Thesis for the Degree of Doctor of Philosophy, Östersund 2010

METABOLIC AND CARDIOVASCULAR RESPONSES DURING VARIABLE INTENSITY EXERCISE

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ISSN 1652-893X
Mid Sweden University Doctoral Thesis 86
ISBN 978-91-86073-76-3

Akademisk avhandling som med tillstånd av Mittuniversitetet framläggs till offentlig granskning för avläggande av filosofie doktorsexamen i Hälsovetenskap med inriktning Idrottsvetenskap den 16 juni 2010, klockan 10.30–13.30 i sal Q221, Mittuniversitetet, Östersund. Seminariet kommer att hållas på engelska.

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Printed by Mid Sweden University Press, Sundsvall, Sweden, 2010
Cover graphical illustration by Tobias Flygar

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ABSTRACT

Previous research investigating endurance sports from a physiological perspective has mainly used constant or graded exercise protocols, although the nature of sports like cross-country skiing and road cycling leads to continuous variations in workload. Current knowledge is thus limited as regards physiological responses to variations in exercise intensity. Therefore, the overall objective of the present thesis was to investigate cardiovascular and metabolic responses to fluctuations in exercise intensity during exercise. The thesis is based on four studies (*Studies I-IV*); the first two studies use a variable intensity protocol with cardiorespiratory and blood measurements during cycling (*Study I*) and diagonal skiing (*Study II*). In *Study III* one-legged exercise was used to investigate muscle blood flow during variable intensity exercise using PET scanning, and *Study IV* was performed to investigate the transition from high to low exercise intensity in diagonal skiing, with both physiological and biomechanical measurements. The current thesis demonstrates that the reduction in blood lactate concentration after high-intensity workloads is an important performance characteristic of prolonged variable intensity exercise while cycling and diagonal skiing (*Studies I-II*). Furthermore, during diagonal skiing, superior blood lactate recovery was associated with a high aerobic power (VO_{2max}) *(Study II).* Respiratory variables such as V_E/VO_2, V_E/VCO_2 and RER recovered independently of VO_{2max} and did not reflect the blood lactate or acid base levels during variable intensity exercise during either cycling or diagonal skiing (*Studies I-II*). There was an upward drift in HR over time, but not in pulmonary VO_2, with variable intensity exercise during both prolonged cycling and diagonal skiing. As a result, the linear HR-VO_2 relationship that was established with a graded protocol was not present during variable intensity exercise *(Studies I-II*). In *Study III*, blood flow heterogeneity during one-legged exercise increased when the exercise intensity decreased, but remained unchanged between the high intensity workloads. Furthermore, there was an excessive increase in muscular VO_2 in the consecutive high-intensity workloads, mainly explained by increased O_2 extraction, as O_2 delivery and blood flow remained unchanged. In diagonal skiing (*Study IV*) the arms had a lower O_2 extraction than the legs, which could partly be explained by their longer contact phase along with much higher muscle activation. Furthermore, in *Study IV*, the O_2 extraction in both arms and legs was at the upper limit during the high intensity workload with no further margin for increase. This could explain why no excessive increase in pulmonary VO_2 occurred during diagonal skiing (*Study II*), as increased O_2 extraction is suggested to be the main reason for this excessive increase in VO_2 (*Study III*).

Keywords: cross-country skiing, cycling, heart rate, lactate, O_2 extraction, O_2 uptake, performance, ventilation

POPULÄRVETENSKAPLIG SAMMANFATTNING PÅ SVENSKA

Majoriteten av tidigare forskning inom uthållighetsidrott har primärt använt arbetsprotokoll med konstant eller stegrande arbetsintensitet, trots att idrotter som exempelvis längdskidåkning och landsvägscykling genomförs med varierad arbetsintensitet. Till dags dato är befintlig kunskap begränsad om hur denna variation i arbetsbelastning inverkar under uthållighetsidrott. Avhandlingen visar att en reducering av blodmjölksyra under pågående arbete efter högintensiva arbetsbelastningar är en betydelsefull egenskap för prestation under uthållighetsidrott med variabel arbetsintensitet. Under längdskidåkning med diagonalteknik var förmågan att reducera mjölksyra i blod relaterad till en hög maximal syreupptagningsförmåga (VO_{2max}). Respiratoriska variabler som V_E/VO_2, V_E/VCO_2 och RER reducerades oberoende av VO_{2max} och återspeglade inte koncentrationen av mjölksyra, basöverskott eller pH i blod vid varken cykel eller diagonalskidåkning med varierad arbetsintensitet. Under cykel och diagonalskidåkning med varierad arbetsintensitet ökade hjärtfrekvensen successivt över tid, men inte VO_2. Detta medför att det linjära förhållandet mellan hjärtfrekvens-VO_2, beräknat utifrån ett stegrande arbetsprotokoll, inte stämmer vid arbete med varierad arbetsintensitet. Däremot ökade VO_2 i muskel vid den efterföljande högintensiva arbetsbelastningen genomförd med enbensarbete trots en oförändrad arbetsbelastning. Denna ökning av VO_2 förklarades främst av en ökad extraktion av O_2 och inte O_2-leverans, blodflöde eller blodflödets distribution. Detta indikerar att en ökning av VO_2 för en given arbetsbelastning är beroende av den aktiverade muskelmassans storlek. För att möjliggöra en ökning måste troligen muskelmassan vara liten eftersom VO_2 inte ökade vare sig med cykel eller med längdskidor vilka båda aktiverar en stor mängd muskelmassa. Vidare visar avhandlingen att armarna har en lägre förmåga att extrahera O_2 än benen vid diagonalskidåkning vilket delvis kan förklaras av armarnas längre kontakttid med underlaget samt högre muskelaktivering jämfört med än benen. När arbetsbelastningen minskar så reduceras armarnas extraktion av O_2 mer än benens. Koncentrationen av mjölksyra i blod minskar mer i armarna jämfört med benen vilket troligtvis kan bero på att armarnas muskelaktivering minskar mer än benens. Avseende uthållighetsarbete med en varierad arbetsintensitet visar avhandlingen sammanfattningsvis att: i) reducering av blodmjölksyra är en viktig egenskap för prestation ii) förhållandet mellan hjärtfrekvens-VO_2 är bristfälligt iii) aktiverad muskelmassa kan påverka responsen VO_2 vid följande högintensiva arbetsbelastningar iv) blodflödet påverkas inte av arbetsintensiteten. Vidare, vid

diagonal skidåkning, kan armarnas lägre extraktion av O_2 jämfört med benens delvis förklaras av skillnader i muskelaktivering.

Nyckelord: andning, cykling, hjärtfrekvens, laktat, längdskidåkning, O_2 extraktion, O_2 upptag, prestation

ABBREVIATIONS

BE	Base excess
B_f	Breathing frequency
Bpm	Beats per minute
CO_2	Carbon dioxide
DIA	Diagonal skiing
DP	Double poling
EMG	Electromyography
Hb	Hemoglobin
HI_{90}	90% of VO_{2max}
HR	Heart rate
HR_{max}	Maximal heart rate
La_{max}	Maximal blood lactate concentration
MI_{70}	70% of VO_{2max}
MVC	Maximal voluntary contraction
O_2	Oxygen
$PaCO_2$	Arterial carbon dioxide partial pressure
PaO_2	Arterial oxygen partial pressure
PET	Positron Emission Tomography
RER	Respiratory exchange ratio
SaO_2	Arterial hemoglobin oxygen saturation
TTE	Time to exhaustion
VCO_2	Carbone dioxide production
V_E	Pulmonary ventilation
V_E/VO_2	Ventilatory equivalent of oxygen uptake
V_E/VCO_2	Ventilatory equvalent of carbon dioxide production
VIP	Variable Intensity Protocol
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen uptake
V_T	Tidal volume
W_{max}	Maximal power
r	Correlation coefficient
r_{xy-z}	Partial correlation
SD	Standard deviation
F	F-distribution

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LIST OF PAPERS

This thesis is based on the following four studies, herein referred to by their Roman numerals:

Study I Björklund G, Pettersson S, Schagatay E. Performance predicting factors in prolonged exhausting exercise of varying intensity. *Eur J Appl Physiol*. 2007 Mar;99(4):423-9.

Study II Björklund G, Laaksonen MS, Holmberg H-C. Blood lactate recovery and respiratory responses during diagonal skiing with variable intensity. *Submitted*

Study III Laaksonen MS, Björklund G, Heinonen I, Kemppainen J, Knuuti J, Kyrölainen H, Kalliokoski KK. Perfusion heterogeneity does not explain excessive muscle oxygen uptake during variable intensity exercise. *Clin Physiol Funct Imaging.* Accepted for publication 2010 Mar 1.

Study IV Björklund G, Stöggl T, Holmberg H-C. Biomechanical influenced differences in O_2 extraction in diagonal skiing: arm vs. leg. *Med Sci Sports Exerc.* 2010 Mar 8. [Epub ahead of print].

1. INTRODUCTION

1.1. Endurance exercise

Endurance in sports can be defined as the ability to maintain exercise intensity over a long period of time and resistance to fatigue. It is well documented that during endurance sports, athletes must regulate their rate of work output in order to optimize their overall performance (Abbiss & Laursen, 2008). During competitions in sports such as road-cycling, cross-country skiing, mountain-biking and even running events, exercise intensity fluctuates (Esteve-Lanao, et al., 2008; Lucia, et al., 1999; Mognoni, et al., 2001; Stapelfeldt, et al., 2004). Furthermore, the variation in exercise intensity increases with mass-start races in cycling and cross-country skiing, compared to individual-start races, due to the tactical component's greater influence. However, the majority of exercise protocols for examining endurance athletes' physiological capacities as regards their physical performance have been achieved with constant or graded protocols (Lucia, et al., 1998; Richardson, et al., 1993; Stegmann, et al., 1981; Stringer, et al., 1995; Wasserman & McIlroy, 1964; Wasserman, et al., 1967). If the causality between variables established with constant or graded protocols is factual, it should remain even though variable intensity protocols are performed.

1.1.1. Constant and graded intensity exercise

The most common methods for describing the intensity of endurance exercise are heart rate (HR), oxygen uptake (VO_2), power (W) and velocity. Percentage of VO_2 is used extensively in the scientific literature in order to describe exercise intensity in both laboratory and field settings, although during the latter direct measures of VO_2 have mainly been used during simulated competitions (Maron, et al., 1976; Mygind, et al., 1994). Mostly, VO_2 has been estimated in order to calculate the percentage of VO_{2max} the athletes maintained during competitions through HR monitoring, using the HR-VO_2 linear relationship that is obtained during graded protocols (Lucia, et al., 1999; Mognoni, et al., 2001; Padilla, et al., 2001). Another method for obtaining endurance or time to exhaustion (TTE) at a specific percentage of VO_{2max} includes critical power (Hill, 1993) or critical velocity models (Billat, et al., 1994).

In general, graded protocols have been used to obtain physiological data such as lactate and ventilatory thresholds, VO_{2peak} and VO_{2max} (Bruce, et al., 1973; Kindermann, et al., 1979; Sjödin & Jacobs, 1981; Wasserman, et al., 1973). There are several different types of graded protocols, which may differ in work increments (i.e. W, $km \cdot h^{-1}$, inclination) and/or ramps of different durations. Work-ramp duration has been suggested to be of minor influence in obtaining VO_{2max} (range 1-3 min) (Roffey, et al., 2007; Zhang, et al., 1991). Furthermore, Froelich et al. (1974) demonstrated no differences between long or short work-ramp durations as regards the reproducibility of VO_{2max} measurements. However, the accumulated test time for a VO_{2max} test should probably exceed 8 min for healthy trained subjects (Yoon, et al., 2007). In addition, cycling protocols that are performed with shorter work-ramp durations demonstrably produce a lower HR_{max} and a shorter TTE, but a higher W_{max} (Roffey, et al., 2007). Moreover, VO_{2max} tests should be sport specific and, in sports such as cross-country skiing and rowing, should involve both the upper and lower body, as it has been shown that whole body exercise produce a ~3-4 % higher VO_2 compared to running or cycling (Holmberg, et al., 2007; Strömme, et al., 1977). Work economy is another important variable for performance in endurance sports and is defined as the energy demand for a given workload, i.e. speed or power output (di Prampero, et al., 1986; Saunders, et al., 2004). Depending on the sport and locomotion, work economy influences performance to a varying degree, as the work economy of highly trained runners is superior to that of their lesser trained counterparts (Morgan & Craib, 1992), while in cycling work economy varies less between different levels of cyclists (Moseley, et al., 2004).

The lactate threshold concept was introduced in the late 1950s (for refs see Faude, et al., 2009; Myers & Ashley, 1997) and established a new physiological method with a high validity for performance which could identify the "aerobic-anaerobic transition" (Kindermann, et al., 1979; Wasserman & McIlroy, 1964). The advantage of lactate threshold tests in comparison to VO_{2max} tests is that it is not necessary to reach physical exhaustion and therefore could be used more frequently to monitor the progression of athletes' training (Mader & Heck, 1986). Various interpretations of lactate thresholds have been used, with both fixed lactate concentrations and individually based ones (Coyle, et al., 1983; Sjödin & Jacobs, 1981; Stegmann, et al., 1981). Although, it has yet to be shown whether the lactate concentration at a given workload obtained during graded protocols is similar during the same workload when performing variable intensity exercise.

