

**Seasonal Variations in Endurance Performance, and Aerobic and Anaerobic Variables in Competitive Cross Country Skiers**

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## ABSTRACT

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Cross country skiing is known as an endurance sport and both aerobic and anaerobic systems have a major impact on performance in cross country skiers. Coaches and athletes use periodized training programs to optimize physiological adaptations and increase performance. Knowing how the major aerobic and anaerobic variables change during the course of one ski season will allow better implementation of training programs. This study examined variations in endurance performance, and how that relates to the variation in different aerobic and anaerobic variables.

There were 19 subjects in the study, 11 male and 8 female. All subjects were competitive cross country skiers. The study took place over the course of one training/competitive year and was split into four different testing periods. Periods took place in May, July/August, October/November and April. The first test was a long maximal aerobic capacity test that looked at time to exhaustion (TTE), peak oxygen uptake ( $VO_{2peak}$ ), aerobic threshold ( $VO_{2AT}$ ), anaerobic threshold ( $VO_{2ANT}$ ), and submaximal economy (V1, V2). The second test was a shorter rollerski treadmill test looking at maximal anaerobic skiing speed (MASS).

There was a significant increase in TTE ( $7.4\% \pm 7.2$ ),  $VO_{2ANT}$  ( $4.8\% \pm 8.7$ ), and MASS ( $7.1\% \pm 4.1$ ) through the preparation periods 1-3 ( $p < 0.05$ ). There was a small decrease in V1 ( $-2.8\% \pm 4.7$ ) and V2 ( $-2.8\% \pm 4.2$ ) submaximal economy between periods 1-3 ( $p < 0.05$ ). There was also no significant variation in  $VO_{2peak}$  or  $VO_{2AT}$  during any periods in the study.  $VO_{2peak}$  ( $r = 0.820$ ,  $p < 0.01$ ),  $VO_{2ANT}$  ( $r = 0.795$ ,  $p < 0.01$ ), and MASS ( $r = 0.687$ ,  $p < 0.01$ ) were significantly correlated with TTE.

The major findings of the study showed that there was an increase in endurance performance during the preparation phase of training. Endurance performance was correlated with  $VO_{2peak}$ ,  $VO_{2ANT}$ , and MASS. With the significant variation in  $VO_{2ANT}$  and MASS during the year, athletes and coaches should focus on trying to increase the anaerobic threshold and neuromuscular performance using a periodized training program.

**Keywords: Cross country skiing, seasonal variation,  $VO_{2peak}$ , ANT, AT, rollerski treadmill**

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# 1 INTRODUCTION

Cross country skiing is a whole body exercise that uses a high amount of muscle mass, and thus uses a high amount of oxygen (Sandbakk et Al., 2014). Performance in endurance sports, and especially cross country skiing, is highly dependent on the ability to intake and use large volumes of oxygen (Carlsson et Al, 2014). It is not just the relative or absolute amount of oxygen that the body intakes that affects performance, but also how efficiently the body uses the oxygen (Larsson et al., 2002).

There are various indices that can be used to measure aerobic and anaerobic fitness. The most commonly used is the peak volume of oxygen uptake ( $VO_{2peak}$ ). Generally, the skier with a higher  $VO_{2peak}$  has a higher chance of succeeding versus an athlete with a lower  $VO_{2peak}$ , but this is not always the case (Larsson et al., 2002). While this is a very important aspect of endurance performance in skiing, there are also many other indices that are also important and required for performance at the highest level. Aerobic (AT) and anaerobic thresholds (ANT) are very good measures to determine the efficiencies of the aerobic and anaerobic systems. Comparing the  $VO_2$  at either threshold to athletes  $VO_{2peak}$  will give a good estimation of the overall efficiency of the cardiovascular systems. Other important determinants of endurance performance include blood lactate concentration, ventilation, respiratory exchange ratio (RER), and others.

The best way to determine aerobic and anaerobic fitness is through maximal aerobic capacity tests. In cross country skiing, the gold standard for determining fitness levels is via a roller ski treadmill test. Although there are minute differences between roller skiing on a treadmill and skiing on snow, it is the best way to ensure reliable and repeatable results (Ainegren et al., 2013).

Over the course of an entire season these values will fluctuate based on many different factors. The two main factors are training status and recovery levels (Losnegard et al., 2013). Typically the time of the year with the highest volume of training is during the summer months (general preparation), and the highest level of intensity is during the fall (specific preparation). Coaches

can use information from performance tests and use feedback from athletes to create training plans to attain the highest level of performance during the racing season (November-March).

## **2 TRAINING AND RACING IN CROSS COUNTRY SKIING**

### **2.1 Physical Demands of Cross-Country Skiing**

Cross-country skiing has been regarded as one of the most physically demanding endurance sports. It has been an event in the Olympics since the first Winter Games were held in Chamonix, France in 1924 (Essex and Chalkey, 2004). Race times in cross-country skiing can range from only a couple minutes during a sprint race, to several hours for a ski marathon (Hoffman & Clifford, 1992). Competition terrain varies greatly from course to course, but there are regulations in place to help homologate race sites. Typical homologated race courses will include about one-third uphill, one-third flat, and one-third downhill distance wise (Sandbakk and Holmberg, 2014). However, nearly 50% of the racing time is spent on the uphill sections, which is where individual performance variation is greatest (Andersson et al., 2010).

The proportion of total energy expenditure that is derived from aerobic systems is similar to that of other endurance sports with similar competition times. Typical aerobic ratio values range from 70-75% in shorter sprint races, and 85-95% across longer distances (Sandbakk and Holmberg, 2014). The remaining 25-30% in sprint races, and 5-15% of the total energy expenditure would come from the anaerobic metabolic systems.

With the focus on the aerobic systems in cross-country skiing, it should come as no surprise that maximal aerobic power and efficiency is identified as one of the main factors that predicts success in cross-country ski racing. Ainegren et al. (2013) conducted a study that compared the economy and efficiency of cross-country skiers of different ability levels. When looking at maximal aerobic power between the three groups (male recreational, male senior elite, and male junior elite) there was a significant difference in  $VO_{2peak}$  between the recreational group and both elite groups in both skate technique ( $M_{rec} = 50.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ,  $M_{sen} = 66.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ,  $M_{jun} = 64.4 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ,  $p < 0.01$ ) and classic technique ( $M_{rec} = 53.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ,  $M_{sen} = 68.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ,  $p < 0.01$ ).

$l \cdot \text{min}^{-1}$ ,  $M_{\text{jun}} = 64.2 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ,  $p < 0.01$ ). In addition to maximal aerobic power, there were significant differences in both economy and efficiency between the recreational and elite level skiers. Ainegren et al. (2013) concluded that skiing economy and gross efficiency, in addition to  $\text{VO}_{2\text{peak}}$ , as being the primary contributors to the differences in performance between recreational and elite level skiers.

Cross-country skiing is an endurance sport that also requires the repeated use of a high amount of muscle mass (Zory et al., 2011). With the introduction of sprint racing to cross-country skiing in the 1990's, there has been a focus on higher anaerobic energy output and greater force production in these shorter races. The ability for a muscle to produce force is highly correlated with the cross-sectional area of the muscle (Häkkinen & Keskinen, 1989). Because of this, body composition plays a key role in successful performances for cross-country skiers. It has been shown that higher lean body mass, especially in the upper-body, is positively related to performance (Larson & Henriksson-Larsen, 2008; Hoff et al., 2002).

There have been several studies that have investigated the body composition of cross-country skiers using a variety of methods including skin-fold calipers (Sandbakk et al., 2012), bioelectrical impedance analysis (Papadopoulou et al., 2012), and dual-emission X-ray absorptiometry (Larson & Henrikson-Larsen, 2008). A more recent study by Carlsson et al. (2014) completed on Swedish national team skiers used a body composition test (DXA) and results from the Swedish National Championships to create a correlation analysis to assess any possible relationships between lean body mass and performance. The major findings of the study showed large to very large correlations between whole body (WB), lower body (LB), and upper body (UB) lean mass and sprint prologue performances in both male (WB = -0.69, UB = -0.66, LB = -0.69,  $P < 0.05$ ) and female (WB = -0.82, UB = -0.81, LB = -0.78,  $P < 0.01$ ). Lean mass was only correlated to performance in women for the distance races (WB = -0.85, UB = -0.86, LB = -0.81,  $P < 0.01$ ). The results show the importance to focus some time and energy into developing whole body muscle mass during the training season.

A study completed by Mahood et al. (2001) demonstrates the importance of upper body strength and power. Using a 1 km UBTT (Upper Body Time Trial) using the double pole technique to

assess upper body power, and a 10 km roller ski skate time trial to assess skiing performance, the researchers were able to demonstrate a strong correlation between upper body power and skiing performance ( $r = .79$ ,  $P < 0.001$ ). A similar result was found in a study completed by Rundell and Bacharach (1995). They also used a 1 km double pole time trial using a double pole ergometer to assess upper body power, and compared it to USBA points for skiing performance. There was a very strong correlation between upper body power and performance ( $r = .95$ ,  $p < 0.05$ ).

## **2.2 Periodization in Cross-Country Skiing**

Endurance training has always been, and probably always will be the major focus for cross-country skiers training. In many research settings, training is split up into 3 different levels of intensity, low, threshold, and high/max (Sandbakk and Holmberg, 2014). This differs for many athletes and coaches outside of the research setting; opting for either 4 or 5 different levels of intensity that are used to implement a training routine. In research settings, there are one or two intensities that correspond with primarily aerobic exercise. One intensity is just below anaerobic threshold, while the other intensity zone is just above anaerobic threshold. The final intensity zone can be labeled as “max” and is uses primarily anaerobic energy systems.

Based on findings from research literature, there are four main training models that cross-country skiers use to periodize their training. High-volume, low-intensity exercise (HVT) uses low training intensities, ~65-75% of peak oxygen uptake or  $< 2 \text{ mmol}\cdot\text{L}^{-1}$  blood lactate (Seiler & Kjerland, 2006), and a prolonged duration to improve  $\text{VO}_{2\text{peak}}$  (Midgley et al., 2006). Low-volume high intensity interval training (HIIT), the opposite of HVT, uses high training intensities with lower volume to contribute to a multitude of aerobic and performance gains (Laursen & Jenkins, 2006). The threshold-training model (THR) uses training intensities that are at, or very near, the lactate threshold to increase performance, especially in untrained individuals (Londeree, 1997). Polarized training is the fourth training model and uses training intensities that are either below or well above the lactate threshold to improve athletic performance (Seiler & Kjerland, 2006). The threshold-training model may elicit the greatest positive adaptations in untrained



athletes, while the polarized-training model may be better in trained, or elite level athletes (Seiler & Kjerland, 2006.)

Stöggl and Sperlich (2014) conducted a study on 48 elite endurance athletes that compared the four different training models over the course of nine weeks. After the nine week program, testing was conducted to evaluate if there were any positive adaptations on the key variables of endurance performance. The polarized group was the only group to improve some of the variables of endurance performance ( $VO_{2peak}$ , TTE,  $V/P_{peak}$ ,  $V/P_4$ ), while HIIT improved  $VO_{2peak}$  only slightly ( $4.8 \pm 5.6\%$ ,  $P > 0.05$ ). Both the HVT and THR groups did not lead to any improvements in endurance in these well trained athletes.

Elite level cross-country skiers can reach a very high volume of training over the course of a season. Elite cross-country skiers may reach a volume of 60-90 hours of endurance training per month in the pre-season (Losnegard et al., 2011). Sandbakk and Holmberg (2014) were able to look at the training schedules of Norwegian and Swedish Sprint and Distance cross-country skiers that have won an Olympic gold medal during the past decade. The distance skiers averaged about 800-900 hrs of training per year (85% aerobic endurance training), while the sprint skiers averaged about 750-850 hrs per year (75-80% aerobic endurance training). The main differences between the distance skiers and the sprint skiers are that the sprint skiers have more anaerobic lactacid training (high blood lactate levels) and also more speed and strength sessions per week (Sandbakk and Holmberg, 2014).

While there is plenty of research on the training models and distribution of training intensity and mode in elite level cross-country skiers (Gaskill et al., 1999; Sandbakk et al., 2011; Sandbakk and Holmberg, 2014; Seiler and Kjerland, 2006), there is very little up to date information regarding the distribution of training in different parts of a full season according to the total volume, intensity, or mode.

Losnegard et al. (2013) provides a rare glimpse into a break down of the training for an elite level cross-country skier over the course of one season. 13 elite level Norwegian skiers took part in the study to look at seasonal variations in  $VO_{2peak}$ ,  $O_2$  cost,  $O_2$  deficit and performance. A

majority of the skiers time training per month was spent during low-intensity training. There was a gradual decrease in total time per month spent using low-intensity training, and a gradual increase in high intensity training time per month as the season went on. Little time was spent in middle intensity zones each month, and there was little change over the course of the season. This training distribution closely resembles the polarized training model.

### **2.3 Performance and Competition in Cross-Country Skiing**

The main goal of racers in competition is to regulate their speed in the most strategically efficient way to finish a race in the shortest time possible (Joseph et al., 2008; St. Clair Gibson et al., 2001). Pacing is a commonly used, important racing strategy in many endurance sports competitions, and is just as important in cross-country skiing.

A review by Abiss and Laursen (2008) describes several factors that influence the distribution of work and pacing during an athletic competition. The key factors include the duration and importance of the competition, course geography and conditions, and the specific activity being performed. One other key factor is the type of race situation. There are two different types of racing situations depending on starting method in cross country skiing: (i) Mass start, characterized by a head-to-head type competition with the entire field of skiers to see who crosses the finish line first, and (ii) interval start, which is characterized by an individual race against the clock to see who has the fastest time. It is in the interval start race situation, without the influences of team strategies, tactics, or the influence of other competitors, where pacing has a much bigger impact on the outcome of the event (Stickland et al., 2004).

It should be noted that although pacing is typically referred to as a measure of time or performance speed (Abiss and Laursen, 2008), this data alone is not reliable enough in cross-country skiing. Course profiles can vary greatly from course to course, and snow conditions can vary greatly on the same course even just days apart. For example the winning time for the mens 30km pursuit race at the 2014 Olympics in Sochi was 1:08:15.4 and the winning time for the same event in 2010 Olympics in Vancouver was 1:15:11.4. The information used to determine pacing strategy must be interpreted in relation to exercise intensity during the event, usually

measured by heart rate (Gilman and Wells, 1993; Gilman 1996). Through the combination of monitoring heart rate and pacing profile, important information about the physiological process behind cross-country skiing may be found (Formenti et al., 2015).

In events last greater than 2 minutes athletes tend to adopt either a varied or even pacing strategy. Under constant conditions, even pacing seems to be the optimal strategy in endurance events (Abiss and Laursen, 2008). This type of pacing can be seen in cross-country skiing when a racecourse has a fairly consistent profile without big changes in elevation throughout the entire course. More often than not elevation profiles change greatly over the length of a course. A variable pacing strategy uses fluctuating levels in exercise intensity that takes advantage of different profiles and conditions through a competition (Atkinson et al., 2007). A variable pacing strategy is more common in cross-country skiing than an even pacing strategy due to the differences in profiles and course conditions.

A study by Formenti et al. (2015) illustrates the pacing strategy of cross-country skiers. Eleven skiers competed in a simulated 10 km skating time trial divided into four laps on snow. The study concluded that heart rate remains very high for most of the event as most of the exercise was performed in HR > 90% and HR = 80-90% zones (figure 1).

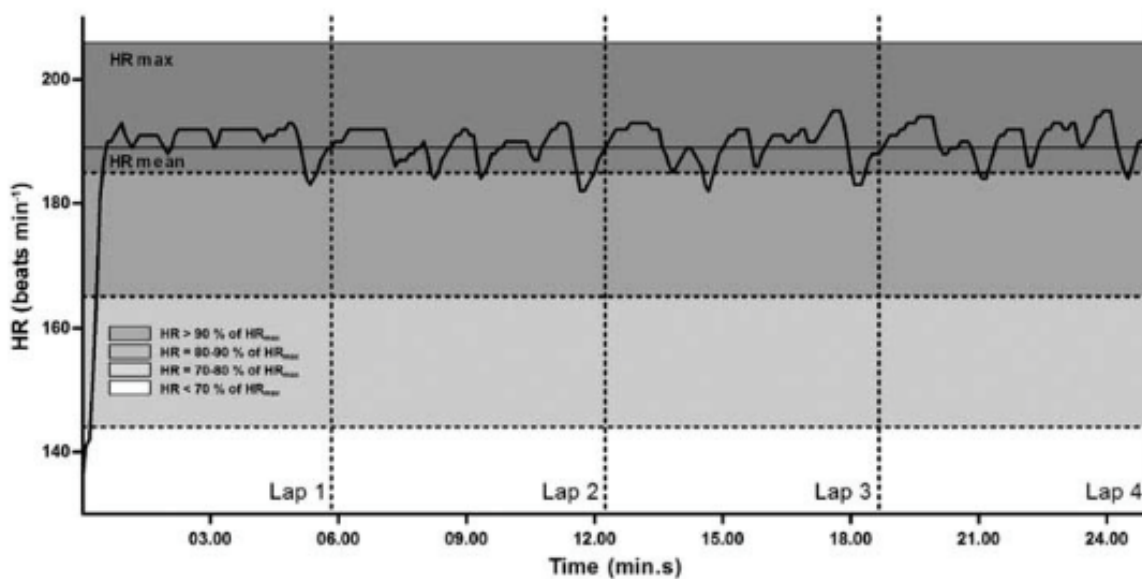


FIGURE 1. 10 km skating time trial workload using heart rate (Formenti et al., 2015)

An analysis of the pacing strategy showed that a variable pace was used. The first lap was performed at the highest speed, second and third laps showed decreased speed, while the fourth produced a final spurt in speed. With these results, it suggests that the skiers adopted a reverse J-shaped pacing strategy described by Abiss and Laursen (2008).

Sprinting events are generally much shorter (3-4 minutes) than standard distance races (+12 minutes). Sprints rely much less on the aerobic system compared to distance events as their main power source. It has been shown that while up to 95% of energy is derived from aerobic systems during distance events, only about 70-75% is derived from aerobic systems during sprint events (Sandbakk and Holmberg, 2014). While it is widely accepted that a high  $VO_{2peak}$  is crucial for performance in endurance sports, it has been shown that anaerobic capacity is also critical when it comes to sprinting performance.

