine the intensity

zones. In addition, training time during running, cycling, skating and classic style skiing (roller skiing and snow-skiing together), strength training (general and maximal) and "other" training (mainly kayak, swimming and soccer) was recorded.

All testing was planned as collaboration between the test leader, coach and subject before conducting the first test (T_1) so the training before every testing session was similar. The subjects were instructed to plan their training so every test was conducted after an easy training period (typical 7 days). Such reduction in training volume during the days before an important test or competition is a well-known strategy for maximizing performance (1). In the present study, the training 7 days before testing was $67 \pm 16\%$ (T_1), $66 \pm 16\%$ (T_2), $62 \pm 17\%$ (T_3) and $71 \pm 8\%$ (T_4) of the mean training volume per week in the respective training month. Hence, the 7 days before every test session, a ~ 30% reduction in training volume was conducted.

Performance level and validity of the 1000 m test. In order to calculate the validity of the 1000 m test, the average of *distance* (Table 1) and *sprint* (< 1.8 km) FIS-points for each subject collected during free technique starts in FIS international competitions during the season were correlated to the 1000 m time at T_4. According to FIS (2), a skier's rank is relative to a 0-point standard established by the top-ranked skier in the world. A skier's total points for a given race are determined by adding race points (from comparing the individual skier's time with the winner's time) and race penalty based on the five best competitors' FIS points in the competition. Hence, superior skiers have the lowest FIS points.

Apparatus. Oxygen consumption was measured by an automatic ergospirometry system (Oxycon Pro, Jaeger Instrument, Hoechberg, Germany), which has been evaluated by Foss &

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Hallén (3). Heart rate was measured with a Polar S610i™ monitor (Polar electro Oy, Kempele, Finland) and blood lactate concentration was measured in unhaemolysed blood, from capillary fingertip samples (YSI 1500 Sport, Yellow Springs Instruments, Yellow Springs, OH, USA). The lactate analyser and Oxycon Pro were calibrated according to the instruction manual and described in detail by Losnegard et al. (14). All testing was performed on a rollerski treadmill with belt dimensions of 3 x 4.5 m (Rodby, Sodertalje, Sweden). The treadmill gradients and speed were checked before, during and after the testing period. Swix CT1 poles (Swix, Lillehammer, Norway) with a tip customized for treadmill rollerskiing were used (pole length 165 ± 6 cm, corresponding to 91 ± 1% of body height). Two different pairs of Swenor Skate rollerskis (Swenor, Sarpsborg, Norway) with wheel type 1 were used depending on the binding system the skiers normally used (NNN, Rottefella, Klokkarstua, Norway or SNS, Salomon, Annecy, France). The rolling friction coefficient (μ) of the skis was tested before, during and after the project using a towing test, previously described by Hoffman et al. (6). All tests were performed after warming up with 15 min of treadmill rollerskiing, which acquired a friction coefficient of 0.020 for both binding systems. The subject's body mass was measured before each treadmill test (Seca, model 708 Seca, Hamburg, Germany). Hemoglobin mass was measured by the optimized CO-rebreathing method as described in Schmidt & Prommer (26).

Statistical Analyses

All data was checked for normality with a Shapiro–Wilk test and presented as mean and standard deviation (SD). First, the traditional approach of determining statistical significance, via the *P* - values, was conducted. The changes in submaximal and maximal parameters during the season were analyzed using a one-way analysis of variance (ANOVA) for repeated measurements followed by the Tukey post-hoc test. Changes from T_4 - T_5 for the separate

group was done with a dependent T-test procedure. Pearson's Product Moment Correlation

Analysis was used for correlations. The following criteria were adopted for interpreting the

strength of correlation (r) between the measures: < 0.1, trivial; 0.1-0.3, small; 0.3-0.5,

moderate; 0.5-0.7, large; 0.7-0.9, very large; and 0.9-1.0, almost perfect (8). Multiple linear

regression analysis was used to determine which of the variables that best predicted the 1000

m time and FIS points. A P - value ≤ 0.05 was considered statistically significant.

Precision of estimation and magnitude-based inferences were also conducted. Confidence

limits for the true mean values for effects were estimated via a spread sheet described in

Hopkins (9). Changes for substantial true effects were verified for a smallest worthwhile

change (SWC), in relation to the typical error (expressed as CV%) for the selected parameters

of 1000 m time, VO_{2peak}-V2, O_2-cost and ΣO_2-deficit (CV%: 2.7%, 2.3%, 1.2% and 8.1%,

respectively). The SWC was calculated as 0.2 times the between-subject SD of the first test

(T_1). Each subjects change score was presented as a percentage via the analyses of log-

transformed values. The spreadsheet provides a precision of the estimates as 90% confidence

limits. The magnitude of differences between sessions was expressed as standardized mean

differences (Cohen`s d effect size; ES). The criteria to interpret the magnitude of the ES

were; 0.0-0.2 trivial, 0.2-0.6 small, 0.6-1.2 moderate, 1.2-2.0 large and >2.0 very large (8).

Statistical calculations were performed with Microsoft Excel, SPSS 18.0 and SigmaPlot 11

software.

RESULTS

Multiple linear regression analysis was conducted with 1000 m time as the dependent variable and VO_{2peak}-V2, O_2-cost and ΣO_2-deficit as the independent variables. This produced the best model summary, with $r^2 = 0.81$ ($P < 0.05$) at T_1. Hence, at T_1 in this group of skiers, 81% of the variation in the 1000 m time was explained by these variables. Further, the model summary was similar in T_2 ($r^2 = 0.78$), T_3 ($r^2 = 0.88$) while at T_4 the model reached a non-significant level ($r^2 = 0.58$, $P = 0.09$). These four variables are shown in Figure 2 as log transformed data for changes in the true mean with 90% confidence limits. The 1000 m time improved significantly from T_1 to T_4 (-7.4 ± 1.9%, $P < 0.05$, ES = 1.37, large). So did also O_2-cost (-3.0 ± 1.2%, $P < 0.05$, ES = 0.63, moderate) and ΣO_2-deficit (24.9 ± 19.5%, $P < 0.05$, ES = 0.94, moderate), while VO_{2peak}-V2 did not change significantly (1.3 ± 2.4%, $P > 0.05$, ES = 0.17, trivial). The subjects body-mass was similar at T_1 (76.8 ± 8.6 kg), T_2 (76.3 ± 8.3 kg) and T_3 (76.5 ± 8.7 kg), but showed a significant decrease from T_3 to T_4 (75.3 ± 8.0 kg) (-1.7 ± 1.0%, $P < 0.05$, ES = 0.14, trivial). Changes in the other variables are presented in Table 2. Within-subject substantial changes between the different testing sessions in 1000 m time, O_2-cost, VO_{2peak}-V2 and ΣO_2-deficit were also conducted. For each variable, the number of subjects who showed a substantial change was calculated (i.e., probability of a positive or negative change > 90%) (Table 3)

<<Table 2 and 3 near here>>

<<Figure 2 near here>>

In the seven subjects that also were tested the following June (T_5), the 1000 m time increased from T_4 to T_5, measured as log transformed data for changes in the true mean ± 90% confidence limits, by 5.6 ± 2.0% (248.4 ± 10.4 vs. 262.4 ± 13.9 s, ES = 1.10, moderate), O_2-

cost increased $2.7 \pm 1.1\%$ (56.6 ± 2.4 vs. 58.1 ± 2.5 mL·kg^{-1}·min^{-1}, ES = 0.54, small) and

body-mass increased $1.8 \pm 1.5\%$ (75.5 ± 5.4 vs.76.9 ± 5.9 kg, ES = 0.21, small), all $P < 0.05$.

However, VO_{2peak}-V2 and ΣO_2-deficit did not change significantly; $-2.2 \pm 13.4\%$ (5.9 ± 0.4

vs. 5.8 ± 0.4 L·min^{-1}, ES = 0.25, small) and $-1.6 \pm 10.8\%$ (68.1 ± 15.6 vs. 66.2 ± 9.7 mL·kg^{-1},

ES = 0.06, trivial), respectively.

The 1000 m time at T_4 was significantly correlated with the subjects FIS *distance* points (r =

0.72, $P < 0.05$, n = 13), but not *sprint* points collected during the season (r = -0.43, $P > 0.05$,

n = 13). Multiple linear regression analysis including FIS *distance* points as the dependent

variable and VO_{2peak}-V2, O_2-cost and ΣO_2-deficit as the independent variables showed the

following summary (r^2) at T_1; 0.39 ($P = 0.31$), T_2; 0.67 ($P < 0.05$), T_3; 0.69 ($P < 0.05$) and T_4;

0.68 ($P < 0.05$).

The subjects had a total annual training volume of 675 ± 103 hrs (range; 469 – 833 hrs). Total

training volume was highest during June - August with a mean $\pm$ SD in these months of $73 \pm$

11 hrs, subsequently decreasing by 14% to 64 ± 14 hrs in September - November (ES = 1.10,

moderate, $P < 0.05$), and by 24% to 48 ± 8 hrs in December - March (ES = 2.10, very large, P

< 0.05). In line with this, the training frequency was highest during June - August with a

mean number of workouts per month of 44 ± 4, then gradually decreasing to 42 ± 6 in

September - November and 36 ± 5 in December - March. The HIT showed a linear increase

throughout the season (r = 0.83, $P < 0.05$) and hence, reduced total training volume was

combined with more HIT (Figure 3).

<<Figure 3 near here>>

In terms of exercise mode, the subjects had a 50-60% ski specific exercise (rollerski and snow-skis) from May to October, while this percentage increased to ~ 80% in the competitive season (December-March) (Table 4). Table 5 shows the training conducted for one week in September including specific training session, duration, exercise intensity and exercise mode in four international-level skiers that all were members of the same professional team.