1.1.2. Intermittent and variable intensity exercise

The ratio between work and rest (work:rest) of 1:2, as well as work periods >30 s above the lactate threshold have been demonstrated to increase the VO_2 for a given workload, i.e. the VO_2 slow component (Turner, et al., 2006). Furthermore, high intensity interval training at a velocity that induces VO_{2max} ($v_{VO_{2max}}$) with a 1:1 work rest ratio (30 s: 30 s) increased the duration at VO_{2max}, but at a lower blood lactate concentration compared to continuous runs (Billat, et al., 2000). However during intermittent exercise with short bursts (~ 30 s), the energy contribution is dominated by the degradation of creatine phosphate (PCr); this might explain the lower blood lactate values during intermittent exercise (Bogdanis, et al., 1996). Although PCr degradation does not require O_2, the aerobic energy contribution becomes more important if short bursts are repeated, as the re-synthesis process of

PCr is O_2 dependent (Sahlin, et al., 1979). Therefore, a high aerobic power (VO_{2max}) probably increases the performance of repeated high intensity bouts.

Exercise intensities fluctuate during competitions in endurance sports such as road cycling, cross-country skiing (Fig. 1), mountain-biking and in running events. This can be attributed to factors like terrain, tactics and fatigue (Bilodeau, et al., 1991; Esteve-Lanao, et al., 2008; Lucia, et al., 1999; Stapelfeldt, et al., 2004). This suggests that there are limitations for transferring and interpreting physiological data obtained using constant or graded protocols to explain cardiorespiratory and metabolic regulation during competition in endurance sports.

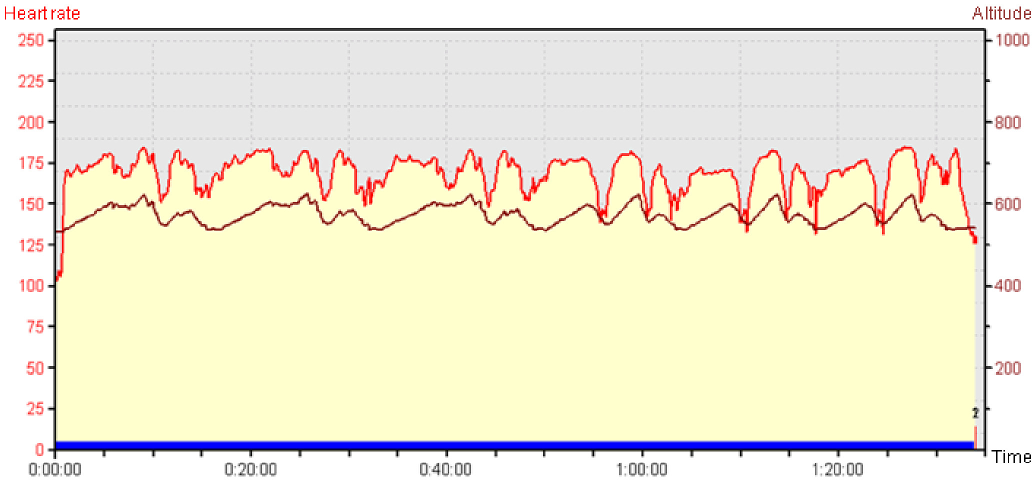

Figure 1. HR and track profile recording from a podium-placed athlete in an FIS World Cup race in cross-country skiing. The figure clearly shows that HR varies during cross-country ski racing.

Previous research investigating the effect of variable intensity exercise on physiological variables has used low to medium exercise intensity protocols (45-75% of VO_{2max}) (Yaspelkis, et al., 1993) with some exceptions (Palmer, et al., 1999). Palmer and co-workers (1999) showed that with a greater variation in exercise intensity (35-77% of Peak Power Output; PPO) glycogen utilization was more pronounced in type I fibres than for constant intensity exercise and vice versa for type II fibres, i.e. a larger glycogen depletion during variable intensity exercise. Previous research investigating acid-base regulation during variable intensity exercise found no differences between trained and untrained subjects, even though there were differences in maximal cycling power (Del Coso, et al., 2009).

The degree of variation in exercise intensity is of importance to the lactate response when comparing variable with constant intensity exercise (Liedl, et al., 1999; Mora-Rodriguez, et al., 2008; Palmer, et al., 1999). Liedl et al. (1999) demonstrated that blood lactate concentration was essentially the same for constant and variable intensity exercise when exercise intensity only varied within ± 5% of the mean power output. However, when the variation in exercise intensity becomes more pronounced (range 35-77% of PPO with an average of 58%) the area under the curve for blood lactate is greater than during constant intensity exercise (Palmer, et al., 1999). This suggests that although the blood lactate concentration increases during high intensity bouts, it does not recover sufficiently between these bouts. Also, during strenuous exercise at intermittent intensities, blood lactate is higher than during exercise with a constant intensity (performed at the same average power output) (Edwards, et al., 1973). On the other hand, no difference in cardiorespiratory variables (VO_2, HR and RER) were detected between variable and constant intensity exercise (Palmer, et al., 1999), while intermittent exercise produced both a higher VO_2 and HR than constant exercise (Edwards, et al., 1973). This demonstrates that the passive recovery between exercise bouts is “active” due to the elevated VO_2, presumably excessive post O_2 consumption (EPOC) (Gaesser & Brooks, 1984).

1.2. Cardiorespiratory and metabolic responses during exercise

1.2.1. Oxygen uptake and heart rate

At the onset of exercise, the muscle's O_2 demands increase. This is met by an increase in pulmonary VO_2, cardiac output and vasodilatation in working muscle. O_2 delivery has been defined using three steps: i) a fast cardio-dynamic phase ii) increased O_2 extraction, i.e. decreased venous O_2 content due to muscle contraction iii) the steady state phase when the first two phases are completed (Jones & Poole, 2005). Depending on the exercise intensity, O_2 delivery usually fulfils the O_2 demand within 2-4 min (Jones & Poole, 2005). The phase II VO_2 kinetics during moderate intensity exercise is more rapidly attained in trained compared to untrained subjects; nevertheless, the effect of training status is diminished at higher exercise intensities, i.e. there are no differences between untrained and trained individuals (Koppo, et al., 2004). The speed of VO_2 kinetics has been associated with endurance performance (Burnley & Jones, 2007) and can be speeded up through a prior high intensity warm-up that exceeds the lactate threshold (Gerbino, et al., 1996). Also, depending on locomotion, the VO_2 kinetics might be different as legs have been shown to have a faster VO_2 kinetics than arms (Koppo, et al., 2002). However, compared to leg exercise only, VO_2 kinetics is not different when using both arms and legs (Roberts, et al., 2005). During repeated high intensity workloads, both pulmonary and limb VO_2 uptake have been shown to increase during repeated bouts (Krustrup, et al., 2001; MacDonald, et al., 2001). Some authors suggest that the excessive increase in VO_2 is associated with lactic acidosis (Turner, et al., 2006). In contrast, Sahlin and colleagues (2005) showed that neither blood nor muscle pH nor lactate were associated with the increased pulmonary VO_2 in the consecutive second high intensity bout. Another explanation for the excessive increase in VO_2 is O_2 delivery restriction at the beginning of exercise, indicating that central and not peripheral factors delay VO_2 at the onset or first bout of exercise (DeLorey, et al., 2007).

The most common method for monitoring athletes' exercise intensity and physical efforts in normal training is the use of HR monitoring. It is also possible to estimate VO_2 by HR monitoring through the accepted linear relationship between HR and VO_2 (Karvonen, et al., 1957). Numerous studies have used this method to estimate VO_2 and exercise intensity during competitive endurance sports like cross-country skiing, cycling and running (Bilodeau, et al., 1991; Costill, 1970; Lucia, et al., 1999; Mognoni, et al., 2001; Padilla, et al., 2000). Later, exercise intensity during cycling competitions was evaluated with power meters (Impellizzeri, et al., 2005; Vogt, et al., 2006). In a study containing both measurements of power and HR during competitive cycling, it was demonstrated that the use of HR monitors overestimated the time spent in the moderate exercise intensity zone and underestimated the time the cyclists spent in the low and high intensity zone (Vogt, et al., 2006). This suggests that HR monitoring has limitations in describing the variations in exercise intensity and that the relationship between HR, VO_2 and workload is altered when exercise intensity varies.

It is widely accepted that HR decreases for a given submaximal workload after endurance training (Blomqvist & Saltin, 1983). However, if the reduction in submaximal HR is small for a given workload (<6 bpm), this might be due to day-to-day variations and not training effects (Lambert, et al., 1997). This day-to-day variation in HR is likely influenced by hydration status, i.e. hypovolemia and hyperthermia which have both been shown to contribute to an increase in HR for a given workload (Gonzalez-Alonso, et al., 1999). During endurance exercise this is mainly explained by a reduced stroke volume due to reduced preload; this is caused by a reduction in returning blood volume and therefore a decreased diastolic filing, which increases the HR for a given workload (Ekelund, 1967; Saltin & Stenberg, 1964). Whether improved physical fitness decreases or diminishes cardiac drift during endurance exercise is still not clear.

Increased VO_{2max} is related to an increase in cardiac output, which is mainly linked to improved stroke volume. This is explained by an increased heart size with enhanced contractility and the thickening of the left ventricle, as well as expanded blood volume (Fagard, 1997). Sporting disciplines in which a large muscle mass is involved enhance the venous return to the heart and subsequently induce a higher preload. In turn, this increases the stroke volume which could explain why elite cross-country skiers and rowers demonstrate the highest cardiac outputs and VO_{2max} reported in endurance athletes (Saltin & Åstrand, 1967; Secher, et al., 1983; Åstrand & Saltin, 1961).

When Hill and colleagues (Hill, 1923) described VO_{2max} and its importance for human performance capacity, the first criterion for cardiopulmonary capacity was established. This has since been the most used criterion for exercise testing of cardiorespiratory fitness. However, in a homogenous group of elite athletes with similar VO_{2max}, this variable's sensitivity for determining which athlete is going to succeed is rather low (Coyle, et al., 1988; Lucia, et al., 1998). di Prampero and colleagues (1986) showed that VO_{2max}, the utilisation fraction of VO_{2max} and the energy cost per unit of distance covered accounted for >70% of the running speed.

1.2.2. Ventilation

When exercise intensity increases from low to moderate there is a linear increase in ventilation with O_2 uptake and carbon dioxide (CO_2) production. When there is a further increase in exercise intensity and the lactate threshold is surpassed, a steeper rise in ventilation for a given O_2 uptake or CO_2 production occurs, offsetting their linear relationship (Wasserman & McIlroy, 1964). Three different ventilatory phases have been established during exercise**:** i) neurological phase ii) metabolic phase iii) compensatory phase. Most studies conducted in order to find a causal relationship for a stimulus that triggers increased ventilation during exercise has been performed with graded or constant protocols (Stringer, et al., 1995; Tanaka, 1991; Wasserman, 1967). The increase in ventilation during exercise has been linked to hypercapnia, metabolic acidosis and an increased concentration of potassium in the blood (Bannister, et al., 1954; Whipp, 1994a), although none of these stimuli explain the feed forward mechanisms for increased ventilation before the onset of exercise (Helbling, et al., 1997). Also, the causality between metabolic acidosis and ventilation has been considered to be biased through experimental design, i.e. the use of graded protocol (Busse, et al., 1992).

The interaction between ventilatory response and changes in blood metabolites was established by Wasserman and co-workers (Beaver, et al., 1986; Wasserman & McIlroy, 1964; Wasserman, et al., 1973). They concluded that the ventilatory phases in which ventilation increases non-linearly to VO_2 or VCO_2 were related to various degrees of lactate accumulation in the blood, i.e. individual lactate thresholds. This is explained through the buffering of lactic acid by sodium bicarbonate or more correctly the hydrogen ion that is released together with lactate (Stringer, et al., 1992; Wasserman, 1967).

1.2.3. Lactate recovery

One of the novel studies on blood lactate kinetics was performed by Ole Bang in the 1930s (Bang, 1936). He identified that the blood lactate concentration was not only dependent on the exercise intensity, but also the duration of work and the rise of blood lactate at the onset of exercise, i.e. the secondary rise. Furthermore, Bang concluded that lactate does not attain steady state during exercise in a similar way as VO_2. This finding has been challenged by the maximal lactate steady state concept (MLSS), where lactate remains constant throughout exercise (Billat, et al., 2003). On the other hand, the relevance of MLSS during endurance exercise has to be questioned as the intensity is rarely constant (Esteve-Lanao, et al., 2008; Mognoni, et al., 2001; Stapelfeldt, et al., 2004).

Blood lactate disappearance, i.e. lactate recovery, is faster with active recovery than passive recovery (Stamford, et al., 1981; Weltman, et al., 1979). The most effective exercise intensity for lactate recovery has been demonstrated to be at approximately 40% of VO_{2max} (Baldari, et al., 2004; Davies, et al., 1970; Dodd, et al., 1984). However there are conflicting results that have proven that even higher exercise intensities could be equally effective for lactate recovery (Hermansen & Stensvold, 1972).