A study by Losnegard et al. (2012) demonstrates that anaerobic capacity is a contributing factor to the difference between sprint cross-country skiers and more traditional distance skiers. The researchers compared the anaerobic capacity of sprint, distance, and long distance skiers using a submaximal roller ski treadmill test to estimate  $O_2$  demand and a

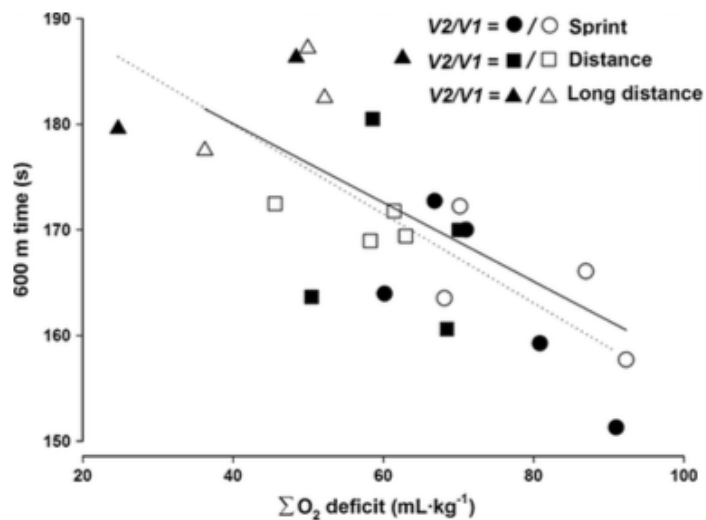


FIGURE 2.  $O_2$  deficit vs. Performance (Losnegard et al., 2012)

600m time trial to determine  $O_2$  deficit and performance. There was a significant correlation between  $O_2$  deficit and the 600 m time in both V1 and V2 techniques (V1 = -0.77, V2 = -.69,  $P < 0.05$ ). In addition to the significant correlation, the 3 slowest skiers in the 600m test, who were all elite long distance skiers, tended to have the lowest  $O_2$  deficit (figure 2). It was also true

that the three fastest skiers were categorized as typical sprint racers and also showed the highest anaerobic capacity (up to  $92 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$ ).

### **3 AEROBIC CAPACITY**

#### **3.1 Aerobic Energy System Contributions during Cross-Country Skiing**

In cross-country skiing, especially distance skiing, the aerobic energy contribution is crucial (Carlsson et al., 2014), emphasized by the relationship between performance and oxygen uptake ( $\text{VO}_2$ ) in elite cross-country skiers (Carlsson et al., 2013). The single most researched topic when it comes to cross-country skiing is oxygen uptake ( $\text{VO}_2$ ), and more specifically maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ). It has been shown many times that an extremely high  $\text{VO}_{2\text{max}}$  or  $\text{VO}_{2\text{peak}}$  is crucial when it comes to top-level performance in cross-country skiing (Carlsson et al., 2013; Hoffman and Clifford, 1992; Larsson et al., 2002).

The main energy source that is used to that is used for contracting muscles while skiing is adenosine triphosphate (ATP). ATP can be created in the muscle cells locally using both aerobic and anaerobic methods. Aerobic production of ATP, called oxidative phosphorylation, occurs in the mitochondria using three different metabolic pathways: the Krebs cycle, beta-oxidation, and the electron transport chain (Powers and Howley, 2009). While the Krebs cycle does not require oxygen to create ATP, it is a vital piece of the electron transport chain as it is the final hydrogen acceptor at the end of the electron transport chain. Oxidative phosphorylation, while requiring time and oxygen to start, creates much more ATP per molecule of glycogen. Each molecule of glycogen can create 32 ATP molecules after both the Krebs cycle and electron transport chain, with the majority of it coming out of the electron transport chain, without any byproducts that can hinder performance (McArdle et al., 2015). That pales in comparison to the amount of ATP that one molecule of triglycerol (fat) can produce. One triglycerol molecule can create up to 460 total ATP after eta-oxidation, electron transport chain, and the Krebs cycle (Powers and Howley, 2009).

Glycolysis begins the process of oxidative phosphorylation with the breakdown of a glycogen molecule. Although it is an anaerobic process, it is a necessary step in order to begin the process. One molecule of glucose goes through glycolysis to create 2 ATP molecules, and 2 pyruvate molecules. In the presence of oxygen, the pyruvate molecules can be converted into acetyl-CoA. If there is no oxygen present, the pyruvate molecules are converted into lactate molecules that can be then used later to create ATP. The ATP formed during glycolysis can be used for energy right away, while the acetyl-CoA molecules created with the oxygen molecules are used in the Krebs cycle to create the hydrogen carrier molecules NADH and FADH (Powers and Howley, 2009).

While not responsible for the creation of a large amount of ATP, the Krebs cycle does play a vital role in oxidative phosphorylation. The acetyl-CoA molecules that are created during glycolysis are used in the Krebs cycle to create the hydrogen carriers (NADH and FADH) that are responsible for rephosphorylation to create ATP in the electron transport chain. 6 NADH and 2 FADH hydrogen carrier molecules are created during the Krebs cycle that can be used during the electron transport chain (Powers and Howley, 2009).

The electron transport chain is responsible for the vast majority of glycolytic ATP production in the muscle cells. Aerobic production of ATP is possible due to the potential energy found in NADH and FADH molecules that are created in the Krebs cycle and beta-oxidation to rephosphorylate adenine diphosphate (ADP) into ATP. While oxygen is not required by the hydrogen carriers do not react directly to oxygen, it is necessary for oxygen to accept the electrons that have been passed down the chain. Without this final process, oxidative phosphorylation is not possible (Powers and Howley, 2009). The NADH and FADH that is created by glycolysis and the Krebs cycle from one glycogen molecule can create 28 ATP molecules.

Breaking down a triglycerol molecule will provide 1 glycerol molecule, which will head through the glycolytic oxidative process to create a small amount of ATP, and 3 molecules of 18-carbon fatty acid that will go through beta-oxidation. While beta-oxidation does not create much ATP similar to the Krebs cycle, it does create a bunch of NADH and FADH molecules that can be

used to rephosphorylate ADP in the electron transport chain. Each 18-carbon fatty acid molecule that completes beta-oxidation and the electron transport chain will result in 147 molecules of ATP that can now be used by the muscles for energy. By combining the 147 molecules of ATP that are created by each of the fatty acid molecules with the 19 ATP molecules created by the glycerol molecule, one triglycerol molecule will result in the production of 460 ATP molecules (McArdle et al., 2015).

## **3.2 Physiological Aspects during Aerobic Exercise**

### **3.2.1 Physiological Aspects of $VO_{2peak}$**

Glycolytic, or anaerobic reactions that produce ATP create relatively little ATP. Aerobic metabolism can provide much more ATP, but requires both oxygen, and time for the system to start working at its full capacity. The  $VO_{2peak}$  provides a quantitative measure of a person's capacity for resynthesizing ATP aerobically (McArdle et al., 2015).

In order to utilize the full capacity of  $VO_{2peak}$ , other physiologic support systems also need to perform at a high level (pulmonary ventilation, hemoglobin concentration, blood volume and cardiac output, peripheral blood flow, and cellular metabolic capacity) (McArdle et al., 2015).

As the  $VO_2$  increases due to the increased oxygen demand of the skeletal muscles during exercise, it is necessary to increase the blood flow to the muscles while decreasing blood flow to less important organs such as the liver, kidney, and GI tract (Powers and Howley, 2009). This redistribution of blood flow will help to achieve a higher  $VO_2$  as it moves oxygen rich blood to the active, working muscles.

There are three physiological mechanisms that cause increases in maximal oxygen uptake. Stroke volume causes half of the increase in  $VO_{2peak}$  that is associated with an increase in workload. The other physiological mechanism that causes an increase in  $VO_{2peak}$  is oxygen extraction in the cells. Training can help improve both stroke volume and oxygen extraction, and therefore increase  $VO_{2peak}$ . Stroke volume increases as the ventricular chambers get stronger and bigger. Oxygen extraction can be increased in two ways. Capillary density in the

muscles can be increased along with mitochondrial number in the cells. The third mechanism that affects  $\text{VO}_{2\text{peak}}$  is heart rate. While it cannot be trained, heart rate affects the cardiac output and how much blood is pumped to the muscles (Powers and Howley, 2009).

Nixon (1988) conducted a study on groups of different physical activity levels that allowed the researchers to identify the importance of these variables on determining  $\text{VO}_{2\text{peak}}$ . The three groups were mitral stenosis patients, normally active subjects, and world-class athletes. The only significant difference between the three groups was the maximal stroke volume (Mitral Stenosis = 43ml, Normal = 112ml, Athletes = 205ml,  $p < 0.05$ ), while the heart rate and a- $\text{VO}_2$  difference had no difference between the groups. Another study by Hutchinson et al. (1991) confirms the results showing that 68% of the variation in  $\text{VO}_{2\text{peak}}$  between men and women is due to left ventricular mass.

### **3.2.2 Physiological Aspects of the Aerobic Threshold**

The aerobic threshold is the level of effort at which the anaerobic energy pathways start to become a significant portion of the energy production. Increasing the aerobic threshold is important for endurance athletes as it will allow them to go faster for longer periods of time before they begin to use anaerobic means of energy production. The aerobic threshold varies between athletes and non-athletes and can be trained to be more efficient as a higher percentage of  $\text{VO}_{2\text{peak}}$ .

There is very little research into the topic of aerobic threshold as the anaerobic threshold is more important when it comes to performance. A study completed on Japanese athlete and untrained subjects demonstrated the differences between activity levels on aerobic threshold (Nemoto and Miyashita, 1980). The aerobic threshold was significantly lower in the untrained subjects versus the trained athletes (non-athletes = 51.0% of  $\text{VO}_{2\text{peak}}$ , athletes = 61.9% of  $\text{VO}_{2\text{max}}$ ). Another study completed on Japanese athletes corroborated the results of the previous study (Nemoto et al., 1988). In this study completed on national level speed skaters, the aerobic threshold was  $61.1\% \pm 7.2\%$  of  $\text{VO}_{2\text{peak}}$ . The researchers were also able to compare the differences between



traditional distance speed skaters, and traditional sprint speed skaters. The traditional distance speed skaters had a significantly higher aerobic threshold than the sprinters.

### **3.3 Seasonal Variations in Aerobic Variables**

Coaches and athletes use feedback from performance and fitness tests to create a training plan that will ideally lead to improved performance during the race season. These are long-term training plans that can last from 1 year, up to 4 years. Changes in performance and fitness influence the training plans. While there is plenty of information about the physiological indices that are used to create training plan, there is very little information about how these indices change during the months and years of cross-country ski training. This information is extremely important to understand training models, and to improve performance and time a peak during the most important competitions.

Effects of a training plan or stimulus have traditionally been evaluated by its effect on  $VO_{2peak}$  (Carlsson et al, 2013; Gaskill et al., 1999; Ingjer, 1991). There has been somewhat conflicting results regarding seasonal variation of  $VO_{2peak}$  in the literature. Ingjer (1992) has documented that there is a slight increase in running  $VO_{2peak}$  until about age 20 in elite junior cross-country skiers. After age 20,  $VO_{2peak}$  seems to plateau with little changes year over year. While Ingjer (1992) describes that there is little change in  $VO_{2peak}$  year over year, he also describes that  $VO_{2peak}$  varies during a season in elite senior cross-country skiers, and that the best skiers have the greatest variation (Ingjer, 1991).

One of the few studies that have looked at seasonal variations in cross-country skiers investigated variations in  $VO_{2peak}$ ,  $O_2$ -cost and  $O_2$ -deficit over the course of one competition season (Losnegard et al., 2013). 11 subjects were tested either 4 or 5 times over the course of one year, looking at the different parts of a season and how the training impacted the various characteristics and performance. Subjects were tested during the early preparation phase (June), middle preparation phase (August), late preparation phase (October), competition phase (January/February), and once again the following seasons early preparation phase (June). Each testing session composed of a submaximal protocol to determine  $O_2$ -cost, and a simulated 1000m

TT on a rollerski treadmill to determine peak O<sub>2</sub> uptake and performance. While the researchers were able to find significant effects for 1,000 m time (performance) and O<sub>2</sub>-cost, there was no significant difference for VO<sub>2peak</sub> in this group of cross-country skiers (Losnegard et al., 2013). These results are in direct contrast with the study completed by Ingier (1991). One possible explanation for the differing results may be due to the training completed prior to the testing session in June. Even though the athletes trained less in May than the rest of the year, they still completed more than 10 hours per week with a significant amount of middle intensity, and high intensity training (Losnegard et al, 2013). These training habits may have changed from the 1980's and 1990's when Ingier completed his study (1991). The results from this study do corroborate with another study complete on world-class road cyclists (Lucia et al., 2000). Lucia et al. (2000) also showed non-significant changes in VO<sub>2peak</sub> over the course of a season of training.

In the same study by Losnegard et al. (2013), seasonal variations in O<sub>2</sub>-cost was found to change significantly over preparation phase (June-October). While no other study has looked at seasonal variations in O<sub>2</sub>-cost in cross-country skiers, Lucia et al. (2000) also looked at O<sub>2</sub>-cost in the study on cyclists. In that study there was no significant change over the course of a season. This may be due to the much more technically demanding movements that are associated with cross-country skiing versus road cycling. Technical improvements over the course of the season are likely to affect the cost of energy and could explain some of the differences in this study.

To the best of my knowledge, there have been no studies that have looked at the seasonal variations in efficiency in cross-country skiers. Because of the difficult technical movements that are involved in cross-country skiing, it would be difficult to draw conclusions based on other endurance sports regarding the topic. Future research is required in order to gain a better understanding of what affects the fluctuations in performance during a competition season.

### 3.4 Methods to Determine Aerobic Variables

#### 3.4.1 Determining $VO_{2peak}$ in Cross-Country Skiing

There are a variety of different testing modes and methods that can be used to determine the maximal oxygen uptake in endurance sports (McArdle et al., 2015). The most standard modes of testing  $VO_{2peak}$  in endurance sports is either cycling or running. There is much evidence that exists to suggest that in order to determine a true  $VO_{2peak}$ , an athlete must use the specific movements that are used during his or her event (Powers and Howley, 2009). While running has commonly been used as a valid testing method for obtaining a  $VO_{2peak}$  in cross-country skiers (Verges et al., 2006), a more specific method for testing  $VO_{2peak}$ , that can also elicit a higher



FIGURE 3. Roller ski treadmill

$VO_{2peak}$  is by using a roller ski treadmill (Losnegard and Hallen, 2014). In the same study Losnegard and Hallen (2014), it has been shown that diagonal stride classic technique can result in a higher  $VO_{2peak}$  versus V2 skating technique (Sandbakk et al., 2014).

While there are many different protocols that can be used during a maximal aerobic capacity test, there are some similarities between tests.  $VO_{2max}$  tests usually begin with a submaximal warm-up that generally last 5-10 minutes (Powers and Howley, 2009). Key components that make up the protocols on a treadmill are stage length, speed and gradient. Stage length is the difference between a ramp protocol and a steady state, or step protocol.  $VO_{2peak}$  can be elicited during both a ramp and a step protocol, but each has their strong points. A ramp protocol can give a clearer picture of the ventilatory thresholds, while a steady state protocol will allow the researchers access to lactate thresholds due to the length of the stages and the test (Astornio et. al., 2000). Speed and grade, or workload, are also very

important. After each stage, workload can be increased by increasing the speed, gradient, or a combination of the two variables. The optimum time for a maximal  $\text{VO}_2$  test is between 8-12 minutes (Astorino et al., 2004). Choosing too high, or too low of a workload will make the test either too long or too short, decreasing  $\text{VO}_{2\text{peak}}$ .

Laboratory roller ski treadmill testing is by far the most used method to determine the  $\text{VO}_{2\text{peak}}$  in cross-country skiers (figure 3). Another method that can also be used is testing in the field. Mahood et al., (2001) conducted a study that looked used a variety of tests to look at the physiological determinants of performance in cross-country skiers. One of the tests was a maximal aerobic capacity test that was conducted in the field on roller skis. It was completed on a 3km course with the first 2km being relatively flat, and the last 1km on a steep incline (10-15%). Subjects were instructed to ski the first kilometer of the course slightly below race pace, then increase to race pace for the next kilometer. During the climb in the final kilometer, subjects were told to finish with an all out effort until volitional exhaustion. None of the subjects were able to complete the course and it was deemed a maximal effort in all cases. The criteria for finding a maximal effort and  $\text{VO}_{2\text{peak}}$  were 1.) plateau in  $\text{VO}_2$ ; 2.)  $\text{RER} > 1.10$ ; and 3.) peak lactate  $> 8 \text{ mmol}\cdot\text{L}^{-1}$ . The  $\text{VO}_{2\text{peak}}$  results that were found in this study did not differ significantly from those that were previously taken on the same subject group (Mahood et al., 2001).

There are many indications as to when to stop a  $\text{VO}_{2\text{max}}$  test and how to determine if  $\text{VO}_{2\text{peak}}$  was achieved or not. While the general indications such as obtaining or nearing age predicted HR max or respiratory exchange ratio ( $\text{RER} > 1.15$ ) (McArdle et al., 2015) provide only information on  $\text{VO}_{2\text{peak}}$ , obtaining  $\text{VO}_{2\text{max}}$  usually requires the subject to go to voluntary exhaustion to see the plateau in  $\text{VO}_2$ .

There has been much debate as to whether to measure maximal oxygen uptake relative to body mass ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) or not ( $\text{L}\cdot\text{min}^{-1}$ ). Bergh (1987) has suggested another method that takes a fraction of body weight into account when analyzing  $\text{VO}_2$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-2/3}$ ). Larsson & Henriksson-Larsen (2005) compared data from both laboratory and field tests found that the strongest correlations to performance was from measuring absolute  $\text{VO}_2$  ( $\text{L}\cdot\text{min}^{-1}$ ) meaning that

heavier cross-country skiers have an advantage over lighter skiers. However, when  $\text{VO}_2$  was expressed as  $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-2/3}$  there was a stronger correlation over steep, uphill sections. This shows that lighter skiers may have an advantage when it comes to climbing longer, steeper inclines.

### **3.4.2 Determining Submaximal Economy in Cross-Country Skiing**

In order to evaluate the capability of a skier's aerobic capacity, oxygen uptake must be measured at different submaximal and maximal intensities using different sub-techniques (Carlsson et al., 2014).

The submaximal economy of cross country skiing has been measured in the field on snow (Clifford and Hoffman, 1990; MacDougall et al., 1979) and roller skis (Hoffman et al., 1998), and also using different techniques roller skiing using different techniques on a roller skiing treadmill (Hoffman et al., 1995; Kvamme et al., 2005). Submaximal efficiency has also been measured both in laboratory settings (Aingegren et al., 2013) and in the field on snow (Niinimaa et al., 1978). Measuring efficiency on snow is much more difficult due to different characteristics in skis, conditions and it is also difficult to maintain a constant velocity.

While it has been shown that there are great differences between cross-country skiers regarding skiing economy (Losnegard et al., 2012), the explanations for the source of these inter-individual variations in skiers are not very well understood (Losnegard et al, 2014). Economy has been studied much more intensively in running and cycling and can possibly help provide some insight into the topic. Coyle et al. (1992) studied economy and efficiency in cyclists and found that there was a correlation between type I muscle fiber and cycling economy. Losnegard et al. (2012) showed that while there were large inter-individual differences in economy, there were little intra-individual differences between techniques. Subjects that were economical in one technique were generally proficient in the other as well, even though biomechanically they are very different (Sandbakk et al, 2014). This suggests that a combination of body composition and technical proficiency may be primary influencers in cross-country skiing economy.

