SKI ECONOMY AND PHYSIOLOGICAL RESPONSES WHILE DOUBLE POLING: CURVED VS. STRAIGHT POLES

Christina Mishica

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Department of Biology and Physical Activity
University of Jyväskylä
Supervisors: Heikki Kyröläinen and Vesa Linnamo

ABSTRACT

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Introduction. Double poling (DP) is commonly used in cross country skiing (XC). It is becoming more and more popular and in some competitions it is the exclusive technique. Ski poles allow a skier to apply power and force to the snow and their composition and design have a significant effect on performance. Different pole lengths and cross sections are some of the differences that have been tested. Advancements in equipment will continue to be introduced so it is important to have research that supports the possible benefits and physiological reasoning behind these changes. The purpose of this study was to investigate and compare ski economy and physiological responses in XC skiing while performing the DP technique with curved and straight ski poles.

Methods. Ten well-trained XC skiers - five males (age 24.2 ±6.8 years 77.1 ± 2.4 kg) and five females (21.8 ± 3.4 years, 60.2 ± 7.0 kg) performed DP in a laboratory with roller skis on a treadmill with one degree of inclination using both straight and curved poles. A sub-maximal test protocol was developed that utilized three speeds (men: 13, 17, 21 km/h/; women: 8, 12, 16 km/h) and 60 seconds of max speed at the end of each test. Tests, in a randomized order, were performed with each pole type for five minutes for reaching a steady state. Heart rate, blood lactate, VO2max and pole forces were collected for analysis. Results were analyzed separately for each gender due to changes in the protocol because faster speeds were needed for male subjects.

Results. No differences were found in heart rate values when comparing pole types with both male (± <4 bpm) and female (± <2 bpm) subjects. There were slightly higher (n.s) blood lactate values with both male and female subjects with curved poles. Although no differences were found with VO2 values there were significant differences ($p<0.05$) found in VE values in speed 1 (8 km/h) for women (curved: 36.9 ± 4.2, straight: 35.3 ± 4.6 L/min) and significant differences ($p<0.05$) in speed 3 (21 km/h) for men (curved: 116.9 ±_23.7, straight: 112.7 ± 21.5 L/min). Gross efficiency did not differ between the two pole types at the tested speeds.

Conclusion. Even though some changes in the studied parameters were visible with curved poles the differences were not significant. This could be due to the testing protocol or because of the subjects' unfamiliarity of skiing with curved poles. It is well known that ski economy has a great effect on performance so it is important to research and search for any possible improvements. Less than one second is often the difference between winning or losing a medal. In the future, research with a testing protocol that is more similar to ski competitions should be used to further investigate the possible gains of using curved ski poles.

Keywords: double poling, ski economy, heart rate, oxygen uptake, minute ventilation

ABBREVIATIONS

DIA	diagonal stride
DP	double pole
GE	gross efficiency
Q	cardiac output
Q_{max}	maximal cardiac output
HR	heart rate
LT	lactate threshold
OBLA	onset of blood lactate accumulation
XC	cross-county
RER	respiratory exchange ratio
RUN	running
SV	stroke volume
VO_{2max}	maximal oxygen uptake
V_E	minute ventilation
V_{max}	maximal velocity

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1. INTRODUCTION

Cross-country (XC) skiing is the oldest type of skiing. The sport began in Norway as a form of transportation and spread to other Nordic countries. It was an easy way to travel over snow covered terrain and it was additionally utilized for hunting and fighting. At the first Winter Olympic Games in 1924, cross country skiing was one of the nine competitive disciplines. This resulted in a growing interest across the world and the sport quickly evolved (Formenti et al., 2005). Today, competitive cross country skiing is a very demanding sport. High maximal oxygen uptake, good skiing technique, fast force production, and a high ability to resist fatigue are all necessary to compete successfully. Ski race distances range from one to fifty kilometers and two different racing techniques, classical and free style techniques, are used. With so many determinants affecting the sport, a detailed analysis and significant research is needed in order to study and determine what is required for successful performance (Rusko, 2003, 5).

At the highest level, improvements are often subtle and require an optimal training program to see even the smallest performance gains. Unlike other endurance sports, successful XC skiers are found to have a wide variation in body height and mass, resulting in many different training regimens and varying strengths and weaknesses between individuals. Due to the varying terrain during races, no one body type is ideal. Studies support this showing that heavier skier excel on the flatter terrain and uphill terrain is more favorable for smaller skiers (Bergh and Forsberg, 1992).

Along with other sports, performance differences are found when comparing genders. The main reason for differences in performance between males and females is based on the differences in body size and composition. Males tend to be larger in size and have lower proportional amounts of fat; in addition, they have a higher aerobic capacity and hemoglobin and hematocrit levels (Coast et al., 2004). Studies have shown that there is even greater differences between genders when the upper body is involved (Sandbakk et al., 2012). XC skiing requires a great deal of upper body strength so it is important that this is taken into consideration when creating training programs or research projects that include both males and females. It may be necessary to develop different training protocols in order to see maximal benefits and obtain more accurate results.

