Thomas Natvig Årstad

Muscle oxygen saturation at different intensities during constant load double poling exercise

BEV3901 Master Thesis

Norwegian University of Science and Technology
Faculty of Medicine
Department of Neuroscience

Trondheim, December 2014

Acknowledgements

I would like to thank my supervisor Mireille van Beekvelt and co-supervisor Øyvind Sandbakk for their help and guidance. I would also thank all the athletes and their coaches for their cooperation during the study. At last I would like to thank my fellow students for valuable help and discussion throughout all the phases of this thesis.

Abstract

Purpose: The present study investigated the effects of constant load exercise at three different intensities on muscle oxygen saturation in the arm (triceps brachii, TB) and the leg (vastus lateralis, VL) during simulated double poling (DP). **Methods:** Nine male elite cross country skiers with a VO_{2max} of 74.5 ± 3.8 ml/kg/min performed two submaximal 4-minute intervals at low (LOW) and moderate (MOD) intensity, and one steady rate maximal all-out (MAX) 3-minute interval. Muscle oxygen saturation in TB and VL was measured during exercise by near-infrared spectroscopy. **Results:** The response in muscle oxygen saturation was different for TB and VL in relation to intensity. TB displayed a clear desaturation already at LOW and thereafter showed no further significant desaturation. However, a trend of further desaturation from LOW to MOD to MAX was evident. VL on the other hand showed no desaturation in LOW, a slight desaturation in MOD and a clear desaturation in MAX. In addition, the desaturation pattern during MAX, where both muscles displayed a clear desaturation, were different between the two muscles. TB showed a rapid desaturation at the onset of exercise, unlike VL that gradually desaturated throughout the whole exercise period. **Discussion:** The difference in muscle oxygenation desaturation in relation to intensity between TB and VL was in agreement with other studies investigating oxygen saturation in these muscles. However, it should be noted that very little research has been done on DP specifically, and the present study revealed similar differences as other studies obtained during arm cranking and cycling. The desaturation pattern of TB during maximal DP was in agreement with previous literature. In contrast, the desaturation pattern in VL during MAX has not been observed in previous studies investigating steady rate exercise. However, DP differs from cycling, and the subjects in the present study might have adjusted their DP technique to involve increasingly more leg-work as they became fatigued during the maximal DP-period. **Conclusion:** The present study has provided more insight into the physiological responses and processes in arm and leg during DP. The present study found a difference in muscle oxygen saturation in TB and VL in relation to intensity during simulated DP. It was also found a difference in the desaturation pattern between TB and VL during maximal DP exercise, but the mechanism behind this remains unclear.

Key words: Near-infrared spectroscopy, muscle oxygen saturation, m. triceps brachii, m. vastus lateralis, double poling exercise, cross country skiing

Table of content

Introduction

Cross-country skiing has gone through some major changes during the last decades. The introduction of mass-start events, the sprint-event, better skis and poles, and better preparations of the tracks have led to an increased overall speed, which has led to more frequent use of the double-poling (DP) technique, which again has led to greater requirements of upper-body strength and endurance capacity because the upper-body is the predominant contributor to propulsion during DP (Stöggl, Lindinger, & Muller, 2006). In fact, today, some athletes choose to use only the DP-technique during sprint events, as well as during the flatter long-distance events, some as long as 90 km. This has led to a rapid development of the DP-technique as it is frequently more and more used. (Stöggl et al., 2006).

An illustration of how DP has developed during the last decades has been provided by Saltin (1997). He showed that during the 1980's, DP-VO_{2peak}, using roller skiing on a treadmill or a DP-ergometer, reached 80% compared to that of uphill running, whereas it reached over 90% in the late 90's, illustrating the skiers increased ability to utilize their capacity in DP. Already in the 1950's, Taylor, Buskirk, and Henschel (1955) showed that VO_{2peak} was higher when more muscle mass was involved (Taylor et al., 1955). Later studies confirmed this, but only up to a certain level of active muscle mass, where the cardiac output can no longer be elevated (for review, see Saltin, 1988). This indicated that the increases in VO_{2peak} during DP was most likely due to activation of a larger muscle mass. The focus on upper body strength has increased over the last decades, which might have resulted in more muscle mass in the upper body (Stöggl et al., 2006). In addition to this, Holmberg, Lindinger, Stoggl, Bjorklund, and Muller (2006) and Bojsen-Møller et al. (2010) have shown that the legs are very active during DP as well, as opposed to earlier studies where DP was mainly seen as an upper body exercise (Hoff, Helgerud, & Wisloff, 1999). The development in DP involved not only more upper-body active muscle mass, but also a larger number of active lower-body muscles, and most likely contributed to the observed increase in VO_{2peak} during DP (Saltin, 1997).