Submaximal skiing economy is fairly simple to obtain with the correct equipment. Assessing skiing economy involves measuring oxygen consumption at a steady-state exercise during a constant workload or velocity (McArdle et al., 2015). Although there is no commonly accepted protocol to determine submaximal skiing economy, many share very similar characteristics. Ainegren et al. (2013) used a protocol that used 4-6 x 4 minute stages with an increasing workload. Workload was increased by increasing velocity, gradient, or a combination of the two. Lactate was obtained after each workload, and after the test was completed. Economy can then be analyzed at different velocities, grade, and technique.

Mechanical efficiency is largely influenced by technical proficiency in cross-country skiing and can be measured in two ways. Gross efficiency calculates the ratio between the required external mechanical power that is needed to complete a movement and the internal metabolic power that is actually created and used (McArdle et al., 2015).

$$\text{Gross efficiency (\%)} = (P_{W \text{ EXT}}/P_{W \text{ INT}}) \cdot 100$$

Delta efficiency attempts to simplify the means to calculate mechanical efficiency in human locomotion. While the concept of mechanical efficiency is quite simple, the calculations are quite complicated due to the different methods used to determine both external mechanical power, and internal metabolic power (Hoffman et al., 1995). The reasoning for the difference in opinions about gross efficiency and delta efficiency is that the baseline metabolism changes when the work rate changes and this affects the gross efficiency, but delta efficiency bypasses this using a change in power instead of total power (Cavanagh and Kram, 1985). Delta efficiency is the measure of the ratio of the change in external work rate to an associated change in energy expenditure (McArdle et al., 2015). It is assumed that for a given technique and velocity, the difference in external work rate at two grades is accounted for by the power produced to overcome gravity and rolling resistance. Oxygen uptake is converted from metabolic energy units (calories) into mechanical energy units (watts) using conversion factors based on the respiratory exchange ratio (Lusk, 1924).

$$\text{Delta efficiency (\%)} = (\Delta P_{W \text{ EXT}}/\Delta P_{W \text{ INT}}) \cdot 100$$

While both gross efficiency and delta efficiency have been used to measure efficiency in cross-country skiers, it is still up for debate as to what method is more accurate and reliable.

### **3.4.3 Determining Aerobic Threshold in Cross-Country Skiing**

Only a limited number of studies have researched the topic of aerobic threshold. Determining aerobic threshold can be done using two different methods. One way to determine the aerobic threshold is by using select respiratory gas exchange variables such as a non-linear increase in ventilation ( $V_e$ ),  $CO_2$  expired ( $VCO_2$ ), and peak  $VO_2 \cdot V_e^{-1}$  (Wasserman et al., 1973). Another method that is used less often to measure the aerobic threshold is by identifying the first change in blood lactate from resting levels.

## **3.5 Effects of Aerobic Variables on Performance**

### **3.5.1 Effects of $VO_{2peak}$ on Performance**

$VO_{2peak}$  provides a quantitative measure of an athlete's capacity for aerobic ATP resynthesis and aerobic performance (McCardle et al., 2015). Knowing that ATP is the main energy source for the muscles, this means that  $VO_{2peak}$  is an important indicator of how well a person can support intense activity for an extended period of time.

In cross-country skiing the single most heavily researched subject, and probably the most important to success in distance skiing is  $VO_{2peak}$ . Maximal oxygen consumption in elite level cross-country skiers can nearly double that of a sedentary population (Saltin and Astrand, 1967). Many studies have looked at the correlation between  $VO_{2peak}$  and performance both on snow (Formenti et al., 2009; Mahood et al., 2001) and in the laboratory (Ainegren et al., 2013; Carlsson et al., 2013; Larsson et al., 2002; Losnegard et al., 2013).

In running, races that last less than twenty minutes are run at 90% to 100% of maximal aerobic power, so the athletes that have the highest  $VO_{2peak}$  have a distinct advantage over others with a lower  $VO_{2peak}$  (Powers and Howley, 2009). In events last longer than 20 minutes, <90% of

$VO_{2peak}$  is used, which means that while a high  $VO_{2peak}$  is still vital for success, other factors such as economy and efficiency will also start to have a greater impact on the outcome of the performance (Powers and Howley, 2009). In events last greater than one hour, environmental factors begin to play a more important role as the muscle and liver glycogen stores try to keep up with the rate at which the energy substrate is being used (Powers and Howley, 2009).

Ingjer (1991) conducted one of the first studies that looked at the relationship between  $VO_{2peak}$  and performance in elite level cross-country skiers. 51 male and female Norwegian were split into 3 different groups (World-Class, medium elite, and less successful elite) based on results at world cup races over the course of 10 years (1980-1989). Subjects completed 4-6 maximal aerobic capacity tests per year while competing and the results from those tests were used for the study. There were significant differences in  $VO_{2peak}$  between the world-class skiers, and both medium and less-successful elite skiers for both men and women. This was the primary factor that explained the differences in performance between the different groups.

Another study was able to compare maximal oxygen uptake and performance in different cross-country skiers of different ability levels (Ainegren et al., 2013). Five different groups were in the study of varying ability levels ( $M_{sen}$ ,  $M_{jun}$ ,  $M_{rec}$ ,  $F_{sen}$ ,  $F_{jun}$ ). While the primary focus of the study was to investigate the differences between cross-country skiing economy and efficiency in elite and recreational skiers, it was also able to show the differences in  $VO_{2peak}$  as well. There was no difference between the two elite groups in either gender ( $M_{sen} = 66.3 \pm 3.3$ ,  $M_{jun} = 64.4 \pm 1.8$ , and  $F_{sen} = 57.0 \pm 8.5$ ,  $F_{jun} = 52.6 \pm 1.9$  ml·kg<sup>-1</sup>·min<sup>-1</sup>). However there was a sizeable, significant difference between the elite and recreational skiers  $VO_{2peak}$  ( $M_{sen} = 66.3 \pm 3.3$ ,  $M_{rec} = 50.8 \pm 4.6$  ml·kg<sup>-1</sup>·min<sup>-1</sup>,  $p < 0.001$ ). Even though there was a big difference in  $VO_{2peak}$  between groups, it was not the only contributing factor to the difference in performance. Both efficiency and economy also significantly differed between the elite and recreational groups.



### 3.5.2 Effects of other Aerobic Variables on Performance

Economy becomes more and more crucial to performance in cross-country ski races the longer the race lasts. During longer events such as ski marathons, primarily all energy comes from aerobic energy systems. At identical submaximal steady-state workloads, the endurance athlete that runs at a lower percentage of  $VO_{2peak}$  is more economical and has a higher chance to succeed during a competition (McArdle et al., 2015).

The opposite in terms of performance can be said while racing at a higher intensity either at or close to the blood lactate or anaerobic threshold. The rate of ATP generation is dependent on the actual  $VO_2$  that can be maintained during a race, which is a function of the subjects  $VO_{2peak}$  and the percent of  $VO_{2peak}$  that can be maintained (Powers and Howley, 2009). Oxygen uptake at the submaximal intensities when the blood lactate concentration reaches  $4\text{mmol}\cdot\text{L}^{-1}$  ( $VO_{2obla}$ ) is also closely related to distance cross-country skiing performance (Larsson et al., 2002; Larsson and Henriksson-Larsen, 2005). At identical percentages of  $VO_{2peak}$ , the athlete that is able to maintain a higher workload or velocity will have a greater chance to have a successful performance. This workload would have to be under the anaerobic threshold in order to be able to maintain the pace.

Although an extremely high maximal oxygen uptake is important for performance in endurance sports, and especially cross country skiing (Carlsson et al., 2013; Hoffman and Clifford, 1992; Larsson et al., 2002), it cannot be fully used during competition with the exception of very short bursts over shorter distances due to muscle fatigue (Allen et al., 2008). A group of intercollegiate skiers attained a  $VO_2$  of only 89% of their  $VO_{2peak}$  during a three minute simulated time trial. This shows that there are other physiological characteristics besides a high maximal oxygen uptake that influence performance, and that the ability for an athlete to utilize a high fraction of  $VO_{2peak}$  becomes much more important in both sprint and distance events.

Larsson et al. (2002) compared different physiological predictors of performance, including both the aerobic threshold and  $VO_{2obla}$ , using treadmill-running tests in elite male and female subjects. The researchers used a non-invasive method to indicate levels of blood lactate to determine the

aerobic threshold and  $\text{VO}_{2\text{OBLA}}$ . In this study the best predictors of performance were TDMA (threshold of decompensated metabolic acidosis) and OBLA. There was no statistical effect of the aerobic threshold on performance, though the researchers hypothesized that it was due to a rather small, homogenous population.

## **4 ANAEROBIC VARIABLES**

### **4.1 Anaerobic Energy System Contributions during Exercise**

The anaerobic energy system is becoming a more and more important aspect for performance in cross-country skiing, especially during shorter events such as sprint races. Gustin (2001) has shown that maximal exercise that lasts from 2.5-minutes in duration the distribution of anaerobic energy supply is ~73% aerobic, ~27% anaerobic in other sports. Losnegard et al. (2012) has shown that this distribution is also similar in cross-country skiing (~74% aerobic, ~26% anaerobic).

As described earlier in chapter 3.1, ATP is the main fuel source for energy in the body. During shorter, more intense bouts of exercise, the body may not be able to supply enough oxygen to meet the demand of the muscles. When the demand is too high, the body will use anaerobic metabolism mechanisms to create energy quickly without the need for oxygen. There are two main methods of anaerobic ATP production, ATP-PC system or phosphagen system, and glycolysis (Powers and Howley, 2009).

The simplest, and most rapid method of producing ATP involves donating a phosphate group from a phospho-creatine (PC) molecule to an ADP molecule to create an ATP molecule. This reaction is catalyzed by the creatine kinase enzyme (Powers and Howley, 2009). The drawback of this system is that there is only a limited amount of PC molecules that can be stored in the muscle. This limits the amount that this system can be used to create ATP to very short term uses ~10-15 seconds in duration (McArdle et al., 2015). This method of creating ATP by using PC in the muscles is not does not primarily benefit cross-country skiers performance.

Glycolysis is a second metabolic pathway that is capable of rapidly producing ATP without the use of oxygen. Glycolysis involves breaking down a molecule of glucose or glycogen to create two ATP molecules, and either two pyruvic acid, or two lactic acid molecules. While glycolysis is a necessary component in aerobic metabolism as it is the process that converts glycogen into pyruvate, which can then be used in the Krebs cycle (Powers and Howley, 2009). Oxygen is needed to interact with the hydrogen ions that are created when removed from the glycogen molecule during glycolysis. In the absence of oxygen, pyruvate can accept the hydrogen ions creating a lactic acid molecule. This recycles the NAD molecule that is required for glycolysis allowing the process to continue again. This process will result in a net gain of 2 or 3 ATP molecules depending on if glycolysis was started with a glucose molecule, or a glycogen molecule (Powers and Howley, 2009).

Creating lactic acid using anaerobic glycolysis does have its drawbacks. Lactic acid is a strong acid that has a powerful effect on other molecules due to its small size and positive charge (Powers and Howley, 2009). As the intramuscular lactic acid levels rise, performance can be impaired in at least two different ways. Firstly, an increase in the intracellular concentration of lactic acid reduces the muscles ability to produce ATP by inhibiting enzymes in both the aerobic and anaerobic mechanisms. Second, the hydrogen ions compete with the calcium ions for binding sites on troponin, inhibiting the contractile process (Powers and Howley, 2009).

The creation of lactic acid can also be used as a potential energy source. The Cori Cycle is used to recycle lactic acid back into glucose, which can then be used again in glycolysis to create ATP. Some of the excess lactate created in the muscles is transported to the liver via blood. Upon entering the liver, lactate undergoes gluconeogenesis to be converted back into glycogen. While this process will create an additional 2 ATP once the newly formed glucose molecule undergoes glycolysis, it requires 4 ATP to complete the Cori Cycle so this process cannot be used indefinitely (Powers and Howley, 2009).

## **4.2 Physiological Responses at Anaerobic Threshold**

Anaerobic threshold, lactate threshold, ventilatory threshold, and the OBLA (onset of blood lactate) are all terms that are used to describe a similar physiologic response in the body during exercise. With the different terms used to describe a similar process (anaerobic threshold, lactate threshold, ventilatory threshold, OBLA), there are different methods and processes to determine each. Anaerobic threshold is a broad term that can describe the point of a systematic rise in blood lactic acid during exercise that occurs when the exercise intensity is above the point where there is a net contribution of energy that is associated with lactate accumulation (Powers and Howley, 2009; Svedahl and MacIntosh, 2003). Lactate threshold is the exercise intensity that is associated with an increase in blood lactate during incremental exercise (Svedahl and MacIntosh, 2003). OBLA is defined as the intensity of exercise at which the blood lactate concentration reaches  $4\text{mmol}\cdot\text{L}^{-1}$  during exercise (Loat and Rhodes, 1993).

Lactate threshold is probably the term that is most commonly used in the literature to describe the anaerobic threshold process. In most cases the use of this term is deemed appropriate, although there are occasions where other terms may be deemed more accurate.

## **4.3 Seasonal Variations in Anaerobic Variables**

There is very little information on seasonal variations in anaerobic capacity. Most studies that investigate seasonal variations in endurance athletes focus on aerobic capacity as it is one of the primary indicators of performance (Ainegren et al., 2013; Carlsson et al., 2013; Larsson et al., 2002; Losnegard et al., 2013). Looking to other sports can help give insights into anaerobic variations in cross-country skiers.

A study completed on world-class level rowers has looked at seasonal variations in different fitness parameters including the ventilatory threshold (Mikulic, 2012). Using a maximal aerobic capacity test on a rowing ergometer, the researchers were able to determine variations in both  $\text{VO}_{2\text{peak}}$  and anaerobic threshold. The  $\text{VO}_{2\text{peak}}$  varied over the course of the season, which contradicts with a previous study completed on cross-country skiers (Losnegard, 2013). The power output that corresponded with the anaerobic threshold increased by 16% over the course

of the season. This increase in power output also corresponded to a 7% increase in percentage of  $\text{VO}_{2\text{peak}}$  at anaerobic threshold.

The study completed by Losnegard et al. (2013) that looked at seasonal variations in  $\text{VO}_{2\text{peak}}$  in cross-country skiers also looked at seasonal variations in  $\text{O}_2$  deficit. Using the  $\text{O}_2$ -deficit method described chapter 4.4.1, the researchers were able to determine seasonal variations in anaerobic capacity. Like the study completed on rowers (Mikulic, 2012), there was a significant increase in anaerobic capacity ( $24.9 \pm 19.5\%$ ,  $p < 0.05$ ) over the course of the season. The researchers hypothesized that the mechanisms behind the change in  $\text{O}_2$  deficit was due to the type of training the athletes did throughout the season, and the physiological demand during races that requires a high level of anaerobic capacity (Losnegard et al., 2012).

## **4.4 Methods to Determine Anaerobic Variables**

### **4.4.1 Determining Anaerobic Capacity in Cross-Country Skiing**

Assessing anaerobic energy release during exercise is much more difficult and less precise than assessing aerobic energy release that is measured by oxygen uptake. There has been much debate regarding the reliability and validity of estimating anaerobic capacity using the  $\text{O}_2$  deficit method (Gastin, 2001). Because there is no direct way to measure  $\text{O}_2$  demand, the best method seems to be using the  $\text{O}_2$  deficit method as an indirect determination of anaerobic energy usage. Anaerobic capacity ( $\text{O}_2$  Deficit) can be estimated by extrapolating the individual linear relationship between work rate and submaximal steady state  $\text{O}_2$  cost ( $\text{O}_2$  Demand) and subtracting the actual  $\text{O}_2$  uptake measured using a metabolic gas analyzer (Medbø et. al., 1988).

$$\text{Anaerobic Capacity (O}_2 \text{ Deficit)} = \text{O}_2 \text{ Demand} - \text{O}_2 \text{ Uptake}$$

The first step to determining anaerobic capacity is to get baseline readings for submaximal oxygen uptake. This can be done in multiple ways via the use of different protocols. Losnegard et al. (2012) used a submaximal protocol that had subjects complete 3 stages at different steady state submaximal workloads. The data from the submaximal tests can then be used to create a regression equation to determine a ratio between work rate and  $\text{O}_2$  cost.

The second step to determine anaerobic capacity is to complete a max test. This test can be of any length, but since more anaerobic energy systems are used in shorter events (Gastin, 2001) tests that are in shorter duration similar to the length of a sprint time trial will be more beneficial. Accumulated O<sub>2</sub> demand is estimated by extrapolating the individual linear relationship between the work rate (W) and steady-state O<sub>2</sub> cost from the submaximal treadmill tests. In order to complete these calculations it is assumed that the individualized ratio of O<sub>2</sub> cost per watt is constant with increasing speed.

#### **4.4.2 Determining the Anaerobic Threshold in Cross-Country Skiing**

Anaerobic threshold is a broad term that can describe the point of a systematic rise in blood lactic acid during exercise that occurs when the exercise intensity is above the point where there is a net contribution of energy that is associated with lactate accumulation (Powers and Howley, 2009; Svedahl and MacIntosh, 2003). This can be demonstrated with different methods using either information from the blood lactate concentration values (lactate threshold and OBLA), or information from ventilatory gases (ventilatory threshold).

The lactate threshold is the most commonly used term in the literature to describe the effects of the anaerobic threshold. There are many different methods that can be used to determine the lactate threshold. Most methods can give individualized points for the anaerobic threshold, while others give a fixed point for all subjects. While all of these techniques can detect an intensity of exercise that is close to the anaerobic threshold, there is individual variability in results when each is compared with each other (Svedahl and MacIntosh, 2003). One method to determine the anaerobic threshold involves specifying a fixed amount (i.e. +1mmol·L<sup>-1</sup>) of blood lactate above <sup>resting</sup> levels. This method is nice for bigger studies that want a simple way to determine an individualized lactate threshold (Powers and Howley, 2009). Another method involves using the blood lactate curve to draw a line tangent to the curve to produce an individualized anaerobic threshold (Svendahl and MacIntosh, 2003).