XC skiing allows skiers to travel faster and further than possible by foot. Elite skiers can maintain speeds for 10 kilometers that would exhaust world-class runners in only a few kilometers. Although the metabolic power available in both sports is the same, the energetic costs of skiing is much lower (Bellizzi et al., 1998). It is unknown why skiing is less costly and a commonly investigated factor in endurance performance velocity is known as 'economy' or 'efficiency.' Efficiency interacts with the performance VO_2 to establish the speed or power that can be generated at this oxygen consumption (Joyner and Coyle, 2008). The ability to efficiently utilize metabolic energy to produce work is necessary for successful results (Sandbakk et al., 2013). In complex exercise modes, such as XC skiing, skiers need to be able to adjust their technique effectively as conditions change. Gross efficiency (GE) is the term often used to describe efficiency rate in XC skiing. It is determined by looking at the work generated and the total energy expended (i.e., metabolic rate) and is shown as a percentage (Sidossis et al., 1992). Numerous studies have investigated work economy in XC skiing (Losnegard et al., 2014, Ainegren et al., 2013, Sandbakk et al., 2013, Millet et al., 2003, Bellizzi et al., 1998, Hoffman et al., 1995). As a whole, these studies prove that aerobic energy costs differ between techniques and depend on the subjects training level. As a result, GE is an important factor to examine when studying different techniques, speeds, terrains and subjects.

Thus, this study investigated the effect curved poles have on the physiological responses, as well as gross efficiency, while performing the double pole technique at three various intensities. The double pole technique was an appropriate technique to be examined due to its increasing popularity in both professional marathon racing and the World Cup circuit. Today, at times, it is the exclusive technique which increases the value on research focusing and finding possible performance gains. No study has previously studied these new curved poles and the physiological responses and economy specifically.

The aim of this study was to determine if curved ski poles showed improvements in double pole performance or reductions in blood lactate and heart rate values by comparing them to traditional straight ski poles. The second aim was to compare the gross efficiency values of the two poles types to see if any differences in ski economy were visible. The third aim was to investigate gender differences and see whether males and females have similar or different responses when performing submaximal tests on a roller ski treadmill with curved ski poles.

2. CROSS COUNTRY SKIING

The two different techniques that XC skiing is divided into are classical style and free or skating style. Each style is comprised of four different techniques and different skis, poles, boots and rules are implemented. The technique used is dependent on the terrains inclination and the snow conditions which frequently changes throughout the course of the race. The lower limbs and the upper body work in combination to move the body forward effectively.

2.1 Classic technique

Double pole technique. Double poling (DP) is a complex movement that involves both the upper and lower body. This poling technique involves both arms working together in unison, a small amount of leg movement and a considerable amount of trunk movement (Rusko, 2003, 42-44, Smith et al., 1996). During this technique, the muscles are activated in sequential order starting with the trunk and hip flexors, followed by shoulder extensors and the elbow extensor triceps brachii (Holmberg et al., 2005). Figure 1 shows the poling and recovery phases of the DP technique. This technique is commonly used on flat sections of the ski track. This technique will be covered in further detail in chapter 3.

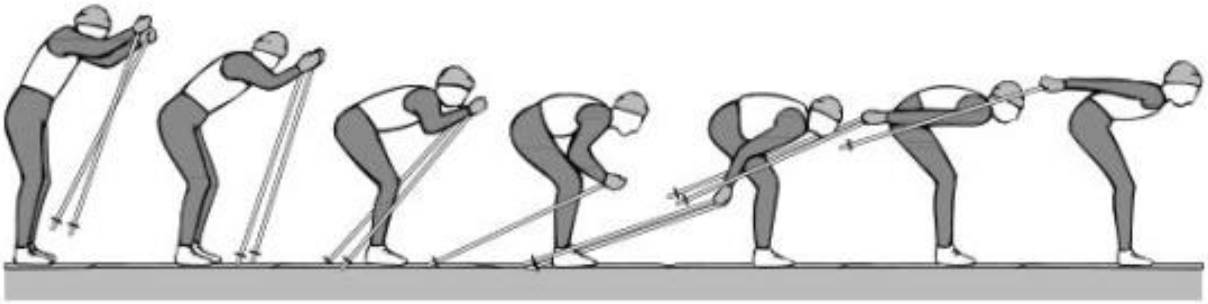


FIGURE 1. The double pole poling phase is shown in positions 2-5 followed by a recovery phase (gliding phase) which is complete once the arms are brought back up to intial starting position (Rusko, 2003, 42).

Kick double pole technique. The DP kick technique is similar to the DP technique but includes a kick phase. Figure 2 shows the kick and poling phases of this technique. The propulsive kick is inserted before the poling phase and this gives additional forward momentum. Generally the kick leg changes from the left to right side. This technique is most commonly used on slight uphill when glide is decreasing. (Nilsson et al., 2004, Rusko, 2003, 44-45)

FIGURE 2. The double pole kick technique is similar to the double pole with an added kick phase. Position 1-3 shows the kick phase followed by the poling phase in position 4-7 (Rusko, 2003, 44)

Diagonal stride technique. The diagonal stride (DIA) technique is a movement that utilizes both the arms and legs. It involves a kicking and poling phase that are shown in Figure 3. The movement follows the basic walking pattern where arms and legs move in opposition to one another. This technique is most commonly used for climbing. When skiing on uphill terrain the glide phase is reduced significantly and this technique allows for greater ability to maintain propulsive force and it's frequency is easy to adjust. (Nilsson et al., 2004, Rusko, 2003, 38-41)