<<Table 4 and 5 near here>>

DISCUSSION

The main finding of the present study is that a significant main effect among testing session was found for 1000 m time, O_2-cost and ΣO_2-deficit. These changes occurred between June (T_1) and October (T_3). On the contrary, no significant main effect among testing session was found for VO_{2peak}-V2. In a multiple linear regression analysis VO_{2peak}-V2, O_2-cost and ΣO_2-deficit explained ~ 80% of the 1000 m time and ~ 70% of the FIS *distance* points collected during the season and the following discussion will focus especially on these variables.

Peak oxygen uptake. The lack of changes in VO_{2peak}-V2 from T_1 to T_4 is in contrast to Ingjer (10) who reported that XC skiers showed a significantly higher VO_{2max} (5-10%) in the competitive season than in the summer. Ingjer (10) also reported that the most successful skiers had the greatest yearly variation. Although not all of the subjects in the present study were at the same level as the best skiers in Ingjer (10) according to competition record or VO_{2max}, the best subjects in the present study were international-level skiers with top 15 finishes in FIS World-cup or World Championship at free technique races during the respective season. These skiers also showed a very high VO_{2max} (~ 85 $mL \cdot kg^{-1} \cdot min^{-1}$), similar to what was found by Ingjer (10) in his World-class skiers. However, even in this group of

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very high level skiers there was no significant changes in VO_{2peak}-V2 from T_1-T_4 ($2 \pm 5\%$, P = 0.33). One reason for the lack of change in VO_{2peak}-V2, may be that even if they trained less in May than the rest of the year, more than 10 training hours per week was performed including a significant amount of MIT and HIT. This training habit may have changed from the 1980`s. Another reason for the difference between Ingjer (10) and the present study may be that the skiers in the present study were tested during a ski specific exercise, treadmill rollerskiing, and not in running. Skiers in the present study trained 30-40% of the total training in the skating technique, which is more than reported in "World-Class" sprint skiers (23), and several of the skiers were ski skating specialists. Therefore, it is unlikely that non-specific training is the reason for unchanged VO_{2peak}-V2. It is also of note that we did not find a significant change in VO_{2peak}-V2 from T_4 to T_5 in the subgroup of seven subjects. The training logs of these seven skiers showed a low volume of ski specific training during the two months before T_5 (< 10 hrs per month), indicating that specific ski skating training did not have a major impact on VO_{2peak}-V2 in this group of skiers.

The unchanged VO_{2peak}-V2 is, however, in accordance with Lucia et al. (15) who studied senior "World-class road cyclists" (VO_{2max}; ~ 75 mL·kg^{-1}·min^{-1}) over 6 months. Lucia et al. (15) suggested that once a certain training level is reached, further increases in training intensity or volume are not associated with improvements in VO_{2max}. However, this is different from what is found in younger athletes (11,30). Hence, it can be assumed that the major development in VO_{2max} occurs around the puberty phase, and that small changes seem to occur in senior male skiers that already have acquired a very high VO_{2max}.

Gaskill et al. (4) studied highly-trained XC skiers over 2 years and suggested that more HIT, and correspondingly less LIT, could be beneficial for skiers that did not increase their

VO_{2max}. Notably, in the present study, the subjects increased HIT and decreased LIT as they were approaching the competition period without any changes in VO_{2peak}-V2, suggesting that the relative distribution from different intensity zones did not impact VO_{2peak}-V2. From a coaching and athlete perspective, this is an interesting finding, as it is assumed that HIT will lead to improved VO_{2max}, as seen in moderately trained subjects (5). Nevertheless, we do not question the importance of VO_{2max} for performance in XC skiers, as VO_{2peak}-V2 at T_4 correlated moderately and significantly to FIS ski skating *distance* points (r = 0.66, *P* < 0.05, n = 13), even in this rather homogenous group of athletes and underscore the role of VO_{2max} as a predictor of performance. We rather conclude that the increased performance during the year was not associated with changes in VO_{2peak}-V2 in the present group of elite XC skiers.

Oxygen-cost. The O_2-cost was significantly reduced during the preparation period from T_1 to T_3. Sassi et al. (25) and Lucia et al. (15) found no significant changes in economy (or efficiency) after 6 months of endurance training in cyclists. Sassi et al. (25) suggested therefore that changes in economy are less evident in elite, compared to non-elite cyclists. In contrast to cycling, XC skiing is a highly technically demanding exercise with involvement of both the arms and legs. Hence, technical improvements through the season are likely to affect the energy cost and could explain some of the changes found in the present study. The non-significant changes from T_3 to T_4 could be due to a lack of specific rollerski training as skiers train on snow skis during this period. However, it is also possible that the subjects had reached their maximum physiological and technical level at T_3, and that during the competition period this level was maintained. In fact, not only the O_2-cost seemed to plateau, but also 1000 m time and most of the other maximal and submaximal indices. For many of these skiers, competitions at the end of November were critical to qualifying for World-cup races, and also for the opportunity to participate in the World Championship.

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The O_2-cost has been reported to correlate significantly with performance ability in XC skiing (16,18,19). In the present study a significant ~ 3% decrease, and a moderate effect size were found from T_1 to T_3. The relative small changes are of special interest with respect to testing and emphasis the high demand of the precision of the measurement system.

Accumulated Oxygen-deficit. A significant improvement and a moderate effect size were found in the ΣO_2-deficit from T_1 to T_3. This is surprising, since high volume of low-intensity and low- to moderate volume of high-intensity training, also reported by our subjects, has not been associated with improvement in the anaerobic energy system. However, in contrast to most other endurance sports, the race profiles contain a combination of short to long climbing, flat or downhill sections. Hence, the physiological demand to achieve supramaximal intensity during parts of a race is clearly important in both distance- (20) and sprint XC skiing (13,24). This will influence the energy system contribution during a race, and further, be an important aspect of performance. The introduction of sprint skiing and mass start competitions has increased the importance of factors that affect top speed of skiers, such as muscular strength and the ability to generate high power. Therefore, focus on maximal strength and speed abilities has also increased. The training logs showed a substantial amount of strength- and speed training (8-10% of total training). Even though we do not believe that this type of training will directly influence the anaerobic energy system in these skiers, it might result together with the endurance training in an improved ability to maintain an effective technique at maximal workload. However, as noted by Joyner & Coyle (12), much remains to be learned about factors that delay fatigue during intensities above VO_{2max}, and further, detect the adaptations in high performers who seem to manage their metabolism in a way that permits maximum efficient energy use.

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Assessment of individual changes. Coaches and athletes, unlike most scientists, are interested in the development of the individual rather than the group as a whole (21). In the present study, we conducted within-subject analyses in the dependent variable of 1000 m time and in the independent variables of O_2-cost, VO_{2peak}-V2 and ΣO_2-deficit. The most number of substantial changes was seen in 1000 m time, followed by the ΣO_2-deficit, while O_2-cost and VO_{2peak}-V2 showed only low numbers of individual substantial changes. A performance test has not been used in similar studies likely due to that athletes/coaches are concerned of potential negative effects of testing, especially during the competition period (25). However, in our experience, when subjects had performed the test over a longer period, they were more motivated and interested in the time component, than the other physiological responses because performance is their ultimate goal. Seiler (28) suggested that time at VO_{2max} or time at ventilatory threshold better predicts intensified training changes in elite athletes with stable VO_{2max}. This statement is in line with the present results, as low number of individual changes occurred in VO_{2peak}-V2 and O_2-cost. Therefore, a specific performance test would contribute to the evaluation of the subject's seasonal changes in elite skiers. This does not mean that it is not important to improve O_2-cost and VO_{2peak}-V2 to reach a higher performance level, but simply that among elite skiers these variables seem to relate poorly to seasonal individual changes. Nonetheless, the present study examined skiers for up to 12 months but training induced changes might require several years for skiers that already are at a high level.

PRACTICAL APPLICATIONS

The training performed by the present elite athletes during the preparation phase of the year improved performance, but not the sport specific VO_{2peak}-V2. The improved performance can be explained by reduced O_2-cost and increased anaerobic capacity as measured as maximal ΣO_2-deficit. The importance of VO_{2max} as a determinant for performance in modern XC skiing is obvious, as VO_{2peak}-V2 correlated significantly to the overall performance measured as FIS *distance* points during the season. However, in high level athletes, VO_{2max} may have reached their maximal genetic potential after many years of training and further increase may be difficult or even impossible, despite the increase in HIT during the season. Hence, testing of VO_{2max} only, may not pick up important training induced changes during a season in elite athletes and regular testing should include a measure of performance.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors. The results of the present study do not constitute endorsement by NSCA.

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FIGURE LEGENDS

Figure 1. Schematic protocol of the study. Steady state VO_2, HR and La^- were measured at all submaximal stages. During the 1000 m test, HR and VO_2 were measured continuously and La^- was measured immediately after the test.

Figure 2. Log-transformed data for true mean changes in A) O_2-cost, B) VO_{2peak}-V2, C) ΣO_2-deficit and D) 1000 m time. T_1 refer to testing conducted in June, T_2: August, T_3: October and T_4: January/February. Dotted lines are upper and lower 90 % confidence limits. $n = 11$. * Significantly different to T_1, ** significantly different to T_2 ($P < 0.05$).

Figure 3. Total training (hours) in the respective training zones from May-March. A) LIT; low intensity training ($< 81\%$ of HR_{max}), B) MIT; moderate intensity training (82-87% of HR_{max}) and C) HIT; High intensity training ($> 88\%$ of HR_{max}). Solid lines indicate the best fitting curve for the respective months vs. training volume. Data are mean $\pm$ SD, $n = 11$.

Table 1. Physiological characteristics in order of FIS-Point (*distance*) ranking.