However, there seems to be quite some differences in the oxygen kinetics between arms and legs (Muraki, Tsunawake, & Yamasaki, 2004). Several studies have examined the differences between arm and leg oxygen kinetics. Rasmussen, Klausen, Clausen, and Trap-Jensen (1975) found the oxygen depletion of venous blood to be more pronounced during leg training compared to arm training performed at the same relative intensity, and Calbet et al. (2005) found the percentage of O_2-extraction to be consistently higher in legs than arms during exercise, whether it being diagonal stride, double poling or leg skiing without using the arms. This gave the idea that the legs extract more O_2 than the arms. Part of the explanation was related to the higher capillary muscle O_2-conductance in the legs compared to the arms, combined with a possibly smaller diffusional area in the arms compared to the legs, and longer diffusional distances in the arms compared to the legs (Calbet et al., 2005). In addition, the majority of histochemical studies showed a higher activity of oxidative enzymes in the arm muscles of elite skiers compared to leg muscles (for review, see Popov & Vinogradova, 2012). However, Rasmussen et al. (1975) and Calbet et al. (2005) did not investigate single muscles when they described the oxygen kinetics of the arms and legs, instead they looked at the limbs as one system. Using EMG during DP, Holmberg, Lindinger, Stoggl, Eitzlmair, and Muller (2005) found large individual differences in upper-arm muscle recruitment. Leg flexion and extension were in a study by Calbet et al. (2005) done in a fairly fixed pattern, with little variation in the activation of the different muscles. Arm and shoulder on the other hand, had more degrees of freedom and could perform their movements in various positions, thus enabling larger possibilities for variations in muscle activation. Therefore, it was harder to conclude which arm-muscles that were active than it was for leg muscles (Calbet et al., 2005). This could lead to an overestimation of the active muscle mass in the arms, and thus an underestimation of the O2-extraction when looking at the whole arm as one (Calbet et al., 2005). Therefore it may be beneficial to study the oxygen kinetics of single muscles, and this can be done using e.g. near infrared spectroscopy (NIRS), which is a non-invasive and continuous method to monitor changes in muscle oxygen saturation (Van Beekvelt, Colier, Wevers, & Van Engelen, 2001). Differences in muscle oxygen saturation during arm cranking and leg cycling, specifically the triceps brachii and the vastus lateralis were studied by Muraki et al. (2004), using NIRS. A rather big difference was found in the desaturation during exercise between the two muscles. During arm cranking, muscle desaturation in triceps brachii stopped at approximately 50% of VO_{2peak}, whereas during leg cycling, desaturation continued until approaching the VO_{2peak} (Muraki et al., 2004). Apparently, the oxygen kinetics is different for arm cranking and leg cycling. The question is if this also hold true for DP?

Few studies have investigated differences in oxygen kinetics between the arms and legs during cross country skiing and more specifically in the DP technique. One study monitored muscle oxygen saturation and blood volume changes in triceps brachii and vastus lateralis using NIRS in outdoor roller skiing during different techniques (Hesford, Laing, & Cooper, 2013). They found a decrease in muscle oxygen saturation in triceps brachii during the DP-phase, but no stable desaturation was observed in vastus lateralis. However, this study consisted of only two subjects and it remains unclear what exercise intensity the measurements were carried out on. In addition, the two subjects were biathletes and most likely not specialized in the DP technique, since all biathlon-races allow skiers to use a freely chosen technique, and therefore the DP-technique is very seldom used.

In summary, arms and legs have shown different oxygen kinetics with regard to muscle oxygen saturation during isolated arm and leg exercise. However, very little research has been done to investigate how the oxygen kinetics in arm and leg behave in combined arm and leg exercise such as DP. The purpose of this study was therefore to investigate the effects of constant work load at various intensities on muscle oxygen saturation in arm (triceps brachii) and leg (vastus lateralis) during simulated double poling.

Methods and materials

Subjects

Nine well-trained healthy cross country skiers participated in the study, and their characteristics are shown in Table 1. All subjects received written and verbal information about the study and their rights in advance, and signed an informed consent prior to the tests. The study was reviewed by the Regional Ethics Committee, Trondheim, Norway, and no official approval was needed, because of the non-invasive nature of the study.

Table 1 Anthropometrics and physiological characteristics of the nine well-trained cross-country skiers. (Mean, SD, MIN, MAX)

	Mean	SD	MIN	MAX
Age *(yrs)*	21.6	3.7	18.0	30.0
Height *(cm)*	182.5	6.3	175.0	194.0
Body mass *(kg)*	76.3	6.7	67.8	86.1
BMI *(kg/m^2)*	22.9	1.4	30.3	24.5
VO_{2max} *(ml/kg/min)*	74.5	3.8	70.0	81.1
Circumference TB *(cm)*	31.4	2.0	29.0	35.0
Circumference VL *(cm)*	50.6	1.8	48.0	53.5
ATT (TB) *(mm)*	7.9	1.9	5.0	11.0
ATT (VL) *(mm)*	11.1	2.7	6.8	14.5

BMI = body mass index. VO_{2max} = maximum whole body oxygen uptake derived from a running, and must not be confused with the VO_{2peak} values during DP-exercise mentioned later in the text. ATT = adipose tissue thickness, TB = triceps brachii, VL = vastus lateralis.

Experimental protocol

When the athletes arrived in the lab, weight and height were measured, and their age was noted. The athletes were allowed to warm-up on a treadmill at low intensity for 10 minutes, followed by a short 2-3 minutes specific warm-up during which they could familiarize with the ergometer. The test consisted of three different parts, where all parts were carried out using the DP technique on a Concept 2 ski-ergometer (Concept2 Inc., Morrisville, VT, USA) where the subjects could observe their watt-production during the test. The first part consisted of 2 constant load 4-minutes submaximal periods, the second part consisted of 3 short sprints, and the last part consisted of a 3-minute all-out exercise at maximal intensity. The subjects were instructed to keep a constant watt-production during all submax-periods, and also during the last all-out stage where they were instructed to start at a pace they could maintain for 3 minutes but, ideally, no more.