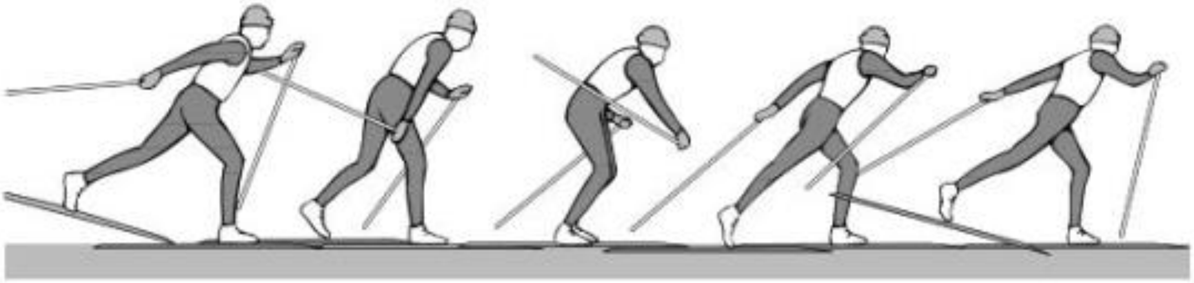


FIGURE 3 The diagonal stride technique includes both a poling and kicking phase. This figure illustrates a left arm poling phase (position 1-4) followed by a right leg kick (position 5) (Rusko, 2003, 38).

Herringbone technique. The herringbone technique is a movement and similar to the DIA, it also follows the basic walking pattern where the arms and legs move in opposition. However, rather than having parallel skis, the skis are angled into a “V-shape” and the edge of the ski is used to grip the snow. This technique is used on very steep terrain when is it hard or not possible to get effective grip with the DIA technique.

2.2 Skating techniques

Skating was introduced in the 1980's and became an official part of international ski races in the 1985-1986 season. Skating technique is predominantly about gliding and generating a propulsive force forward on the ski. Unlike classical skiing, static friction is not used and the ski is set down at an angle to the forward direction while gliding. The angle used depends on the steepness of the terrain (Nilsson et al., 2004, Rusko, 2003, 45).

V1 skating. A lower gear (also termed as gear 2) that is used primarily for uphills and when there a high resistance. It includes a DP motion that is synchronized with a skating motion. The poling motion occurs on one side of the body and this is referred to as the strong side while the opposite side is where only skating occurs and is referred to as the weak side. The arm movements during this technique consist of two phases with the pole plant to the pole life off being the thrust phase and the pole lift-off to the pole plant in the subsequent cycle being termed as the swing phase. Similar phases occur with the legs. (Figure 4) (Nilsson et al., 2004, Rusko, 2003, 45-50).

V2 technique. The V2 technique (also termed gear 3) consists of a DP action that is performed with each skating stroke, therefore, it is a symmetrical technique. The poling phase has a short interval of time and begins during the second part of each skate stroke. This technique is mostly used on flat or slight uphills (Nilsson et al., 2004, Rusko, 2003, 45-50).

Open field. Similar to the V1 technique, open field (also termed gear 4) involves a poling motion on only one side of the body. However, the timing of poling and skating differs for this technique and it is primarily used for fast snow conditions and relatively flat terrain. The DP movement is performed after the initial glide phase and end of the poling movement is right before the transfer of the body to the weak side ski (Nilsson et al., 2004, Rusko, 2003, 45-50).

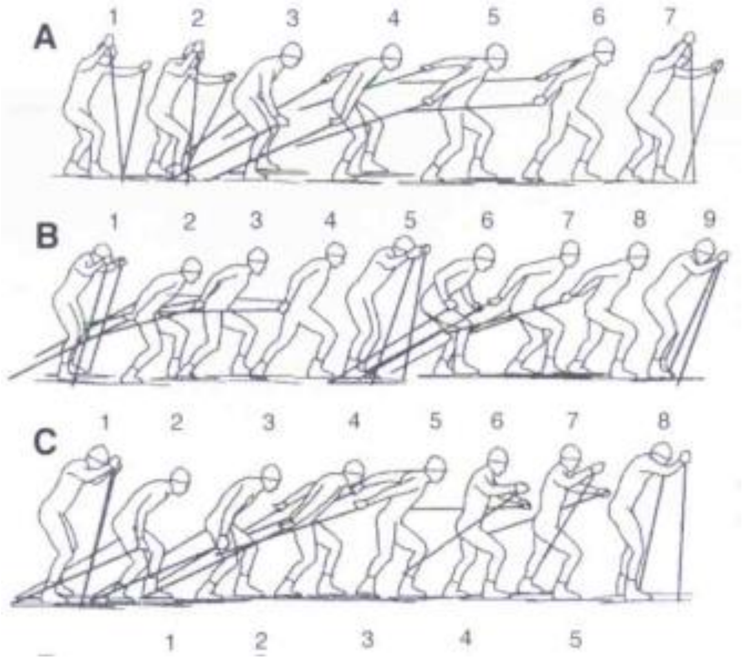


FIGURE 4. The movement cycles for three different skating techniques. Gear 2 (A) shows pole plant to pole lift off in positions 1-4 (thrust phase) followed by pole lift off to the next pole plant in positions 4-7 (swing phase). Gear 3 (B) shows a thrust phases at position 1-2 and 5-7 each followed by swing phases at positions 2-5 and 7-9. Gear 4 (C) shows the thrust phase in positions 1-4 followed by the swing phase in positions 4-8. Modified by Nilsson et al. (Nilsson et al., 2004).

3 PHYSIOLOGICAL FACTORS ARE IMPORTANT IN CROSS COUNTRY SKIING

XC skiing involves both endurance and speed components so it is necessary to utilize both aerobic and anaerobic energy production systems. Because of the high demands in the sport, skiers are known to have high maximal oxygen consumption values. In addition, high aerobic power and capacity are both necessary factors in cross country skiing. The ability of the neuromuscular system to resist fatigue and to recruit muscle for power and force production is also important. Furthermore, anaerobic and aerobic energy production are essential in cross country skiing and as with all endurance sports blood lactate production cannot be ignored. As a result, it is necessary to consider many different factors when investigating the sport of cross country skiing.