The reason for the conflicting results regarding optimal exercise intensity could be explained by differences in the study subject's aerobic power as a higher VO_{2max} has been associated with improved lactate recovery (Gmada, et al., 2005). This is likely to be caused by peripheral changes, as leg lactate clearance increases significantly with improved endurance training (Bergman, et al., 1999) and is associated with a high capillary density (Messonnier, et al., 2002) and an increased number of lactate transporters (Thomas, et al., 2005).

Several studies have shown that blood lactate recovery is an important characteristic for performance at various exercise intensities and in various exercise modes (Greenwood, et al., 2008; Messonnier, et al., 1997; Messonnier, et al., 2002), while some have failed to make this connection to lactate recovery and performance (Weltman, et al., 1979).

Lactate recovery during exercise could also be affected by the differences in muscle recruitment between the limbs, with arms producing more lactate for a given submaximal workload than the legs (Ahlborg & Jensen-Urstad, 1991). Furthermore, legs have been demonstrated to be the major site for lactate oxidation during both leg cycling and during whole body exercise (Bergman, et al., 1999; Van Hall, et al., 2003). McGrail et al. (1978) demonstrated that following strenuous combined arm and leg exercise, leg exercise is more effective for lactate recovery than arm exercise.

1.2.4. Muscle blood flow and oxygen extraction

Skeletal muscle blood flow increases in order to deliver O_2 and meet the elevated metabolic demand of working skeletal muscle. Depending on the exercise intensity skeletal muscle blood flow reaches a steady state within ~ 10-150 s (Rådegran & Saltin, 1998). During intermittent static contraction, blood flow has been shown to fluctuate during the relaxation phase and to be dependent on MVC (Kagaya & Ogita, 1992). Blood flow has been suggested to be completely occluded from 50-64% of MVC depending on the limb (Sadamoto, et al., 1983). Endurance trained individuals possess less heterogeneous skeletal muscle blood flow than untrained subjects at the same workload (Kalliokoski, et al., 2001). Additionally the O_2 extraction is higher and the blood transit time longer for the endurance trained subjects. These results have been obtained primarily during knee extensor and lower limb exercise. Increased blood flow heterogeneity probably impairs the O_2 extraction (Kalliokoski, et al., 2003). Low intensity dynamic exercise induces a higher and less heterogeneous blood flow compared with isometric one-legged exercise (Laaksonen, et al., 2003). This could be explained by higher muscle activation and also increased muscle pump during dynamic exercise, compared to isometric exercise at the same workload.

Although it has been demonstrated that the leg O_2 extraction can reach above 90% of arterial O_2 content (Calbet, 2000) in endurance trained individuals, O_2 extraction in the arms has been shown to be lower than the in legs, independent of aerobic power in arm-trained individuals, i.e. rowers and cross-country skiers (Calbet, et al., 2005; Volianitis, et al., 2004). This is thought to be attributed to a shorter mean transit time, increased heterogeneity and a smaller diffusion area in the arms compared to the legs (Piiper, 2000). In the upper-body muscles the sympathetic neurons override the reactive hyperaemia, i.e. vasodilatation induced by metabolites (Thomas & Segal, 2004). Nevertheless, blood flow, O_2 extraction and VO_2 responses have mainly been assessed during constant or repeated bouts of exercise.

1.3. Biomechanics

1.3.1. Electromyography (EMG)

Muscular contraction is obtained when the α-motor neuron fires and stimulates the nerve-muscle synapse to potentiate an action potential and excitation contraction coupling (Guyton & Hall, 2006). This electric current along the muscle fibre can be measured by the use of surface electromyography (EMG). EMG is expressed as an index of the highest achieved EMG during isometric maximal voluntary contraction (MVC) (Holmberg, et al., 2005). Firstly, the integrated EMG (IEMG) has been proven to be linearly related to VO_2 during both concentric and eccentric work (Bigland-Ritchie & Woods, 1976). Secondly, it has been suggested that blood flow decreases when 25-30% of MVC is surpassed (Kilbom & Persson, 1982; Sadamoto, et al., 1983; Sjögaard, et al., 1988). Today there are limited data for EMG measurements combined with different physiological measures, especially during cross-country skiing (Holmberg, et al., 2005; Komi & Norman, 1987; Vähäsöyrinki, et al., 2008) and, so far, studies combining EMG measurements with invasive physiological measurements are lacking.

1.3.2. Kinetics

Measurements of leg force in sports such as cross-country skiing and cycling are mainly obtained with force plates, pressure insoles, strain gauges or ski bindings with integrated force transducers (Ekström, 1981; Holmberg, et al., 2005; Komi, 1987; Lindinger, et al., 2009; Norman, et al., 1989; Vogt, et al., 2006). These methods can be used both in laboratory and field measurements but, as regards the force plate system, only limited measuring space is available. Measuring upper body force is usually only of interest in sports when the whole body is involved, e.g. cross-country skiing, rowing and kayaking. In cross-country skiing this is mainly obtained through strain gauges attached to the skiing poles (Millet, et al., 1998), specially constructed pole force systems (Holmberg, et al., 2005; Stöggl, et al., 2008) and force plates (Komi, 1987). Greater, as well as shorter, time to peak force has been suggested to be related to performance in endurance sports, rather than increased cycle rate (Holmberg, et al., 2005; Weyand, et al., 2000). This is achieved with higher muscle activation, represented as percent of MVC, in the working muscles, increasing blood flow during the recovery phase (Kagaya & Ogita, 1992).

1.3.3. Kinematics

Kinematic measurements during sports are preferably obtained using 3D analysis (e.g. joint movements, movement of trajectories, velocities, etc.) (Lindinger, 2006; Smith, 1992). However, 2D measurements are sufficient to determine cycle characteristics as: cycle rate, cycle time, cycle length and poling time (by knowing treadmill speed). This is especially useful in a stationary situation like treadmill roller skiing (Calbet, et al.; Lindinger, et al.; Stöggl, et al., 2007; Stöggl & Muller, 2009). There are studies that investigate how different movement patterns influence physiological responses. For example, in speed skating it has been demonstrated that prolongations of the leg thrust phase restrict leg blood flow (Foster, et al., 1999) and, in cycling, the muscle oxygenation of the legs is influenced by the crank angle (Takaishi, et al., 2002). In cross-country skiing, different technical strategies in double poling have been shown to elicit differences in HR and blood lactate concentrations as well as in ventilatory response (Holmberg, et al., 2006). However, there is still a need for further investigation that combines kinematics and physiological measurements in cross-country skiing and its multiple skiing techniques.

2. AIMS

The overall objective of this thesis is to examine and extend the understanding of the physiology of continuous variable intensity exercise. More specific aims were to investigate:

1. The prognostic value of heart rate (HR), blood metabolites and respiratory variables for performance during exhausting exercise with varying intensity. (*Study I*)
2. The physiological responses, i.e. ventilation, lactate, heart rate (HR), oxygen uptake (VO_2), when endurance exercise is performed with variable intensity. (*Studies I-II*)
3. Blood lactate recovery and respiratory responses, as well as association to performance during variable intensity during diagonal skiing in skiers with different aerobic power. (*Study II*)
4. Whether muscle blood flow or blood flow heterogeneity are associated with alterations in muscle VO_2 during variable intensity exercise. (*Study III*)
5. If muscle activation and force production contributes to differences between the arms and legs as regards O_2 extraction and blood lactate concentration during diagonal skiing. (*Study IV*)
6. How a reduction from high to moderate exercise intensity influences biomechanical and physiological variables during diagonal skiing. (*Study IV*)

3. METHODS

3.1. Subjects

Thirty-seven healthy subjects volunteered to take part in different studies in the present thesis. The characteristics of the subjects are summarized in Table 1. *Study I* comprised of subjects who were competitive cyclists at a national level, while *Studies II* and *IV* included both former and current competitive cross-country skiers ranging from national to world class level. Only *Study III* included non-athletes with a limited training background. All studies were performed in accordance with the Declaration of Helsinki and approved by the Regional Ethical Review Board in Umeå, Sweden (*Studies I, II* and *IV*) or the Hospital District of South-Western Finland (*Study III*).

Table 1. Subject characteristics in *Studies I-IV*, mean ± SD (range).

Study	*n*	Age (yr)	Body mass (kg)	Height (cm)	VO_{2max} ($L \cdot min^{-1}$)	VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)
Study I	8	26±4 (18-31)	76±9 (63-87)	183±7 (172-190)	4.7±0.4 (3.9-5.1)	61.5 ± 4.0# (55.0-67.2)
Study II	12	31±5 (20-39)	79±7 (66-91)	183±4 (175-192)	5.2±0.6$ (4.4-6.3)	66.8±7.4$ (53.9-83.0)
Study III	8	24±3 (19-26)	73±6 (66-84)	180±8 (167-190)	n/a	n/a
Study IV	9	21±3 (18-28)	78±7 (66-85)	182±4 (173-189)	5.3±0.3$ (4.8-5.7)	68.2±3.2$ (63.7-72.5)

#, cycling; $, diagonal skiing

3.2. Procedures and assessment

A summary of the methods is given here. For more details the reader is referred to the individual articles.

3.2.1. Physiological measurements

Pulmonary and muscle oxygen uptake (*Studies I-IV*)

In *Studies I, II* and *IV* an on-line metabolic cart, AMIS 2001 model C, was used to measure VO_2 (Innovision A/S, Odense, Denmark), based on the mixed expired method using an inspiratory flowmeter. This system has been shown to be valid for elite athlete testing (Jensen, et al., 2002). Before each test the gas analysers were calibrated with a high-precision two-component gas mixture (16.0% O_2, 4.0% CO_2, Air Liquide, Kungsängen, Sweden). Calibration of the flowmeter was performed with a 3 L air syringe (Hans Rudolph, Kansas City, MO, USA) for low, medium and high flow rates. Ambient conditions were checked with an external apparatus (Vaisala PTU 200, Vaisala OY, Helsinki, Finland). The AMIS 2001 model C metabolic cart was validated twice a year, using the Douglas bag method with an accuracy of ~1-3% (CV <4%) for VO_2, VCO_2 and V_E. In *Study III*, muscle VO_2 was calculated by the equation: O_2 uptake = (a-v) O_2 diff. × muscle blood flow. Regional muscle blood flow in the entire exercising muscle (mm. quadriceps femoris, QF) was used when calculating muscle VO_2.

Heart rate (*Studies I, II and IV*)

HR was measured using the HR monitor Polar S610 (*Studies I, II* and *IV*) (Polar Electro OY, Kempele, Finland). In *Studies I, II* and *IV* the metabolic cart AMIS 2001 model C heart rate receiver was used in parallel with the HR monitor.

Blood metabolites (*Studies I-IV*)

Blood lactate concentration was determined in *Studies I, II* and *IV* through the use of the Biosen 5140 (EKF-diagnostic GmbH, Magdeburg, Germany) and in *Study III* by the Modular P800 automatic analyzers (Roche Diagnostics GmbH, Mannheim, Germany). The Biosen 5140 lactate analyser was calibrated with a control solution of 4.8-6.4 $mmol \cdot L^{-1}$ and a lactate standard of 12.0 $mmol \cdot L^{-1}$. Lactate measurements were performed with haemolysed blood samples (20 μl).

Blood gas, acid base and electrolytes (*Studies II-IV*)

O_2 and CO_2 content, SO_2, pO_2, pCO_2, HCO_3^-, and base excess (BE) were measured in *Studies II* and *IV* with the ABL 800 and 80 respectively (Radiometer, Copenhagen, Denmark) and in *Study III* with the Ciba-Corning 865 (Ciba-Corning Diagnostics Corp., Medfield, MA, USA). Sodium (Na^-), potassium (K^+) and pH were measured in *Studies II* and *IV* with the ABL 800 and 80 respectively (Radiometer, Copenhagen, Denmark) and in *Study III* with the Modular P800 automatic analyzer (Roche Diagnostics GmbH, Mannheim, Germany).

Skeletal muscle blood flow and limb O_2 extraction (*Studies III-IV*)

In *Study III*, skeletal muscle blood flow was measured using positron emission tomography (PET). This was performed by placing venous catheters for injection of the tracer and for blood sampling of the working limb, as well as an arterial catheter for blood sampling and radioactivity measurements. A transmission scan for photon attenuation correction preceded all muscle blood flow measurements, which were performed immediately after an intravenous injections of $[^{15}O]H_2O$ tracer (811 ± 102 MBq). Arterial blood, collected with a pump, was used to determine the blood time-activity curve. The positron-emitting tracer was produced as previously described (Sipilä, 2001). Image acquisition was obtained using the three-dimensional mode of the ECAT EXACT HR+ scanner (Siemens/CTI, Knoxville, TN, USA) using an axial field of view of 15.5 cm to produce 63 transaxial slices with a slice thickness of 2.4mm. All PET data were collected and processed as previously described (Alenius & Ruotsalainen, 1997; Kalliokoski, et al., 2001; Laaksonen, et al., 2003; Ruotsalainen, et al., 1997). Muscle blood flow was calculated using an autoradiographic method (Laaksonen, et al., 2003; Ruotsalainen, et al., 1997). Regions of interest (ROIs) surrounding the knee-extensors (QF) were drawn into six subsequent cross-sectional planes in both thighs by one experienced investigator, as previously described (Kalliokoski, et al., 2003). Blood flow heterogeneity was determined from pooled data by using the coefficient of variation (CV) of blood flow values in each voxel (16 mm^3) from the defined ROIs (Heinonen, et al., 2007; Laaksonen, et al., 2003). An example of a blood flow image is given below (Fig. 2). O_2 extraction (%) was calculated with the equation: muscle O_2 uptake / (muscle perfusion x O_2 content in arterial blood) while the limb O_2 extraction in *Study IV* was calculated from the arterial O_2 content minus the venous O_2 content. Blood O_2 content was calculated from the specific vessels SO_2 and Hb concentration [Hb], i.e. (1.34 x [Hb] x SO_2) + (0.003 x PO_2).