Onset of blood lactate accumulation is defined as the intensity of exercise at which blood lactate reaches  $4 \text{ mmol}\cdot\text{L}^{-1}$  during incremental exercise (Sjödín et al., 1981). This method assumes that the anaerobic threshold happens concurrently at an absolute blood lactate concentration of  $4 \text{ mmol}\cdot\text{L}^{-1}$ . One reason for selecting  $4 \text{ mmol}\cdot\text{L}^{-1}$  as the concentration that coincides with the anaerobic threshold is that blood lactate and muscle lactate are related at  $4 \text{ mmol}\cdot\text{L}^{-1}$ . This is not the case at both higher and lower concentrations (Jacobs and Kaiser, 1982). The transport of lactate out of the muscle reaches a peak rate as the lactate reaches  $4\text{-}5 \text{ mmol}\cdot\text{L}^{-1}$  (Jorfeldt et al., 1978). While this method does provide a very objective method to assess the lactate threshold, it is not sensitive to the wide degree of variability between individuals.

Ventilatory threshold can be defined as the exercise intensity where the increase in ventilation ( $V_e$ ) becomes disproportional to mechanical power output during incremental exercise (Svendahl and MacIntosh, 2003). The ventilatory threshold can sometimes be mistaken for the lactate threshold, but as only ventilatory gases are measured and used, the use of the term lactate threshold is incorrect. Many various techniques have been reported to detect the anaerobic threshold using ventilatory gases. One technique uses nonlinear increases in ventilation ( $V_e$ ) and carbon dioxide output ( $V\text{CO}_2$ ). Another technique uses an increase in the respiratory exchange ratio (RER). There are two main issues that arise when using these methods. The first is that it is difficult to discern a clear breakpoint in ventilation, and because of this interpretation of the data is not completely objective and results can vary depending on the researcher (Powers et al., 1984). The second issue that can occur while measuring the ventilatory threshold is that several physiological parameters can affect the increase in ventilation during exercise. Because of this, the detected increase in ventilation cannot be solely contributed to the buffering of lactic acid (Powers et al., 1984).

Incremental exercise is required to determine the anaerobic threshold in athletes. These incremental tests must have stages that are 3-4 minutes in duration in order to achieve steady state exercise. The mode of test can vary from running to cycling to skiing and many others. It is suggested for the test to be as sport specific as possible (Powers and Howley, 2009).

The  $D_{\max}$  method can be used to help create more accurate, objective criteria for obtaining the lactate threshold. The  $D_{\max}$  method involves calculating the point that yields the maximal perpendicular distance to the straight line formed by the 2 end data points of the lactate vs workload curve (figure 4) (Fabre et al., 2010). Fabre et al. (2010) demonstrated that a modified  $D_{\max}$  method is reliable in cross-country skiers. The modified  $D_{\max}$  method uses the same final lactate point as one of the two points and the other is the point preceding an increase of lactate concentration greater than  $0.4 \text{ mmol}\cdot\text{L}^{-1}$ . Using three different methods of determining the ventilatory threshold ( $D_{\max}$ ,  $D_{\max \text{ mod}}$ , and OBLA), the  $D_{\max \text{ mod}}$  method seemed to be the most reliable method to determine the lactate threshold in cross-country skiers.

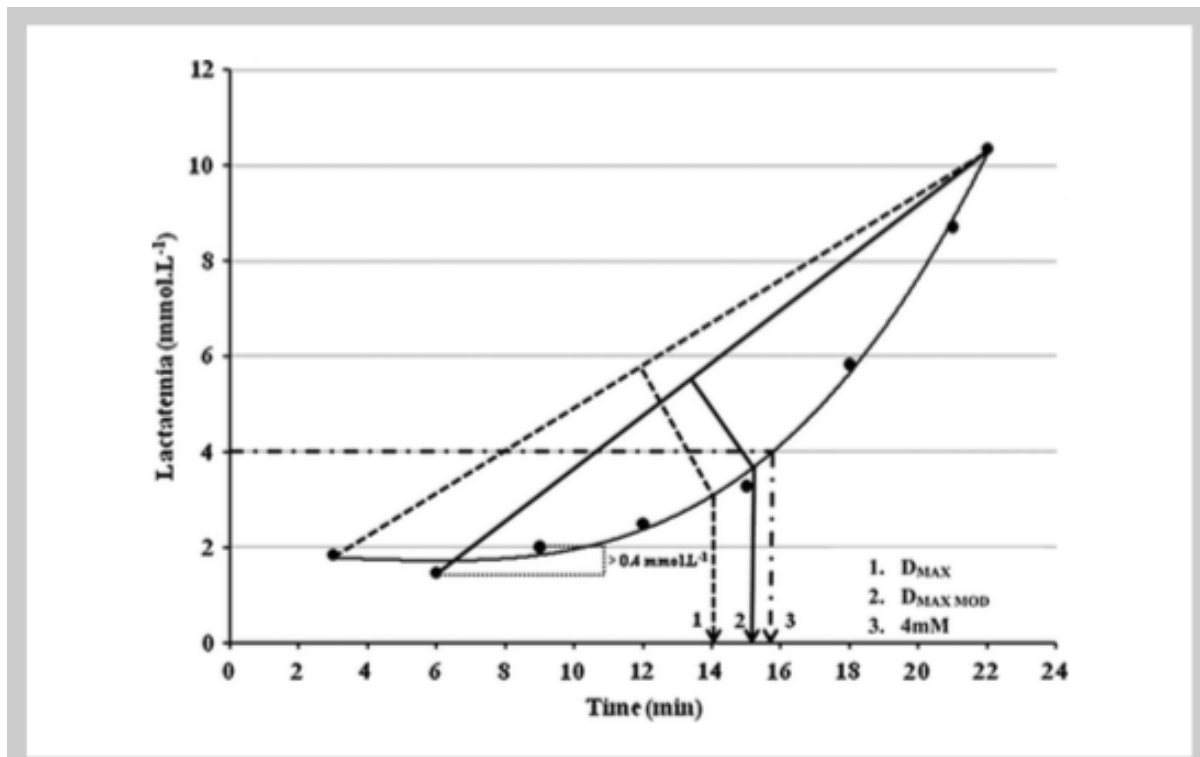


FIGURE 4. Determining the anaerobic threshold using the Dmax method. (Fabre et al., 2010)

#### 4.5 Effects of the Anaerobic Capacity on Performance

Since the introduction of sprint competitions in cross-country skiing, anaerobic capacity has had a made a bigger impact in performance. The average time to complete a sprint competition can range from between 2.5 minutes up to 4 minutes. It has been shown in many studies using running and cycling tests of similar duration that the distribution of aerobic versus anaerobic



energy supply is ~70% aerobic, ~30% anaerobic (Gastin, 2001). In longer races the distribution begins to use less of the anaerobic mechanisms and more of the aerobic mechanisms to fuel energy. Distance races of 10km or longer may only use 5-15% anaerobic energy (Sandbakk and Holmberg, 2014). Even though the distribution of anaerobic energy is low, it is used in the most important parts of the races where most of the time is spent (uphills) and also in the final part of the race as the speed increases and the sprint to the finish begins (Losnegard et al., 2012).

Losnegard et al. (2012) completed a study that investigated the connection between anaerobic capacity and performance in cross-country sprint skiing. 12 elite level Norwegian male cross-country skiers completed both a submaximal and maximal roller ski treadmill tests to determine anaerobic capacity using the O<sub>2</sub> deficit method described previously in chapter 4.4.1, and also a 600 meter roller ski treadmill time trial on a treadmill to determine sprint performance. O<sub>2</sub> deficit was the primary contributor to explain the differences in time trial times between individuals. Although all the subjects were categorized as elite level skiers, they had different specialties between sprinting, distance, and marathon racing. The three slowest skiers in the 600 meter time trial were categorized as elite marathon skiers also had the lowest levels of anaerobic capacity. The same could be said for the fastest 4 skiers who were all categorized as sprinters based on their racing history and had the highest levels of anaerobic capacity.

In the same study by Losnegard et al. (2012), the researchers were also able to look at the impact that the differences between V1 and V2 skate technique had on anaerobic capacity and sprint performance. There was no differences between techniques on either sprint time trial time, O<sub>2</sub> deficit, O<sub>2</sub> demand, or O<sub>2</sub> uptake. These results indicate that the optimal technique for a certain speed/gradient may be different between individuals based on ability level and specialization.

#### **4.6 Effects of the Anaerobic Threshold on Performance**

While many studies have only looked at the connection between maximal aerobic capacity and performance, there are other physiological determinants that are also important for performance. Formenti et al. (2015) demonstrated that in a 10km time trial that the exercise intensity lays between 85% and 95% of maximum. This suggests that the transition between aerobic and

anaerobic energy systems (anaerobic threshold) at higher intensities is also important in addition to a high  $\text{VO}_{2\text{peak}}$ .

Larsson et al. (2002) used treadmill running tests on 16 elite male and female junior cross-country skiers to determine physiological predictors of performance. Performance was calculated from results during the previous four competitions that took place immediately before testing. The researchers were able to find that the best predictors of performance were TDMA (threshold of decompensated metabolic acidosis) and OBLA (onset of blood lactate accumulation). Although this study was completed on a running treadmill, there is a high correlation between running and skiing in cross-country skiers (Gaston et al., 2002). Even so, it is still recommended to test as specific as possible to obtain the most valid and reliable results possible (Powers and Howley, 2009).

Oxygen uptake at the submaximal intensity that is associated with OBLA has also been shown to be related to performance in cross-country skiing (Larsson et al., 2002; Larsson and Henriksson-Larsen, 2005). Ten elite male Swedish cross-country skiers completed roller skiing treadmill tests at different intensities and techniques to help predict performance in sprint racing (Carlsson et al., 2014). Performance was determined using a 1.25 km sprint qualification time trial and also by using FIS (International Ski Federation) sprint points to rank skiers. There was a high correlation between both  $\text{VO}_{2\text{peak}}$  ( $R = 0.86$ ,  $P = 0.0069$ ) and  $\text{VO}_{2\text{obla}}$  ( $R = 0.79$ ,  $P = 0.021$ ) with performance from the sprint qualification time trial. Using statistical modeling based on the results,  $\text{VO}_{2\text{obla}}$  was able to explain 61% of the variance in race speed during the time trial. These results indicate that it is very important for elite level cross-country skiers to have a high oxygen uptake when OBLA occurs.

## 5 PURPOSE OF THE STUDY

The purpose of the study was to examine the variations in various aerobic and anaerobic characteristics in competitive cross-country skiers through four different training periods over the course of one ski season.

The research problems and hypothesis are as follows:

1) How much does maximum oxygen uptake vary over the course of a ski season in competitive cross country skiers?

- There will be no change in maximum oxygen uptake over the course of one ski season.

Previous literature has shown that there is very little fluctuation in maximal oxygen uptake from year to year in athletes ages 20 and up (Ingier, 1992). In a small study that looked at seasonal changes in cross-country skiers, they also showed no significant differences in maximal oxygen uptake (Losnegard, 2013).

2) How much does the aerobic threshold vary over the course of a ski season in competitive cross country skiers?

- There will not be a significant difference in aerobic threshold in relation to O<sub>2</sub> consumption, but will differ significantly in relation to threshold speed over the course of one ski season.

There have been no previous literature on the topic of seasonal variations of aerobic threshold in athletes of any type. Losnegard (2013) looked at variations in O<sub>2</sub>-cost and there was a significant difference in O<sub>2</sub> cost. While there were no significant differences at higher intensities, as evidenced by no changes in maximal oxygen uptake, there were significant differences at lower intensities. With the aerobic threshold occurring at lower intensities, it is hypothesized that there will also be a significant difference in aerobic threshold.

3) How much does submaximal economy vary over the course of a ski season in competitive cross country skiers?

- There will be a significant difference in submaximal economy over the course of one ski season.

Similar to seasonal variations in aerobic capacity, there will be a difference in submaximal economy. Submaximal economy will lower significantly over the course of a season due to an increase in skiing efficiency as training becomes more significant.

- 4) How much does anaerobic threshold variate over the course of a ski season in competitive cross country skiers?
  - There will be a significant difference in anaerobic threshold of the course of one ski season.

There has been little research on seasonal variation in anaerobic capacity. One study completed on world-class level rowers has shown there to be significant increase in power output at anaerobic threshold (Mikulic, 2012). While rowing is not directly linked with cross country skiing, with it being an endurance sport some comparisons can be made between the two. Because of this, it is hypothesized that there will be a significant increase in skiing speed at the anaerobic threshold.

- 5) How do aerobic and anaerobic characteristics affect performance over the course of a ski season in competitive cross country skiers?
  - There will be a positive correlation between the aerobic and anaerobic thresholds as well as submaximal economy in relation to performance.

Losnegard (2013) has shown that there is a decrease in  $O_2$ -cost over the course of a season in cross country skiers and that this decrease was due to an increase in efficiency. Mikulic (2012) demonstrated that there is an increase in power in relation to the anaerobic threshold in world class rowers over the course of a season. Both anaerobic threshold and aerobic threshold have been shown to be linked with performance (Formenti et al., 2015, Larsson et al., 2002,

- 6) How does maximal anaerobic skiing speed variate over the course of a ski season in competitive cross country skiers?
  - There will be a significant increase in the speed related to maximal anaerobic skiing.

To the best of my knowledge this is the first study that has investigated seasonal variations in maximal anaerobic skiing speed. With increases in efficiency and as training becomes more and more specific through a season the maximal anaerobic skiing speed will increase.

## 6 METHODS

### 6.1 Subjects

The subjects were both male and female competitive cross country skiers. The males were 18-29 years old (Mean =  $23 \pm 3$  years) and the females were 18-31 years old (Mean =  $23 \pm 4$  years) (table 1). At the beginning of the study there was 12 males and 13 females involved in the study. Due to illness/scheduling conflicts, only 12 males and 8 females fully completed all four test periods. Only subjects involved in all testing periods were included in the results.

Prior to the study all the subjects were informed of the experimental design and the possible risks and rewards involved in the study. Every subject was required to provide written consent prior to the beginning of the study, and fill out a health questionnaire before each test period.

**Table 1 - Subject anthropometric data**

	Male (n=11)	Female (n=8)
Age (yrs)	23 ( $\pm 3$ )	23 ( $\pm 4$ )
Height (cm)	183.1 ( $\pm 5.2$ )	167.6 ( $\pm 3.9$ )
Body Mass (kg)	74.8 ( $\pm 7.0$ )	58.7 ( $\pm 4.9$ )

### 6.2 Experimental Design

The yearlong study began in May of 2015, and went through the end of April 2016. The study was broken up into four test periods with three that were spaced evenly through the preparation period (May-October), and one more test period located at the end of the competition season in April. Athletes were tested once during each of the test periods, for a total of four test sessions per athlete.

In each test session an identical protocol was used for each athlete. The athlete arrived at the test facility at 8:00 AM for blood tests and a strength test that were for a different part of the present study. Athletes were finished with the strength testing session by 10:30 and had at least 3 hours in between the strength session and the endurance session. It was decided that there was not any

interference between the strength and endurance test sessions from data gathered during pilot testing. There were two tests completed during the endurance test session, one long test on a roller ski treadmill to look at both aerobic and anaerobic variables, and one short test on a roller ski treadmill to look at maximum anaerobic skiing speed.

*Period 1.* The first period began in May of 2015. This period coincides with the early parts of the preparation phase. The focus of training during this period was on increasing maximal strength, aerobic capacity, and increasing anatomical adaptations.

*Period 2.* The second period took place between late July and early August 2015. This period takes place in the middle of the preparation phase. The focus of training during this period was on increasing maximal strength and endurance, aerobic endurance, and beginning to develop the anaerobic capacity.

*Period 3.* The third period of the study started in October of 2015. This period takes place at the very end of the preparation phase as the athletes are beginning to transition to the competition phase. The focus on this period for training is on increasing anaerobic capacity, anaerobic endurance and performance. Athletes are beginning to transition from increasing muscular strength and endurance to maintaining muscular strength and endurance.

*Period 4.* The fourth period of the study occurred during April of 2016. This period takes place at the end of the competition period during the transition phase. There is no focus on training during this phase as the athletes are using the time off to recover for the next training cycle.

### **6.3 Measurements**

Subjects reported to the laboratory at the same time each day through each of the four test periods ( $\pm 2$  hours) and used the same roller skis, boots, and poles for each test. Each session consisted of both a long for measuring aerobic and anaerobic variables, and a short roller ski treadmill test for measuring maximal anaerobic skiing speed. Total time for each session including warm-up and cool-down was 1 hour and 30 minutes.

*Long Treadmill Test.* Before the test, subjects warmed up using a set protocol that let the athlete get used to variable speeds and techniques on the roller ski treadmill (figure 5 & 6). The skate technique was to be used throughout the duration of the long test, with both V1 and V2 subtechniques used at different speeds. Technique would be switched from V1 to V2 skate when the subject hit the 11.0 km/h stage. The athletes were asked to use V1 technique during the 4 slower stages, and V2 technique during the 10 km/h and 11km/h stages to get the feeling of the treadmill and different technique. There was approximately 5 minutes of passive rest between the warm-up and the start of the long treadmill test for the researchers to get the metabolic analyzer set-up for the subject. Assessments for the long treadmill tests included steady-state oxygen uptake, heart rate, and blood lactate concentration. The entire long test used a gradient of 5.2%. For the male subjects the test started at 6.6 km/h, and for the female subjects the test started at 5.0 km/h. The speed increased by 1.5 km/h every stage. Each stage lasted 3 minutes, and at the end of each stage the treadmill was stopped for 30 seconds to obtain lactate measurements. Subjects were motivated by the researchers to stay on the treadmill until complete exhaustion. Lactate samples were also taken immediately after the test, post 3 minutes recovery [passive], and post 9 minutes recovery [4 minutes passive + 5 minutes active]. The 5 minutes of active recovery post test was at 6.6 km/h for males, and 5.0 km/h for females.