3.1 Adaptations to training

Adaptations that occur in response to training are based on the stress theory. Similar to physiological stress, physical exercise is a stimulus to the human body and it responds in various ways. Muscles are recruited, hormones are secreted, energy yield is increased, functional reserves are mobilized and defense mechanisms are activated as a response to exercise (Rusko, 2003, 62, Åstrand, 2003, 516). With continued exercise stress, the human body changes and adapts to these responses. Training-induced adaptations provide an increased ability to prevent a future disturbance of homeostasis. Although skiing involves speed and the anaerobic energy system, a large portion of the training is focused on endurance. Therefore, the main adaptations that occur are a result of endurance training.

Endurance Training. Endurance can be defined as the ability to withhold a given velocity or power for as long as possible. As a result, it is heavily dependent on the aerobic re-synthesis of ATP and requires adequate oxygen supply as well as carbohydrates and lipids for a source of fuel (Jones and Carter, 2000). Enhancing cardiovascular endurance is a primary goal for endurance sports, such as XC skiing. Endurance training causes different physiological adaptations then resistance or anaerobic training. (Hoffman, 2002, 110) Training to the respiratory muscles may prolong the constant-intensity exercise abilities and reduce blood lactate concentrations during exercise (Spengler et al., 1999). The exact order that the training adaptations occur is not clear. However, it is believed an increase in the recruitment of muscle is first. This is followed by an increase in enzyme concentration which results in an increased force production and greater blood flow. Three main parameters that are affected by endurance training are the maximal oxygen uptake (VO_{2max}), exercise economy, and blood lactate accumulation/lactate threshold (LT) and they will be examined in further detail in the following chapter (Hoffman, 2002, 110-119).

3.1.1 Maximal oxygen uptake

Maximal oxygen uptake (VO_{2max}) is a fundamental measure of exercise physiology and it is defined as the highest rate of oxygen consumption achieved during maximal exercise (Bassett and Howley, 2000). As exercise intensity increases, oxygen consumption also increases. Eventually, the oxygen consumption reaches a plateau and no longer increases. This point is known as the VO_2max (Hoffman, 2003, 110) In scientific literature, the most common method to show a training effect is by showing increases in VO_2max values (Bassett and Howley, 2000). Most literature suggests that this training should be of a high intensity at about 80-100% of VO_{2max} (Jones and Carter, 2000). A brief 10-day training period proved that training results in rapid and continuous improvements in aerobic capacity with a 10% increase in VO_{2peak} values for untrained subjects (McArdle et al., 2001, 484). Although VO_{2max} values commonly increase with intense training, there are still many physiological factors that can cause possibly limitations (Joyner and Coyle, 2008). Figure 5 shows several common limiting factors for maximal oxygen uptake and endurance performance.