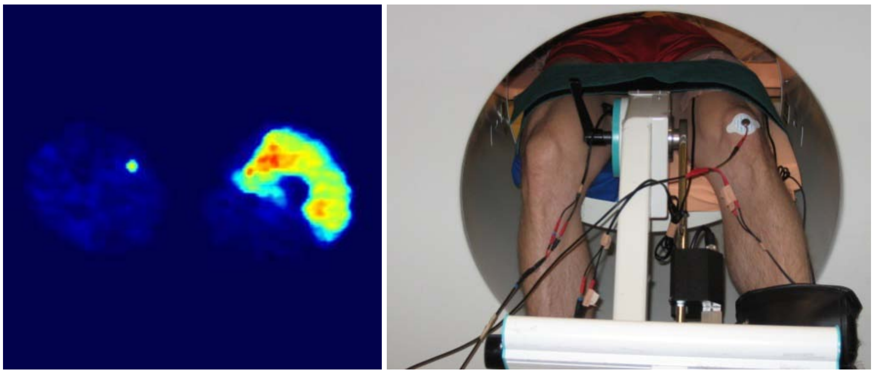

Figure 2. A PET scan image showing the thighs' ROIs for blood flow in exercising and resting knee-extensors (left). The yellow and red colours represent high tissue blood flow, whereas dark colours refer to low tissue blood flow. The isometric one-legged Diter Petkin dynamometer set-up and EMG electrodes are fixed to the working leg (right).

Bicycle ergometer (*Study I*)

In *Study I*, a SRM high performance bicycle ergometer was used (SRM, Schoberer Rad Messtechnik, Julich, Germany) which measures power with strain gauges attached to the cranks that were calibrated before each test in accordance with the manufacturer's recommendations.

Treadmills (*Studies II* and *IV*)

In *Studies II* and *IV* the subjects performed DIA on specially designed motor-driven ski treadmills (Rodby RL 2500 and Rodby RL 3000 treadmill, Rodby Innovation AB, Vänge, Sweden).

Dynamometer (*Study III*)

In *Study III* the subjects performed one-legged intermittent isometric knee-extension exercise using a Diter Petkin dynamometer (Diter-Elektroniikka, Oy, Turku, Finland).

3.2.2. Biomechanical measurements

EMG (*Studies III-IV*)

In *Study III* surface EMG activity was recorded for the m. vastus medialis (VM) with surface electrodes (Beckman miniature skin electrodes, Beckham Instruments, Inc. 650437 Schiller Park, IL, USA) and, in *Study IV*, for the m. triceps brachii, m. latissimus dorsi, m. rectus abdominis, m. gluteus maximus, m. rectus femoris and m. gastrocnemius (medial head) of the subject's right side using pre-gelled bipolar Ag/AgCl surface electrodes (Skintact, Leonhard Lang GmbH, Innsbruck, Austria). Prior to all electrode fixations the skin surface was shaved, lightly abraded, degreased, and disinfected with alcohol. Electrodes were placed longitudinally on the surface of the muscle belly according to international standards (Hermens, et al., 1999) with an inter-electrode distance of 20-30 mm on the surface of the muscle belly. In *Study III* the EMG signals were preamplified with a factor of 200, by an on-the-electrode mounted preamplifier to minimize possible electrical noise. In *Study IV*, the reference electrode was attached to the tibia and the active and reference electrodes for each muscle were connected to single differential amplifiers (base gain 500; input impedance >100 MΩ; common mode rejection ratio >100 dB, input range ±10 mV).

EMG processing

In *Study III*, the EMG amplification factor was 500 (bandwidth from 10 Hz to 1 kHz per 3 dB^{-1}). To obtain the quantity of EMG, the signals were full-wave rectified and integrated (IEMG). In *Study IV*, prior to calculating the EMG variables, the raw EMG signals were digitally band-pass filtered (10–400 Hz; Butterworth 2^{nd} order) to remove low and high frequency noise (Winter, 1990). The cut-off frequency of the filter was based on a visual inspection of the power spectra of the EMG signals. The integrated EMG (IEMG) and the EMG root mean square (RMS) were calculated for all muscles over defined phases within the cycle.

Figure 3. The biomechanical "belt" including Pedar and Noraxon units (left) and a athlete on roller skis on the treadmill attached to catheters, metabolic cart and EMG, as well as foot and pole force measuring devices (right).

Kinetic methods (*Study IV*)

Specially constructed carbon-fibre racing poles that were adjustable in length were used for force measurements. The ground reaction force was measured along the length of the pole by a strain gauge force transducer (60 g) mounted directly below the pole grip (Hottinger–Baldwin Messtechnik GmbH, Darmstadt, Germany) which were calibrated with a calibration apparatus and standard weights (5, 10, 15, 25, 50 kg). Pole force validation was performed on an AMTI force plate (Engineering Services, Watertown, MA, USA) with a sampling rate of 1000 Hz. Plantar ski reaction forces were recorded by a Pedar mobile system (Novel GmbH, Munich, Germany) at a sampling frequency of 100 Hz. The insole calibration was performed with a Pedar calibration device using homogenous air pressure.

3.3. Test protocols

3.3.1. Bicycle ergometer protocols (*Study I*)

a) Incremental test

An incremental test according to (Padilla, et al., 1999), was used to establish the subject's VO_{2max} with a modification of the start resistance to 85 W. Each workload was 4-min long with 35 W increments interspersed with 1-min periods performed at 50 W. In both the incremental and VIP test subjects were instructed to keep their cadence between 80-90 revolutions per minute (rpm) throughout the test. The test was performed to exhaustion or terminated if the cadence fell below 70 rpm.

b) Variable intensity protocol (VIP)

The VIP consisted of six workloads at 90% of VO_{2max} for 3-min (HI_{90}) interspersed with 6-min periods at 70% of VO_{2max} (MI_{70}). In total, the VIP was 48-min in duration.

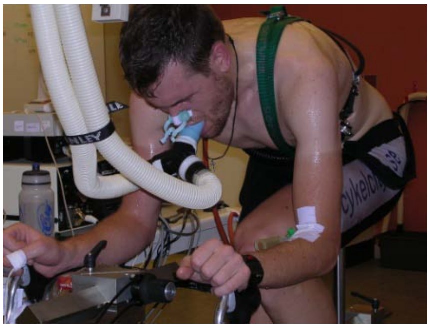

Figure 4. Cyclist performing the VIP protocol in *Study I.*

3.3.2. DIA protocols (*Studies II* and *IV*)

Study II

a) Incremental test

The incremental protocol was performed with DIA starting at an inclination of 4° with a velocity of either 10 or 11 km h^{-1} depending on the subjects training background, where the faster starting velocity was used on the better trained subjects. The inclination was increased by $1°\cdot min^{-1}$ until exhaustion.

b) VIP

The VIP consisted of six HI_{90} workloads for 3-min interspersed with five MI_{70} workloads for 6-min. In total, the VIP was 48-min in duration.

Figure 5. Overall setup in *Study IV* (left) and a elite cross-country skier (right)

Study IV

a) Incremental test

The incremental protocol was performed with DIA in the same way as in *Study II* with a set velocity of $11\ km\cdot h^{-1}$.

b) VIP

The VIP consisted of one 3-min HI_{90} workload followed by one 6-min long MI_{70} workload. The protocol was performed at a fixed inclination of 6.5° with adjustments in velocity to obtain the target exercise intensity.

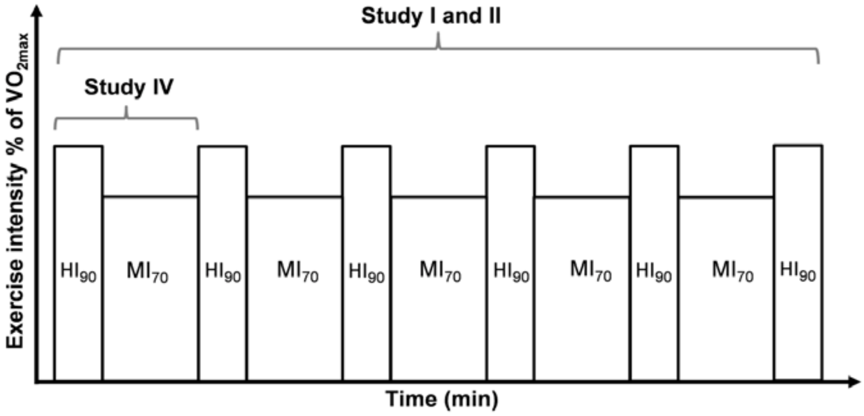

Figure 6. Experimental protocols for *Studies I, II* and *IV*.

3.3.3. Isometric one-legged exercise protocols (*Study III*)

a) Pre test

The test started with a low intensity 5-min warm-up period followed by measurement of maximal isometric voluntary contraction force (MVC) using the left knee-extensor muscles with a dynamometer (Diter Petkin, Oy Diter-Elektroniikka, Turku, Finland) at a knee angle of 40°. MVC measurements were performed with three 5-s periods of continuous maximal isometric tension with a 30-s rest period in between. The highest tension of the three repetitions was used as MVC.

b) VIP

Subjects performed continuous isometric knee-extension exercise (1-s on 2-s off). Three different exercise protocols were performed (A, B and C) in a randomized order at an intensity that was determined as a percentage of MVC. Protocol A consisted of 6-min at 50% of MVC (HI-1), 6 minutes at 10% of MVC (LOW), and 6-min at 50% MVC (HI-2), Protocol B of 6-min at 50% of MVC (HI-1), 6-min at 10% of MVC (LOW) and Protocol C of 6-min at 50% of MVC (HI-1). A 60-minute recovery period was applied to ensure adequate recovery between protocols and due to the radioactive decay of the tracer (T½ 2.05 minutes for [^{15}O]H_2O). Muscle blood flow was measured in protocols C, B and A for HI-1, LOW and HI-2, respectively. MVC were repeated after protocol A.

3.4. Statistical analysis

Statistical analyses were carried out with SPSS software (SPSS Inc, Chicago, IL, USA, version 12.0 to 17.0). Standard statistical methods were employed to calculate mean, standard deviation (SD) and standard error of mean (SEM) (*Studies I-IV*). Normally distribution was assessed with Shapiro Wilk's (*Studies II* and *IV*) or Kolmogorov-Smirnov tests (*Study III*). Paired Student t-test (*Studies I-IV*) and Wilcoxon signed rank test (*Study III*) were used for comparisons between variables obtained from the same subjects on different occasions. Independent Students t-test was used for group comparisons (*Study II*). For repeated measures (>2) a one-way ANOVA with a Tukey's honestly post-hoc test (*Studies I, III* and *IV*) or a Friedman test (*Study III*) was used. Two-way factorial ANOVA with repeated measures was used in *Study II* (group x exercise intensity) and *Study IV* (exercise intensity x extremity). Correlations between variables that were not normally distributed were performed with Spearman rank test (*Study I*) while Pearson correlation was used on normally distributed variables (*Studies II, III* and *IV*). Partial correlation was used when controlling for confounding variables when assessing relationships between variables (*Studies II* and *IV*).

4. RESULTS

4.1. Performance (*Studies I-II*)

In *Study I*, all subjects completed at least four HI_{90} workloads with an average TTE of 37.4 ± 7.4 min (range 28-48 min). Only one subject was able to complete the whole VIP. TTE during the VIP was inversely related to the decrease in blood lactate concentration after the first HI_{90} and the following MI_{70} (r =-0.714; P=0.047; Fig. 7A) and the lactate threshold expressed as % of VO_{2max} (VO_{2LT}) (r =0.738; P=0.037; Fig. 7B). In *Study II*, ET had a longer TTE than MT during the VIP (ET 45.0 ± 7.3 vs. MT 31.4 ± 10.4 min; P<0.05), achieved with both a higher speed and a steeper inclination.