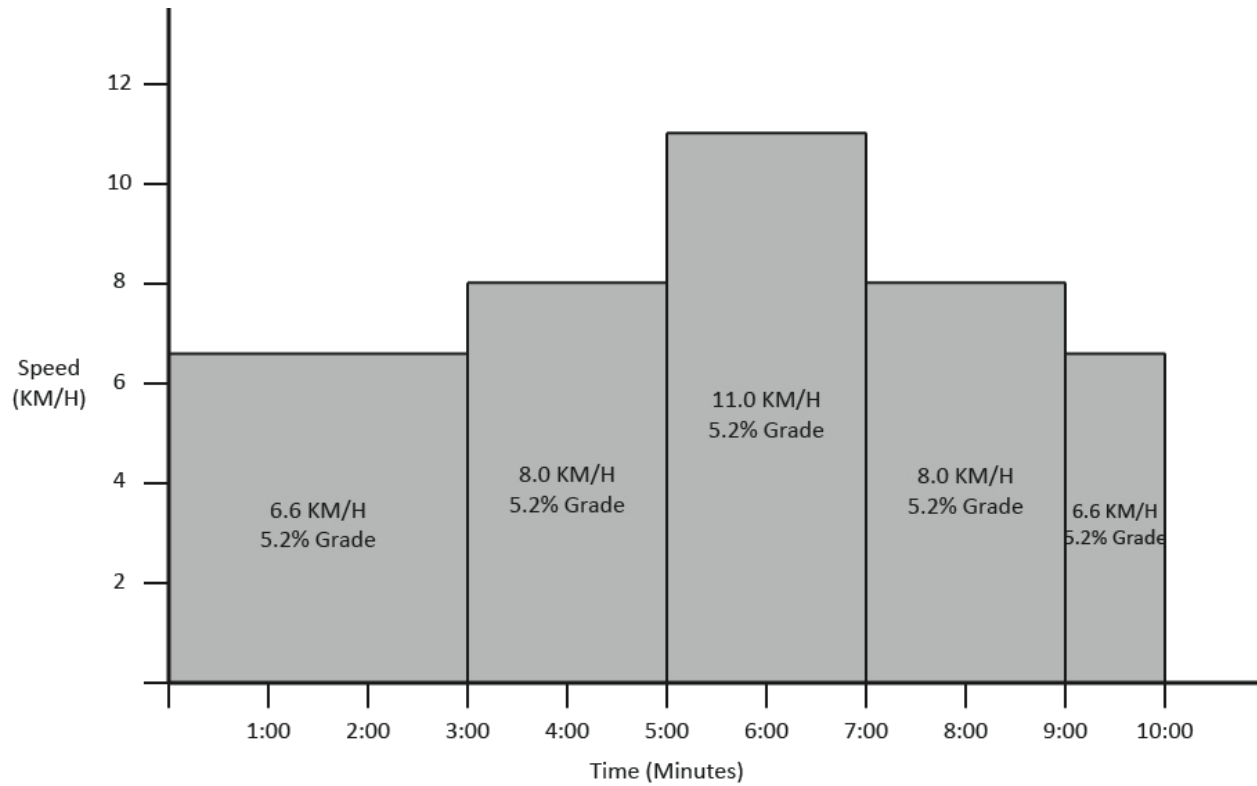


FIGURE 5. Long Test Male Warm-up Protocol

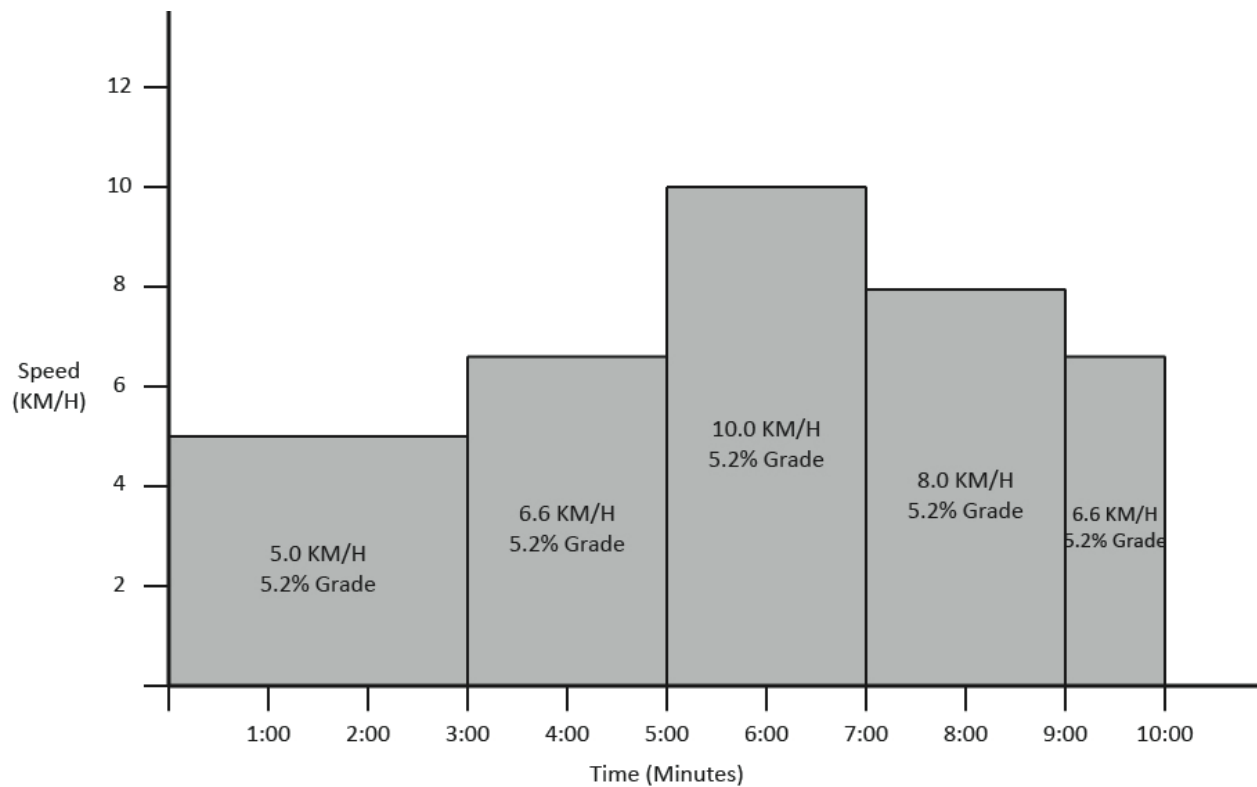


FIGURE 6. Long Test Female Warm-up Protocol



*Maximal Anaerobic Skiing Speed Test.* Immediately after the active recovery from the long treadmill test, subjects were given 6 minutes of passive rest to change equipment and rehydrate if necessary. The maximal anaerobic skiing speed test used the double pole technique and the gradient would be at 3.5% for the entire test. Assessments for the maximal anaerobic skiing speed test included skiing speed and blood lactate concentration. They used the same boots and roller skis that were used during the long treadmill test, switching to shorter poles in a height similar to their classic poles. A short 5 minute warm-up was used for the athletes to get used to the double pole technique on the treadmill and to get acquainted with the starting speed of the test. There was 2 minutes in between the warm-up for the maximal anaerobic skiing speed test and the start of the test to explain the instructions to the subject and to obtain a lactate sample. The subject skied started at 14 km/h for males and 10 km/h for females 30 seconds prior to the test to ensure the treadmill could get to the correct speed quickly. After the 30 second pre-stage, the test started at 18 km/h for males and 14 km/h for females. The speed increased by 1 km/h every 15 seconds until exhaustion. Lactate samples were taken immediately after the completion of the test and also 3 minutes post-test.

*Equipment.* Oxygen consumption was measured using a portable automatic ergospirometry system using 20 second averages for recording (Oxycon Mobile; Jaeger Instrument, Hoechberg, Germany), which had been verified by Overstreet et al. (2016). Heart rate was measured with a Polar RS800CX monitor (Polar Electro Oy, Kempele, Finland). Blood lactate concentration was measured in non-hemolyzed blood, using capillary fingertip samples (Biosen C-Line, EKF Diagnostics, Penarth, United Kingdom). The blood lactate analyzer and Oxycon Mobile analyzer were calibrated according to instruction manuals. All testing was conducted on a roller ski treadmill (Rodby RL3500E, Rodby Innovation AB, Vänge, Sweden). Roller skis used during the treadmill tests were homologated prior to study and subjects used the same roller skis through the entirety of the project (Marwe 610, Marwe Roller Skis, Finland).

*Calculations of the Aerobic Threshold.* Aerobic threshold was calculated using the blood lactate concentration measurements taken during the long treadmill test. The stage of which the aerobic threshold occurred was during between the stages where the first change greater than 0.30 mmol·L<sup>-1</sup> over the lowest blood lactate concentration. VO<sub>2</sub> at aerobic threshold was determined

to be the average of  $VO_2$  for the stage prior to and the stage where the blood lactate change occurred.

*Calculations of the Anaerobic Threshold.* Anaerobic threshold was also calculated using the blood lactate concentration measurements taken during the long treadmill test. The determination of anaerobic threshold was determined to be the second non-linear rise in blood lactate concentration.  $VO_2$  at anaerobic threshold was determined to be the average of  $VO_2$  for the stage prior to and the stage where the blood lactate change occurred.

*Calculations of  $VO_{2peak}$ , and submaximal economy.* Oxygen uptake was measured continuously through the long test (20 second period averages).  $VO_{2peak}$  was calculated as the highest 1-minute average of oxygen uptake. V1 submaximal economy was measured as the last minute of the 8.0 km/hr stage for both men and women. V2 submaximal economy was measured as the last minute of the 12.6 km/hr stage for both men and women.

*Calculations of Peak Lactate.* Peak lactate was determined to be the highest lactate value recorded during the long treadmill test, including the post 3 minute passive recovery lactate measurement.

## **6.4 Statistical Analysis**

The data for the study was analyzed using IBM SPSS Statistics v.22. All data was checked for normality using a Shapiro-Wilk test and presented as mean and SD. Determining statistical significance was determined using the p-value of  $\leq 0.05$  and  $\leq 0.01$ . The changes in both submaximal and maximal values over the project was analyzed using a 1-way analysis of variance for repeated measurements (1-way ANOVA) followed by the Tukey post-hoc test. Pearson's correlation analysis was used for correlations. The criteria for measuring correlations between the measures were:  $< 0.1$ , trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; 0.9-1.0, near perfect.

Changes for substantial effects within subject were verified for smallest worthwhile change (SWC) for TTE,  $VO_{2peak}$ ,  $VO_{2AT}$ ,  $VO_{2ANT}$ , and MASS. The smallest worthwhile change was calculated to be at least 0.3 times change in mean over between subject SD ( $\Delta mean/SD$ ) of the first period as described by Hopkins (2011).

## **7 RESULTS**

### **7.1 Seasonal Variations of Aerobic and Anaerobic Variables**

1-way analysis of variation for repeated measurements was used on all submaximal and maximal variables. Mean values and SD for all variables during each period are presented in table 2 for each gender. Significant variation between periods were presented with a p-value of  $< 0.05$ .

**Table 2 - Seasonal variations of aerobic and anaerobic variables for male and female groups**

	<b>Period</b>	<b>P<sub>1</sub></b>	<b>P<sub>2</sub></b>	<b>P<sub>3</sub></b>	<b>P<sub>4</sub></b>
<b>Male (n = 11)</b>	VO <sub>2peak</sub> (ml/kg/min)	64.2 ± 5.7	64.2 ± 5.2	64.5 ± 4.8	62.8 ± 6.3
	TTE (min)	0:28:49 ± 0:03:09	0:30:09 ± 0:02:18 <sup>P1</sup>	0:30:37 ± 0:02:42 <sup>P1</sup>	0:28:43 ± 0:02:53 <sup>P3</sup>
	VO <sub>2AT</sub> (ml/kg/min)	38.9 ± 2.0	40.9 ± 4.4	39.3 ± 4.3	40.2 ± 3.3
	VO <sub>2ANT</sub> (ml/kg/min)	52.9 ± 4.7	56.1 ± 3.5 <sup>P2</sup>	55.3 ± 4.3	53.7 ± 4.6
	%VO <sub>2AT</sub>	61.0 ± 5.2	63.8 ± 5.1	61.0 ± 5.8	64.2 ± 5.4
	%VO <sub>2ANT</sub>	82.6 ± 6.6	87.5 ± 4.8 <sup>P1</sup>	85.8 ± 4.4	85.7 ± 4.6 <sup>P2</sup>
	V1 SME (ml/kg/min)	32.8 ± 2.0	32.5 ± 2.3	32.1 ± 2.2	32.0 ± 2.0
	V2 SME (ml/kg/min)	47.5 ± 2.6	47.1 ± 2.9	46.9 ± 2.4	46.6 ± 2.4
	MASS (km/h)	23.8 ± 0.9	24.5 ± 1.4	25.4 ± 1.3 <sup>P1, P2</sup>	24.9 ± 1.3 <sup>P1</sup>
	La <sub>Peak</sub> (mMol)	12.3 ± 2.1	12.2 ± 1.8	13.4 ± 1.8 <sup>P2</sup>	12.0 ± 2.8
	HR <sub>peak</sub> (bpm)	194.2 ± 8.4	195.1 ± 7.7	196.5 ± 7.7 <sup>P1</sup>	195.4 ± 7.5
	<b>Period</b>	<b>P<sub>1</sub></b>	<b>P<sub>2</sub></b>	<b>P<sub>3</sub></b>	<b>P<sub>4</sub></b>
<b>Female (n = 8)</b>	VO <sub>2peak</sub> (ml/kg/min)	54.6 ± 4.5	53.6 ± 5.2	54.3 ± 5.3	53.7 ± 4.6
	TTE (min)	0:25:26 ± 0:03:01	0:26:05 ± 0:03:11	0:27:23 ± 0:02:51 <sup>P1, P2</sup>	0:26:16 ± 0:02:48
	VO <sub>2AT</sub> (ml/kg/min)	36.6 ± 3.6	36.4 ± 2.7	35.1 ± 2.6 <sup>P2</sup>	35.4 ± 4.2
	VO <sub>2ANT</sub> (ml/kg/min)	45.2 ± 4.7	46.4 ± 5.0	47.0 ± 5.3	47.5 ± 4.6
	%VO <sub>2AT</sub>	67.1 ± 6.7	68.3 ± 5.1	64.9 ± 4.9 <sup>P2</sup>	66.0 ± 6.8
	%VO <sub>2ANT</sub>	82.8 ± 6.7	86.6 ± 5.1	86.4 ± 2.0	88.5 ± 4.0
	V1 SME (ml/kg/min)	33.4 ± 1.3	32.9 ± 1.7	32.1 ± 1.5 <sup>P1</sup>	32.0 ± 1.5
	V2 SME (ml/kg/min)	47.4 ± 0.9	46.0 ± 1.9 <sup>P1</sup>	45.2 ± 3.0 <sup>P1</sup>	46.0 ± 2.2
	MASS (km/h)	18.5 ± 1.9	19.5 ± 2.0 <sup>P1</sup>	19.9 ± 1.9 <sup>P1</sup>	19.9 ± 1.9 <sup>P1</sup>
	La <sub>Peak</sub> (mMol)	10.8 ± 3.2	12.1 ± 2.2	12.5 ± 1.9	10.6 ± 2.6
	HR <sub>peak</sub> (bpm)	195.1 ± 7.7	197.5 ± 8.1 <sup>P1</sup>	195.6 ± 7.4	196.3 ± 8.5

Seasonal variation of aerobic and anaerobic variables. VO<sub>2</sub> = oxygen uptake; AT = aerobic threshold; ANT = anaerobic threshold; SME = submaximal economy; MASS = maximal anaerobic skiing speed; La = blood lactate concentration; HR = heart rate. P1 = significantly different from period 1; P2 = significantly different from period 2; P3 = significantly different from period 3; p < 0.05.

Mean relative percentage change values between periods 1-2, 2-3, 3-4, 1-3, and 1-4 for VO<sub>2peak</sub>, TTE, VO<sub>2AT</sub>, VO<sub>2ANT</sub>, %VO<sub>2AT</sub>, %VO<sub>2ANT</sub>, and MASS were also presented (table 3). P-value was set at p < 0.05 (\*) and p < 0.01 (\*\*).

**Table 3 - Mean relative % changes in aerobic and anaerobic variables**

Period	P <sub>1-2</sub>	P <sub>2-3</sub>	P <sub>3-4</sub>	P <sub>1-3</sub>	P <sub>1-4</sub>
VO <sub>2peak</sub>	-0.3 ± 6.2	0.4 ± 3.6	-1.7 ± 6.9	0.1 ± 5.9	-1.9 ± 6.7
TTE	4.2 ± 7.6*	3.1 ± 4.5**	-5.0 ± 6.8**	7.4 ± 7.2**	1.7 ± 9.1
VO <sub>2AT</sub>	3.2 ± 11.4	-3.5 ± 7.9	2.4 ± 13.85	-0.8 ± 9.5	1.2 ± 13.0
(n = 19) VO <sub>2ANT</sub>	5.2 ± 9.4*	0.0 ± 6.6	-0.9 ± 7.4	4.8 ± 8.7*	3.7 ± 10.8
%VO <sub>AT</sub>	3.8 ± 10.4	-4.2 ± 8.1*	4.4 ± 11.3	-1.2 ± 8.8	3.0 ± 12.6
%VO <sub>ANT</sub>	5.9 ± 8.6**	-1.1 ± 6.1	1.0 ± 5.6	4.6 ± 7.8*	5.8 ± 9.7*
V1 SME	-0.9 ± 5.1	-1.9 ± 4.7	0.0 ± 5.5	-2.8 ± 4.7*	-2.9 ± 4.7**
V2 SME	-1.7 ± 3.6*	-0.9 ± 3.8	0.6 ± 5.6	-2.8 ± 4.2*	-2.2 ± 4.9
MASS	4.1 ± 5.6**	2.8 ± 3.5**	-0.8 ± 3.2	7.1 ± 4.7**	6.1 ± 4.2**

Mean changes in aerobic and anaerobic variables. VO<sub>2</sub> = oxygen uptake; AT = aerobic threshold; ANT = anaerobic threshold; SME = submaximal economy; MASS = maximal anaerobic skiing speed. Significance set at: \* = p < 0.05; \*\* = p < 0.01.

Both time to exhaustion and maximal anaerobic skiing speed varied greatly through multiple periods during the study. TTE in males was significantly longer in periods 2 and 3 compared to period 1, and significantly shorter in period 4 compared to period 3. TTE in females was significantly longer in period 3 compared to both period 1 and 2 (figure 7).

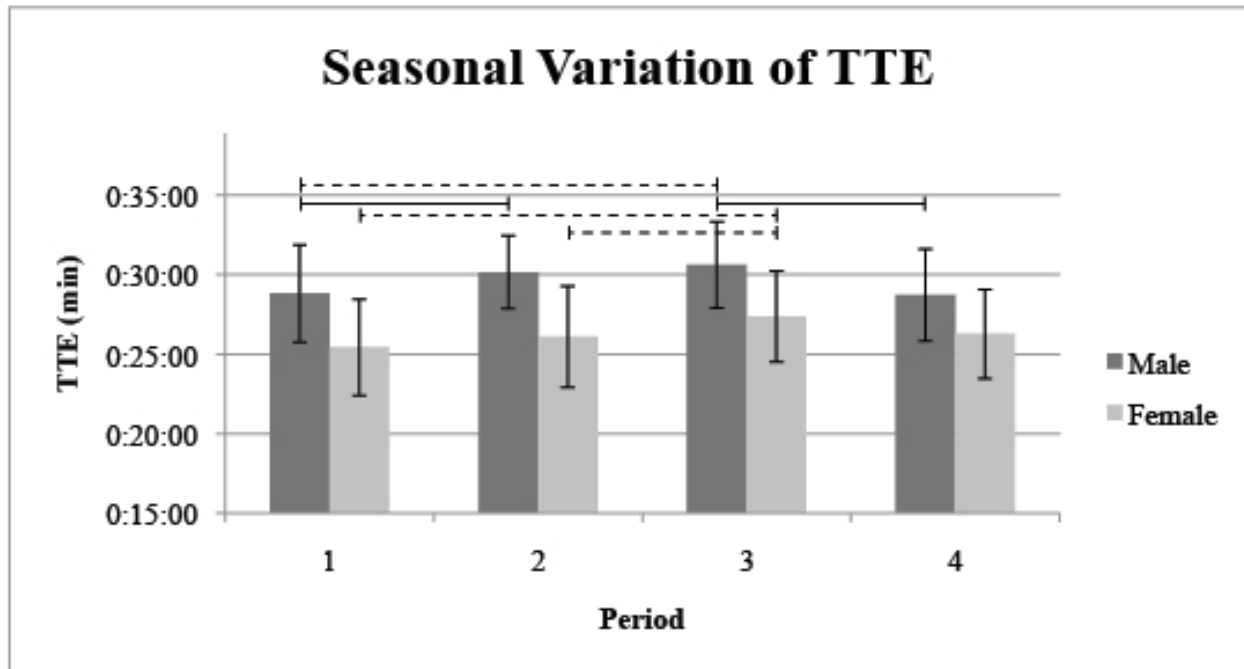


FIGURE 7. Seasonal variation of time to exhaustion in male and female cross country skiers. TTE = Time to exhaustion. Solid line = significance of  $p < 0.05$ ; dashed line = significance of  $p < 0.01$ .