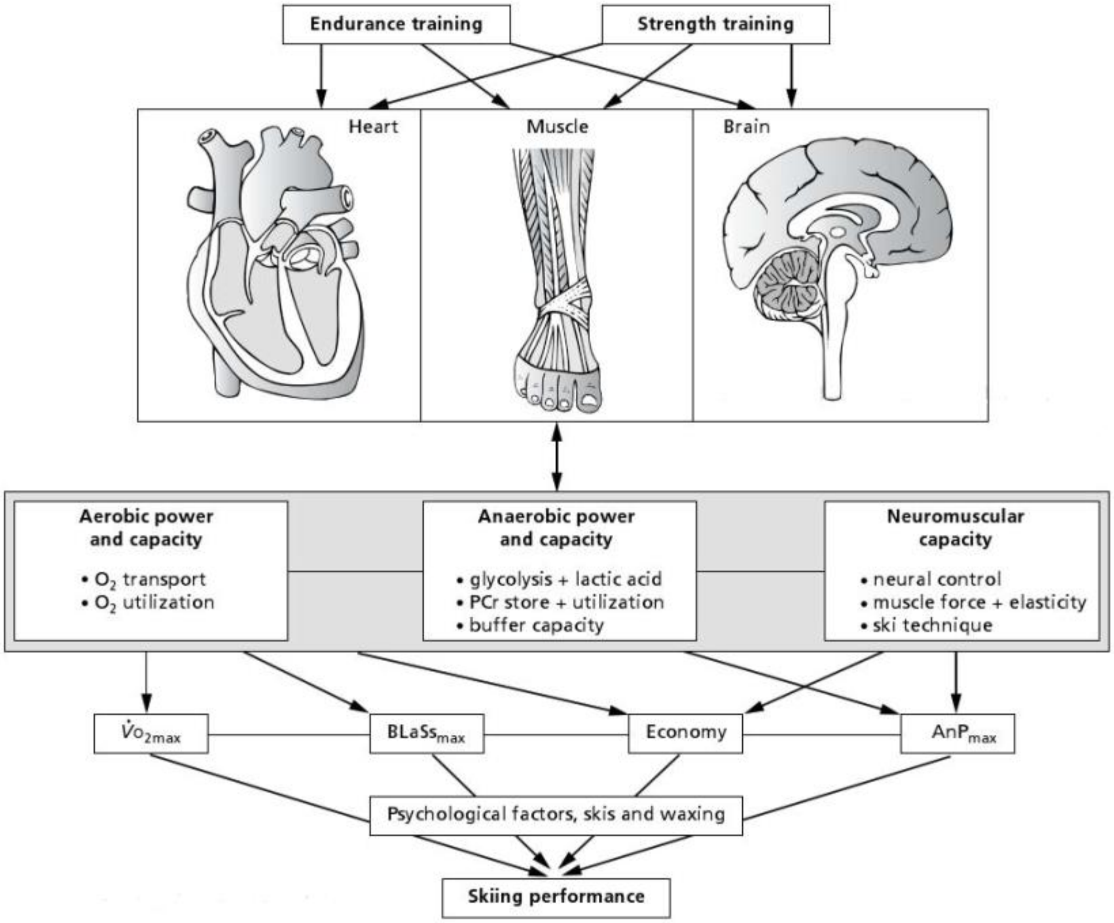


FIGURE 5: Physiological factors that may limit VO_{2max} while exercising.(Rusko, 2003, 18)

In agreement with much research, Jones and Carter (2000) also supported that VO_{2max} values are highly related to the maximal cardiac output (Q_{max}). Cardiac output (Q) generally refers to the amount of blood that is pumped by the heart in one minute and is the product of heart rate (HR) and stroke volume (SV). During exercise, Q is increased along with a redistribution of blood flow to the working muscles. At rest skeletal muscles receive about 15% of the Q and exercise increases this value to 80-85% (Åstrand, 2003, 161). When comparing a muscle to a trained muscle, it requires less blood flow for the same submaximal exercise due to an increase in arterio-venous oxygen difference. Training causes increases in SV which allows for a reduced HR and an increased ability of the exercising muscle to extract oxygen and therefore, a greater VO_{2max} (Jones and Carter, 2000). It is argued that endurance training causes an increase in mitochondria and the trained muscles become adapted to endurance exercise and can oxidize fat at a higher rate, which spares blood glucose and muscle glycogen. There is also a decrease in lactate production which will be discussed in more detail in section 2.1.3. These muscle adaptations are an important part in explaining increases in endurance performance (Bassett and Howley, 2000).

Unlike other sports, XC skiing involves almost all of the major muscle groups. As a result, elite XC skiers' success is largely dependent on their bodies' ability to uptake oxygen and therefore, they typically have high VO_{2max} values. In a study comparing VO_{2max} values in various athletes they found that XC skiers had the highest values in both male and female subjects (Saltin and Åstrand, 1967).

3.1.2 Exercise Economy

Exercise economy is defined as the oxygen uptake required at a given absolute exercise intensity (Jones and Carter, 2000). This can be shown by plotting oxygen uptake values versus the velocity. When looking at studies done with endurance running, there is a linear relationship between submaximal running velocity and individual VO_2 values. However, there is a considerable amount of variation in how much oxygen is used to run at a given speed when comparing individuals. This can be explained by looking at exercise economy (Bassett and Howley, 2000). The high amount of inter-individual variability in exercise economy may explain the differences in performance with athletes that have similar VO_{2max} values. When improvements in technique are made this helps reduce the energy demand needed for a given exercise velocity, resulting in a more economical performance (Hoffman, 2002, 113). In addition to technique, factors such as weight, body temperature, and wind resistance also effect exercise economy. (Figure 6) It is apparent that greater exercise economy is an advantage in endurance sports because it results in the utilization of a lower percentage of the VO_{2max} at specific exercise intensities. As a result, relatively low VO_{2max} measurements in elite athletes can be explained by exceptional exercise economy (Jones and Carter, 2000). Today, as elite athletes continue to reach faster times in endurance events. This is partly explained by advancements in equipment but it is also important to consider the effects of exercise economy.

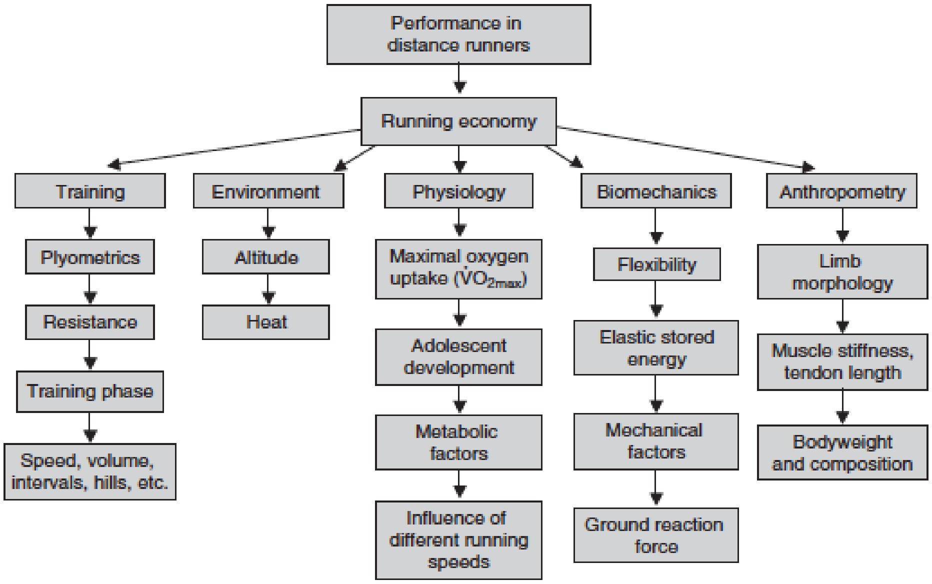


FIGURE 6: Factors affecting Running Economy (Saunders et al., 2004).