In the first part, all subjects performed 2 submaximal periods at low (LOW) and moderate (MOD) intensity, separated by a 2 minute break. The intensity was subjectively controlled by the athletes themselves, rating their perceived exertion (RPE) following the Borg Scale (6-20). Thus, all athletes performed according to their own performance level and internal effort. The athletes were well trained, and had trained cross-country skiing for at least 10 years. From this, we assumed that they were able to distinguish well between different intensities, and after a thoroughly explanation of the Borg Scale, the athletes were instructed to exercise at a RPE of 10 at the Borg scale (LOW) and 16 at the Borg scale (MOD), with 10 corresponding to intensity 1 and 16 corresponding to intensity 3 in the Norwegian Olympic Committee intensity-scale (Seiler & Tønnessen, 2009). A lactate sample was taken after each period and served as an objective control of intensity, again according to the Norwegian Olympic Committee intensity-scale (Seiler & Tønnessen, 2009). After the first part, the athlete had a 3-minute break followed by two 10-second sprints, a 3-minute break and then a 30-second sprint. This part of the test falls beyond the scope of this thesis and is not included in further analysis. Following the second period, the subject had a 5-minute break and then performed a 3 minute all-out period (MAX), which aimed for 20 at the Borg Scale, corresponding to intensity 5 in the Norwegian Olympic Committee intensity scale (Seiler & Tønnessen, 2009). The maximal VO_2 and HR-value obtained during this period were assumed to be the subject's peak-value for DP, and were used to assess how hard the subject worked in LOW and MOD as a percentage of HR_{peak} and VO_{2peak} (see table 2).

Double poling ergometer

All tests were performed on a modified Concept2 Ski Ergometer (Concept2 Inc., Morrisville, VT, USA) designed to imitate the DP technique in the best possible way. The damper setting was set to level 1. The design of the ergometer allowed the subjects to see their own watt-production throughout the test. To ensure that the subjects did not change their position during the test, and performed all exercise at the same distance from the ergometer, markers were put on the floor to clarify where each subject should keep their feet.

Physiological measurements

Oxygen consumption and respiratory variables were measured continuously using open-circuit indirect calorimetry (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The apparatus was calibrated each test day, using a known gas mixture (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany) to calibrate the O_2 and CO_2 gas analysers, and a 3L syringe (Hans Rudolph Inc., Kansas City, MO) to calibrate the expiratory flow meter. Blood lactate concentration was measured from a 20µL blood sample taken from the fingertip (Biosen C_line Sport lactate analyzer, EKF-diagnostic GmbH, Barleben, Germany) and was measured immediately after each period. Heart-rate was measured continuously using a Suunto t6c heart rate monitor (Suunto Oy, Vantaa, Finland).

NIRS-measurements

Near-infrared spectroscopy (Portamon, Artinis Medical Systems, The Netherlands) was used to assess the changes in muscle oxygen saturation (SmO_2). Near-infrared spectroscopy is a non-invasive optical technique using light in the near-infrared region (750-950nm) which is very well suited to penetrate biological tissue, and mainly absorbed by hemoglobin and myoglobin. Oxygenated blood and deoxygenated blood, oxyhemoglobin/myoglobin (O_2Hb/O_2Mb) and deoxyhemoglobin/myoglobin (HHb/HMb) have different absorption-spectra, and by using a modified Beer-Lambert law, it is possible to calculate the changes in O_2Hb and HHb. Hemoglobin and myoglobin have identical absorption-spectra and can therefore not be distinguished from each other, but in this study this has no practical implications.

The Portamon-system which was used in this study is a portable 4-channel system with wavelengths of 761 and 845 nm consisting of three transmitters and one receiver with distances from the different transmitters to the receiver being 30, 35 and 40 mm. The NIRS optodes were wrapped in clear plastic foil to protect them from sweat, and taped on top of two different muscles: m. triceps brachii (TB), and m. vastus lateralis (VL). Care was taken to ensure that the optodes were placed on the muscle belly, and securely fastened using elastic bandages and medical tape. After placement on the skin, the optodes were covered in aluminum foil to protect from simultaneously ongoing pro-reflex measurements. After the tests, skinfold thickness and limb circumference were measured at the point of NIRS optode placement. The skin fold thickness was determined by the average of two caliper measurements and limb circumference was measured once with a tape-measure.

Data analysis

Raw NIRS-data was exported to matlab-files, and thereafter divided into separate parts, LOW, MOD and MAX. Start and end of each period was defined and saturation values were set to zero at the start of each period. The data was thereafter filtered using a low-pass Butterworth filter (50hz, 8^{TH} order, zero lag) to remove the artifacts resulting from the rhythmic contractions and relaxations of the muscles during DP. The group response during the three exercise periods was computed with an interval of 10 seconds, with one data point being the average of the measurements obtained in the previous 10 seconds. End-exercise saturation values of the last 30 seconds of each period were also averaged and used for comparison. In this thesis, only the SmO_2 values were used. Filtering and processing of data was done using MATLAB (R2012a Mathworks Inc., Natick, MA, USA). The HR and VO_2 data was recorded during the whole test, but only the last value obtained at the end of each period was used for analysis.

Statistics

All data were checked for normality using Shapiro-Wilk test of normality. All tables are presented with mean, standard deviation and range (min and max), and all figures are presented with means and standard deviation. A two-way repeated measure ANOVA was used to test if there was a difference in desaturation between TB and VL as intensity increased. If Mauchly's test of sphericity was violated, the Greenhous-Geisser was used for adjusted significance. A one-way ANOVA was used to investigate differences in desaturation in each muscle over the three intensities, and to investigate differences in lactate, VO_2, HR, power, RPE and RER. At last a paired samples t-test was used to assess the differences in desaturation in each muscle on the same intensity. Significance level was set to 95%, corresponding to $p < 0.05$. All statistical analyses were performed using SPSS version 21.0 (SPSS, Inc., Chicago, IL, USA).