MASS in males was significantly higher in period 3 compared to both period 1 and 2, and higher in period 4 compared to period 1. In females, MASS was significantly higher in periods 2, 3 and 4 compared to period 1 (figure 8).

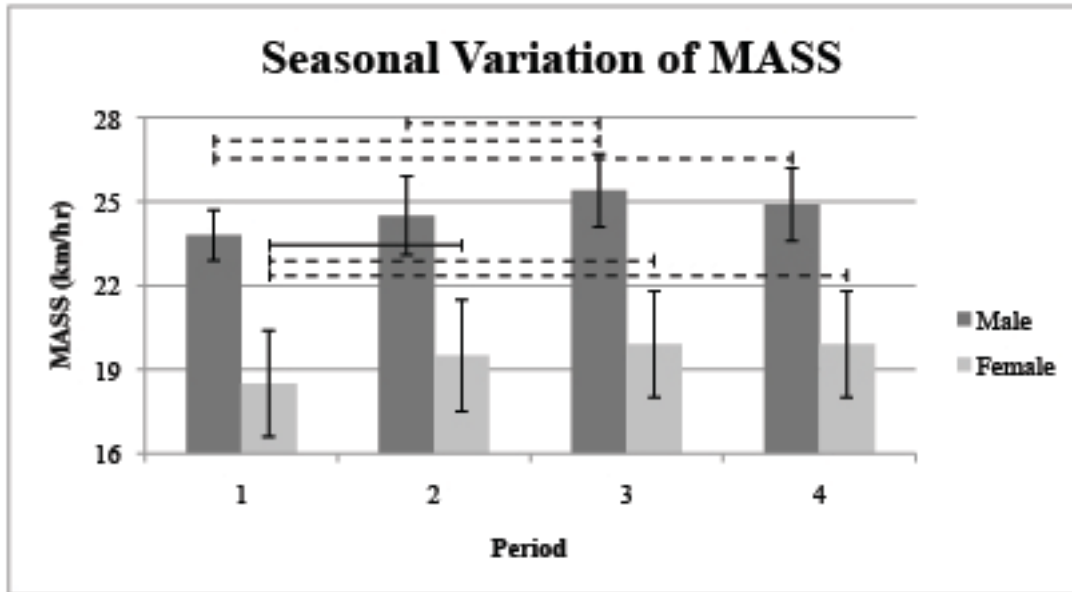


Figure 8 - Seasonal variation of maximal anaerobic skiing speed in male and female cross country skiers. MASS = maximal anaerobic skiing speed. Solid line = significance of  $p < 0.05$ ; dashed line = significance of  $p < 0.01$ .

## 7.2 Individual Variations of Aerobic and Anaerobic Variables

Within subject substantial changes between periods 1-2, 1-3, 1-4, and 3-4 were also calculated for TTE,  $VO_{2peak}$ ,  $VO_{2AT}$ ,  $VO_{2ANT}$ , and MASS. For each variable, the number of subjects who showed a substantial change was calculated (table 4). There were both positive and negative individual differences in all variables measured in between each period.



**Table 4 - Within subject substantial changes**

	<b>Period</b>	<b>P<sub>1</sub> to P<sub>2</sub></b>	<b>P<sub>1</sub> to P<sub>3</sub></b>	<b>P<sub>1</sub> to P<sub>4</sub></b>	<b>P<sub>3</sub> to P<sub>4</sub></b>
<b>Male (n = 11)</b>	TTE (min)	+6; 3; -1	+8; 2; -1	+5; 1; -4	+1; 4; -6
	VO <sub>2peak</sub> (ml/kg/min)	+2; 4; -5	+4; 3; -4	+4; 1; -6	+3; 3; -5
	VO <sub>2AT</sub> (ml/kg/min)	+6; 1; -4	+4; 2; -5	+6; 3; -2	+3; 4; -4
	VO <sub>2ANT</sub> (ml/kg/min)	+8; 1; -2	+8; 1; -2	+7; 1; -3	+3; 2; -6
	MASS (km/h)	+8; 0; -3	+8; 3; -0	+7; 4; -0	+5; 5; -1
<b>Female (n = 8)</b>	TTE (min)	+3; 4; -1	+6; 2; -0	+3; 4; -1	+3; -1
	VO <sub>2peak</sub> (ml/kg/min)	+2; 2; -4	+3; 2; -3	+2; 3; -3	+2; 5; -1
	VO <sub>2AT</sub> (ml/kg/min)	+2; 3; -3	+1; 4; -3	+2; 2; -4	+2; 3; -3
	VO <sub>2ANT</sub> (ml/kg/min)	+3; 4; -1	+4; 2; -2	+5; 2; -1	+5; 1; -2
	MASS (km/h)	+6; 1; -1	+7; 1; 0	+7; 1; 0	+3; 2; -2

Shows the number of subjects with differences over 0.3 of  $\Delta$ mean/SD. (Positive +; No differences; Negative -)

### 7.3 Correlations of Aerobic and Anaerobic Variables

#### 7.3.1 Time to exhaustion vs. VO<sub>2peak</sub>

There was a significant correlation between time to exhaustion (TTE) and VO<sub>2peak</sub> in both men and women through periods 1 (Male  $r = 0.79$ ,  $p < 0.01$ ; Female  $r = 0.91$ ,  $p < 0.01$ ), 2 (Male  $r = 0.61$ ,  $p < 0.05$ ; Female  $r = 0.87$ ,  $p < 0.01$ ), 3 (Male  $r = 0.80$ ,  $p < 0.01$ ; Female  $r = 0.71$ ,  $p < 0.5$ ) and 4 (Male  $r = 0.832$ ,  $p < 0.01$ , Female  $r = 0.81$ ,  $p < 0.05$ ) (figure 9).

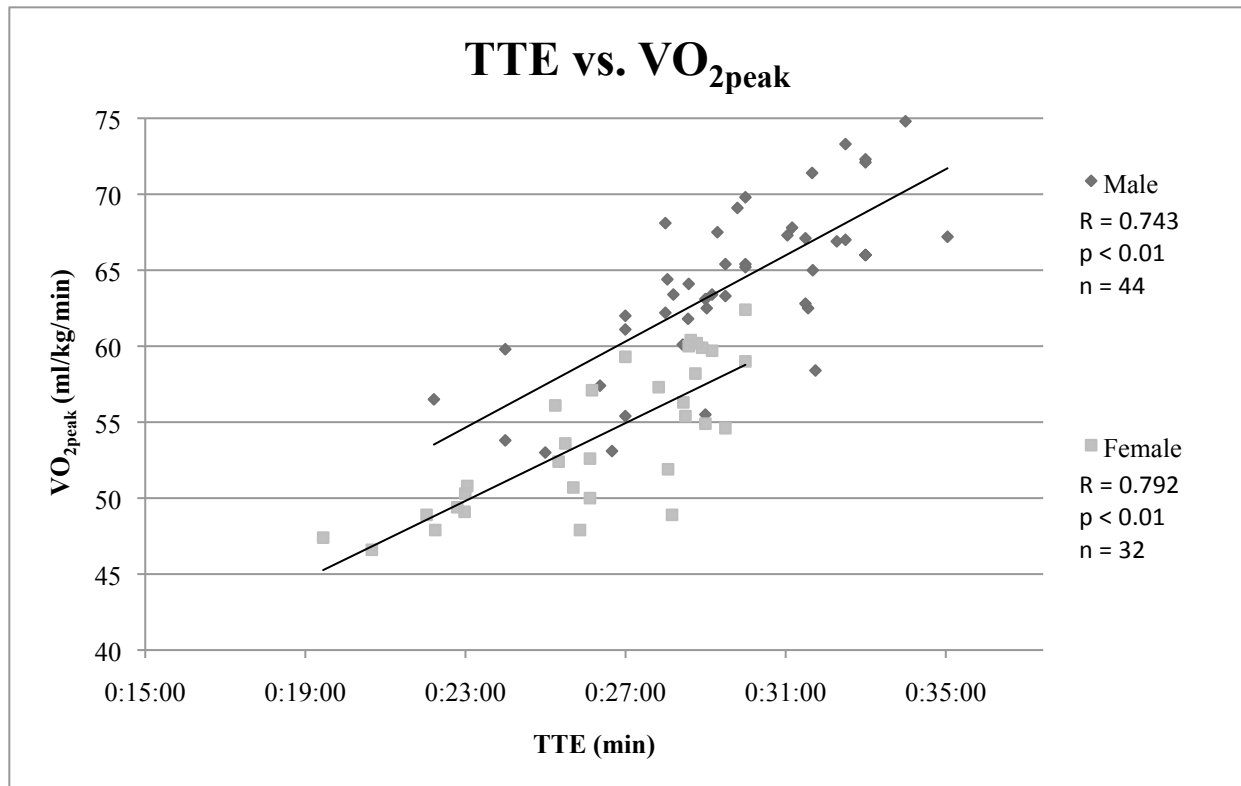


FIGURE 9. TTE vs. VO<sub>2peak</sub> in males and females through periods 1, 2, 3, 4.

### 7.3.2 Time to exhaustion vs. VO<sub>2AT</sub>

There was not a significant correlation between TTE and VO<sub>2AT</sub> in either the male or female groups through any of the testing periods (figure 10).

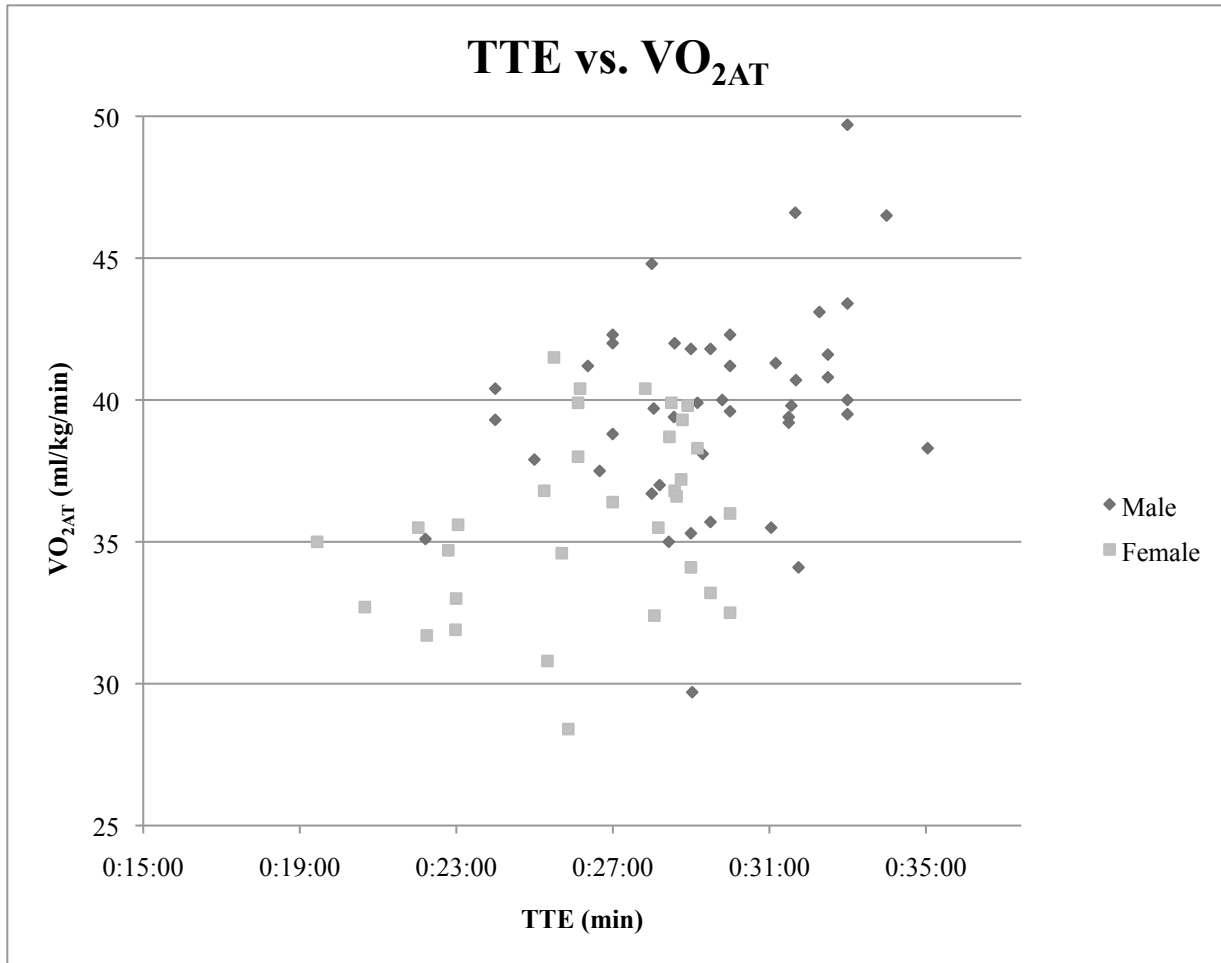


FIGURE 10. TTE vs. VO<sub>2AT</sub> in both males and females through periods 1, 2, 3, and 4.

### 7.3.3 Time to exhaustion vs. VO<sub>2ANT</sub>

There was a significant correlation between TTE and VO<sub>2ANT</sub> in men through periods 1 ( $r = 0.61$ ,  $p < 0.05$ ), 2 ( $r = 0.68$ ,  $p < 0.05$ ), 3 ( $r = 0.67$ ,  $p < 0.05$ ), and 4 ( $r = 0.75$ ,  $p < 0.01$ ), and in women through periods 2 ( $r = 0.90$ ,  $p < 0.01$ ), 3 ( $r = 0.71$ ,  $p < 0.05$ ), and 4 ( $r = 0.78$ ,  $p < 0.05$ ) (figure 11).

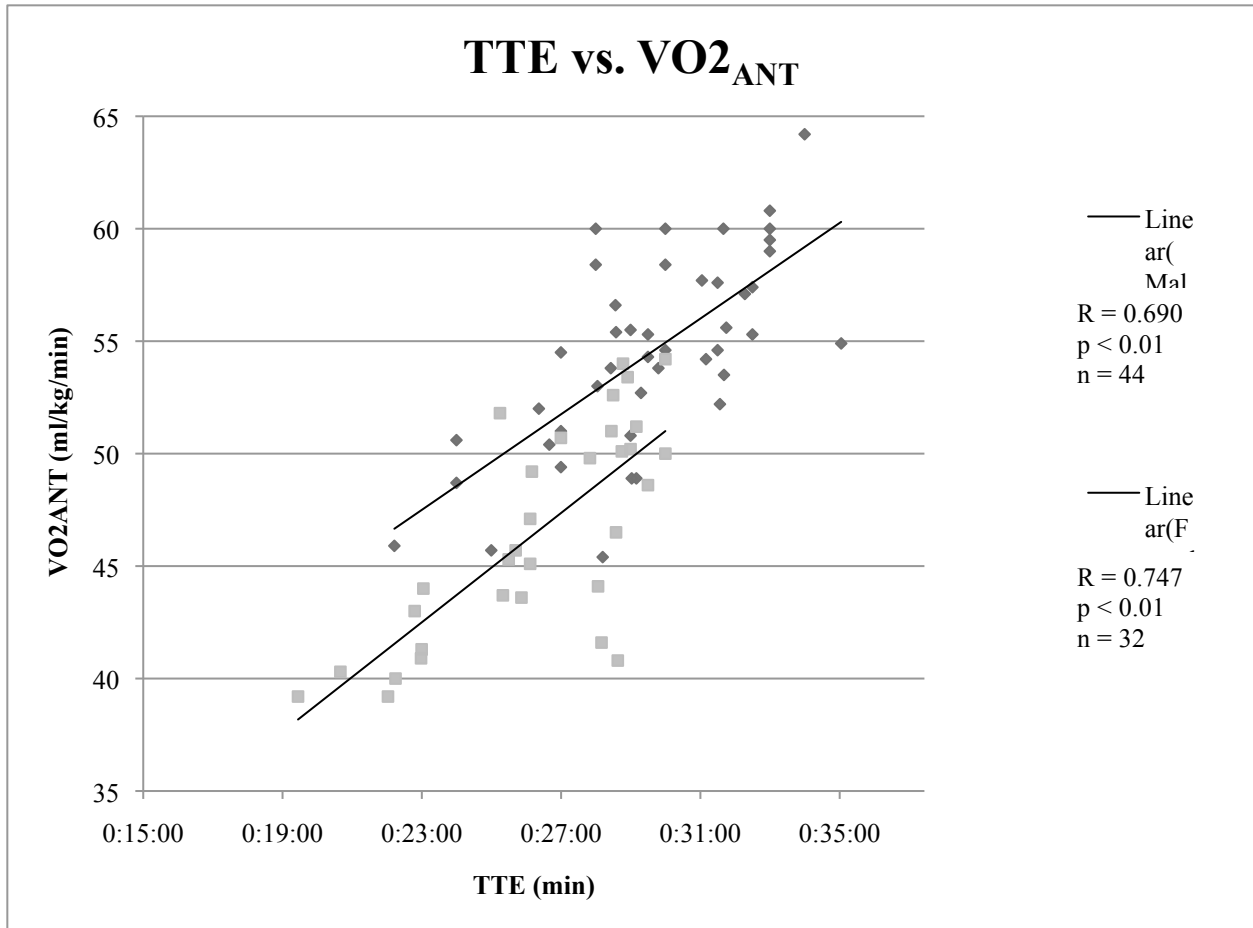


FIGURE 11. TTE vs. VO<sub>2</sub>ANT in males and females through periods 1, 2, 3, and 4.