	FIS-points	VO_{2max}-V2 (mL·kg^{-1} min^{-1})	VO_{2max}-V2 (L·min^{-1})	VO_{2peak}-Run (mL·kg^{-1}·min^{-1})	VO_{2peak}-Run (L·min^{-1})	Hb mass (g)
	27	84.3 (T_1)	5.43 (T_1)	90.8	5.84	1015
	32	83.8 (T_1)	5.70 (T_1)	83.8	5.72	1153
	34	79.9 (T_4)	6.67 (T_3)	84.0	7.14	1385
	41	84.4 (T_4)	5.64 (T_2)	-	-	981
	43	76.8 (T_2)	5.82 (T_3)	80.1	6.19	1094
	56	85.5 (T_4)	6.13 (T_4)	84.4	6.08	991
	79	81.4 (T_3)	7.28 (T_3)	-	-	1375
	80	74.4 (T_4)	5.97 (T_4)	73.5	5.91	1045
	83	77.1 (T_3)	5.84 (T_3)	74.8	5.72	1002
	84	79.8 (T_1)	5.95 (T_1)	-	-	1088
	102	76.9 (T_2)	5.41 (T_2)	74.0	5.20	969
	111	72.2 (T_4)	6.38 (T_3)	72.8	6.46	1251
	117	74.1 (T_4)	5.75 (T_4)	73.0	5.80	1068
Mean	68	79.3	6.00	79.1	6.00	1109
SD	32	4.4	0.52	6.4	0.52	143

Note: VO_{2max} during treadmill roller skiing (V2) is the highest value obtained during the season and the number in parentheses (T_x) refer to the testing session where this VO_{2max} was obtained; T_1 = June, T_2 = August, and T_3 = October, T_4 = January / February. VO_{2peak} during running (Run) was tested between T_2 and T_3. Subject nr 12 and 13 were only tested at T_3, T_4 and T_5 (June). FIS-points are the average points collected during ski skating distance races during the respective season.

Table 2. Submaximal and maximal indices at the 4 testing sessions (n = 11).

Variables	T_1	T_2	T_3	T_4
Submaximal test (5°, 3 m·s^{-1})				
Mean external power (W)	252 ± 27	250 ± 26	251 ± 27	247 ± 26$^{T1, T3}$
O_2-cost (mL·kg^{-1}·min^{-1})	58.1 ± 2.6	57.2 ± 1.9	56.1 ± 1.6^{T1}	56.4 ± 2.4^{T1}
HR (beat·min^{-1})	166 ± 12	164 ± 13	163 ± 15	162 ± 14
La$^-$ (mmol·L^{-1})	2.2 ± 0.7	2.0 ± 0.8	1.7 ± 0.7^{T1}	1.8 ± 0.6^{T1}
RPE (6-20)	15.2 ± 1.4	14.5 ± 1.3	14.2 ± 1.8^{T1}	14.0 ± 1.7^{T1}
Maximal test (6°)				
Mean external power (W)	367 ± 40	379 ± 39^{T1}	387 ± 41^{T1}	385 ± 40^{T1}
1000 m time (s)	270.0 ± 14.3	259.0 ± 9.2^{T1}	254.6 ± 11.1^{T1}	250.0 ± 10.4^{T1,T2}
VO_{2peak}-V2 (mL·kg^{-1}·min^{-1})	76.0 ± 5.5	76.3 ± 3.6	76.2 ± 4.2	76.9 ± 4.5
VO_{2peak}-V2 (L·min^{-1})	5.8 ± 0.5	5.8 ± 0.5	5.8 ± 0.7	5.8 ± 0.5
O_2-uptake (mL·kg^{-1}·min^{-1})	68.4 ± 4.6	68.6 ± 2.5	68.2 ± 3.8	68.3 ± 3.9
HR_{peak} (beat·min^{-1})	185 ± 12	186 ± 10	185 ± 10	183 ± 12
V_{Epeak} (L·min^{-1})	190 ± 18	195 ± 18	193 ± 19	192 ± 20
La$^-_{peak}$ (mmol·L^{-1})	8.5 ± 0.7	8.5 ± 1.0	8.4 ± 0.8	9.8 ± 1.3^{T1,T2,T3}
ΣO_2-deficit (mL·kg^{-1})	61.0 ± 12.7	69.2 ± 14.1	73.1 ± 7.5^{T1}	76.0 ± 15.2^{T1}
ΣO_2-deficit (%)	16.6 ± 3.4	18.9 ± 3.4	20.2 ± 1.9^{T1}	21.1 ± 4.0^{T1}
Fractional utilization (%)	90.0 ± 1.7	90.0 ± 1.7	89.5 ± 2.1	88.8 ± 1.1

Note: Data are mean ± SD. T_1 = June, T_2 = August, and T_3 = October, T_4 = January / February. ^{T1} significant different from T_1; ^{T2} significant different from T_2; ^{T3} significant different from T_3. O_2-uptake is the ΣO_2-uptake divided by time. Fractional utilization (%) is measured as the ΣO_2-uptake divided by time and VO_{2peak}-V2.

Table 3. Within-subject substantial differences (frequency) between the different testing sessions in 1000 m time, O_2-cost, VO_{2peak}-V2 and ΣO_2-deficit.

	T_1 to T_2	T_1 to T_3	T_1 to T_4	T_3 to T_4
1000 m time (s)	5	8	8	-
O_2-cost (mL·kg^{-1}·min^{-1})	1	2	2	-
VO_{2peak}-V2 (mL·kg^{-1}·min^{-1})	2 (>1;<1)	4 (>2;<2)	2	1
ΣO_2-deficit (mL·kg^{-1})	4	5	7 (>6;<1)	3(>2;<1)

Note: For each variable, the number of subjects who showed a substantial difference is shown (i.e., probability of a positive or negative difference > 90%). When individual differences were found in opposite directions, the number of subjects increasing (>) or decreasing (<) are reported in parentheses. T_1 = June, T_2 = August, and T_3 = October, T_4 = January / February, n = 11.

Table 4. Relative training distribution of total training during different parts of the season.

	May-Jun	Jul-Aug	Sep-Oct	Nov-Dec	Jan-Feb	Mar-Apr
Distribution (%)						
Endurance LIT (< 81% of HR_{max})	82 ± 7	82 ± 4	79 ± 6	81 ± 6	79 ±6	72 ± 10
Endurance MID (82–87% of HR_{max})	4 ± 3	5 ± 2	5 ± 3	4 ± 2	4 ± 3	5 ± 3
Endurance HIT (> 88% of HR_{max})	4 ± 2	4 ± 1	5 ± 2	7 ± 2	9 ± 3	12 ± 9
Strength	7 ± 4	6 ± 2	8 ± 2	6 ± 4	6 ± 3	9 ± 7
Speed	2 ± 2	2 ± 2	2 ± 2	1 ± 1	1 ± 1	1 ± 1
Other	1 ± 1	1 ± 2	1 ± 1	1 ± 1	1 ± 2	1 ± 2
Total	100 %	100 %	100 %	100 %	100 %	100 %
Endurance exercise mode (%)						
Running	27 ± 12	29 ±13	27 ± 11	11 ± 6	8 ± 6	15 ± 16
Classic technique	22 ± 17	22 ± 8	26 ± 8	38 ± 10	45 ± 15	34 ± 15
Skating technique	27 ± 9	27 ± 5	31 ± 8	43 ± 7	40 ± 12	37 ±16
Cycling	16 ± 11	16 ± 8	8 ± 6	1 ± 2	1 ± 2	2 ± 3
Other	8 ± 5	6 ± 4	8 ± 5	7 ± 6	6 ± 5	12 ± 15
Total	100 %	100 %	100 %	100 %	100 %	100 %

Note: Ski training (classic and skating technique) includes roller skiing and snow skiing. In the "Exercise mode" analysis, only data from the LIT, MID and HIT training are included. "Other" referes to soccer, kayak or swimming. Data are mean ± SD, n = 11.

Table 5. Example of a typical medium load training week performed by four international-level elite senior XC skiers in September. Total training volume for this week is 20 hrs.

Variables	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Endurance LIT (< 81% of HR_{max})	(I)3:00 RC		(I)2:30 R	(II)2:45 RC		(I)4:00 C	
Endurance MIT (82–87% of HR_{max})		(I)1:30 – 6x8 min RS					
Endurance HIT (> 88% of HR_{max})				(I)1:15 6x5 min NW			(I)1:30 7x3min RS
Strength	(II)1:00				(I)1:00		
Speed			(II)0:45 - 8x15s RC			(II)0:45- 10x10 s RS	

Note: (I) is workout one and (II) is workout two on the respective day. Training time is referred as hr:min for the whole session (including warm up and cool down). C = Cycling, R = running, RC = Rollerski classic, RS = Rollerski skate, NW = Nordic walking.