Results

Physiological responses

There was a significant lower ATT in TB as compared to VL and a significant lower limb circumference in TB compared to VL (both $p < 0.001$, Table 1). All values for lactate, VO_2, HR, power output, RPE and RER for the three intensities were normally distributed and are displayed in Table 2. The RPE-values for LOW, MOD and MAX were approximately one value lower than requested. Looking at the range of RPE, LOW and MOD showed fairly big variations, while all subjects reported high values at and close to 20 at MAX.

Table 2 Physiological responses in nine cross-country skiers performing double poling at three different exercise intensities presented as Mean (SD, MIN-MAX)

	LOW	MOD	MAX
Lactate (*mmol/l*)	1.93 (0.6, 1.27-2.77)b,c	4.95 (0.66, 4.29-6.13)a, c	14.34 (2.43, 8.92-17.80)a, b
VO_{2peak} (*ml/kg/min)*	32.3 (4.6, 23.9-39.0)b, c	52.5 (4.8, 47.4-59.4)a, c	68.3 (3.9, 61.3-74.1)a, b
$_{\%}VO_{2peak}$ (%)	47 (5, 39-54)b, c	77 (7, 64-85)a, c	100 (0, 100-100)a, b
HR (*bpm*)	127 (9.9, 110-139)b, c	168 (6.9, 159-179)a, c	185 (3.6, 179-189)a, b
$_{\%}HR_{peak}$ (%)	69 (6, 59-74)b, c	91 (4, 84-96)a, c	100 (0, 100-100)a, b
Power (Watts)	109 (16.4, 84-134)b, c	195 (24.9, 169-235)a, c	286 (28.9, 247-335)a, b
Requested RPE	10	16	20
RPE	8.9 (1.23, 7-11)b, c	14.8 (1.48, 12-17)a, c	19.2 (0.67, 18-20)a, b
RER	0.90 (0.01, 0.88-0.93)b, c	0.99 (0.03, 0.95-1.06)a, c	1.07 (0.06, 0.98-1.14)a, b

HR = heart rate, RPE = perceived rate of exertion, RER = respiratory exchange ratio.

[a] = Significantly different from LOW, [b] = significantly different from MOD, [c] = significantly different from MAX.

Group response

The mean group response, as displayed in Fig 1, showed little desaturation in VL compared to TB during LOW and MOD. At MAX, a clear desaturation was seen in both TB and VL with both muscles reaching similar desaturation levels towards the end of the test period. The end-exercise SmO_2 displayed in Fig. 2 highlights this difference, and also shows how the TB has a very profound desaturation already at LOW. A main effect of intensity was found on muscle oxygen saturation in TB ($p = 0.036$), but the Bonferroni post-hoc tests found no significant differences in desaturation from LOW to MOD ($p = 0.119$), from MOD to MAX ($p = 0.803$)

or from LOW to MAX ($p = 0.184$). VL on the other hand, showed a rather small, but significant desaturation from LOW to MOD ($p < 0.05$), and a large desaturation from MOD to MAX ($p < 0.05$). A two-way ANOVA revealed that the reduction in saturation for TB and VL was the same between LOW and MOD ($p = 0.567$), but not between MOD and MAX ($p < 0.05$). Looking at the value of desaturation in each muscle over the same intensity, there was a significant difference between TB and VL in LOW and MOD ($p < 0.05$) but no difference in MAX ($p = 0.296$).

A clear difference in the deosaturation pattern between the two muscles was observed when studying Fig. 1C. Both TB and VL display a clear desaturation, but TB has a rapid, almost instant increase in desaturation at the onset of exercise, while VL seems to display a more gradual increase in desaturation lasting until the end of exercise.

As shown in Fig. 2, end-exercise desaturation values show a high variability in TB at all three intensities. Interestingly, the upper band of the variance was at a fairly constant value for all three intensities, as opposed to the lower band which decreased at approximately the same rate from LOW to MOD to MAX. This could give the idea that some subjects was at maximal desaturation already at LOW, while others were not. However, by looking at the individual desaturation values of TB in each subject, this was not the case. This effect was mainly due to one subject, but it is unclear whether this was due to methodological errors or to physiology. Looking at the raw-data for this subject, there is a possibility that the values obtained was due to noise in the signal, but it is hard to conclude. Removing this subject from the dataset resulted in a lower variability in MAX and a desaturation value in MAX of – 26% compared to – 28% with the subject, bringing the group mean values for MOD and MAX closer together. Without this subject, the variability reflects the differences in mean value both in the upper and lower band. Removing this subject from the dataset did not yield any differences affecting the significance of the statistics mentioned above, and because there was no physiological or methodological reason to exclude the subjects, the subject was included in the analysis, and no conclusion was drawn from the variability showed in figure 2.