### 7.3.4 Time to exhaustion vs. maximal anaerobic skiing speed

There was a significant correlation between TTE and MASS in females through periods 1 ( $r = 0.91$ ,  $p < 0.01$ ), 2 ( $r = 0.92$ ,  $p < 0.01$ ), 3 ( $r = 0.81$ ,  $p < 0.05$ ), and 4 ( $r = 0.82$ ,  $p < 0.05$ ) (figure 12). There was no correlation between TTE and MASS between males in any of the periods.

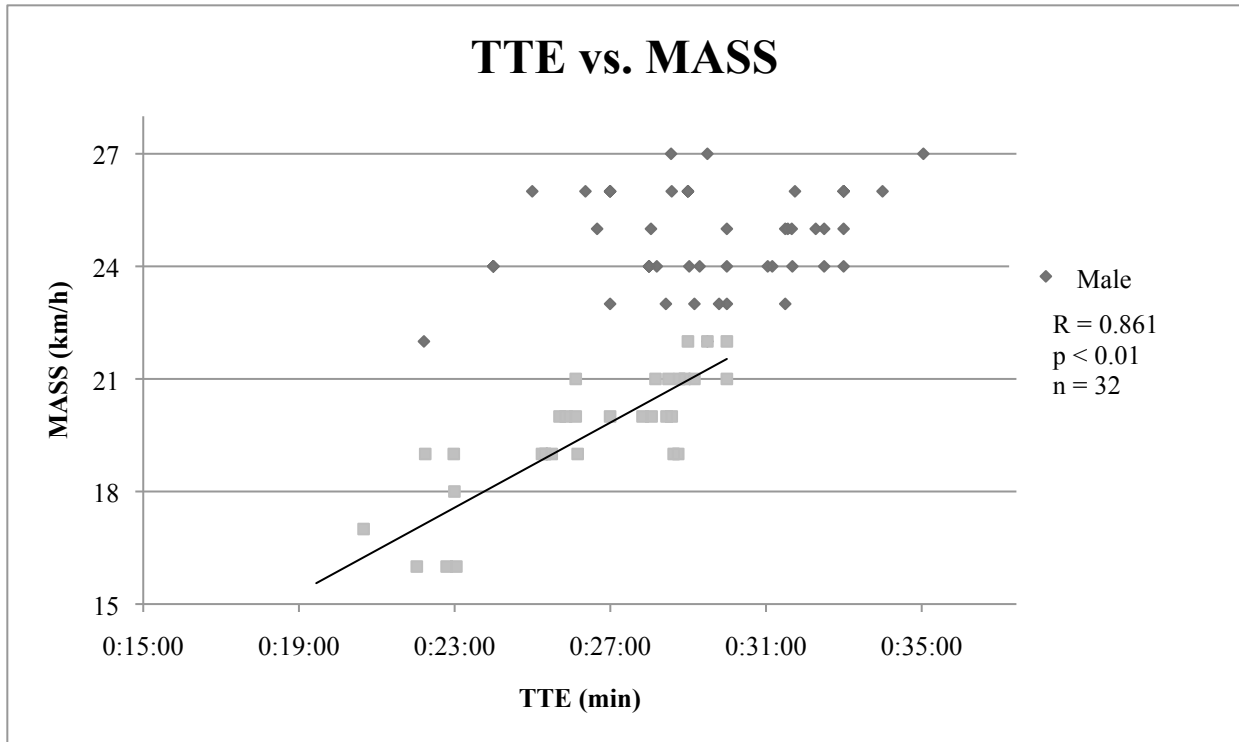


FIGURE 12. TTE vs. Maximal anaerobic skiing speed in females during periods 1, 2, 3, and 4.

## **8 DISCUSSION**

The purpose of the study was to examine the variations in various aerobic and anaerobic variables in competitive cross-country skiers through four different training periods over the course of one ski season. The main findings from the study were:

- 1)  $VO_{2peak}$  and  $VO_{2AT}$  did not significantly change over the course of one season in male or female competitive cross country skiers as a whole.
- 2) Performance and  $VO_{2ANT}$  changes significantly over the course of one season in both male and female competitive cross-country skiers as a whole.
- 3) There was a significant correlation between  $VO_{2peak}$  and performance in both males and female cross country skiers during all four testing periods.
- 4) There was a significant correlation between  $VO_{2ANT}$  and performance in both male and female cross country skiers during all four testing periods.
- 5) There was a significant correlation between maximal anaerobic skiing speed and performance in only female cross country skiers during all four testing periods, while there was no correlation in male cross country skiers during any of the four testing periods.

### **8.1 Seasonal Variations in Performance**

It has been previously shown that there is variation in performance during one season in cross country skiers (Losnegard et al., 2013). Losnegard et al. (2013) demonstrated that there was a significant increase in performance during a 1,000m time trial between June and October ( $270.0 \pm 14.3$  seconds vs.  $254.6 \pm 11.1$  seconds). This is further documented by Ingjer (1991) who

demonstrated both an increase in performance and  $VO_{2peak}$  during the competition season versus the preparation season.

In the current study there was a statistically significant variation in performance over the course of a season in both male and female cross-country skiers. In the male group the time to exhaustion increased from periods 1 to 2 and also 1 to 3. In the female group, the time to exhaustion increased from periods 1 to 3 and also 2 to 3. In both groups the highest TTE occurred just prior to the beginning of the competition phase in testing period 3 (figure 7). The findings in this study correlate with those in previous studies shown by Losnegard (2013) and Ingjer (1991).

There was also a significant decrease in performance from the beginning of the competition season in testing period 3 to the end of the competition season in testing period 4 in the male group. In the female group, there was not a significant decrease in performance during the same time period, but there was a trend of a decrease. When combining groups, the mean percentage change did decrease by  $-5.0\% \pm 6.8$  ( $p < 0.01$ ). These results shows how the buildup of stress over the competition along with the reduction in training volume can decrease performance in cross country skiers.

While not a groundbreaking finding, this shows the importance of the preparation season in order to achieve an athletes maximum performance capability during the competition period. The physiological adaptations made through the preparation season with a focus on long, easy workouts in the beginning of the preparation phase transitioning into a focus on harder, more stressful training towards the end of the preparation phase helps to increase performance. During the competition phase, a combination of stress-build up and lack of low intensity training causes a regression in performance (Sandbakk et al., 2016).

## **8.2 Seasonal Variations in Aerobic and Anaerobic Variables**

*VO<sub>2peak</sub>*. There have been previous studies that have shown both a variation (Ingjer, 1991) and no variation (Losnegard et al., 2013) in  $VO_{2peak}$  over the course of one season in cross country

skiers. The key difference between the two studies is the testing method used to find  $VO_{2peak}$ . Losnegard et al. (2013) was able to use a roller-ski treadmill for a ski specific test, while Ingjer tested using a running treadmill. Traditionally, skiers use a high volume of ski specific motions during training, which will help to stabilize the variations of  $VO_{2peak}$  in a specific motion such as a test on a roller ski treadmill versus a non specific motion such a test using a running treadmill.

The results from this study align closely with the results from Losnegard et al (2013).  $VO_{2peak}$  remained very stable in both the male and female subjects. The greatest change in mean percentage  $VO_{2peak}$  between any of the periods was between periods 1 and 4 in men ( $-1.9\% \pm 6.7$ ) (table 3). There was no significant change between any of the periods in either the male or female groups.

Similar to the variations of performance over the four testing periods, there was a high amount of individual variation in  $VO_{2peak}$ . These individual responses highlight the fact that each athlete responds differently to the type of training and stressors. Being able to adequately monitor training and recovery loads will help to limit the amount of negative physiological impacts (Drew and Finch, 2016).

*Aerobic Threshold.* There has been very little, if any research completed on the topic of seasonal variations of the aerobic threshold. Studies completed by Nemota and Miyashita (1980) and Nemoto et al. (1988) on Japanese athletes and non-athletes have shown a significant difference between the populations suggesting that the aerobic threshold can be developed with a proper training program.

This study demonstrated no significant variation in either  $VO_{2AT}$  or  $\%VO_{2AT}$  in both the male and female groups. The biggest mean percentage change between was between periods 2 and 3 in males ( $-5.0\% \pm 7.9$ ). Regardless of the wide range of values and large standard deviations,  $VO_{2AT}$  was not expected to variate much during the course of one year in trained cross country skiers. The training completed by cross country skiers is targeted at increasing the efficiency and performance of the higher end anaerobic energy systems. This in combination with multiple years of training prior will create a very stable base for most cross country skiers.



*Anaerobic Threshold.* Similar to seasonal variations in aerobic threshold, only limited research has been completed on the topic of seasonal variations in anaerobic threshold, especially on cross country skiers. One study by Mikulic (2012) used world class level rowers to investigate the seasonal variations in various fitness parameters, including the ventilatory threshold. Instead of using oxygen uptake to define the ventilatory threshold, Mikulic (2012) used power output which is a much more common unit of measurement in rowing. Using a maximal aerobic capacity test on a rowing ergometer, Mikulic (2012) was able to find that the power output corresponding to the ventilatory threshold increased by 16% through the season.

While there were still highly individualized responses with  $VO_{2ANT}$  in the current study, there was a trend of a positive adaptation of the anaerobic threshold through the preparation period to the beginning of the competition period in the male subjects ( $52.9 \text{ ml/kg/min} \pm 4.7$  vs.  $55.3 \text{ ml/kg/min} \pm 4.3$ ) (table 2). When both males and females are combined, there was a significant change in  $VO_{2ANT}$  between periods 1 and 3 (table 3). It has been shown that there is a link between the anaerobic threshold and performance through previous studies completed on cross country skiers (Larsson et al., 2002; Larsson and Henriksson-Larsen, 2005). Carlsson et al. (2014) used ten Swedish World-Cup athletes to determine which physiological variables best correlated with performance.  $VO_{2OBLA}$  was found to be responsible for 61% of the variance in performance using a linear regression formula.

Analyzing the percent utilization of  $VO_{2peak}$  at anaerobic threshold ( $\%VO_{2ANT}$ ) did show a significant difference over the season, especially during the periods where training/racing prior to the testing had occurred (periods 2, 3, and 4). The  $\%VO_{2ANT}$  during period 1 was significantly lower than any of the other periods (table 3). This increase in percent utilization at  $VO_{2ANT}$  may be linked with the minor increase in  $VO_{2ANT}$  and with the stable  $VO_{2peak}$  values. There is some debate as to the link between performance and percent utilization of  $VO_{2peak}$  discussed in section 8.3.

The efficiency and level of the anaerobic threshold was still able to maintain quite high between the beginning of the competitive phase (period 3) and the end of the competitive phase (period

4). This is in contrast to the trend of a decrease in performance during the same time period with the reduced TTE on the roller ski treadmill. The majority of the training that occurs during the competitive season is target at either developing anaerobic performance, or to enhance recovery and reduce fatigue. In combination with the high number of races that can take place, most of the training time is spent focusing the anaerobic systems. This leads to the anaerobic threshold maintaining a relatively similar level through the competition phase, while the build-up of fatigue and reduction of base will decrease performance (Sandbakk et al., 2016).

*Maximal Anaerobic Skiing Speed.* This is the first study of its kind to investigate seasonal changes in maximal anaerobic skiing speed (MASS). Previous studies using a MASS test have looked at the links between MASS and sprint performance (Mikkola et al., 2010) as well as to look at the correlation between concurrent endurance and explosive strength training in endurance athletes (Mikkola et al., 2007). Both of these studies used a MASS test protocol that was conducted on an indoor track instead of a roller ski treadmill like the current study.

There were statistically significant changes occurring between all periods in both the male and female groups. Similar to the time to exhaustion, there was an increase in maximal anaerobic skiing speed from periods 1 to 3 (table 2). Instead of a decrease in MASS from period 3 to period 4 similar to what was seen in TTE, MASS was able to maintain a more constant level through the competition season with no statistical change between periods. This further enforces the theory that the anaerobic performance does not deteriorate as easily as performance in competitive cross country skiers with the increased anaerobic stress associated with racing (Losnegard et al., 2013).

### **8.3 Association between Performance, Aerobic and Anaerobic Variables**

*Performance vs.  $VO_{2peak}$ .* There have been many studies that have looked at the correlation between skiing performance and  $VO_{2peak}$  (Formenti et al., 2009; Mahood et al., 2001; Ainegren et al., 2013; Carlsson et al., 2013; Larsson et al., 2002; Losnegard et al., 2013). In each of these studies the primary findings have all been similar showing a high correlation between performance and  $VO_{2peak}$ . The aerobic energy systems are able to create the highest amount of

ATP which is the fuel source for the muscles. In addition to being able to create a large amount of energy, there is very little if any build-up of harmful by-products such as lactic acid. Therefore, if an athlete is able to utilize a higher amount of oxygen, they should also have a higher performance potential.

The results from this study align with the previous studies found in the literature. There was a very high significant correlation between TTE and  $VO_{2peak}$  in all four testing periods between both the male and female groups. The athletes with the highest  $VO_{2peak}$  values were associated with those that could last on the treadmill for the longest time. This very high correlation is illustrated in figure 8.

While being one of the primary predictors of performance in cross country skiers, it is often increasingly difficult to increase  $VO_{2peak}$  with training as an athlete becomes more developed. It is not uncommon to see a 10-20% improvement in  $VO_{2peak}$  in a similarly aged untrained population (Makrides et al., 1990). Makrides et al., demonstrated a 14% increase in  $VO_{2peak}$  after a 12 week training program. In the current study on competitively trained cross country skiers, there was no statistical change in  $VO_{2peak}$  during the course of one season of training. Therefore while  $VO_{2peak}$  is an extremely important part of a successful cross country skier, it should not be a physiological characteristic that should be focused on during development in the preparation period.

*Performance vs. Aerobic Threshold.* Little research has been completed investigating the link between the aerobic threshold and performance in cross-country skiers. One study that has investigated the correlation looked at multiple different physiological variables to find the best predictor of performance in cross-country skiers (Larsson et al., 2002). Larsson et al. (2002) found that the best predictors of performance was the intensity where the respiratory exchange ratio = 1, OBLA, and  $VO_{2peak}$ . The aerobic threshold was not found to be significantly correlated with performance in this study. The correlation between the aerobic threshold and performance in the current study was also not statistically significant (figure 10).

*Performance vs. Anaerobic Threshold.* There have been numerous studies looking at the correlation between performance and the anaerobic threshold, and the findings have all been similar suggesting there is a strong correlation between the two variables (Larsson et al., 2002; Larsson and Henriksson-Larsen, 2005; Carlsson et al., 2014). Larsson and Henriksson-Larsen (2005) used a combination of field testing and treadmill testing to analyze performance in elite level cross country skiers. They were able to discover that the three components that best correlated with performance were  $VO_{2peak}$ , respiratory exchange ratio, and the anaerobic threshold. The correlation between the anaerobic threshold and performance was  $r = -.64$   $p < 0.05$ . While  $VO_{2peak}$  was still the most influential factor affecting performance, anaerobic threshold had a sizeable impact.

The current study produced results that correlated with the previous studies in the literature. Nearly all periods in both male and female demonstrated a correlation between performance and  $VO_{2ANT}$  (figure 10). The only period to not produce a correlated result was period 1 in the female group. There was one outlier in the female group with a much lower result than in any of the other test periods that greatly affected the results in such a small group. Without the one outlier it is believed that all periods would have demonstrated a strong correlation between performance and  $VO_{2ANT}$ .

There have been relatively few studies that have looked at the relationship between percent utilization of  $VO_{2peak}$  at the anaerobic threshold and performance. One study that has investigated percent utilization of  $VO_{2peak}$  and performance was done at the 5km race pace of world class runners (Støa et al., 2010). The results of the study demonstrated that there was no correlation between the percent utilization of  $VO_{2peak}$  and performance. The results from the current study had similar findings, as there was no significant correlation between the %  $VO_{2ANT}$  and TTE.

These results indicate that not only is it important for a competitive level cross country skier to have a high  $VO_{2peak}$ , it is also important to have a high  $VO_{2ANT}$ . The difference between the two is that  $VO_{2ANT}$  is more trainable and can potentially be developed during the season as

demonstrated in table 2. Athletes and coaches can create a training program that will help to develop the  $VO_{2ANT}$  through the preparation phase through the competitive phase.

*Performance vs. Maximal Anaerobic Skiing Speed.* There have only been limited studies performed on cross-country skiers that look at maximal anaerobic skiing speed (MASS) (Mikkola et al., 2007; Mikkola et al., 2010). While many of these tests have been completed on an indoor track versus a roller ski treadmill like the current study, the duration of the tests were quite similar so results can be comparable. In Mikkola et al. (2010) there was some correlation between maximal anaerobic velocity and performance in a simulated sprint time trial in some heats and not others. This shows that overall there was only little correlation between the two variables.

In the current study there was also some conflicting data. In the female group there was a very high correlation between maximal anaerobic skiing speed and performance during all periods, while in the male group there was no statistical significance at all in MASS (figure 12).

These results were very surprising. We hypothesized that there was going to be a correlation between the maximal anaerobic skiing speed and performance determined by the time to exhaustion during the long test. While there were two separate techniques used for each test (V2 vs. double pole), the V2 technique used during the long test uses a very similar biomechanical motion to double poling and it has been shown that the two techniques are connected (Mahood et al., 2001). Taking into consideration that the difference between techniques is not the primary reason for the inconsistent results, another theory must be used. Mikkola et al. (2010) theorized the reason for a weak correlation between the two variables may be due to the increased focus on the aerobic systems in the long test, versus a high neuromuscular focus in the shorter test. In the male test group, there were individuals that had could have had a very developed neuromuscular system in comparison to their aerobic system. This could lead to individuals being able to perform better in the shorter test versus the longer test. There was a much greater spread in the MASS for the womens group, with the individuals having the shortest TTE on the long test clearly having the slowest MASS. These individuals greatly strengthened the statistical

correlation and without them the female group may have lost its significance similar to the male group.

While not having a strong correlation between performance and maximal anaerobic skiing speed, these results do show the importance of also developing the neuromuscular system. During sprint racing, or in the final stages of a distance race, the high speeds used require a high amount of neuromuscular function. Coaches and athletes should also spend time developing the neuromuscular system through the preparation phase to achieve maximum performance potential.

## 9 PRACTICAL APPLICATIONS AND CONCLUSIONS

This study indicated that the primary indicators for performance in cross-country skiers are  $VO_{2peak}$ ,  $VO_{2ANT}$ , with MASS having some effect as well. With results found during this study, as well as previous studies it has been shown that  $VO_{2peak}$  does not change significantly through a season in a competitive athlete, while  $VO_{2ANT}$  and MASS shows some fluctuations. Therefore, coaches and athletes should spend more time during the preparation season focusing on developing both the anaerobic system and the neuromuscular system.