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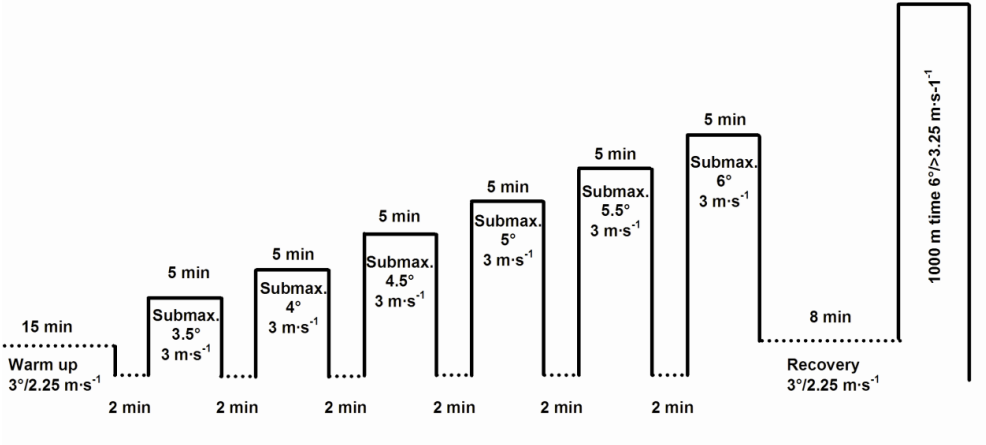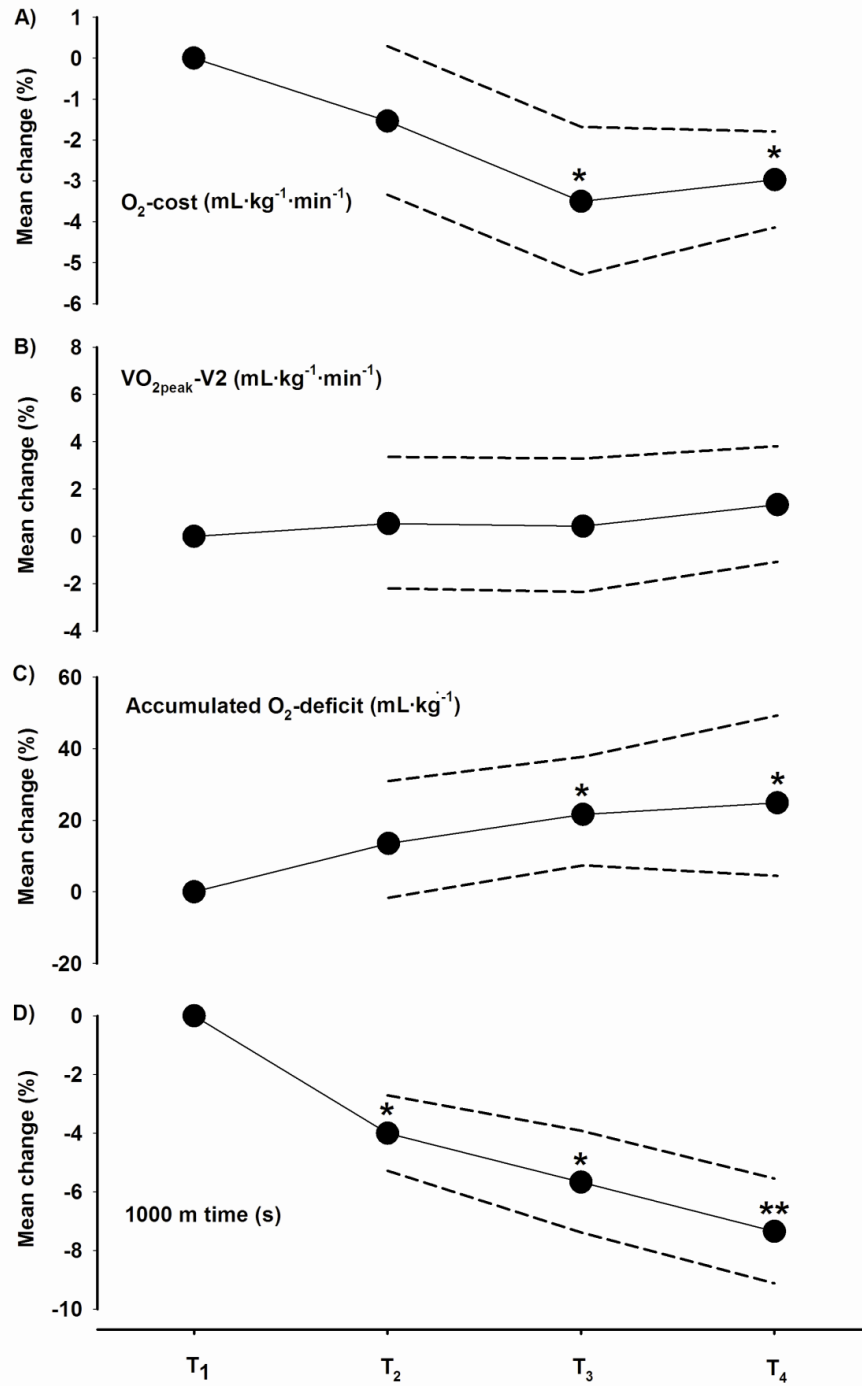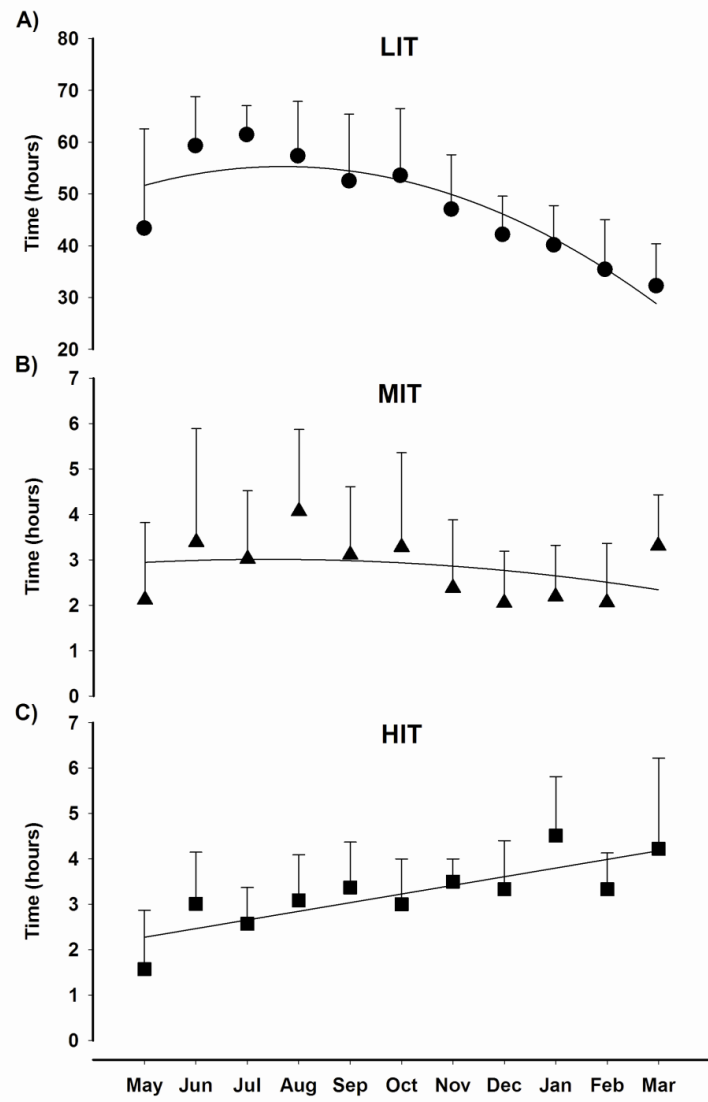**Figure 1.**

Figure 2.

Figure 3.

Muscle use during double poling evaluated by positron emission tomography

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Bojsen-Møller J, Losnegard T, Kemppainen J, Viljanen T, Kalliokoski KK, Hallén J. Muscle use during double poling evaluated by positron emission tomography. *J Appl Physiol* 109: 1895–1903, 2010. First published October 14, 2010; doi:10.1152/japplphysiol.00671.2010.—Due to the complexity of movement in cross-country skiing (XCS), the muscle activation patterns are not well elucidated. Previous studies have applied surface electromyography (SEMG); however, recent gains in three-dimensional (3D) imaging techniques such as positron emission tomography (PET) have rendered an alternative approach to investigate muscle activation. The purpose of the present study was to examine muscle use during double poling (DP) at two work intensities by use of PET. Eight male subjects performed two 20-min DP bouts on separate days. Work intensity was ~53 and 74% of peak oxygen uptake ($\dot{V}o_{2peak}$), respectively. During exercise 188 ± 8 MBq of [^{18}F]fluorodeoxyglucose ([^{18}F]FDG) was injected, and subsequent to exercise a full-body PET scan was conducted. Regions of interest (ROI) were defined within 15 relevant muscles, and a glucose uptake index (GUI) was determined for all ROIs. The muscles that span the shoulder and elbow joints, the abdominal muscles, and hip flexors displayed the greatest GUI during DP. Glucose uptake did not increase significantly from low to high intensity in most upper body muscles; however, an increased GUI ($P < 0.05$) was seen for the knee flexor (27%) and extensor muscles (16%), and for abdominal muscles (21%). The present data confirm previous findings that muscles of the upper limb are the primary working muscles in DP. The present data further suggest that when exercise intensity increases, the muscles that span the lumbar spine, hip, and knee joints contribute increasingly. Finally, PET provides a promising alternative or supplement to existing methods to assess muscle activation in complex human movements.

[^{18}F]fluorodeoxyglucose; glucose uptake; Nordic skiing; cross-country skiing

THE NATURE OF CROSS-COUNTRY SKIING (XCS) has evolved over the last decades, and due to, e.g., the introduction of sprint skiing and mass starts, greater emphasis has been put on the high-speed propulsion techniques such as double poling (DP) (18, 32, 33). Therefore the ability to exert upper-body muscle power has become increasingly important (11, 19, 29, 31), but performance also relies on activation of muscles of the lower body (hip flexors, extensors, and hamstring muscles) (10, 39). The complex patterns of muscle activation during XCS in general, and more specifically the distribution of upper vs. lower body muscle exertion within all the different ski propulsion techniques, are not well examined. Further, limited information exists as to how muscle activation changes with increasing work intensity. Such information would increase the

understanding of how the different techniques are optimally executed and would be beneficial for optimization and evaluation of training preparation and competition strategies.

Recent studies have assessed neuromuscular activation of both upper and lower body musculature during DP (11, 17) or other XCS techniques (20, 26, 34, 38, 41) by applying surface electromyography (SEMG). SEMG displays certain methodological limitations in general (5, 15), and specifically when applied during dynamic contractions (4). Moreover, by the nature of the method SEMG only enables assessment of superficial muscles. Therefore, when investigating complex whole body movements such as DP, supplemental and/or alternative methodologies are warranted.

Recent gains in three-dimensional (3D) imaging techniques such as positron emission tomography (PET) and magnetic resonance imaging (MRI) have enabled acquisition of more detailed information with respect to muscle activation (6–8, 12, 14, 16, 22, 24, 35). Despite the high spatial resolution, PET has only been applied to a limited extent in complex sports movements such as cycling or running (8, 16, 23, 36), and not previously in movement tasks where both muscles of the upper and lower limbs contribute to propulsion such as in XCS.