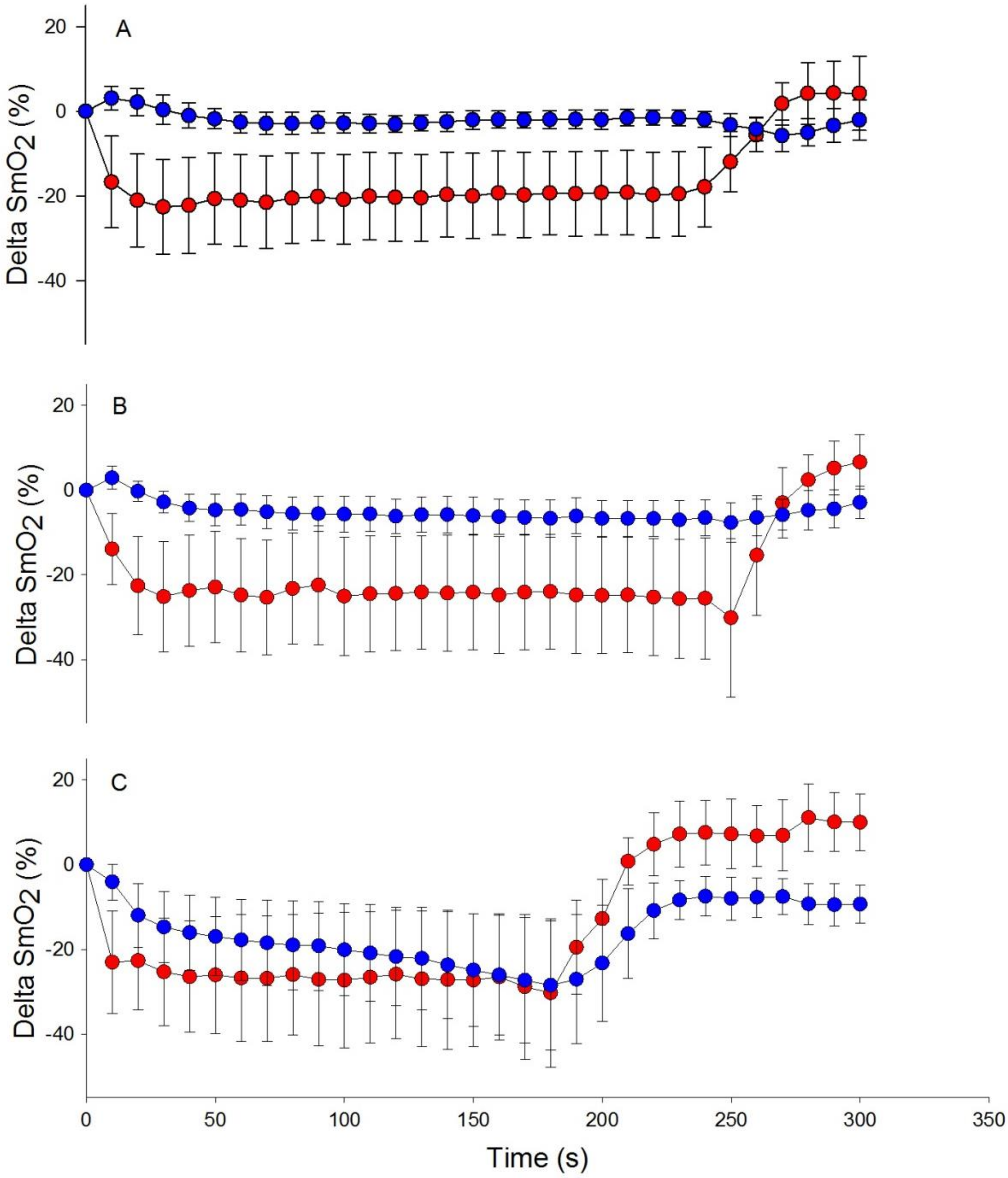

Figure 1, Mean group response (± SD) of muscle oxygen saturation changes in the triceps brachii (TB, red dots) and the vastus lateralis (VL, blue dots) during A) low intensity DP exercise (LOW), B) moderate intensity DP exercise (MOD) and (C DP at maximal intensity (MAX). Note that the exercise period for LOW and MOD ended after 240 seconds, while for MAX, it ended after 180 seconds.

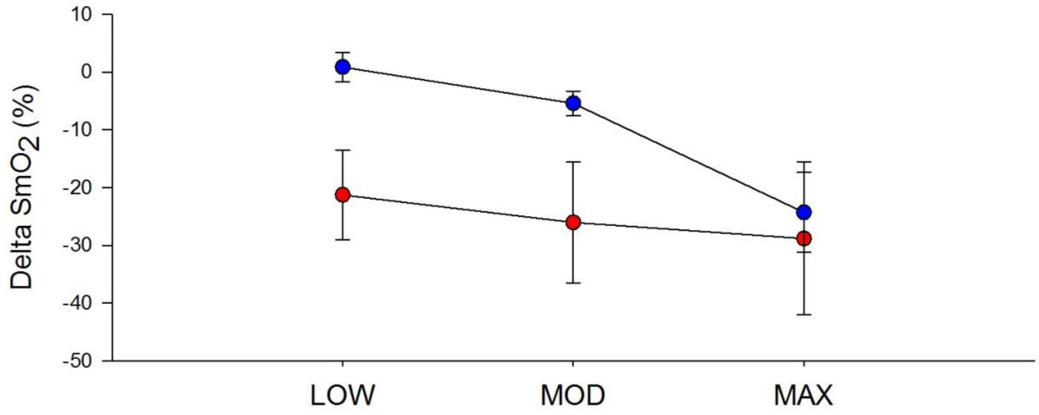

Figure 2, Mean end-exercise delta value ± SD for muscle oxygen saturation averaged over the last 30 seconds of each period for the triceps brachii (TB, red dots) and the vastus lateralis (VL, blue dots).