In XC skiing, the differences in economy are even greater than that of running because there is a greater demand on technique and many different techniques to utilize. In addition, the skis and wax used depends on the given conditions and this can have a considerable effect on the exercise economy at that time (Hoffman, 2002, 26). Literature in skiing is in agreement with findings of comparable sports that aerobic capacity and efficiency are important determinants of performance. Ainegren et al. (2013) compared skiers of all levels and found large ranges in skiing economy and efficiency. They felt that these factors are highly influential on individual results and could even have as large of an effect as peak VO_2 values have on performance (Ainegren et al., 2013). XC skiing training involves a large amount of low intensity training which is believed to increase the ski economy. World-class skiers perform a greater amount of endurance (85%) and speed training and therefore, have higher gross efficiency. Gross efficiency (GE) is the term often used to describe efficiency rate in XC skiing. It is determined by looking at the work generated and the total energy expended (i.e., metabolic rate) and is shown as a percentage (Sidossis et al., 1992). Therefore, similar to economy higher values most likely show an increase in performance. XC skiing is a complex technical endurance sport, so it is reasonable to suggest these differences are due to a better efficiency in technique, hence improved exercise economy (Sandbakk et al., 2011, Moxnes et al., 2009).

Sandbakk et al. (2010) further investigated the physiology of world-class skiers against national-class skiers to see if physiological differences were visible. They found no significant differences in VO_{2max} or V_E (minute ventilation), but the world-class skiers worked at a significantly lower percentage of their VO_{2peak}. As a result, the world-class skiers showed higher aerobic capacities in addition to an 8% higher VO_{2peak} during maximal tests and a higher gross efficiency (Figure 7). Therefore, these physiological advantages, as well as better gross efficiency, possibly explain the improved efficiency that resulted in a higher exercise economy.

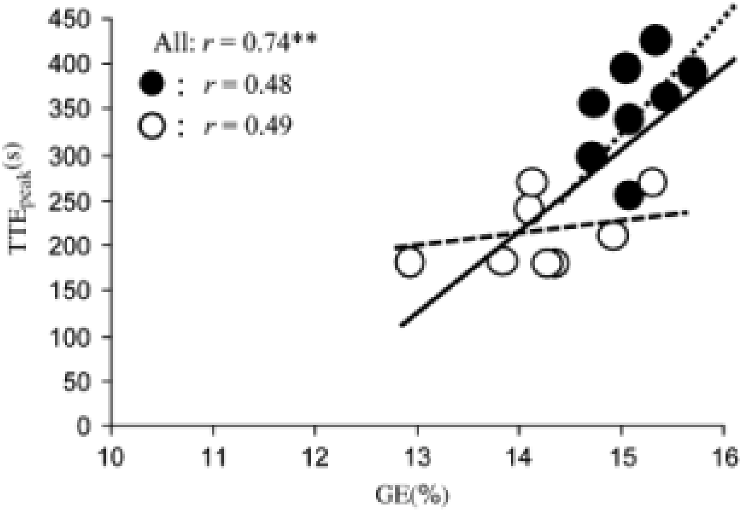


FIGURE 7. Correlations between treadmill performance in the G3 technique (TTE_{peak}) and gross efficiency (GE). Correlations and linear regression lines are shown for the two groups and for all skiers pooled. **P<0.01. Dark circles show world-class and white shows national class. (Sandbakk et al., 2010)

3.1.3 Lactate Threshold

Lactate threshold (LT) is the exercise intensity that corresponds to the increase in blood lactate above resting levels. (Jones and Carter, 2000) Numerous studies have shown how LT is an important factor in endurance sports (Bassett and Howley, 2000, Jones and Carter, 2000). It has been well researched that endurance exercise will result in increases in lactate threshold levels, due to a rightward shift, which allows for a higher exercise intensity to be reached. Carter et al. (1999) performed a 6 week endurance training study that included continuous running sessions at LT and interval sessions that were about 10 bpm above LT. They found 9.9% increases in VO_2 with the training group in addition to changes in heart rate and blood lactate. Figure 8 shows the blood lactate and heart rate response they found after the 6 week training period with the training and control group.

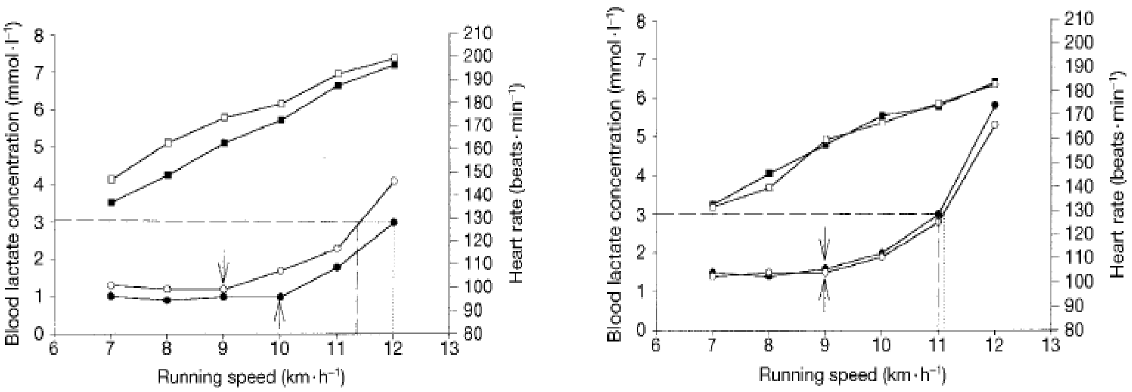


FIGURE 8. Left graph shows the training groups blood lactate and heart rate response to the 6 week endurance training program. The right graph shows the control groups measurements. Lactate threshold are represented with arrows and dashed lines indicate the running speed where 3 mmol/L blood lactate was reached. Circles represent the blood lactate measurements and squares represent HR with solid filled shapes indicating they are post-training concentrations (Carter et al., 1999).