The purpose of the present study was therefore to investigate muscle activity patterns and the relative contribution of single muscles or muscle groups during double poling at two different work intensities (distance training and high-intensity training) by using PET/MRI imaging.

MATERIALS AND METHODS

Ethical approval. All subjects were informed about the study procedures and potential risks and provided written informed consent before participation. The participants were subjected to a an effective radiation dose of 7.1 ± 0.2 mSv. The study was conducted according to Good Clinical Practice and conformed to the Declaration of Helsinki and was approved by the Ethics Committee of the Intermunicipal Hospital District of Southwest Finland (34/180/2009).

Subjects. Eight healthy males (23 ± 2 yr of age, 182 ± 5 cm, 78 ± 4 kg), all highly skilled cross country skiers, volunteered for the study. All subjects had 10–15 yr of XCS training background; five subjects could be considered present or previous national elite-level skiers. Inclusion criteria were a maximal oxygen uptake > 60 ml·kg^{-1}·min^{-1} (running test), high technical skiing abilities as evaluated by expert skiing coaches, and age between 20–30 yr. Exclusion criteria were any musculoskeletal injury that would interfere with DP, any metallic component operated into the body, and any regularly/periodically used medication.

Experimental overview. The subjects participated on seven separate experimental days. *Days 1–4* included ergometer familiarization and assessment of O$_2$ uptake at different exercise intensities. On *days 5* and *6* the subjects performed one 20-min bout of ergometer double poling at low and high intensities, respectively (see below) with the tracer [^{18}F]fluorodeoxyglucose ([^{18}F]FDG) infused, and subsequently the subjects underwent a full-body PET scan. On *day 7* a full-body

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MRI scan was performed to serve as anatomic reference to the PET images.

Study protocol. On *days 1* and *2*, the subjects performed two 40-min familiarization training sessions in a commercially available DP ergometer (Thoraxtrainer, Holbæk, Denmark) fitted with customized snow ski poles (Swix CT1, Lillehammer, Norway) (Fig. 1). The resistance setting on the ergometer was set to "4" during all experiments. Individual pole lengths were used in all ergometer exercise bouts based on self-selected pole length during snow skiing (153 ± 4 cm or 84% of body height). Based on the power reading (W) on the ergometer display the subjects were asked to identify two individual target work loads, one that would correspond to the intensity of a 2–3 h of low-intensity training bout (distance training), and one corresponding to that of a hard 30-min constant-pace training session (high-intensity training). The defined target work loads were on average 70 ± 13 and 105 ± 20 W, and the subjects were required to exercise at their individual target intensities in the remaining part of the study (hereafter termed "low intensity" and "high intensity").

It was not feasible to measure O_2 uptake ($\dot{V}O_2$) on the days of PET scanning, so $\dot{V}O_2$ during low and high intensities was therefore assessed in a separate session on *day 3*: the subjects did a brief warm-up and thereafter two 6-min bouts of DP on low and high intensity, respectively, was performed. Oxygen uptake was measured continuously, and $\dot{V}O_2$ values were noted after 4–5.5 min of exercise (averaged over 90 s). Subsequent (5 min) to the high intensity bout the subjects underwent a DP peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) test: work load was set to high intensity for 1 min and hereafter increased by 15 W. After 2 min the subject was asked to increase the intensity with the goal of complete exhaustion between 4 and 6 min. $\dot{V}O_2$ was measured continuously, and the highest value averaged over 1 min was taken to represent $\dot{V}O_{2peak(DP)}$ in this session.
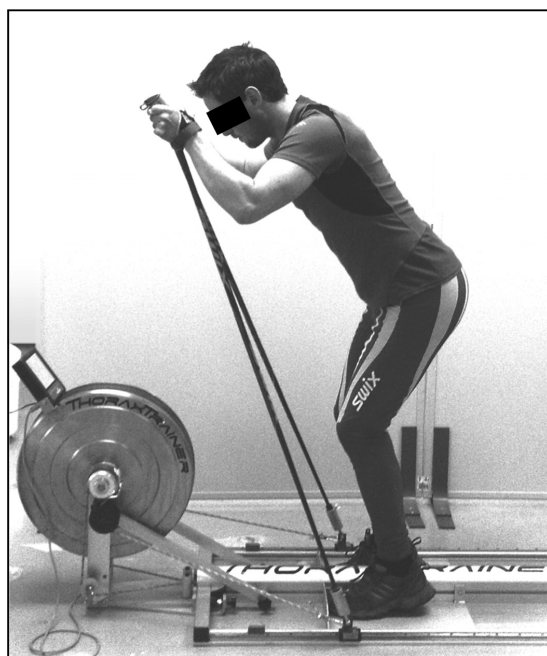

Fig. 1. The ski ergometer. Subjects exercised on a ski ergometer (Thoraxtrainer, Holbæk, Denmark). The ski poles were attached to 2 sleds that moved independently and were connected to a flywheel that provided resistance. A computer displayed work output (W) and poling frequency in real time.

On *day 4* a maximal running test was conducted on a treadmill (Woodway, Weil am Rein, Germany) to assess $\dot{V}O_{2peak}$ during running [$\dot{V}O_{2peak(R)}$]. Details regarding the equipment, protocol and measurement of $\dot{V}O_{2peak(R)}$ have been described recently in a paper from the present lab (19), but in brief, the subjects ran on a 10.5% incline with increasing speeds each minute until exhaustion. *Days 1–4* were conducted for each subject within a 2-wk period, and each session was separated by at least 48 h.

The experimental protocol was similar on *days 5* and *6*: the subjects reported fasting (6 h) to the laboratory, and no strenuous exercise was allowed in the 24 h preceding the experiment. An electrical goniometer (G180, Penny and Giles, Biometrics, Gwent, UK) was firmly secured on the lateral aspects of the upper arm and forearm to enable assessment of the elbow joint angle during DP. A biphasic contact switch (Noraxon, Inline Footswitch, Scottsdale, AZ) was positioned on the hypothenar at the point of contact between the pole rim and the hand to register the timewise onset of load in the poling phase. The goniometer and the contact-switch were connected to a wireless transmitter (Noraxon Telemyo 2400T G2) from which signals were relayed to a personal computer (TM2400 wireless receiver PC card), enabling 500-Hz sampling of the goniometer and contact switch signals. The system allowed for real-time signal visualization during experiments. The wireless transmitter was secured to the lumbar-pelvic region with a waist belt, and a heart rate (HR) transmitter was positioned around the thorax to enable HR sampling using a Polar S610i(Polar Electro, Kempele, Finland).

The subjects rested in a supine position for ~20 min during which an intravenous catheter was inserted into the antecubital vein. A small amount of saline was continuously administered to keep the catheter clear. The total amount of saline infused during the experiment was <100 ml. After an initial blood sampling via the catheter, the subjects were positioned in the ergometer and commenced exercise at the prescribed target intensity. The order of exercise intensity on *days 5* and *6* was randomly chosen such that four subjects performed low intensity on *day 5* and high intensity on *day 6*, and vice versa for the remaining subjects. During exercise, the subjects chose their DP technique freely with respect to poling frequency and joint range of motion, and a real-time power display (W) enabled subjects to keep the required target intensity throughout the task (monitored also by the experimental leader). After 5 min of exercise 188 ± 8 MBq of [^{18}F]FDG in 2 ml of saline was infused during a brief exercise recess (<1 min), and hereafter exercise was continued for an additional 15 min. During exercise the goniometer and contact switch signals were sampled in six 1-min periods spread evenly across the 20-min work period. HR and poling frequency (read from the ergometer display) were registered in the same time periods. Immediately after exercise cessation a blood sample was drawn to determine lactate concentration. Blood lactate concentration was measured in plasma (YSI 1500 Sport; Yellow Springs Instruments). For technical reasons the lactate (La$^-$) data were based on six subjects only. Immediately after exercise the subject was placed supine in anatomic position on a scanner bed that facilitated longitudinal displacement into the gantry of the PET scanner (Siemens ECAT HR+, Knoxville, TN). Caution was taken to minimize any muscle activation after termination of exercise.

[^{18}F]FDG was produced as previously described (9). The PET imaging was performed either using GE Advance (General Electric Medical Systems, Milwaukee, WI) or CTI ECAT HR+ (Siemens Medical Systems, Knoxville, TN) PET scanner, which both operated in two-dimensional (2D) mode. The same scanner was used on both days for each individual. The GE Advance and HR+ scanners consist of 18 and 32 rings of bismuth germanate detectors (BGO) yielding 35 and 63 transverse slices spaced by 4.25 and 2.46 mm, respectively. The imaging field of view is 55 cm in diameter in both scanners and 15.2 cm (GE Advance) and 15.5 cm (HR+) in axial length. The whole body, starting from the head, was scanned in the alternating phases of a 5-min emission scan/position and a 2-min post-emission transmis-

sion scan/position. Altogether, scanning of the whole body took ~110 min.

In a separate session (*day 7*) a full-body MRI scanning (Philips Intera 1.5 T scanner, Philips Medical Systems, Best, The Netherlands) was performed to enable anatomic reference for the regions of interest (ROIs) within the PET images. During PET scanning radioactive markers were positioned at anatomic landmarks (acromion, christa iliaca, and caput fibula), and lipid pills were similarly positioned during MRI scanning to enable reference between MR and PET images.

Biomechanical analysis. During subsequent offline analysis the goniometer and contact switch data were evaluated by use of the Noraxon MyoResearch XP1.04 signal analysis software package (Noraxon). The elbow joint angle amplitude (ROM) (°), poling frequency (Hz), duration of the total poling cycle (s), and the poling phase (s) and recovery phase (s) as defined by Holmberg et al. (11) were determined based on the goniometer and contact-switch signals. Approximately 100 poling cycles/subject were averaged.

PET image processing. All datasets were corrected for dead time decay and measured photon attenuation, and the images were reconstructed using iterative reconstruction. The axial and in-plane resolution of the reconstructed images was ~5 mm full-width at half-maximum.