Discussion

The present study investigated the effects of constant load exercise at various intensities on muscle oxygen saturation in arm (TB) and leg (VL) during simulated DP. The main finding was that the muscle oxygen saturation responses of TB and VL were different in relation to intensity. At low (LOW) intensity, muscle oxygen saturation in VL remained at baseline, in contrast to TB which showed a clear desaturation. From LOW to moderate (MOD) intensity, the increase in desaturation was approximately the same for both muscles, but from MOD to maximal (MAX) intensity there was a much more prominent desaturation in VL compared to TB. In addition, a different desaturation pattern between the two muscles was evident at MOD and MAX with TB displaying a rapid desaturation at the onset of exercise and thereafter remaining at stable values throughout the period in contrast to VL which showed a steady increasing desaturation over the whole period.

The lack of an increasing desaturation in TB from LOW to MAX seems to be in agreement with previous literature. In 2004, Muraki et al. (2004) found that desaturation in TB during incremental arm cranking exercise stopped at approximately 50% of VO_{2peak} in non-specifically arm-trained women. In the present study, the mean intensity of the lowest work rate (LOW) was 47% of VO_{2peak}, which might suggest that TB desaturation already here was close to its maximum desaturation capacity. However, a trend of enhanced desaturation was observed from LOW to MAX, although not significant. This trend might be explained by the fact that the subjects were well-trained cross-country skiers, hence specifically arm-trained. In a study by Terzis, Stattin, and Holmberg (2006), the training-effects on TB after 20 weeks of increased upper-body training in already well-trained cross country skiers was examined which showed an improvement in cross-sectional area of both type I and IIA muscle fibers, as well as an increase in the capillaries per fiber (Terzis et al., 2006). This indicates that an enhanced capillarization might lead to a larger blood flow with a maintained mean transit time and a larger surface area for gas exchanges. Therefore, it is not surprising that athletes who has trained their upper body for several years, as was the case for the subjects in the present study, could have different oxygen kinetics in TB than the subjects used by Muraki et al. (2004). This might explain why a slight increase in desaturation in TB was observed above 50% of VO_{2peak} in the present study. Another possible explanation is that DP combines arm and leg work, while in the study by Muraki et al. (2004), arm cranking was done without any leg work. It is difficult to conclude whether the arms work at the same VO_{2peak} as the whole body during DP, but activation of arm muscles was shown to be more profound than that of leg muscles during DP both at 70 % and 90 % of VO_{2max} (Stöggl, Björklund, & Holmberg, 2013). Therefore, when we observed an exercise intensity of 47% of VO_{2peak} during DP, it is reasonable to assume that the arms was working at least at 47% of their relative VO_{2peak}, which is in agreement with the work of Bojsen-Møller et al. (2010) who showed that during low intensity DP corresponding to 53% of VO_{2peak}, mainly the upper body was working. Increasing intensity to 74% of VO_{2peak} showed no more involvement of the upper body, meaning that more work in the lower body was responsible for the increase in VO_2. As no more activation of the arms occurred after 50% of VO_{2peak}, one could expect no further desaturation. However,Volianitis, Krustrup, Dawson, and Secher (2003) studied the effects of transition from arm to combined arm and leg work, and found that on the transition from arm to combined arm and leg work, there was a reduction in the blood flow to the active biceps brachii muscle together with a reduction in mean arterial pressure and arm vascular conductance, thus compromising arm oxygen uptake and muscle oxygen saturation. Biceps brachii (BB) showed a different desaturation pattern compared to TB during incremental exercise with BB showing no plateau at submaximal intensity as displayed in TB in the present study (Bhambhani, Maikala, & Buckley, 1998). However, the reduced blood flow to the exercising arm muscles when involving more leg work should apply also for TB, thus probably compromising muscle oxygen saturation also here. This gives a possible explanation for the slight increase in desaturation observed in TB from LOW to MAX, since DP can be considered as mainly arm work at low intensity and combined arm and leg work at higher intensities (Stöggl et al., 2013).

VL displayed differences in desaturation during the three intensities compared to TB. In LOW VL displayed baseline values of saturation. In MOD and MAX on the other hand, there was a clear desaturation, with the desaturation in MAX being much more prominent than in MOD. This was in agreement with Muraki et al. (2004) who showed a similar pattern for the VL during incremental cycling exercise. Immediately after onset of exercise, on very low intensity corresponding to approximately 20-30% of $VO_{2peak,}$ significantly higher muscle oxygen saturation values was found compared to rest. Thereafter there was an increase in desaturation until reaching 100% of VO_{2peak}, which reached a significant difference from rest at approximately 55% of VO_{2peak}. In addition, findings of Miura, Araki, Matoba, and Kitagawa (2000) and Grassi, Quaresima, Marconi, Ferrari, and Cerretelli (1999) showed a rapid desaturation in VL starting at approximately 60% of VO_{2peak} . Compared to these results, knowing that VO_{2peak} in LOW in the present study averaged 47%, and also knowing from the findings of Bojsen-Møller et al. (2010) that the legs were probably not very active during low intensity DP, it gives meaning that no desaturation in VL was observed at LOW in the present study. Actually one could argue that one should expect a slight increase in muscle oxygen saturation compared to rest, if any difference were to be expected. At MOD our subjects exercised at an intensity of 77% of VO_{2peak}. At this intensity, Muraki et al. (2004) found a more profound desaturation in VL during incremental cycling than observed in this study. However, considering the work of Stöggl et al. (2013), where arm had a higher activation than leg during DP, and Bojsen-Møller et al. (2010) showing that legs became more active at higher intensity, it is reasonable to assume that VL in the present study was working at a lower rate than the observed whole-body percentage VO_{2peak}, and therefore leading to lower desaturation values at the same percentage of VO_{2peak} compared to what was obtained by Muraki et al. (2004). At MAX a pronounced desaturation in VL was observed, which was in agreement with the findings of Muraki et al. (2004), Stöggl et al. (2013) and Bojsen-Møller et al. (2010).