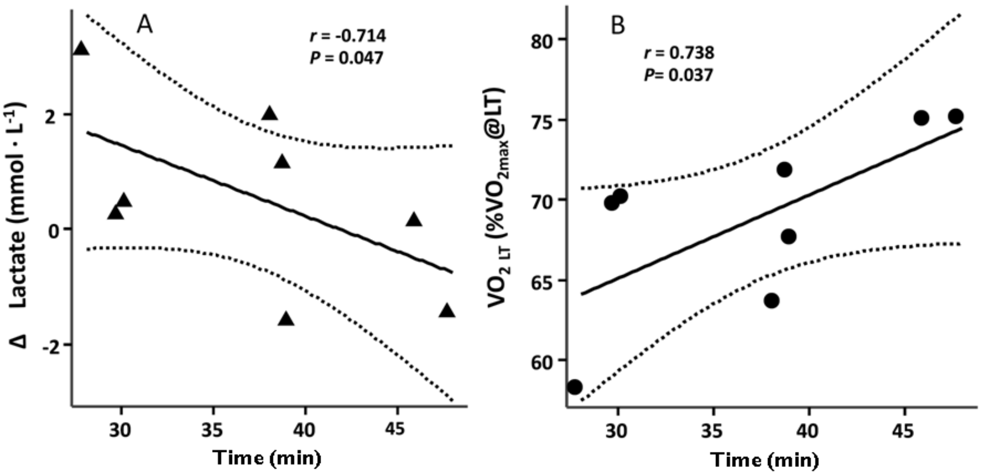

Figure 7A-B. Correlations between TTE and changes in blood lactate concentration during the first transition between HI_{90} and MI_{70} (**A**) and VO_{2LT} (**B**)

4.2. Pulmonary and muscle VO_2 (*Studies I-IV*)

In *Study I*, VO_2 during the first HI_{90} and MI_{70} were 4.2 ± 0.4 L·min^{-1} (three consecutive HI_{90}; 4.2 ± 0.4, 4.2 ± 0.4 and 4.2 ± 0.5 L·min^{-1}) and 3.4 ± 0.4 L·min^{-1} (two consecutive MI_{70}; 3.5 ± 0.3 and 3.5 ± 0.3 L·min^{-1}), respectively. VO_2 did not differ between consecutive HI_{90} or MI_{70} workloads. In *Study II*, the ET skiers had higher absolute VO_2 than the MT group at HI_{90} (5.0 ± 0.5 vs. 4.3 ± 0.4 L·min^{-1}; P<0.05) but not at the MI_{70} workloads (4.1 ± 0.5 vs. 3.7 ± 0.3 $L \cdot min^{-1}$; $P>0.05$). VO_2 did not differ between consecutive workloads for HI_{90} or MI_{70} for either group. VO_2 data for both cyclists (*Study I*) and cross-country skiers (*Study II*) are presented in Fig. 8.

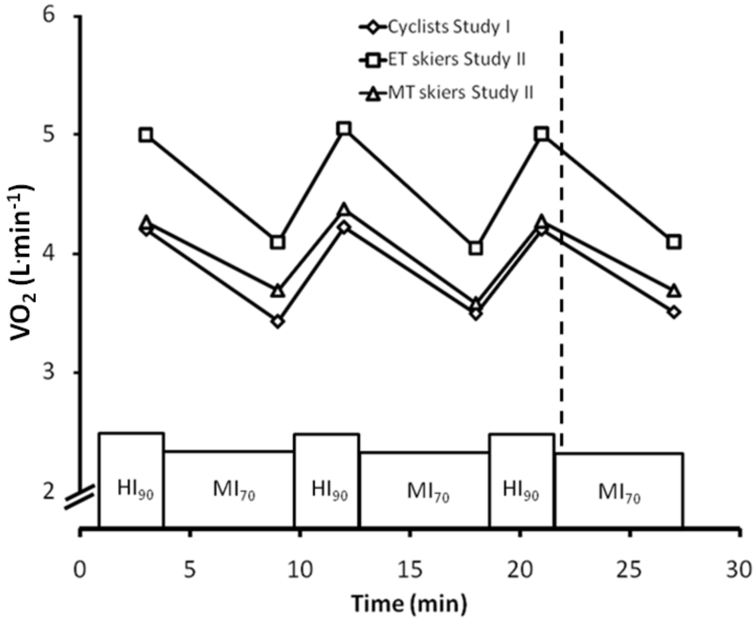

Figure 8. VO_2 during the VIP protocol obtained from both cyclists and cross-country skiers (*Studies I* and *II*). No increase was shown in VO_2 for HI_{90} or MI_{70} for either exercise model. All subjects still included of the left side of the dashed line.

In *Study III*, muscle VO_2 was higher at both HI workloads (HI-1 3.3±0.4 and HI-2 4.1±0.6 $mL \cdot 100g^{-1} \cdot min^{-1}$) than LOW (1.4±0.4 $mL \cdot 100g^{-1} \cdot min^{-1}$; $P<0.01$), and 25% higher at HI-2 than HI-1 (Figure 11C; $P<0.05$). VO_2 values in *Study IV* at the HI_{90} and MI_{70} workloads were 63.1 ± 2.1 and 51.1 ± 2.3 $mL \cdot kg^{-1} \cdot min^{-1}$ respectively.

4.3. Heart rate (*Studies I, II* and *IV*)

In *Study I*, HR increased when the exercise intensity changed from MI_{70} to HI_{90} ($P<0.05$). Furthermore, HR increased for each consecutive HI_{90} and MI_{70} workload ($P<0.05$; Fig. 9).

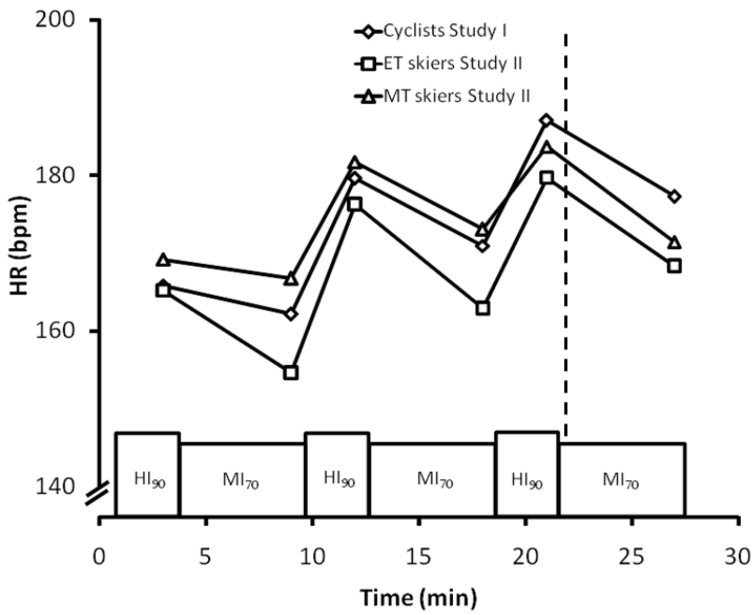

Figure 9. HR during the VIP protocol obtained from both cyclists and cross-country skiers (*Study I* and *II*). All subjects still included of the left side of the dashed line.

In *Study II,* the HR for both ET and MT skiers increased in a similar way as for the cyclists in *Study I* (Fig. 9). Furthermore, the HR and VO_2 linear relationship calculated for each group (ET and MT), using a simple linear regression model from the preliminary incremental protocol, showed that during the VIP for the first HI_{90} the HR was 12 ± 3 (ET) and 10 ± 4 bpm (MT) lower than the calculated HR. At the third HI_{90} the HR was higher with 3 ± 3 (ET) and 5 ± 5 bpm (MT) than calculated ($P<0.05$). At the second MI_{70} and third $MI_{70,}$ the HR was higher than calculated with 14 ± 7 (ET) and 19 ± 8 bpm (MT) and 19 ± 7 and 21 ± 9 bpm for each group at these two MI_{70} workloads. In study IV, the HR decreased from 178 ±9 to 168 ±10 bpm ($P<0.05$) when the intensity was reduced from HI_{90} to MI_{70} using the DIA.

4.4. Ventilatory variables (*Studies I, II* and *IV*)

In *Study I*, RER increased when the exercise changed from MI_{70} to HI_{90} and decreased it changed from HI_{90} to MI_{70} (P<0.05). At the first HI_{90}, RER was 1.05 ± 0.06 and increased by 2 ± 4%, 5 ± 4% and 8± 5% respectively during the three consecutive HI_{90} workloads. In *Study II* there was a significant effect for exercise intensity and V_E/VO_2, V_E/VCO_2 and RER (P<0.001). Furthermore, in comparison with ET, MT had an increased V_E/VO_2 at the second and third HI_{90} workload and an increased V_E/VCO_2 at the third HI_{90} workload (group x exercise intensity) (P<0.001). No interaction effect (group x exercise intensity) was observed for RER.

4.5. Lactate and acid base (*Studies I-IV*)

In *Study I*, with cycling, the lactate concentration increased when the exercise intensity changed from MI_{70} to HI_{90} (P<0.05). The lactate concentration during the first HI_{90} workload was 2.8 ± 1.3 mmol L^{-1} and increased during the three consecutive HI_{90}. In *Study II*, the ET group had lower lactate than MT during the VIP (P<0.01; Fig. 10)

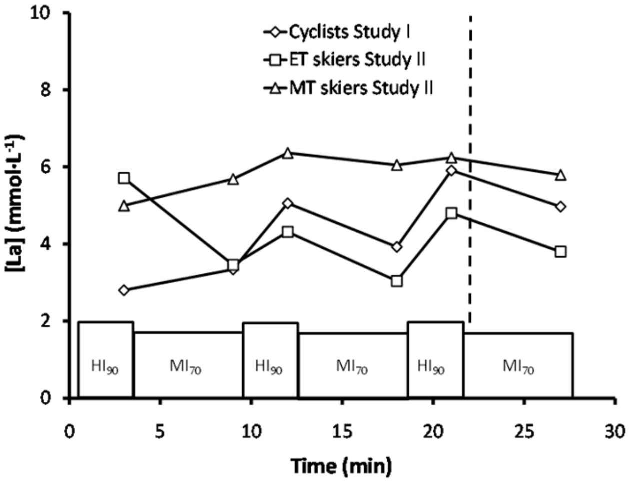

Figure 10. Blood lactate kinetics during VIP for cross-country skiers and cyclists (*Studies I* and *II*) presented as mean. All subjects still included of the left side of the dashed line.

In *Study II*, lactate, BE and pH changed due to variations in exercise intensity during DIA (all $P<0.05$). Lactate remained lower and BE were less negative in ET than MT skiers during the VIP (all $P<0.01$). Blood lactate was similar between groups during the first HI_{90}, whereas the ET skiers decreased their lactate concentration in comparison with MT during all three transitions from HI_{90} to MI_{70} (-2.3 ± 0.9 vs. 0.7 ± 1.2, -1.3 ± 0.3 vs. -0.1 ± 0.7 and -1.0 ± 0.3 vs. 0.8 ± 1.6 $mmol·L^{-1}$; all $P<0.05$). In contrast to MT, BE did not decrease for ET at any of the three transitions from HI_{90} to MI_{70} (0.3 ± 1.3 vs. -2.9 ± 1.3, 0.6 ± 0.4 vs. -0.2 ± 1.6 and 0.2 ± 0.3 vs. -3.4 ± 3.1 $mmol·L^{-1}$; all $P<0.05$). Furthermore, in *Study II* with DIA, VO_{2max} correlated only to lactate when controlling for respective variables during the first MI_{70} ($r_{lactate,\ VO_{2max}\ \ RER}=-0.805$; $P=0.005$; $r_{RER,\ VO_{2max}\ \ lactate}=-0.170$; $P=0.638$) and the second MI_{70} ($r_{lactate,\ VO_{2max}\ \ V_E/VO_2}=-0.819$; $r_{lactate,\ VO_{2max}\ \ V_E/VCO_2}=-0.877$; both $P<0.01$).

In *Study III*, performed with one-legged exercise, no alterations in arterial or venous concentration of lactate or pH were observed. During DIA (*Study IV*) when the exercise intensity was reduced (HI_{90} to MI_{70}), blood lactate concentration decreased at all sampling sites, but with the smallest reduction in the femoral vein (-0.51±0.50 $mmol·L^{-1}$). Furthermore, when exercise intensity was reduced, the lactate a-vDiff increased in the legs (HI_{90}: -0.19 ± 0.46; MI_{70}: 0.05 ± 0.35 $mmol·L^{-1}$, $P<0.05$), but not in the arms (HI_{90}: 1.20 ± 0.58; MI_{70}: 1.00±0.41 $mmol·L^{-1}$). During HI_{90}, pH was the lowest in the subclavian vein compared to all three sampling sites ($P<0.001$). Both subclavian and femoral venous pH increased when the exercise intensity was reduced to MI_{70}, although both remained lower than the arterial pH (-0.11 ± 0.02, $P<0.001$ and -0.10±0.02, $P<0.001$). Arterial pH remained unchanged between the intensities.

4.6. Blood flow and O_2 extraction (*Studies III-IV*)

In *Study III*, blood flow in resting QF was similar between workloads (HI-1 2.5 ± 1.1, LOW 2.7 ± 1.5, HI-2 2.4 ± 1.2 $mL \cdot 100g^{-1} \cdot min^{-1}$; *P*=0.886) but was higher in the contra lateral exercising muscle during HI-1, LOW and HI-2. Furthermore, blood flow was 78% and 91% higher in the exercising QF during HI-1 and HI-2 compared to LOW with no difference between HI-1 and HI-2 (Fig. 11A). The calculated muscle O_2 delivery demonstrated a similar pattern (Fig. 11B).