PET analysis. To enable an overview, 3D volume-rendered images of the whole body were constructed by use of MRIcro 1.4 software (Chris Rorden, Georgia Institute of Technology, Atlanta, GA) (Fig. 2). Cross-sectional (transversal plane) ROIs were determined bilaterally for the following muscles/muscle groups on both the high-intensity and the low-intensity day: knee joint extensors, knee joint flexors (that also exerts a hip extension moment), hip extensors (gluteus maximus), hip flexors (psoas major), lumbar erector spinae, rectus abdominis, latissimus dorsi, teres major, pectoralis major, anterior and posterior deltoideus, upper trapezius, cervical erector spinae, triceps brachii, and biceps brachii. ROIs were also attained in the myocardium at the widest circumference of the heart. During analysis PET and MR images were placed in isometry on the same computer screen by use of the Vinci v.3. software (Max-Planck-Institute for Neurological Research, Köln, Germany), and PET ROI cross-sectional profiles were

drawn based on MR images from the relevant anatomic site (Fig. 3). Depending on the anatomic configuration of muscles (length), the ROIs were constructed by combining three to eight adjacent scanning planes (each ~5 mm thick), from approximately the middle portion (longitudinally) of the relevant muscles. ROI volume and size were similar in the images obtained on the 2 days (Table 1) (the computer software enables ROIs to be copy-pasted between PET images). Standardized uptake value (SUV) of each muscle was calculated as SUV = tissue radioactivity concentration/(injected dose/subject body wt).

To serve as baseline reference for each day, additional PET ROIs were drawn within large bones: the femur condyles, the proximal tibia, and the calcaneus. A total of 12 bone ROIs was defined for each subject on each day. The passive tissue ROI volume was $18,270 \pm 5,636$ mm³ on the low-intensity day and $17,126 \pm 3,808$ mm³ on the high-intensity day, with mean SUV of 186 ± 40 and 190 ± 50, respectively. No significant difference was observed between days in either volume or mean reference tissue SUV, and a highly significant correlation ($R^2 = 0.80$, $P < 0.05$) was observed in bone tissue SUV between days (Fig. 4). During subsequent analysis the GUI in the respective ROIs was calculated by dividing the tissue radioactivity (SUV) with bone radioactivity (SUV) $\times$ 100%, and GUI values below are given as SUV% of baseline (bone) values.

Statistics. Student's two-tailed paired t-tests were used to evaluate differences in biomechanical parameters and GUI for all ROIs between low- and high-intensity days. Interday reproducibility for bone tissue SUV was assessed with linear regression analysis, and systematic bias was tested by use of a paired t-test. An alpha level of $P < 0.05$ was considered significant. Results are reported as group means ($\pm$SD).

RESULTS

Work intensity and physiological response. The $\dot{V}O_2$ during low- and high-intensity exercise was ~53 and 74% of $\dot{V}O_{2peak(DP)}$ as measured during preexperimental days. The actual work intensities (W) and HR were comparable at the

Fig. 2. Positron-emission tomography (PET) images. Three-dimensional (3D) volume-rendered images of the whole body of one subject. Constructed by use of MRIcro 1.4 software (Chris Rorden, Georgia Institute of Technology, Atlanta, GA). The images reveal high glucose uptake (red) in the triceps brachii, the muscles situated around the shoulder, abdominal muscles, and knee flexor muscles. Note also the high intensity in cervical extensor muscles.
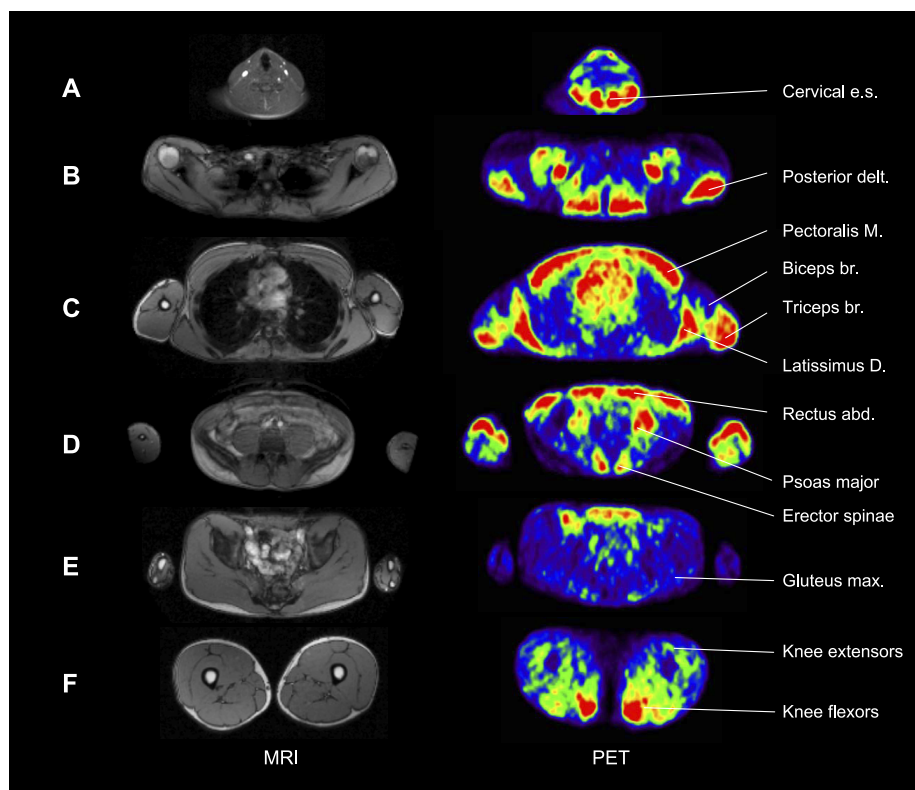
Fig. 3. PET and MR images. Transverse PET and corresponding MR images at 6 different sites: cervical region (*A*), shoulder at caput humerus level (*B*), torso at midhumerus level (*C*), torso at crista iliaca level (note the small radioactive marker on the left side of the PET image that was used for reference) (*D*), pelvis level (*E*), and midthigh level (*F*). Red color denotes glucose uptake. Cervical e.s., cervical erector spinae; posterior delt., posterior deltoid; pectoralis M., pectoralis major; biceps br., biceps brachii; triceps br., triceps brachii; latissimus D., latissimus dorsi; rectus abd., rectus abdominis; gluteus max., gluteus maximus.

low- and high-intensity exercise bouts on *day 3* vs. those on the experimental days (*days 5* and *6*; Tables 2 and 3).

On *days 5* and *6* (PET scanning days), the average work intensity (W) was 55% greater on the high-intensity day compared with that of the low-intensity day (Table 3). The corresponding HR was 29% greater on the high-intensity day relative to that of the low-intensity day, and blood lactate increased significantly (pre-post exercise) and sevenfold more during the high-intensity exercise compared with the low-intensity exercise bout (Table 3).

Biomechanical analysis. The elbow ROM during DP increased 8% from the low- to the high-intensity exercise. Poling frequency increased 14%, while the poling cycle time, the duration of the poling phase and the recovery phase decreased by 12% between intensities (all changes, $P < 0.05$) (Table 3).

PET analysis. For the upper extremity muscles, the triceps brachii displayed by far the greatest GUI in general ($\sim$4,400%; data averaged between low-intensity day and high-intensity day), followed by the latissimus dorsi ($\sim$2,800%), the teres major ($\sim$2,300%), the pectoralis ($\sim$1,700%) and the posterior deltoid muscles ($\sim$1,500%). The biceps brachii and the ante-

rior deltoid muscles exhibited less GUI in comparison ($\sim$800% and 400%, respectively) (Fig. 5).

Most upper extremity muscles exhibited higher numerical GUI values on the high-intensity day compared with that of the low-intensity day, but no significant differences were observed for this group of muscles between days. A tendency to a decrease in GUI was seen from low to high intensity for the triceps brachii (22%, $P < 0.1$), and oppositely, a tendency to an increase (7%, $P < 0.1$) was seen for the biceps brachii (Fig. 5).

For the central muscles of the body that span the lower spine a considerable GUI was observed ($\sim$1,600%), and a significant increase of 21% ($P < 0.05$) from the low- to the high-intensity day was seen for the rectus abdominis.

For the muscles that span the hip and knee joint the general GUI was lower compared with the muscles of the upper extremity (knee extensors: $\sim$500%; knee flexors: $\sim$800%; hip flexors: $\sim$1,100%; and hip extensors: $\sim$600%), but a significant increase ($P < 0.05$) was observed from low to high intensity for the knee extensors (16%) and for the knee flexors (27%), while a tendency to increase ($P < 0.1$) was seen for the hip flexors (82%).

Table 1. *ROI volumes*

	Low Intensity	High Intensity
Knee flexors	449,413 ± 41,271	427,370 ± 44,311
Knee extensors	418,294 ± 59,785	395,654 ± 75,922
Hip flexors	48,911 ± 9,333	47,320 ± 6,657
Gluteus maximus	217,941 ± 43,191	212,598 ± 40,655
Rectus abdominis	54,976 ± 12,329	52,982 ± 9,774
Erector spinae (lumbar region)	123,522 ± 25,149	118,772 ± 22,777
Pectoralis major	114,589 ± 6,304	111,875 ± 8,045
Latissimus dorsi	195,973 ± 25,350	189,822 ± 24,681
Teres major	35,268 ± 4,999	36,064 ± 4,499
Anterior deltoid	35,192 ± 8,784	35,456 ± 9,218
Posterior deltoid	63,331 ± 9,186	63,363 ± 9,248
Triceps brachii	191,875 ± 27,353	193,499 ± 27,006
Biceps brachii	56,576 ± 4,460	60,017 ± 5,189
Cervical erector spinae	19,117 ± 4,403	19,208 ± 4,507
Trapezius	43,321 ± 15,903	43,235 ± 14,843

Values are means ± SD. Data are "total volumes" in mm^3 such that regions of interest (ROIs) of contralateral muscles are added. No significant differences were observed between ROI volumes in any muscle or muscle group.