Both aerobic and anaerobic systems have a high impact on cross-country skiing, but they are not the only pieces of the puzzle that makes up a successful cross-country skier. Many other equally important factors need to be focused on during preparation and competition to achieve the maximum performance potential including strength, nutrition, recover, psychology and many more. When a coach and athlete need to make a concerted effort to not only create a program that will increase the aerobic and anaerobic systems, but also to create a program that will create an environment for the athlete to succeed, which includes all of the necessary components of a successful cross-country skier.

## 10 REFERENCES

- Abbiss C. & Laursen P. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Medicine* 38(3), 239-252.
- Ainegren M., Carlsson P., Tinnesten M. & Laaksonen M. (2013). Skiing economy and efficiency in recreational and elite cross-country skiers. *Journal of Strength and Conditioning Research* 27(5), 1239-1252.
- Allen D., Lamb G. & Westerblad H. (2008). Skeletal muscle fatigue: Cellular mechanisms. *Physiology Review* 88(1), 287-332.
- Andersson E., Supej M., Sandbakk Ø., Sperlich B., Stöggl T. & Holmberg H. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *European Journal of Applied Physiology* 110(3), 585-595.
- Astorino T., Reitschel J., Tam P., Taylor K., Johnson S. & Freedman T. (2004). Reinvestigation of optimal duration of  $VO_{2max}$  testing. *Journal of Exercise Physiology* 7(6), 1-8.
- Astorino T., Robergs R., Ghiasvand F., Marks D. & Burns S. (2000). Incidence of the oxygen plateau at  $VO_{2max}$  during exercise testing to volitional fatigue. *Journal of Exercise Physiology* 3(4)
- Atkinson G., Peacock O. & Law M. (2007). Acceptability of power variation during a simulated hilly time trial. *International Journal of Sports Medicine* 28, 157-163.
- Berh U. (1987). The influence of body mass in cross-country skiing. *Medicine & Science in Sports & Exercise* 19(4), 324-331.



- Carlsson M., Carlsson T., Knutsson M., Malm C. & Tonkonogi M. (2014). Oxygen uptake at different intensities and sub-techniques predicts sprint performance in elite male cross-country skiers. *European Journal of Applied Physiology* 114, 2587-2595.
- Carlsson M., Carlsson T., Hammarstrom D., Malm C. & Tonkonogi M. (2014). Prediction of race performance of elite cross-country skiers by lean mass. *International Journal of Sports Physiology and Performance* 9, 1040-1045.
- Carlsson M., Carlsson T., Hammarstrom D., Malm C. & Tonkonogi M. (2014). Time trials predict the competitive performance capacity of junior cross-country skiers. *International Journal of Sports Physiology and Performance* 9, 12-18.
- Carlsson T., Carlsson M., Felleki M., Hammarstrom D., Heil D., Malm C. & Tonkonogi M. (2013). Scaling maximal oxygen uptake to predict performance in elite-standard men cross-country skiers. *Journal of Sport Sciences* 31(16), 1753-1760.
- Cavanagh P. & Kram R. (1985). The efficiency of human movement--a statement of the problem. *Medicine & Science in Sports & Exercise* 17(3), 304-308.
- Cetin E., Bilgin U., Schurmann B., Yarim I. & Dolck B. (2013). Blood lactate level responses and comparison with submaximal running and roller skiing in cross-country skiers. *College Antropology* 37, 867-870.
- Coyle E., Sidossis L., Horowitz J. & Beltz J. (1992). Cycling efficiency is related to the percentage of type I muscle fibers. *Medicine & Science in Sports & Exercise* 24, 782-788.
- Drew M. & Finch C. (2016). The relationship between training load and injury, illness and SOreness: A systematic and literature review. *Sports Medicine* 46(6), 861-83.
- Essex S. & Chalkley B. (2004). Mega-sporting events in urban and regional policy: A history of the winter olympics. *Planning Perspectives* 19(2), 201-204.

- Fabre N., Balestreri F., Pellegrini B. & Schena F. (2010). The modified  $D_{\max}$  method is reliable to predict the second ventilatory threshold in elite cross-country skiers. *Journal of Strength and Conditioning Research* 24(6), 1548-1552.
- Fabre N., Passelergue P., Bouvard M. & Perrey S. (2008). Comparison of heart rate deflection and ventilatory threshold during a field cross-country roller-skiing test. *Journal of Strength and Conditioning Research* 22(6), 1977-1984.
- Formenti D., Rossi A., Calogiuri G., Thomassen T., Scurati R. & Weydahl A. (2015). Exercise intensity and pacing strategy of cross-country skiers during a 10 km skating simulated race. *Research in Sports Medicine: An International Journal* 00, 1-14.
- Gaskill S., Serfass R., Bacharach D. & Kelly J. (1999). Responses to training in cross-country skiers. *Medicine & Science in Sports & Exercise* 31(8), 1211-1217.
- Gastin P. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Medicine* 31(10), 725-741.
- Gaston A., Hapkova I. & Durand F. (2014). Exercise induced hypoxemia at moderate altitude: Comparison between running and roller skiing field test in young elite biathletes. *Journal of Sports Medicine, Physiology, and Fitness*
- Gilman M. (1996). The use of heart rate to monitor the intensity of endurance training. *Sports Medicine* 21(2), 73-79.
- Gilman M. & Wells C. (1993). The use of heart rates to monitor exercise intensity in relation to metabolic variables. *International Journal of Sports Medicine* 12(6), 339-344.
- Häkkinen K. & Keskinen K. (1989). Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance- trained athletes and sprinters. *European Journal of Applied Physiology* 59(3), 215-220.

- Hoff J., Gran A. & Helgerud J. (2002). Maximal strength training improves aerobic endurance performance. *Scandinavian Journal of Medical & Science in Sports* 12, 288-295.
- Hoffman M., Clifford P., Watts P., O'Hagan K. & Mittelstadt S. (1995). Delta efficiency of uphill roller skiing with the double pole and diagonal stride techniques. *Canadian Journal of Applied Physiology* 20(4), 465-479.
- Hoffman M., Clifford P., Snyder A., O'Hagan K., Mittelstadt S., Roberts M., . . . Gaskill S. (1998). Physiological effects of technique and rolling resistance in uphill roller skiing. *Medicine & Science in Sports & Exercise* 30(2), 311-317.
- Hoffman M. & Clifford P. (1990). Physiological responses to different cross country skiing techniques on level terrain. *Medicine & Science in Sports & Exercise* 22(6), 841-848.
- Hoffman M. & Clifford P. (1992). Physiological aspects of competitive cross-country skiing. *Journal of Sport Sciences* 10, 3-27.
- Hoffman M., Clifford P., Watts P., Drobish K., Gibbons T., Newbury V., . . . O'Hagan K. (1994). Physiological comparison of uphill roller skiing: Diagonal stride versus double pole. *Medicine & Science in Sports & Exercise* 26(10), 1284-1289.
- Hopkins W. (2004). How to interpret changes in an athletic performance test. *Sports Science* 8, 1-7.
- Hutchinson P., Cureton K., Outz H. & Wilson G. (1991). Relationship of cardiac size to maximal oxygen uptake and body size in men and women. *International Journal of Sports Medicine* 12(4), 369-373.
- Ingjer F. (1991). Maximal oxygen uptake as a predictor of performance ability in women and men elite cross-country skiers. *Scandinavian Journal of Medical & Science in Sports* 1, 25-30.

- Ingjer F. (1992). Development of maximal oxygen uptake in young elite male cross-country skiers: A longitudinal study. *Journal of Sport Sciences* 10(1), 49-63.
- Jacobs I. & Kaiser P. (1982). Lactate in blood, mixed skeletal muscle, and FT or ST fibres during cycle exercise in man. *Acta Physiologica Scandinavica* 114(3), 461-466.
- Jorfeldt L., Juhlin-Dannfelt A. & Karlsson J. (1978). Lactate release in relation to tissue lactate in human skeletal muscle during exercise. *Journal of Applied Physiology* 44(3), 350-352.
- Joseph T., Johnson B., Battista R., Wright G., Dodge C., Porcari J., . . . Foster C. (2008). Perception of fatigue during sprint competition. *Medicine & Science in Sports & Exercise* 40(2), 381-386.
- Kvamme B., Jakobsen V., Hetland S. & Smith G. (2005). Ski skating technique and physiological responses across slopes and speeds. *European Journal of Applied Physiology* 95(2-3), 205-212.
- Larson A. (2006). Variations in heart rate at blood lactate threshold due to exercise mode in elite cross-country skiers. *Journal of Strength and Conditioning Research* 20(4), 855-860.
- Larsson B., Ologsson P., Jakobsson E., Burlin L. & Henriksson-Larsen K. (2002). Physiological predictors of performance in cross-country skiing from treadmill tests in male and female subjects. *Scandinavian Journal of Medical Science Sports* 12, 347-353.
- Larsson P. & Henriksson-Larsen K. (2005). Combined metabolic gas analyser and dGPS analysis of performance in cross-country skiing. *Journal of Sport Sciences* 23(8), 861-870.
- Larsson P. & Henriksson-Larsen K. (2008). Body composition and performance in cross-country skiing. *International Journal of Sports Medicine* 29, 971-975.

- Laursen P. & Jenkins D. (2002). The scientific basis for high-intensity interval training: Optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Medicine* 32(1), 53-73.
- Leirdal S., Sandbakk O. & Ettema G. (2013). Effects of frequency on gross efficiency and performance in roller ski skating. *Scandinavian Journal of Medical Science Sports* 23, 295-302.
- Loat C. & Rhodes E. (1993). Relationship between the lactate and ventilatory thresholds during prolonged exercise. *Sports Medicine* 15(2), 104-115.
- Londeree B. (1997). Effect of training on lactate/ventilatory thresholds: A meta-analysis. *Medicine & Science in Sports & Exercise* 29(6), 837-843.
- Losnegard T. & Hallén J. (2014). Elite cross-country skiers do not reach their running  $VO_{2max}$  during roller ski skating. *Journal of Sports Medicine, Physiology, and Fitness* 54(4), 389-393.
- Losnegard T., Mikkelsen K., Ronnestad B., Hallen J., Rud B. & Raastad T. (2011). The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scandinavian Journal of Medical Science Sports* 21, 389-401.
- Losnegard T., Myklebust H., Spencer M. & Hallen J. (2013). Seasonal variations in  $VO_{2Max}$ ,  $O_2$  cost,  $O_2$  deficit, and performance in elite cross-country skiers. *Journal of Strength and Conditioning Research* 27(7), 1789-1799.
- Losnegard T., Schäfer D. & Hallén J. (2014). Exercise economy in skiing and running. *Frontiers in Physiology* 5(5)

- Losnegard T. & Hallen J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *International Journal of Sports Physiology and Performance* 9, 25-31.
- Losnegard T., Myklebust H. & Hallen J. (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Medicine & Science in Sports & Exercise* 6, 673-681.
- Losnegard T., Myklebust H. & Hallen J. (2012). No differences in  $O_2$ -cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *Journal of Strength and Conditioning Research* 26(5), 1340-1347.
- Lucía A., Hoyos J., Pérez M. & Chicharro J. (2000). Heart rate and performance parameters in elite cyclists: A longitudinal study. *Medicine & Science in Sports & Exercise* 32(10), 1777-1782.
- Lusk G. (1924). Analysis of the oxidation of mixtures of carbohydrate and fat. *Journal of Biological Chemistry* 59, 41-42.
- MacDougall J., Hughson R., Sutton J. & Moroz J. (1979). The energy cost of cross-country skiing among elite competitors. *Medicine & Science in Sports* 11(3), 270-273.
- Mahood N., Kenefick R., Kertzer R. & Quinn T. (2001). Physiological determinants of cross-country ski racing performance. *Medicine & Science in Sports & Exercise* 33(8), 1379-1384.
- Makrides L., Heigenhauser G. J. & Jones N. L. (1990). High-intensity endurance training in 20- to 30- and 60- to 70-yr-old men. *Journal of Applied Physiology* 69(5), 1792-1798.
- Malcata R. & Hopkins W. (2014). Variability of competitive performance of elite athletes: A systematic review. *Sports Medicine* 44, 1763-1774.

- McArdle W., Katch F. & Katch V. (2015). *Exercise physiology: Nutrition, energy, and human performance* (8 painos). Baltimore, MD: Wolters Kluwer Health.
- Medbo J., Mohn A., Tabata I., Bahr R., Vaage O. & Sejersted O. (1988). Anaerobic capacity determined by maximal accumulated O<sub>2</sub> deficit. *Journal of Applied Physiology* 64(1), 50-60.
- Midgley A., McNaughton L. & Wilkinson M. (2006). Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners?: Empirical research findings, current opinions, physiological rationale and practical reccomendations. *Sports Medicine* 36(2), 117-132.
- Mikkola J., Laaksonen M., Holmberg H., Vesterinen V. & Numela A. (2010). Determinants of a simulated cross country skiing sprint competition using V2 skating technique on roller skis. *Journal of Strength and Conditioning Research* 24(4), 920-928.
- Mikkola J., Rusko H., Nummela A., Paavolainen L. & Hakkinen K. (2007). Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *Journal of Strength and Conditioning Research* 21(2), 613-620.
- Mikulic P. (2012). Seasonal changes in fitness parameters in a world champion rowing crew. *International Journal of Sports Physiology and Performance* 7, 189-192.
- Mourot L., Fabre N., Andersson E., Willis S., Buchheit M. & Holmberg H. (2015). Cross-country skiing and postexercise heart-rate recovery. *International Journal of Sports Physiology and Performance* 10, 11-16.

- Moxnes J. & Hausken K. (2009). A dynamic model of nordic diagonal stride skiing, with a literature review of cross country skiing. *Computer Methods in Biomechanics and Biomedical Engineering* 12(5), 531-551.
- Nakai A. & Ito A. (2011). Net efficiency of roller skiing with a diagonal stride. *Journal of Sport Sciences* 29(4), 423-429.
- Nemoto I., Iwaoka K., Funato K., Yoshioka N. & Miyashita M. (1988). Aerobic threshold, anaerobic threshold, and maximal oxygen uptake of japanese speed-skaters. *International Journal of Sports Medicine* 9(6), 433-437.
- Nemoto I. & Miyashita M. (1980). Aerobic and anaerobic threshold of japanese male adults. *Journal of Human Ergology* 9(2), 183-189.
- Niinimaa V., Dyon M. & Shephard R. (1978). Performance and efficiency of intercollegiate cross-country skiers. *Medicine & Science in Sports* 10(2), 91-93.
- Nixon P. (1988). Human circulation regulation during physical stress. *Stress Medicine* 4(2), 124-125.
- Overstreet B., Bassett D., Crouter S. & Parr B. (2016). Portable open-circuit spirometry systems: A review. *Journal of Sports Medicine, Physiology, and Fitness*
- Papadopoulou S., Gouvianaki A., Grammatikopoulou M., Maraki Z., Pagkalos I., Malliaropoulos N., . . . Maffulli N. (2012). Body composition and dietary intake of elite cross-country skiers member of the greek national team. *Asian Journal of Sports & Medicine* 3(4), 257-266.
- Powers S., Dodd S. & Garner R. (1984). Precision of ventilatory and gas exchange alterations as a predictor of the anaerobic threshold. *European Journal of Applied Physiology* 52(2), 173-177.



- Powers S. & Howley E. (2009). *Exercise physiology: Theory and application to fitness and performance* (7th ed.). New York, NY: McGraw-Hill.
- Rundell K. & Bacharach D. (1995). Physiological characteristics and performance of top U.S. biathletes. *Medicine & Science in Sports & Exercise* 27(9), 1302-1310.
- Saltin B. & Astrand P. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology* 23(3), 353-358.
- Sandbakk Ø., Hegge A., Losnegard T., Skattebo Ø., Tønnessen E. & Holmberg H. (2016). The physiological capacity of the world's highest ranked female cross-country skiers. *Medicine & Science in Sports & Exercise* 48(6), 1091-1100.
- Sandbakk O., Leirdal S. & Ettema G. (2014). The physiological and biomechanical differences between double poling and G3 skating in world class cross country skiers. *European Journal of Applied Physiology* 115(3), 483-487.
- Sandbakk O., Ettema G. & Holmberg H. (2012). Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scandinavian Journal of Medical Science Sports* 24, 28-33.
- Sandbakk O., Ettema G. & Holmberg H. (2012). The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. *European Journal of Applied Physiology* 112, 2829-2838.
- Sandbakk O., Ettema G., Leirdal S. & Holmberg H. (2012). Gender differences in the physiological responses and kinematic behaviour of elite sprint cross-country skiers. *European Journal of Applied Physiology* 112, 1087-1094.
- Sandbakk O. & Holmberg H. (2014). A reappraisal of success factors for olympic cross-country skiing. *International Journal of Sports Physiology and Performance* 9, 117-121.

- Sandbakk O., Welde B. & Holmberg H. (2011). Endurance training and sprint performance in elite junior cross-country skiers. *Journal of Strength and Conditioning Research* 25(5), 1299-1305.
- Seiler S. & Kjellerud G. (2006). Quantifying training intensity distribution in elite endurance athletes: Is there evidence for an "optimal" distribution? *Scandinavian Journal of Medical & Science in Sports* 16, 49-56.
- Sjödin B. & Jacobs I. (1981). Onset of blood lactate accumulation and marathon running performance. *International Journal of Sports Medicine* 2(1), 23-26.
- St. Clair Gibson A., Schabort E. & Noakes D. (2001). Reduced neuromuscular activity and force generation during prolonged cycling. *American Journal of Physiology. Regulatory, Integrative, and Comparative Physiology*. 281(1), 187-196.
- Stickland M., Jones R., Haykowsky M. & Petersen S. (2004). Lactate steady state during 20km simulated cycle racing. *Research in Sports Medicine* 12(1), 59-70.
- Støa E., Støren Ø., Enoksen E. & Ingjer F. (2010). Percent utilization of VO<sub>2</sub> max at 5-km competition velocity does not determine time performance at 5 km among elite distance runners. *Journal of Strength and Conditioning Research* 24(5), 1340-1345.
- Stöggl T. & Sperlich B. (2014). Polarized training has greater impact on key endurance variable than threshold, high intensity, or high volume training. *Frontiers in Physiology* 5(33), 1-9.
- Svedahl K. & MacIntosh B. (2003). Anaerobic threshold: The concept and methods of measurement. *Canadian Journal of Applied Physiology* 28(2), 299-323.
- Vergés S., Flore P., Laplaud D., Guinot M. & Favre-Juvin A. (2006). Laboratory running test vs. field roller skiing test in cross-country skiers: A longitudinal study. *International Journal of Sports Medicine* 27(4), 307-313.

Wasserman K., Whipp B., Koyal S. & Beaver W. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology* 35(2), 236-243.

Zory R., Molinari F., Knaflitz M., Schena F. & Rouard A. (2011). Muscle fatigue during cross country sprint assessed by activation patterns and electromyographic signals time-frequency analysis. *Scandinavian Journal of Medical & Science in Sports* 21, 783-790.