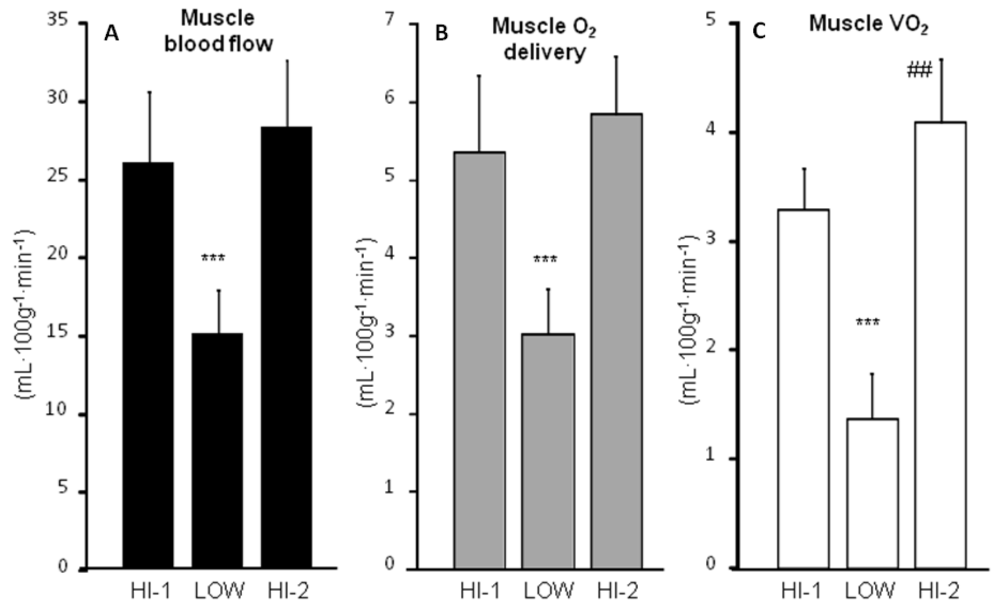

Figure 11A-C. Muscle blood flow (A), O_2 delivery (B) and VO_2 (C). ****P*<0.001 in comparison to HI-1 and HI-2; and ##*P*<0.01 in comparison to the value for HI-1. Results are presented as mean ± SD.

Blood flow heterogeneity was higher during LOW than HI-1 and HI-2 exercise, with no difference between HI-1 and HI-2 (Fig. 12). O_2 extraction exhibited similar changes, and tended to be higher during HI-2 than HI-1 exercise (HI-1 62±7 and HI-2 70±7 %; *P*=0.078). Muscle blood flow demonstrated a linear relationship to muscle VO_2 during HI-1 (r=0.719, P<0.05) and LOW (r=0.879, P<0.01), but not during HI-2 exercise (r=0.545, P=0.162).

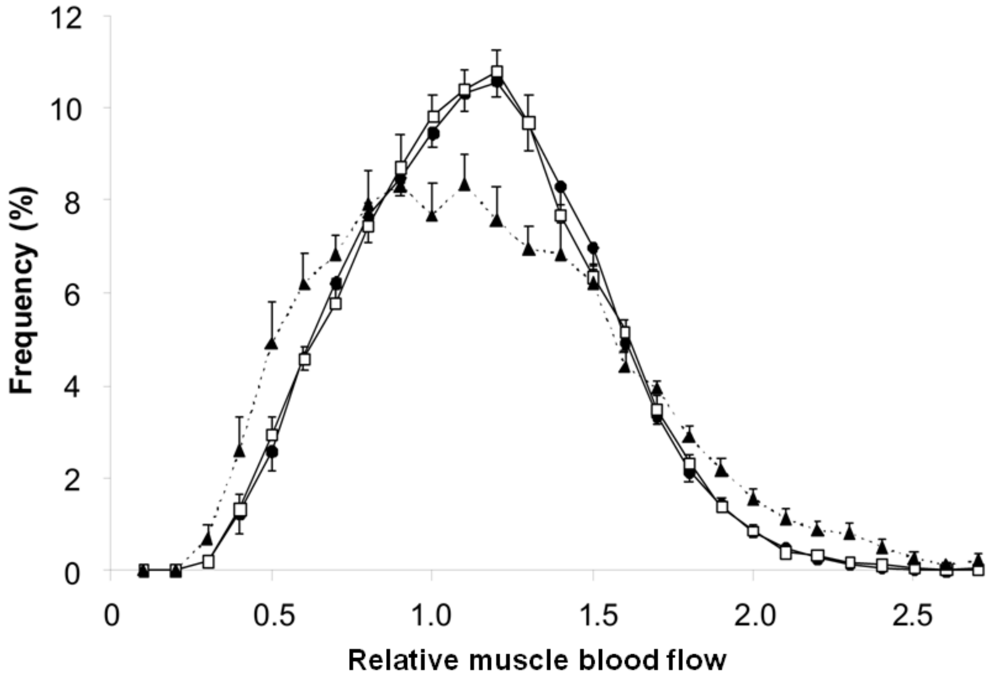

Figure 12. Distribution histogram (CV) of relative muscle blood flow during HI-1 (●), LOW (▲) and HI-2 (□). The figure shows equal distribution during the HI workloads, whereas during LOW blood flow heterogeneity is increased.

In *Study IV*, O_2 content was lowest in the femoral vein independent of exercise intensity and increased when the intensity was reduced from HI_{90} to MI_{70} for both the femoral and subclavian vein, although most in the subclavian vein (13.8 ± 9.8 ml·L^{-1}). Arterial O_2 content remained unchanged between exercise intensities (193 ± 19 vs. 192 ± 15 ml·L^{-1}). O_2 extraction was higher for the legs than the arms at both exercise intensities (HI_{90}: 92 ± 3 vs. 85 ± 6%, P<0.05; MI_{70}: 90 ± 3 vs. 77 ± 9%, P<0.001) and decreased for both arms and legs when intensity was reduced (P<0.001 and P<0.05). The reduction in O_2 extraction was greater in the arms than in the legs (-10.6 ± 7.7% vs. -2.6 ± 2.8%, P<0.01; Fig. 13).

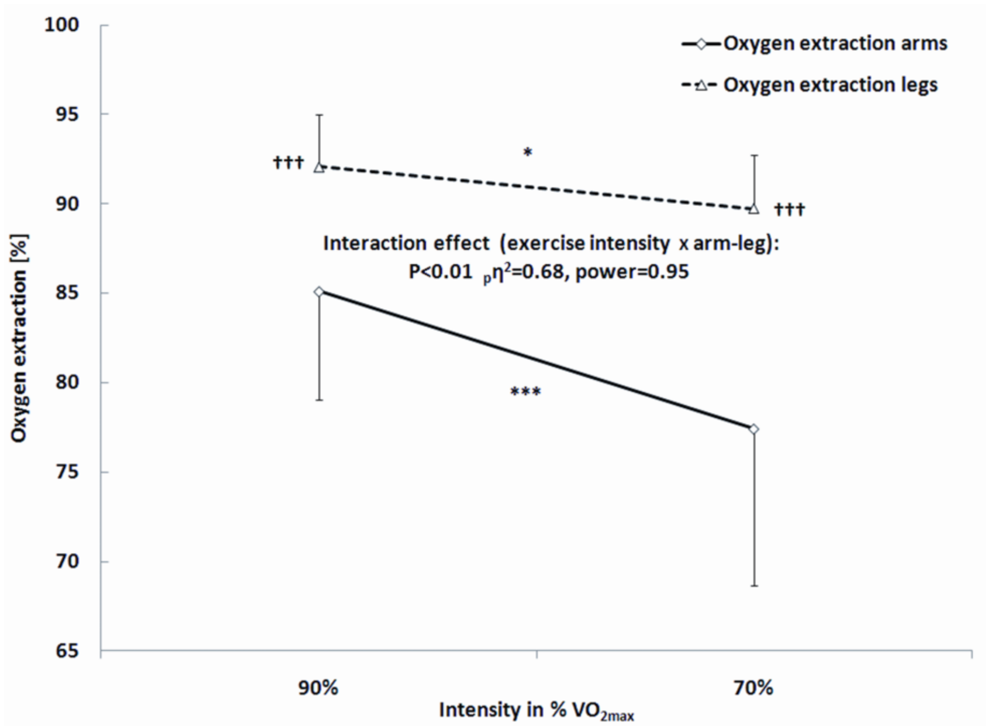

Figure 13. O_2 extraction in the arms (—) and the legs (---). †††*P*<0.001 in comparison to the arms. **P*<0.05 and ****P*<0.001 for 90% vs. 70% of VO_{2max}. Results are presented as mean ± SD.

4.7. Biomechanics (*Studies III-IV*)

In *Study III*, with one-legged static intermittent exercise, MVC (MVC_{pre} 537 ± 87 N vs. MVC_{post} 476 ± 37 N; *P*<0.05) and maximal EMG activity (pre 0.370 ± 0.175 vs. post 0.310 ± 0.130 mV; *P*<0.05) decreased similarly when pre and post values were examined. During the variable intensity protocol EMG activity was significantly lower during the LOW (0.123 ± 0.109 mV; *P*<0.05) than during HI-1 (0.269 ± 0.095 mV) or HI-2 exercise (0.282 ± 0.097 mV), with no significant difference between the latter two workloads. In *Study IV*, with DIA, the IEMG activity was different between the indicator muscles and showed the highest activity in the m. latissimus dorsi and lowest in the m. rectus abdominis. When the exercise intensity was reduced from HI_{90} to MI_{70}, the IEMG activity decreased in all muscles except for m. gastrocnemius (*P*<0.01). There were no differences in muscle activity (IEMG) for the whole movement cycle when comparing arm with lower body muscles. The magnitude of muscle activation during the propulsion and recovery phases, represented by EMG_{RMS}, was higher in the arm muscles than in the leg muscles. When exercise intensity was reduced, the EMG_{RMS} decreased during the propulsion phase for both arm and leg muscles, whereas the reduction was greatest for the triceps muscle ($P<0.05$).

When the exercise intensity was reduced from HI_{90} to MI_{70}, using DIA (*Study IV*), both cycle length ($P<0.001$) and cycle rate ($P<0.001$) decreased along with an increase in absolute and relative poling time (0.55 ± 0.07 to 0.66 ± 0.09 s, 42 ± 3 to 46 ± 4%; both $P<0.001$). Absolute recovery time for the arms remained constant, whereas relative recovery time (% cycle time) decreased (57.9 ± 3.3 to 53.8 ± 3.5%; $P<0.001$). Ground contact, gliding, push-off and recovery time for the legs increased when exercise intensity decreased (all $P<0.001$), whereas the relative values (% cycle) remained constant. Arm recovery and poling time were longer compared to leg recovery and leg push-off time at both intensities (all $P<0.001$). When exercise intensity was reduced the poling time increased more than leg push-off time ($P<0.05$). An example of both the plantar and pole forces during a DIA cycle is illustrated in Fig. 14.

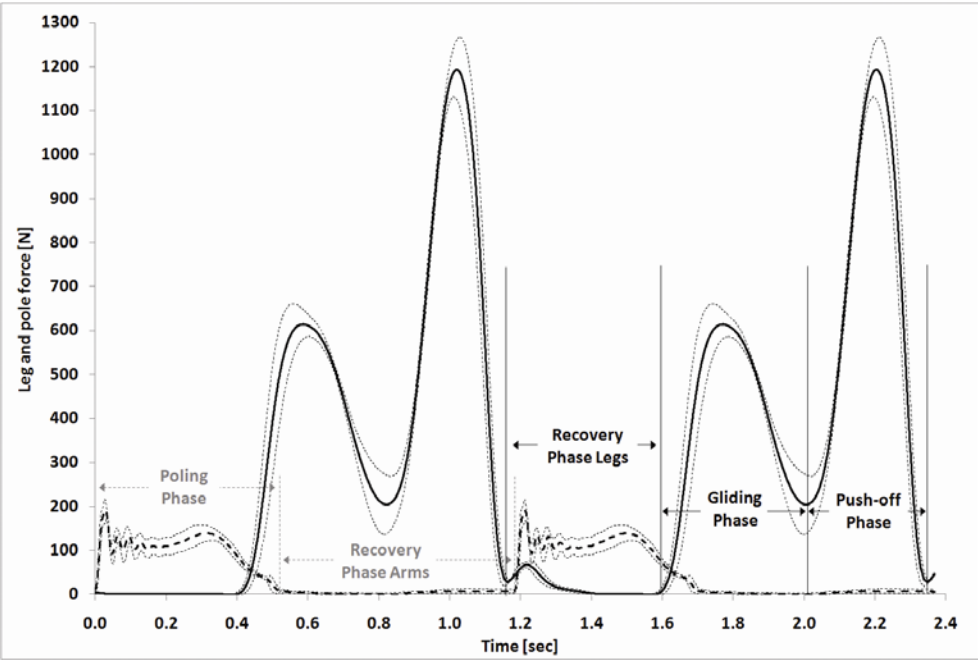

Figure 14. An example of measured plantar (bold line) and pole forces (dashed line) within a single DIA cycle at an intensity of 90% of VO_{2max}. The time courses depicted are mean ± SD of five successive cycles.