Looking at the desaturation pattern in TB, it is clear that for LOW, MOD and MAX, an initial drop in saturation occurred (Fig. 1), with no further desaturation during the rest of the exercise period, in contrast to VL which displayed a gradually desaturation throughout the exercise period, at least in MAX. Little research has been done on muscle oxygen saturation in TB during constant load exercise at different intensities. One recent study by Hesford et al. (2013) looked at TB oxygen saturation during outdoor roller skiing in different terrain and using different techniques, among others the DP-technique on flat ground. They used only two subjects, and data was presented separately for each subject. In their first subject, the desaturation pattern of TB seemed to be consistent with the findings in the present study. However, in their second subject, the desaturation pattern was harder to interpret because of several inconsistent spikes in the signal, although the rapid desaturation at the onset of exercise seemed to be present, as well as a fairly consistent desaturation value during the first part of the exercise period. During the second part of the exercise period, however, there seems to be a resaturation towards the end. More research has been done on the desaturation pattern in VL during constant load exercise, but mainly in cycling. In one study by Miura et al. (2000), they performed six 5-minute intervals where the highest work rate corresponded to 80% of $VO_{2max.}$ However, they did not find the same desaturation pattern as observed in this study. Instead they observed a rapid desaturation at the onset of exercise, and a steady saturation thereafter throughout the whole interval. The study by Hesford et al. (2013) also investigated the desaturation in VL. They did not report any desaturation at all during DP, but nothing was said about the exercise intensity during double poling, making conclusions hard to draw. They also measured desaturation during steep uphill skiing; however without mentioning what ski-technique was used, but surely it involved legwork. Here there was a clear desaturation in VL, but the desaturation pattern was not consistent with the findings of the present study, but more like the findings by Miura et al. (2000). The reason for this disagreement in desaturation pattern of VL in the present study and previous studies may be explained by the fact that the MAX DP period used in this study was an all-out period where the subjects were instructed to exercise as hard as they could for 3 minutes, but still hold a constant work rate. This might have led to that the subjects started a bit conservatively, and increased the work rate towards the end of exercise, leading to the MAX period being more of an incremental period instead of a constant load period, with the legs being increasingly active as intensity possibly increased towards the end of the period. However, there was a trend of gradually increasing desaturation in VL during MAX for almost all subjects in this study, and as the subjects were told to keep a constant work rate throughout the whole period, it is hard to conclude that the deviation between this study and earlier studies can be explained solely by all subjects consciously failing their task. One possible reason, and perhaps the most logical one, could be related to the subjects unconsciously changing their DP strategy as they became increasingly more tired towards the end of the MAX period. As found by Stöggl et al. (2013), arm muscles were more active during DP than leg muscles, but when the subjects became fatigued during the MAX period, they might have reduced the activation of the arms, and put more work on the legs, thus explaining why there was a gradual increase in desaturation in the legs during MAX. If this change of strategy is true, one could perhaps expect to find a decrease in desaturation in arm, but as explained earlier, the arms were already working very hard at low intensity, and therefore this reduction in activation during MAX would probably not be enough to cause a resaturation in the arms.

This study consisted of some limitations and possible error sources worth mentioning. First of all, the NIRS-data were not corrected for adipose tissue thickness (ATT). A study by Grieger, Geraskin, Steimers, and Kohl-Bareis (2013) highlighted the differences in the saturation measurements caused by the ATT. However, it was also mentioned how many studies circumvent this problem by choosing subjects with low ATT, and mentioning the lack of adjustment for ATT as mainly a weakness in studies investigating subjects with high ATT. In the present study the subjects were well trained athletes, with relatively low ATT, and this is therefore not considered to be a major limitating factor. As this study investigated the technique of double poling in cross country skiing, it is important to highlight that the testing was carried out indoor on an ergometer. Even though the ergometer was designed to replicate outdoor double poling on snow in the best possible way, it was impossible to replicate it one hundred percent. It might be that the subjects were applying different DP-strategies and coordination patterns on the ergometer compared to a treadmill or on snow outdoor.

In conclusion, the present study showed differences in muscle oxygen saturation in the TB compared to the VL during simulated DP exercise. In the TB there was a very profound desaturation already at low intensity, with no further significant desaturation at higher intensity. However, a trend of slight desaturation at the intensities higher than LOW was observed. The VL on the other hand showed no desaturation during low intensity, a slight desaturation during moderate intensity, and a very profound desaturation during maximal DP exercise. When comparing the desaturation pattern for the TB and the VL during MAX, a difference between muscles was observed, with TB displaying a rapid desaturation at the onset of exercise, and thereafter no further desaturation during the exercise period. VL on the other hand displayed a gradual desaturation during the whole exercise period, a pattern previously observed during incremental cycling exercise. More research should be done on the difference in the desaturation patterns between the TB and VL at maximal DP intensity to investigate if the observed differences could be related to the subjects changing their DP-strategy, gradually involving more leg-work as they become increasingly fatigued. It would also be interesting to further investigate the relationship between increasing leg work and arm muscle oxygen saturation during DP as the intensity increases.

References

Bhambhani, Y., Maikala, R., & Buckley, S. (1998). Muscle oxygenation during incremental arm and leg exercise in men and women. *European Journal of Applied Physiology and Occupational Physiology, 78*(5), 422-431.