Since XC skiing is also an endurance sport, research done with running as the mode of exercise often show similar results making them comparable. However, as previously mentioned, ski races involve both upper and lower body and range from 1-50 kilometers in distance so the contribution of aerobic and anaerobic energy differs depending on this race distance. Distance races are not often performed at VO_{2max} values and aerobic energy is utilized and it is necessary to reach a steady state of lactate production and lactate removal. Studies based on threshold research define the average maximal lactate steady state as 3-4 $mmol \cdot l^{-1}$ higher than resting values but this value changes from one individual to the next and could be as high as 7 $mmol \cdot l^{-1}$ (Rusko, 2003, 24). Literature has also found 4 $mmol \cdot l^{-1}$ to be the most common starting point of accelerated blood lactate accumulation and therefore, it is often known as the onset of blood lactate accumulation (OBLA). Although there is some controversy the understanding of lactate metabolism will continue to improve and it will continue to be an important factor in endurance sport (Åstrand, 2003, 252).

4 THE DOUBLE POLE TECHNIQUE

In the past few decades, the importance of DP has increased in competitive XC skiing. Advancements in ski equipment, technical preparation of tracks and a greater emphasis on improving elite skiers' upper body capacity have influenced these changes. In addition, increased demands have been made on a skier's ability to reach high DP velocities due to the introduction of short sprint races and mass starts (Lindinger et al., 2008). These new training methods have resulted in physiological adaptations which are important to investigate. DP is a main technique and critical component in XC skiing and is often an exclusive technique in competitions today.

As previously mentioned, the DP technique is most commonly utilized on horizontal tracks or on slight to moderate downhills. When there are fast track conditions and for elite skiers with (sufficient) upper body power the DP technique is also used on slight uphills. For steeper uphills a high poling frequency and a large amount of force would be required to DP effectively (Lindinger et al., 2008) which results in a higher lactate concentrations and therefore, is an insufficient technique on that terrain. The actual physiology of the DP technique will be described in further detail in this section.

One DP cycle is the period from the start of the pole ground contact to the start of the subsequent pole ground contact (Holmberg et al., 2005). This technique includes a poling and a recovery phase. The poling phase consists of the arm movement above the shoulders, the pole and snow contact point and the pole follow through and release. (Figure 1) The recovery phase is the gliding phase and the length of this phase depends on the intensity and speed that is applied. The DP technique is complex movement with many factors affecting the results.

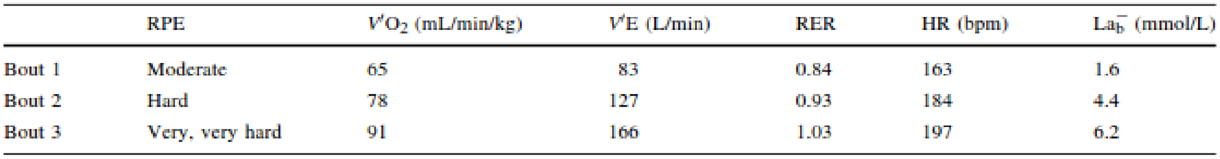
4.1 Physiology of the DP technique

Extensive research has been done focusing on the DP technique in competitive XC skiing and as a result, it has been concluded that there is both upper and lower body are involvement. (Pellegrini et al., 2011, Lindinger et al, 2009, Holmberg et al., 2006, Holmberg et al., 2004) Holmberg and his colleges (2006) examined movement patterns of the lower legs during DP and found that active leg muscles allowed for greater peak pole forces and higher propulsion in addition to their known stabilizing properties. So although DP technique is predominantly relying on an individual's upper body strength, it is important to study and investigate the lower body. The muscle activation and biomechanics of the DP technique have a significant effect on ski performance and need substantial attention in the scientific world. Therefore, the following sections will focus on the research and results that have been conducted on the physiological and biomechanical characteristics of cross country skiing focusing on the DP technique.

4.1.1 VO_2max values and measurements

As previously noted, XC skiers have some of the highest VO_{2max} measurements recorded. This is largely due to the high demands when exercising with both the arms and legs simultaneously. The highest maximal aerobic powers currently reported are 94 ml/kg/min for men and 77 ml/kg/min for female cross country skiers (Åstrand et al., 2003). Burtschur et al., (2011) performed a case study on the upper aerobic limits with an Olympic gold medal cross country skier and in addition to a VO_{2max} value of 90.6 mL/min/kg, they found a high hemoglobin concentration, high fat oxidation and low blood lactate levels during submaximal exercise (Burtschur et al., 2011). (Table 1)

TABLE 1. The ratings of perceived exertion (RPE), oxygen uptake values ($V'O_{2)}$, minute ventilation (V’E), respiratory exchange ratio (RER), heartrate (HR), and blood lactate concentrations (L_ab^-(mmol/L)) during three bouts of exercise on a roller ski treadmill. The reported values are averages for bout 1 and 2 and maximal values for bout 3 (Burtschur et al., 2011).