Pole and leg peak forces, together with the rate of force development during leg push-off, decreased with the reduction in exercise intensity ($P<0.001$), whereas the impulses of forces remained constant. When exercise intensity decreased, both peak arm and peak leg force decreased, but the relative reduction was largest for peak arm force (arm 16.8 ± 14.0% vs. leg 12.5 ± 4.7 %).

5. DISCUSSION

Performance

In both *Studies I* and *II*, TTE was used as performance criterion during the VIP protocol. The results from *Study II* showed that VO_{2max} was an important characteristic for performance during variable intensity exercise involving cross-country skiers of different aerobic power. It is well established that VO_{2max} has a major decisive role for endurance performance in a heterogeneous group of subjects (Costill, et al., 1973). However in *Study I*, performed with a homogenous population of cyclists with similar aerobic power, no relationship was observed between TTE and the cyclists VO_{2max}. Previous studies performed with cycling, as well as running, showed that performance is usually distinguished by other factors such as high lactate and ventilatory thresholds, as well as differences in technique and work economy when comparing subjects of similar aerobic power (Coyle, et al., 1991; di Prampero, et al., 1986; Lucia, et al., 1998; Morgan, et al., 1989). The results of *Study I* confirmed that a high lactate threshold is an important characteristic for performance during variable intensity exercise. Furthermore in *Study II*, compared to moderately trained skiers, the elite skiers' higher lactate threshold shows that from a group level perspective, lactate threshold could also partly explain the differences in performance. This may be influenced by the elite skiers' higher VO_{2max}, compared to that of the moderately trained skiers, as the muscle's aerobic capacity has shown to be related to the lactate threshold in a heterogeneous group of subjects (Ivy, et al., 1980). Results from *Studies I* and *II* demonstrate that lactate recovery between high intensity workloads is an important attribute for performance during variable intensity exercise. The impact of lactate recovery and its association with performance have primarily been studied during post exercise recovery (Tomlin & Wenger, 2001). In both *Studies I* and *II*, performance was determined with closed-end test at a given percent of VO_{2max}, which is one approach to determining endurance performance. Other procedures include open-end tests without a pre-set time limit, for example, or time trials with a fixed distance or duration in which the athlete is able to adjust the workload during the experiment (Jeukendrup, et al., 1996; Nilsson, et al., 2004; Schabort, et al., 1998). The interesting finding from both *Studies I* and *II* with cycling and cross-country skiing is that lactate recovery could be a useful tool for performance evaluation with subjects of either a homogenous or a heterogeneous VO_{2max}.

Pulmonary and muscle VO_2 response

Pulmonary VO_2 changed due to variations in workloads during cycling and DIA (*Study I* and *II*) with no observed excessive increase in the VO_2. However, when one-legged exercise was performed using a variable intensity protocol (*Study III*), there was an increased muscle VO_2 over the exercising leg. These results show that when exercise is performed with a limited amount of muscle mass, as with one-legged exercise, VO_2 can increase although there is no change in workload. On the other hand when exercise is performed with a larger muscle mass, e.g. two-legged or combined arm and leg exercise as in *Studies I* and *II*, pulmonary VO_2 does not increase. However, a number of previous studies have demonstrated an excessive increase in VO_2 when the exercise exceeds the lactate threshold, despite no increase in workload (Whipp, 1994b). This occurred when the lactate threshold was surpassed, which was interpreted as if an increased blood lactate concentration is a necessity for VO_2 slow component (Turner, et al., 2006; Whipp & Wasserman, 1986). Further support of the lactate explanation was that as long as lactic acidosis takes place, the VO_2 slow component seems to occur for both trained and untrained subjects (Henson, et al., 1989). However, Sahlin et al. (2005) provided evidence that VO_2 slow component occurred despite no elevations in muscle or blood lactate and pH. Our results from both cycling and cross-country skiing (*Studies I* and *II*) show that blood lactate increases well above the lactate threshold during variable intensity exercise, but without any excessive increase in VO_2. Furthermore *Study III*, performed with one-legged exercise, showed an excessive increase in VO_2 during repeated high intensity workloads which could not be explained by lactic acidosis as there were no increases in either venous or arterial lactate or pH. A possible contributing factor to the unchanged VO_2 in *Study I* during cycling might be alterations in cadence (range 80-90 rpm) in order to maintain a high work efficiency i.e. to maintain as low energy expenditure as possible throughout the protocol (Ansley & Cangley, 2009). Altogether, these results show that lactate acidosis cannot be the cause of an excessive increase in VO_2 during exercise with either small or larger muscle mass, which is in accordance with lactate infusion studies (Poole, 1994).

Heart rate

The results from *Studies I* and *II* show that HR increases throughout exercise at variable intensities. This is in accordance with previous findings performed with constant workloads (Ekelund, 1967; Saltin & Stenberg, 1964), known as the "cardiovascular drift" phenomena (Coyle & Gonzalez-Alonso, 2001). However, HR was influenced differently depending on the exercise intensity; medium intensity exercise induced a larger HR drift than the workload of higher exercise intensities during variable intensity exercise. In contrast to HR, the VO_2 values were not influenced by exercise time. This provides evidence that HR may not reflect energy production during this type of exercise, which is mainly explained by insufficient HR recovery following high intensity workloads. As the VO_2 was not influenced by time and there was no decrease or increase in workloads for either exercise intensity, using either cycling or DIA protocols (*Study I* and *II*), it is reasonable to suggest that cardiac output remained unaffected during the VIP. It is highly likely that this upward drift in HR could be explained by a decreased stroke volume in order to maintain cardiac output (Saltin & Stenberg, 1964). The question is then whether such an upward drift could be is influenced by aerobic power? The results from *Study II* show that during variable intensity exercise both world-class and former competitive cross-country skiers show a similar HR pattern, which indicates that an upwards drift in HR is not affected by differences in VO_{2max}. Further support of this finding is that improvements in VO_{2max} had no effect on the HR drift, as this has been shown to remain unchanged in magnitude at an exercise intensity of 75% of VO_{2max} (Ekblom, 1970). Thus the linear relationship between HR and VO_2 obtained during graded exercise is somewhat flawed. Results during DIA for both groups (*Study II*) show that at the first high intensity bout, the HR lagged behind even though the correct VO_2 was obtained and, furthermore during the moderate intensity periods, the HR was well above what was expected from the linear relationship obtained with a graded protocol for the target VO_2 (>10 bpm). As the results are outside <6 bpm it can not only be accounted for by day-to-day variations in HR (Lambert, et al., 1997). In all, this shows that HR is a rather rough estimate for VO_2 during variable intensity exercise, independent of aerobic power, as well as during both whole body and two-legged cycling exercise.

Ventilatory variables

In graded and constant exercise it has been postulated that ventilatory derived variables, such as V_E/VO_2, V_E/VCO_2 and RER can indirectly demonstrate lactate acidosis (Stringer, et al., 1995; Wasserman, et al., 1967), although the relationship between ventilation and lactate acidosis has been said to be biased due to experimental design (Busse, et al., 1992). However, the results from both *Studies I* and *II* with variable intensity exercise show that blood lactate concentrations do not attain a similar pattern to that of V_E/VO_2, V_E/VCO_2 or RER. *Study II* demonstrated that blood lactate recovery during variable intensity exercise was affected by VO_{2max} and further, in both *Studies I* and *II* related to performance. However, the ventilatory response in regards of V_E/VO_2, V_E/VCO_2 and RER was not associated with performance in either *Study I* or *II*. This indicates that lactate *per se* does not influence the respiratory pattern during the exercise intensities used (90 % and 70% of VO_{2max}). Interestingly, studies performed with lactate clamping showed that an elevated blood lactate concentration did not provoke hyperventilation, but on the contrary, induced hypoventilation (Chiolero, et al., 1993; Miller, et al., 2002). This was explained by lactate acting as a buffer, i.e. a proton acceptor and inducing hypocapnia. Furthermore, Meyer et al. (2004) showed that the respiratory compensatory point was delayed in graded exercise when pH was increased with bicarbonate infusions. These results provide evidence that protons influence ventilation, but still provide no evidence that lactate *per se* causes increased ventilation. Dissociation between ventilatory thresholds and lactate has also been demonstrated where subjects obtained the ventilatory threshold with different plasma lactate concentrations (Cecca, et al., 1986). However, RER was influenced by the *rate* rather than the *amount* of CO_2 that was produced (Wasserman, et al., 1967). Therefore, especially the longer duration of the moderate intensity workload in *Studies I* and *II* (6 min) might be a confounding factor for the ventilatory variables. This time factor could therefore be one reason why the ventilatory variables, especially RER, recovered independently of performance level and training background. Although, in support of the results in the present thesis, previous research conducted with variable intensity exercise showed no difference in respiratory compensation or recovery of respiratory variables, such as V_E/VCO_2, between trained and untrained subjects (Del Coso, et al., 2009). This suggests that assessment of the recovery of respiratory variables during variable intensity exercise is not a sensitive enough marker to evaluate training progression for endurance athletes.

Blood lactate

In *Study I*, using cycling, the group's mean blood lactate concentration was lower compared to that of ET or MT skiers using DIA, although the intensity was the same for all groups as regards percent of VO_{2max}. This suggests that the increased blood lactate concentration at the onset of exercise depends on whether arm exercise is added to leg exercise (whole body work) rather than differences in athletes' VO_{2max}. This is likely to be a result of the arm's higher lactate production than that of the legs during DIA (Van Hall, et al., 2003). Interestingly, in *Study I*, using cycling, there was a trend towards a higher lactate concentration at the first high intensity workload for the cyclists that had the longest TTE. This supports the finding that a slightly elevated lactate concentration *pre* start could be positive for cycling performance (Burnley, et al., 2005). The ET skiers' higher lactate threshold compared to the moderately trained skiers in *Study II* (ET 79% vs. MT 72% of VO_{2max}) could have been assumed to induce a lower blood lactate concentration at the onset of exercise. It is likely that the ET skiers had a lower lactate production than the MT skiers, but they had a superior lactate/H^+ transport (Pilegaard, et al., 1999) and faster lactate efflux (Bassett, et al., 1991), resulting in a similar blood lactate concentration for both groups at the first high intensity workload. Both cycling and cross-country skiing studies (*Studies I* and *II*) demonstrated the importance of lactate recovery for performance during variable intensity exercise. In *Study I*, with cyclists with relatively homogenous aerobic power, superior lactate recovery might be explained by a higher lactate threshold. With DIA, it was demonstrated that enhanced lactate recovery was associated with a higher VO_{2max}. The impact of an improved or high VO_{2max} on lactate recovery has previously been demonstrated for the same relative exercise intensity expressed as percent of VO_{2max} (Evans & Cureton, 1983), as well as percent of the ventilatory threshold (Gmada, et al., 2005). Further support for VO_{2max}'s role in lactate recovery is that trained subjects, compared to untrained subjects, are able to remove lactate at higher exercise intensities (Davies, et al., 1970; Dodd, et al., 1984; Hermansen & Stensvold, 1972; Stamford, et al., 1981; Weltman, et al., 1979). The reason why a high VO_{2max} is of importance for lactate recovery might be explained by its role in an increased absolute metabolic rate, which has been suggested to favor lactate oxidation and removal (Van Hall, et al., 2003). In *Study II*, the trend toward a higher absolute VO_2 for elite skiers, when compared with the moderately trained skiers at 70% of VO_{2max} (4.1 vs. 3.7 $L \cdot min^{-1}$), supports the importance of an increased metabolic rate for lactate recovery. Other factors that increase with improved physical fitness that could contribute to a superior lactate recovery are lactate dehydrogenase (LDH) (Messonnier, et al., 2001), blood flow (Juel, et al., 2004) and muscle capillarization (Messonnier, et al., 2002). The latter two are probably interrelated. When comparing blood lactate data between cycling and cross-country skiing, the arms may influence the results depending on their contribution to the total work. As demonstrated in *Study IV* with a relatively homogenous group of cross-country skiers during DIA, the arms (v. subclavia) had a higher blood lactate concentration than the legs (v. femoralis), but reduced their blood lactate concentration more than the legs. The higher lactate concentration in the subclavian compared to the femoral vein was of no surprise because the arms, in comparison with the legs', have higher content of type II fibres and glycolytic enzymes with less developed capillarization (Johnson, et al., 1973; Mygind, 1995; Terzis, et al., 2006). Furthermore, the results from *Study IV* showed that the legs had a negative and the arms a positive lactate a-vDiff, which indirectly supports the legs being the main site for lactate uptake, while the arms are that of lactate production during DIA (Van Hall, et al., 2003). However, this difference between the arms and the legs was attenuated when the exercise intensity was reduced. In all, a high blood lactate concentration at the onset of exercise might be influenced by the additional use of arm exercise to leg exercise compared to leg exercise only. Furthermore, results from both cycling and DIA show that a higher lactate concentration at the onset of exercise is not detrimental to performance, but instead a decrease in blood lactate concentration is crucial when the exercise intensity is reduced. During DIA, blood lactate recovery could also be influenced by changes in the arms' muscle activation.