Bojsen-Møller, J., Losnegard, T., Kemppainen, J., Viljanen, T., Kalliokoski, K. K., & Hallen, J. (2010). Muscle use during double poling evaluated by positron emission tomography. *J Appl Physiol (1985), 109*(6), 1895-1903. doi: 10.1152/japplphysiol.00671.2010

Calbet, J. A. L., Holmberg, H.-C., Rosdahl, H., van Hall, G., Jensen-Urstad, M., & Saltin, B. (2005). Why do arms extract less oxygen than legs during exercise? *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 289*(5), R1448-R1458. doi: 10.1152/ajpregu.00824.2004

Grassi, B., Quaresima, V., Marconi, C., Ferrari, M., & Cerretelli, P. (1999). Blood lactate accumulation and muscle deoxygenation during incremental exercise. *J Appl Physiol (1985), 87*(1), 348-355.

Grieger, S., Geraskin, D., Steimers, A., & Kohl-Bareis, M. (2013). Analysis of NIRS-based muscle oxygenation parameters by inclusion of adipose tissue thickness. *Adv Exp Med Biol, 789*, 131-136. doi: 10.1007/978-1-4614-7411-1_18

Hesford, C., Laing, S., & Cooper, C. (2013). Using Portable NIRS to Compare Arm and Leg Muscle Oxygenation During Roller Skiing in Biathletes: A Case Study. In S. Van Huffel, G. Naulaers, A. Caicedo, D. F. Bruley & D. K. Harrison (Eds.), *Oxygen Transport to Tissue XXXV* (Vol. 789, pp. 179-184): Springer New York.

Hoff, J., Helgerud, J., & Wisloff, U. (1999). Maximal strength training improves work economy in trained female cross-country skiers. *Med Sci Sports Exerc, 31*(6), 870-877.

Holmberg, H. C., Lindinger, S., Stoggl, T., Bjorklund, G., & Muller, E. (2006). Contribution of the legs to double-poling performance in elite cross-country skiers. *Med Sci Sports Exerc, 38*(10), 1853-1860. doi: 10.1249/01.mss.0000230121.83641.d1

Holmberg, H. C., Lindinger, S., Stoggl, T., Eitzlmair, E., & Muller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med Sci Sports Exerc, 37*(5), 807-818.

Miura, H., Araki, H., Matoba, H., & Kitagawa, K. (2000). Relationship among oxygenation, myoelectric activity, and lactic acid accumulation in vastus lateralis muscle during exercise with constant work rate. *Int J Sports Med, 21*(3), 180-184. doi: 10.1055/s-2000-301

Muraki, S., Tsunawake, N., & Yamasaki, M. (2004). Limitation of muscle deoxygenation in the triceps during incremental arm cranking in women. *Eur J Appl Physiol, 91*(2-3), 246-252. doi: 10.1007/s00421-003-0962-8

Popov, D. V., & Vinogradova, O. L. (2012). Comparison of the aerobic performance of leg and arm muscles in cross-country skiers. *Human Physiology, 38*(5), 508-513. doi: 10.1134/s0362119712050106

Rasmussen, B., Klausen, K., Clausen, J. P., & Trap-Jensen, J. (1975). Pulmonary ventilation, blood gases, and blood pH after training of the arms or the legs. *J Appl Physiol, 38*(2), 250-256.

Saltin, B. (1988). Capacity of blood flow delivery to exercising skeletal muscle in humans. *The American Journal of Cardiology, 62*(8), 30E-35E. doi: http://dx.doi.org/10.1016/S0002-9149(88)80007-9

Saltin, B. (1997). The physiology of competitive c.c. skiing across a four decade perspective; with a note on training induced adaptations and role of training at medium altitude. In E. Müller, H. Schwameder, E. Kornexl & C. Raschner (Eds.), *Science and Skiing* (pp. 435–469). London: E. and F.N. Spon.

Seiler, S., & Tønnessen, E. (2009). Intervals, thresholds, and long slow distance: the role of intensity and duration in endurance training. *Sportscience, 13*, 32-53.

Stöggl, T., Björklund, G., & Holmberg, H. C. (2013). Biomechanical determinants of oxygen extraction during cross-country skiing. *Scand J Med Sci Sports, 23*(1), e9-e20. doi: 10.1111/sms.12004

Stöggl, T., Lindinger, S., & Muller, E. (2006). Reliability and validity of test concepts for the cross-country skiing sprint. *Med Sci Sports Exerc, 38*(3), 586-591. doi: 10.1249/01.mss.0000190789.46685.22

Taylor, H. L., Buskirk, E., & Henschel, A. (1955). *Maximal Oxygen Intake as an Objective Measure of Cardio-Respiratory Performance* (Vol. 8).

Terzis, G., Stattin, B., & Holmberg, H. C. (2006). Upper body training and the triceps brachii muscle of elite cross country skiers. *Scand J Med Sci Sports, 16*(2), 121-126. doi: 10.1111/j.1600-0838.2005.00463.x

Van Beekvelt, M. C., Colier, W. N., Wevers, R. A., & Van Engelen, B. G. (2001). Performance of near-infrared spectroscopy in measuring local O(2) consumption and blood flow in skeletal muscle. *J Appl Physiol (1985), 90*(2), 511-519.

Volianitis, S., Krustrup, P., Dawson, E., & Secher, N. H. (2003). Arm blood flow and oxygenation on the transition from arm to combined arm and leg exercise in humans. *J Physiol, 547*(Pt 2), 641-648. doi: 10.1113/jphysiol.2002.034496