In the cervical region a high GUI was seen for the cervical part of the erector spinae ($\sim$2,400%), while the trapezius displayed a more moderate GUI ($\sim$800%).

The GUI in the myocardium was high ($\sim$3,000%) and decreased significantly ($-$39%, $P < 0.05$) from the low-intensity day to the high-intensity day (Fig. 5).

DISCUSSION

The present study adds to previous studies on muscle activation during double poling by providing a more detailed 3D picture of the involvement of different muscles. Novel findings are that the hip flexors seem to be highly involved especially at high intensity, but also that the posterior deltoid muscles and cervical spine extensors display high glucose uptake during DP. The data confirm previous studies in that the upper extremity muscles are important contributors, but more importantly it seems that these muscles only to a limited extent increase their glucose uptake when work intensity increases from 53 to 74% of $\dot{V}o_{2peak}$. This indicates that the increased whole body energy output seems to be brought about by a relatively greater increase in activation of central muscles in the body that are situated around the lower spine and hip, and also muscles of the lower extremity.

The present study is to our knowledge the first to apply PET to a complex exercise type where both upper and lower limb muscles are involved. Previous studies have investigated tissue glucose uptake with PET in simple tasks such as isometric muscle contractions (1, 13), dynamic strength exercises (24), but also in more complex endurance work tasks such as ergometer cycling, walking, running, and sprinting (7, 8, 12, 16, 21, 23, 35, 36). It should be noted that the PET methodology only accounts for muscle glucose uptake and it is clear that other substrates such as free fatty acids (FFA), muscle glycogen, and lactate are metabolized in the active muscle cells. Hence, the present method is not suitable to directly quantify the increase in energy turnover in respective tissues. Nonetheless, previous studies have confirmed that glucose oxidation increases with incrementing exercise intensities, and that glucose uptake increases somewhat in proportion to glycogen utilization when exercise intensity rises (27, 28, 40).

Taken together with findings in previous PET studies (REF) it seems plausible that an augmented GUI as seen between intensities in the present experimental setting is an indicator of increased muscle activation.

Muscle use during DP. Assuming that the GUI reflects muscle activation, the present data confirm that the main effector muscles in DP include the triceps brachii, latissimus dorsi, teres major, and the pectoralis muscles that all span the shoulder joint (11). The posterior deltoid muscles that belong to the same group but have not previously been assessed seem also to play an important role in DP.

Muscles of the lower extremity display markedly lower GUI; however, during simultaneous arm and leg exercise, glucose uptake can only to a limited extent be used to infer about the relative energy turnover of lower and upper limb muscles due to a high contribution from lactate oxidation to the energy turnover in the legs (39). In fact, the study of van Hall et al. (39) indicates an insignificant glucose uptake and a high lactate uptake and oxidation during double poling although it cannot be excluded that the preceding 40-min exercise in that experiment had an effect on the distribution between lactate and glucose utilization. The same experiment showed that oxygen uptake was similar in the lower and upper limbs during double poling at an intensity comparable to that of the high-intensity exercise in the present study (3). Hence, since the muscle mass is much greater in the legs, the activation relative to its maximum is likely much less. The relatively low leg muscle GUI in the present study is thus most likely a consequence of both a moderate activation and a high contribution from lactate oxidation, and the present data thus seem to fit well with previous work. Nonetheless, the present data add to previous studies by showing that muscle activation in the legs does not seem to be uniform, that the knee flexors are more activated than the extensors, and that muscles of the lower legs are only minutely activated.

Based on GUI, the central muscles of the body, i.e., the abdominal muscles that exert flexion in the lower spine and the hip flexors, seem to contribute significantly to DP. Moreover,
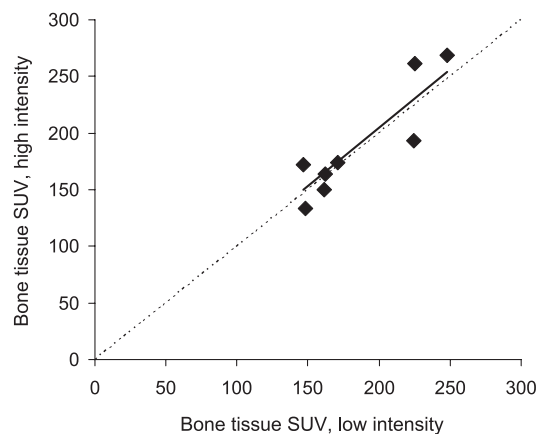

Fig. 4. Day-to-day variation in passive tissue glucose uptake. A highly significant correlation ($R = 0.89$, $P < 0.05$) was seen between passive tissue (bone) standardized uptake value (SUV) between high- and low-intensity days. Dotted line, line of identity; solid line, trend line.

Table 2. *Work load and physiological response at low, high, and maximal intensity in double poling and maximal intensity during treadmill running*

Days 3 and 4	Double Poling					Running $\dot{V}_{O_2peak(R)}$
	Low Intensity	% of Max	High Intensity	% of Max	$\dot{V}_{O_2peak(DP)}$	
Work load, W	69 ± 13	40 ± 3	106 ± 20	62 ± 6	172 ± 32	
$\dot{V}_{O_2}$, l/·min	2.5 ± 0.4	53.4 ± 5.1	3.5 ± 0.5	74.1 ± 6.6	4.7 ± 0.6	5.3 ± 0.6*
$\dot{V}_{O_2}$, ml·kg^{-1}·min^{-1}	32.8 ± 5.0		44.1 ± 5.0		59.6 ± 5.1	68.0 ± 5.3*
HR, beats/min	139 ± 7	74 ± 4	164 ± 7	88 ± 4	187 ± 4	195 ± 4*
$\dot{V}_E$, l/min	63.9 ± 7.0	35.8 ± 4.4	105.4 ± 17.0	59.1 ± 10.8	179.4 ± 17.1	182.4 ± 19.2
RER	0.88 ± 0.02		0.95 ± 0.02		1.11 ± 0.02	1.14 ± 0.03*

Values are means ± SD. All data were acquired on *days 3* and *4*. "% of Max" denotes the value relative to that of maximal intensity double poling (DP). $\dot{V}_{O_2}$, oxygen uptake; HR, heart rate; $\dot{V}_E$, ventilation; RER, respiratory exchange ratio; $\dot{V}_{O_2peak(DP)}$, peak $\dot{V}_{O_2}$ during DP; $\dot{V}_{O_2peak(R)}$, peak $\dot{V}_{O_2}$ during running. *Significant difference ($P < 0.05$) between exercise type (DP or treadmill running) at maximal intensity.

moderate to high glucose uptake was seen in hip and spine extensors, which likely do not contribute to external work as such, but rather play a role in postural stabilization and the extension of the body that takes place in the recovery phase. The GUI values of these muscles suggest that although hip and spine extensors do not add to propulsion per se, they perform a significant amount of work during DP, that for the lower back extensors are comparable to that of the abdominal flexor muscles.

A novel finding of the present investigation was that high GUI was observed in the posterior cervical region. Increased uptake in the upper trapezius muscles could be explained by external rotation of the scapula that is required for shoulder flexion/abduction in the final part of the recovery phase; however, only moderate activity was seen in the upper trapezius muscles. The high GUI values were seen in neck extensor muscles that likely do not contribute to external work. It seems conceivable, however, that significant muscle activation is needed in this region to keep the posture of the head and neck during the latter part of the poling phase where the hip and lower spine is highly flexed, and where the torso and head experiences a significant downward vertical acceleration. In fact, a recent study reported a negative correlation between the mass of the head and DP performance, which may well be

Table 3. *Work load, physiological response, and biomechanical data acquired during low- and high-intensity DP on experimental days 5 and 6*

Days 5 and 6	Low-Intensity Day	High-Intensity Day	Difference Between Intensities, %
Work load, W	68 ± 14	106 ± 18*	55
HR, beats/min	128 ± 9	165 ± 4*	29
La$^-$ before exercise, mmol/l	1.0 ± 0.2	1.0 ± 0.4	0
La$^-$ after exercise, mmol/l	2.3 ± 1.6	9.4 ± 2.7*	309
Elbow ROM, °	75 ± 17	80 ± 13*	8
Cadence, strokes/min	44 ± 6	50 ± 7*	14
Poling frequency, Hz	0.74 ± 0.11	0.83 ± 0.11*	14
Poling cycle, s	1.38 ± 0.25	1.23 ± 0.19*	−11
Poling phase, s	0.91 ± 0.22	0.80 ± 0.19*	−12
Recovery phase, s	0.48 ± 0.11	0.42 ± 0.12*	−12

Values are means ± SD. Work load, HR, and poling data are averaged over the exercise bout. Blood samples for lactate (La$^-$) were drawn before and after exercise. ROM, range of motion. *Significant difference ($P < 0.05$) between low- and high-intensity exercise.

related to excessive force exertion in the associated postural muscles (30).

One previous study has performed detailed SEMG measurements during DP at 85% of maximum DP velocity (11). In this investigation the teres major, rectus abdominis, latissimus dorsi, pectoralis major, triceps, and gluteus maximus displayed high EMG activity, while lower extremity muscles scored medium to low EMG activity. Other studies have indicated that the triceps brachii and muscles around the shoulder joint are the main propulsors during DP (11, 17, 37), and as such the present PET data are comparable to previous findings obtained with SEMG. Differences in work intensity between present and previous studies, and further the different experimental setting (treadmill DP on roller skis vs. DP ergometer in the present study), may account for dissimilarities between studies. The present biomechanical data are not quite identical to what has previously been reported in treadmill and snow skiing: while poling frequencies were similar, the current poling times were longer, leading to a different phase distribution within the entire cycle (11). These differences likely pertain to mechanical constraints introduced by the ergometer such as flywheel inertia and resistance.