Blood flow and O_2 extraction

In *Study III*, blood flow as well as blood flow heterogeneity was studied using variable intensity model with one-legged exercise. The results showed that skeletal muscle blood flow and oxygen uptake decreased and blood flow heterogeneity increased with a reduction in exercise intensity. When the exercise intensity increased again, going to an equally high intensity workload, blood flow increased and blood flow heterogeneity decreased. However, compared to the first high intensity workload, the muscle VO_2 was elevated at the second one although there was no increase in absolute workload. Some studies have implied that this increase in VO_2 is due to increased O_2 delivery and blood flow during consecutive bouts (Krustrup, et al., 2001; MacDonald, et al., 2001). Our results could not confirm this, as O_2 delivery and its distribution were unchanged between the two high intensity workloads. Instead the increased VO_2 was likely explained by increased O_2 extraction. Present results show that O_2 extraction decreases when exercise intensity is reduced, for both one-legged exercise (*Study III*) and combined arm and leg exercise (*Study IV*). However, during combined arm and leg exercise, i.e. DIA, the arms' O_2 extraction is lower than the legs, which confirms previous test results performed with DIA (Calbet, et al., 2005). The arms' lower O_2 extraction could partly be explained by the extended poling phase compared to leg push-off phase, and higher muscle activation (% MVC) which shortens the arms' mean transit time and negatively influences the O_2 extraction (Saltin, 1985). When the exercise intensity was reduced, the arms decreased their O_2 extraction more than the leg, which suggests that the cardiovascular system´s capacity to deliver O_2 to the working muscles was not limited, as there was a reduction in activated muscle mass during moderate exercise. This could also be explained by the arms' larger decrease in muscle activation (EMG_{RMS}) than that of the legs. As O_2 extraction was the main reason for an excessive increase in VO_2 in *Study III*, this could explain why an increase in VO_2 did not occur during DIA (*Study II*), as O_2 extraction is more or less at its limit (approximately 90%) for both arms and legs at 90% of VO_{2max} (*Study IV*). Furthermore, during the higher exercise intensity (90% of VO_{2max}), there was an association between the DP/DIA ratios and arm O_2 extraction. This indicates that a higher training level in the upper body, i.e. higher ratio, enables a higher arm O_2 extraction, which could explain why upper body power is important for performance in cross-country skiing using the classical style containing DIA (Alsobrook & Heil, 2009).

Integrative physiological and biomechanical explanatory models

In *Study IV*, the arms had a longer propulsive phase and also higher muscle activation than the legs. The arms' muscle activation at 90% of VO_{2max} during the poling phase, represented as EMG_{RMS} (%MVC), exceeded values that have previously been suggested as occluding blood flow during static exercise (Sadamoto, et al., 1983). Such a high muscle activation would also increase blood flow velocity during the recovery phase (Kagaya & Ogita, 1992), which is likely to decrease the arms' mean transit time in comparison to the legs. Moreover, the arms had a longer push-off phase than the legs during DIA, implying that the blood flow was restricted for a longer time in the arms than in the legs contributing to the lower O_2 extraction. Both peak and average pole forces were lower than the peak and average leg forces at a ratio of >1:6, which is also true when taking the amount of muscle mass into consideration (ratio of muscle mass arms: legs of ~1:3, (Larsson & Henriksson-Larsen, 2008)). This demonstrates that the higher lactate concentration in the subclavian vein compared to the femoral vein is not a result of higher force, but rather higher muscle activation in the arms than the legs during DIA. However, the greater lactate recovery in the arms compared to the legs, might be explained by the arms' larger reduction in both muscle activation and peak and average forces when exercise intensity is reduced. However, the impulses of both arm and leg forces remained constant when the exercise intensity decreased. In *Study III*, IEMG was similar for both high intensity bouts. However, MVC was lower post-exercise than pre-exercise, therefore IEMG was relatively higher, but not in absolute values. This indicates that the fibre recruitment included more type II fibres contributing to the increased VO_2 during the second high intensity workload due to their lower efficiency (Krustrup, et al., 2008). Overall, *Study III* and, in particular, *Study IV* suggest that integrated models, with combined physiological and biomechanical measurements, are necessary in order to obtain a more sophisticated picture of the underlying mechanism regarding how human movement influences the physiological response to exercise.

Methodological considerations

The present thesis utilizes several methods for physiological and biomechanical measurements. In *Studies I, II* and *IV* pulmonary VO_2 was measured using a metabolic cart with a mixing chamber. This system demonstrated good reliability and accuracy when compared to the Douglas-Bag system for the relevant measurement range. The lactate analyzer was checked for linearity before each study, as well as being controlled for CV for lactate concentration in the blood over a range from 1-15 $mmol \cdot L^{-1}$, with a result of <1%. Catheterization, as well as blood sampling, using arterial and venous catheters in the arms and legs is a challenge during roller skiing. One challenge is the timing for obtaining blood samples from the different sampling sites, as well as to reducing the possible occurrence of ateriospasms from the arterial catheter during DIA. The methodological choice to use PET has several advantages when compared to other methods for determining blood flow, which include determining the perfusion of the actual muscle and not only the flow in the vessel, which can be measured with thermodilution and Doppler ultrasound. PET scanning also provides information about blood flow distribution, providing a unique opportunity in contrast to other methods. The drawback, however, is that only a limited amount of skeletal muscle can be investigated when the subject is fixed to the PET scanner and, additionally, the motion of the investigated limb is restricted. The EMG amplitude provides a qualitative measure of the changes in muscle activation, although it does not quantify precise changes. Furthermore, EMG measurement provides information about the start of excitation of the muscle, making it suitable for use when studying synchronization in activation patterns between different muscles. In addition, the application of MVC normalization means that muscle activity can be compared among skiers and between muscles. The applied pole and foot force (Pedar Mobile) systems provide detailed information about cycle characteristics and information on peak forces and impulse of forces. The data can be recorded online by wireless data transmission (Bluetooth and telemetric) at sampling rates of 3000 Hz for the pole force system and 100 Hz for the Pedar System. A drawback of these methods is that only the resultant force is recorded, i.e. the force along the shaft of the pole, and the forces perpendicular to the sole of the foot. The data is sufficient to provide information about the actual force that is applied via poles and legs, which contributes useful information in the context of physiological variables associated with force application. However, without simultaneous recording of 3D kinematics, information about how much of these forces are used in propulsion cannot be answered. Altogether, the combination of methods used in the current thesis provides a vast amount of information. Future studies are needed to verify the present results using other exercise modes, as well as additional methods, in order to gain further knowledge of how the human body responds to variations in intensity during ongoing exercise.

6. SUMMARY AND CONCLUSIONS

The results in *Study I* indicate that the magnitude of the decrease in lactate concentration between the first high intense workload bout and the consecutive moderate intense workload could be a predictor for performance during intense exercise of varying intensities, together with a high VO_{2LT}. Furthermore, HR but not VO_2 increases for a given workload indicating that the HR-VO_2 relationship is altered in variable intensity exercise. Progression in training may thus be measured by determining lactate concentration during recovery from strenuous workloads. Additionally, caution should be taken when using HR to calculate VO_2 during variable intensity exercise.

The results in *Study II* show that elite skiers with a higher VO_{2max} have superior blood lactate recovery at an exercise intensity of 70% of VO_{2max} in comparison to moderately trained skiers with a lower VO_{2max}. The decreases in RER, V_E/VO_2 or V_E/VCO_2 do not differ between elite and moderately-trained skiers which suggest that respiratory variables should not be used as performance indicators or used to mirror blood lactate changes during variable intensity exercise. Additionally, the HR-VO_2 linear relationship was offset in both elite and moderately trained skiers, which shows that HR should not be used for calculation of VO_2 during varying workloads.

Skeletal muscle blood flow, blood flow heterogeneity and O_2 delivery were unchanged between the two high intensity workloads in *Study III*, whereas muscle VO_2 increased during the second high-intensity workload. On the other hand, O_2 extraction tended to increase in the second high intensity workload, compared to the first one. No change in acid-base and lactate was observed. Therefore, the excess muscle VO_2 during the second high-intensity workload for one-legged knee-extension cannot be explained by changes in O_2 delivery, distribution of blood flow or lactate acidosis. Consequently excess muscle VO_2 is likely derived from the working muscle cells *in situ*, as the O_2 extraction tended to increase, as well as the relative muscle activation.

In *Study IV* the arms had a lower O_2 extraction than the legs, which could be contributed to the arms' higher muscle activation in %MVC and longer ground contact time than the legs. This would shorten the mean transit time for blood flow and act negatively on the arms' O_2 extraction. In addition, O_2 extraction decreased more in the arms than in the legs when exercise intensity was reduced. The greater lactate recovery in the arms than the legs might be explained by the arms' greater reduction in both muscle activation (%MVC) and peak and average forces when the exercise intensity is reduced. Overall, the integrated model, with a combination of physiological and biomechanical measurements, provides a more sophisticated picture of how human movement influences the physiological response to exercise.

7. PRACTICAL IMPLICATIONS

This thesis was produced in order to investigate the physiological and biomechanical responses to variable intensity exercise. One important, as well as challenging, aspect of sport science is to provide practical applications for how research could be used by athletes and coaches in order to enhance performance. One of the findings was that the heart rate response during cycling and diagonal skiing was not linearly related to the athlete's oxygen uptake, regardless of their performance level. In practice, this implies that training sessions at variable intensity need to be supplemented by other measurement variables, such as velocity and power output, in order to adequately guide and evaluate intensity during this type of exercise. Another interesting result was that the ability to recover from high concentrations of blood lactate during ongoing exercise is important to performance; also the association between lactate recovery and aerobic power stresses the importance of aerobic conditioning in other sports that comprise of repeated high intensity bouts with limited time to recuperate, e.g. ice hockey, soccer etc. The present thesis also provides support for the theory that oxygen extraction in the arms is lower than in the legs during whole-body exercise. Interestingly, even the well-trained athletes differed significantly in their upper-body aerobic power although they had similar maximal oxygen uptake. This reinforces the hypothesis that upper-body training is an important training objective for competitive cross-country skiers as regards improving overall performance, and when monitoring cross-country skiers. The present results suggest that analyzing lactate recovery after high intensity workloads during ongoing exercise might be an interesting new test for skiers. Finally, when investigating sports that use multiple techniques and complex movement patterns, such as cross-country skiing, it appears that it is necessary to use both physiological and biomechanical measurements. Biomechanical measurements have the potential to add useful information about how differences in technique and movement patterns, for example, affect the physiological variables related to performance.

8. ACKNOWLEDGEMENT

A completion of PhD thesis is not accomplished without tremendous support from several people who dedicate and sacrifice precious time of their own. Therefore I wish to thank the following people:

My head-supervisor, Associate Professor Hans-Christer Holmberg, for his extraordinary and dedicated support both as a mentor and supervisor, before and during my years as a PhD-student. This thesis would not have been possible without your unselfish help and encouraging pep-talks.

My co-supervisors Marko Laaksonen, PhD, and Thomas Stöggl, PhD, for their great support and friendship.

Professor Bengt Saltin for his supervision, inspiration as well as to share his unsurpassed knowledge in exercise physiology.

Professor Erika Schagatay, who took me under her wings during my first half as a PhD-student and contributed to provide Mid Sweden University their first "own" PhD from start to finish in Sport and Exercise Science.

My colleagues at the Swedish Winter Sports Research Centre, Jonas Enqvist, Lars Carlsson, Mikael Swarén, Martina Höök, Sture Espwall and Ola Ravald for contributing to a great and friendly atmosphere. Wish you all the best in your future projects.

Ski-trainer Mattias Persson for interesting talks regarding training and providing me with lunch discounts

Stefan Lindinger, PhD, Billy Sperlich, PhD, and Øyvind Sandbakk, MSc. PhD-student for contributing to the international environment at Swedish Winter Sports Research Centre as well all the stimulating coffee sessions and support in various ways.

Thanks to the staff and my doctoral student colleagues at the Department of Health Sciences, Mid Sweden University. Sport Science covers everything from the humanities to the natural sciences and is truly interdisciplinary. The current thesis covers one specific area of interest in Sport Science, but I hope that those who come after me at Mid Sweden University will add to and contribute to knowledge in all the various fields of Sport Science in the future.

Former colleagues at the Environmental Physiology Group, Robert de Bruin and Matt Richardson. Sofia Pettersson, PhD, for her provided assistance in numerous ways.

My Co-authors from Mid Sweden University, Salzburg University and Turku PET centre.

Participating subjects in all four Studies and all the athletes that I have had the privilege to work with over the years at Swedish Winter Sport Research Centre.

Former colleagues at J-H Idrottsförbund for support in various ways and especially Bertil Karlsson for employing me as the first and (l)on(e)ly full time working exercise physiologist/laboratory chief during the first three years at Swedish Winter Sport Research Centre.

My inner circle, Jonas Myrholm, for contributing to myriads of great times often in the "parallel world", Niklas Wångdahl, for always reminding me that I need to practice what I preach, Kristian Hallsten, for inspiration, Andreas Sjöberg, for great music and reminding me that I am a Västgöte, Robert Matevski, and Henrik Lindqvist.

William Wallström with family, for help in various ways to endure everyday life as a parent.

Marita with family.
Solveig and Bo, for being who you are, Thanks.

My beloved wife Malin.
And by far the most of all, my precious daughters, Saga and Nora…*Always With Me, Always With You*

The studies were supported by grants from Jämtland Härjedalens Sport Association, Centrum för Idrottsforskning (CIF) and Swedish Olympic Committee.

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