Low to high intensity. As noted the PET method is better suited to infer about changes between intensities within the same muscle or muscle group. The present data revealed similar values or nonsignificant gains between days in GUI for most muscles that exert moments about the shoulder joint. Concurrently, muscles in the lower part of the body (hip, spine, and leg muscles) showed significant increases in GUI from low to high intensity, which suggests that the relative contribution from these muscles increases with increasing work intensity. A recent study that examined diagonal stride found that blood flow, regional O_2 delivery, and $\dot{V}_{O_2}$ increased to a greater extent in legs compared with that of arm muscles when work intensity increased from submaximal to maximal efforts (2, 3). Although different ski techniques and intensities were used, and although the present study applies a highly different methodology, the studies, taken together, may indicate that arm and shoulder muscles reach a plateau in energy output at submaximal levels, and that further increases in whole body exercise intensity during DP is covered by muscles in the lower part of the body. This mechanism may also be related to muscle size, such that the relatively small muscles that operate about the shoulder and elbow joints are perhaps sufficient to keep a certain work intensity; however,
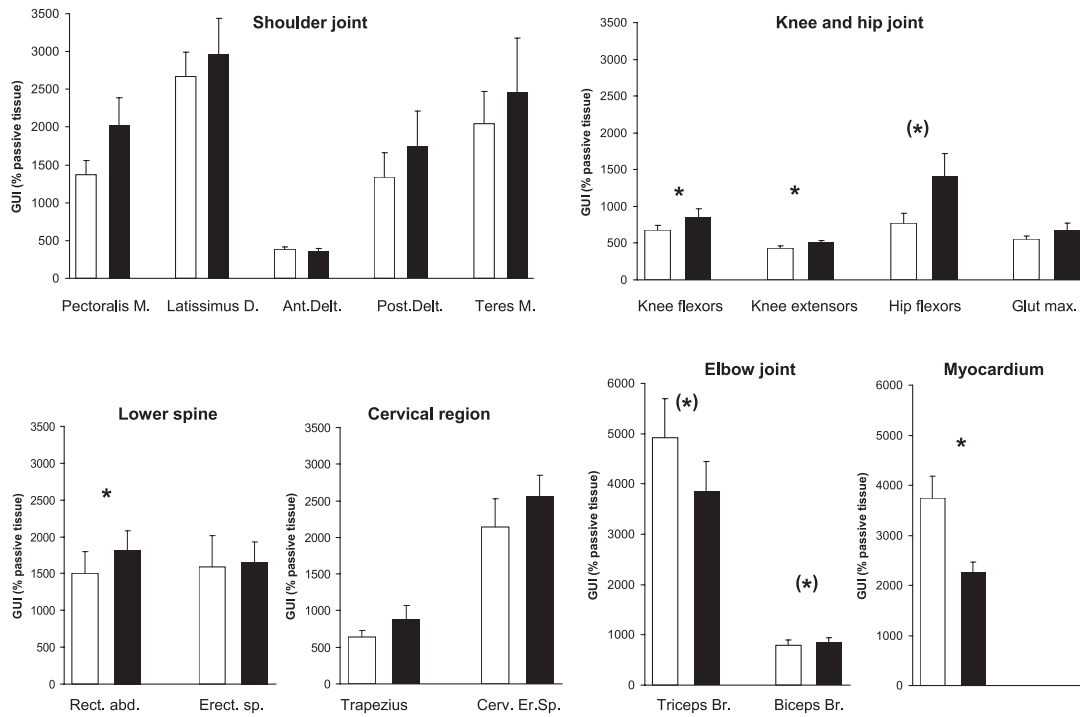
Fig. 5. Muscle glucose uptake index (GUI). GUI for relevant muscles and muscle groups. Open bars denote GUI on the low-intensity day, while filled bars represent uptake on the high-intensity day. $*P < 0.05$ from day to day. (*)$P < 0.1$. Note individual y-axis scaling for the elbow joint and myocardium plots. Teres M., teres major.

when intensity increases above a certain level the greater muscle mass of the lower body is required to encounter the global energy demand. In the present study a tendency to a decrease in triceps brachii GUI was observed from low to high intensity, which underscores this notion; however, these findings should be seen in the light of the above

discussion on the limitation of the PET method that only quantifies glucose uptake and does not account for metabolization of other substrates. Nonetheless, it seems plausible that an increase in intensity can only be accomplished by a change in the DP technique toward greater involvement of muscles in the central and lower body.
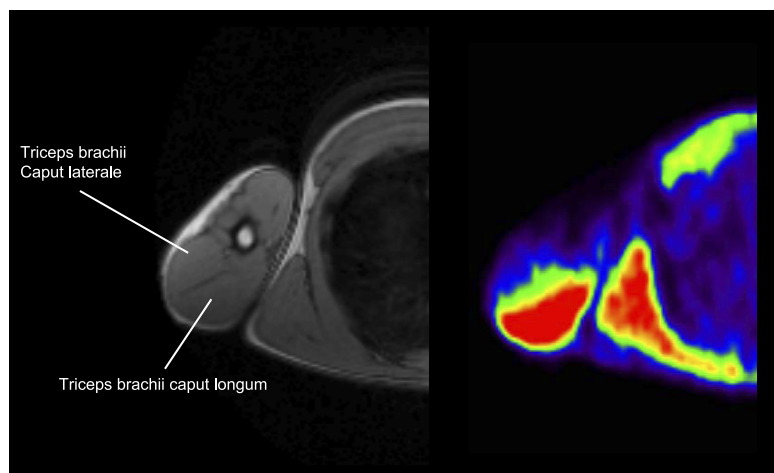

Fig. 6. Heterogeneous activation of the triceps brachii. PET enables assessment of uneven activation within single muscles or muscle groups. The present individual displayed an activation strategy in which mainly the medial head of the triceps was activated. This difference would not have been accounted for in a study using surface electromyography (SEMG) if electrodes were only placed on one portion of the muscle as has previously been done. Red color denotes greatest glucose uptake.

Although not strictly pertinent for the general aim of the study, also ROIs were drawn in the heart muscle. This was deemed applicable since only a few previous studies have examined subjects in full-body PET scanning subsequent to two work intensities. In line with previous work (12, 16), a significant reduction in myocardial GUI was observed from the low to high intensity, which is likely attributed to utilization of lactate as muscle fuel in the heart. In the present study the reduction was ~40%, and thus the present data confirm those of Kemppainen et al. (16), who found a reduction of ~27% when going from a work intensity of 55% $\dot{V}_{O_{2max}}$ to 75% (cycling exercise).

PET methodology. The following issues should be kept in mind when interpreting PET data. PET displays poor time resolution such that if subjects change technique during exercise this is not reflected in results. It should further be noted that some tracer may remain in the blood at the cessation of exercise and may thus be taken up during the scan. Based on blood radioactivity, previous studies have estimated the remaining amount of tracer to be small (16), and combined with the fact that in the present study the scans were performed identically between days, the influence on day-to-day results is likely nominal. Moreover, with PET it is necessary to normalize glucose uptake when comparing tasks performed on different days: When glucose uptake is measured at rest, arterial or arterialized venous blood samples are taken, and quantitative glucose uptake values are calculated using graphical analysis, as described by Patlak and Blasberg (25). Blood sampling during complex dynamic tasks is challenging and therefore other approaches have been used. In simple strength tasks, where only limited muscle mass is activated, normalization has been done relative to passive muscle that is not affected by contraction (13, 24). In more complex endurance type work tasks, the glucose uptake has been quantified, for example, relatively to resting control groups (35). Thus no "gold standard" exists for exercise studies, but in the present study, muscle glucose uptake was related to that of bone tissue, assuming that glucose uptake here is largely unaffected by exercise intensity. The SUV of the reference tissue was low and similar between days with a high interday correlation (Fig. 4), despite a marked difference in exercise intensity. Taken together, the selected approach seems a feasible alternative for whole body exercise studies with FDG-PET.

PET vs. EMG. When comparing the methods it becomes clear that SEMG is a more practical method and thus seems more feasible to apply when investigating muscle use. SEMG does, however, present issues with respect to signal cancellation and cross talk, and in complex movements during which body segments are moving at high frequencies, also issues with respect to displacement of the skin (and thus electrodes) relative to the underlying muscles are apparent (4). EMG has a high time resolution, but poor spatial resolution, and in fact only the portion of muscle below the electrodes can be inferred about. Moreover, EMG requires normalization to maximal or peak EMG, which especially during dynamic contractions where muscle lengths change during the executed joint range of motion presents a confounding factor. In comparison, PET is more costly, complex, and time consuming; however, PET presents excellent spatial resolution, which allows for investigation of deeper lying muscles and portions of muscle that are not accessible with SEMG. Also individual activation strategies can be accounted for with PET: for example, one subject of the present study only used the medial portion of the triceps brachii in DP, which would not have been observed if the present experiment was conducted with for example EMG electrodes positioned on only one of the triceps portions (Fig. 6).

In conclusion, PET imaging may be considered a promising supplement or alternative to more traditional methods for investigating muscle use during complex human movements. The present data further suggest that although double poling is an upper body effort, also muscles that exert moments about the lumbar spine, hip, and knee joint play an increasingly important role for propulsion when exercise intensity increases.

Perspectives

The PET data and biomechanical assessments seem largely comparable to previous investigations (11, 31). The currently used DP ergometer resembles thus to a reasonable extent the DP movement during at least treadmill skiing and may thus be considered a relevant instrument for training and further research. The present study further suggests that low-intensity training may not be sufficient to target all muscles that are involved in high-speed DP, and specifically training intensities must be high to impact on muscles of the lower body. Surprisingly, a high GUI was observed in posterior neck muscles that do not contribute to propulsion. Personal communications with top-level skiers have confirmed that tiredness or specific muscle pain can be experienced in this region after excessive DP bouts. Specific resistance training of neck flexor muscles and/or stretching/mobilization may be relevant for athletes that frequently are engaged in high-speed DP.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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