	RPE	$V'O_2$ (mL/min/kg)	$V'E$ (L/min)	RER	HR (bpm)	La_b^- (mmol/L)
Bout 1	Moderate	65	83	0.84	163	1.6
Bout 2	Hard	78	127	0.93	184	4.4
Bout 3	Very, very hard	91	166	1.03	197	6.2

It is well known that VO_{2max} values can increase with training and are also affected by many factors such as: gender, fitness level, genetics, body composition/weight, and age (Åstrand, 2003). In XC skiing, this value also changes depending on the technique that is being utilized. In research, when comparing DIA and DP in a maximal exercise protocol, similar peak HR and blood lactate values have been found. However, differences as great as a 15-20% decrease in the maximal oxygen consumption were recorded when comparing the DP technique to the DIA technique (Holmberg et al., 2007, Watts et al., 1993). Originally, it was suggested that the lower VO_2 values can be explained due to the decreased muscle mass in DP when the upper body is the primary contributor, but it also reflects the lower oxygen extraction that is associated with a lower oxygen conductance in the upper body when compared to the lower extremities (Calbet et al., 2005). VO_{2max} is about 70% lower in arm compared to leg exercise and the intra-arterial blood pressure is higher for arm only exercises which cause a higher demand for the heart (Åstrand et al., 2003). When comparing the change in efficiencies for uphill roller skiing with DP and DIA research results showed a higher metabolic demand for skiing up a steeper incline in the DP technique. This additionally supports the result that DP has a lower peak oxygen uptake and results in a higher and less efficient work rate compared to DIA (Hoffman et al., 1995). Van Hall et al. (2001) further investigated this idea by comparing leg and arm lactate during exercise. Since the legs contain more muscle than the arms they expressed arm and leg data per kilogram of muscle. They discovered similar work and net glucose values but higher lactate uptake paired with a lower lactate release for the leg muscles, suggesting that the arm muscles have a lower ability to utilize lactate paired with a higher ability to produce lactate (Van Hall et al.,2001). In addition, it is also possible that there is a greater degree of heterogeneity in the distribution of blood flow in the arm verses leg muscles. Holmberg et al. (2005) findings support this idea by finding large inter-individual differences in the upper arm muscles in the degree of recruitment when performing DP while measuring electromyographic activity (Holmberg et al., 2005).

Another study (Holmberg et al., 2006), investigated the influence DP, DIA and running (RUN) had on the lung function and oxygen uptake (Figure 9) with seven elite international-level XC skiers. They found the VO_{2peak} to be the lowest in the DP technique for both maximal and submaximal treadmill tests (Table 2) and significant differences in the absolute VO_2 for all three exercise modes (Holmberg et al., 2006).

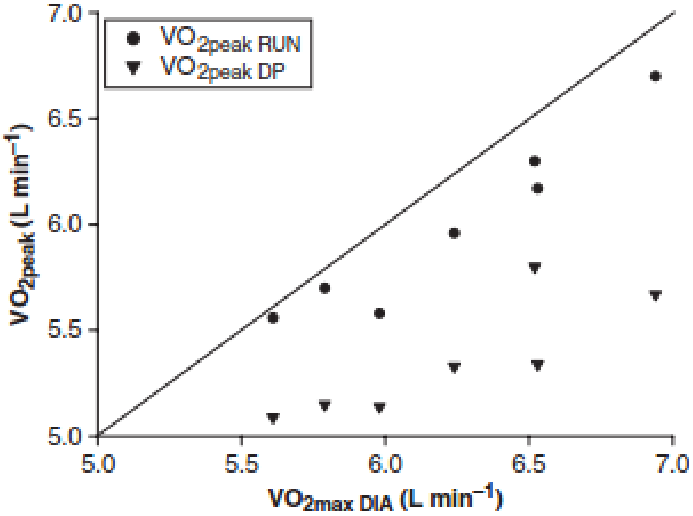
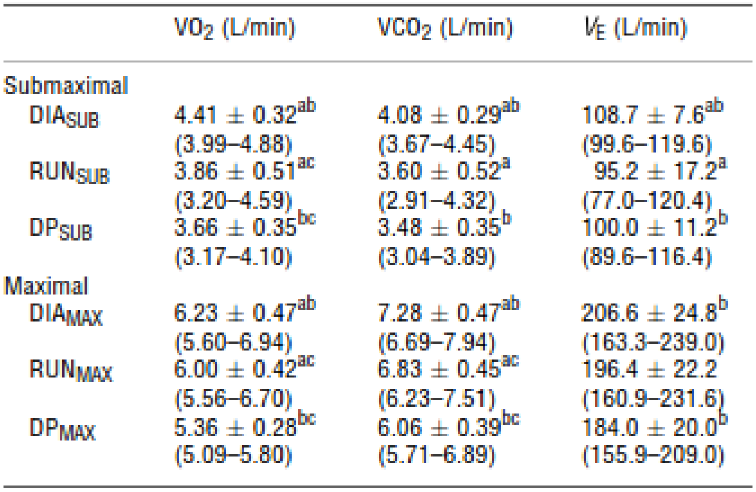


FIGURE 9. Individual values for $VO_{2peak\ RUN}$ and $VO_{2max\ DP}$ vs $VO_{2max\ DIA}$ (L/min). Line of identity is also shown. (Holmberg et al. 2006)

TABLE 2. Submaximal and maximal values for seven cross country skiers performing diagonal skiing (DIA), running (RUN), and double pole (DP) Values are means ± SD. ^{a}Difference between DIA and RUN (P<0.05). ^{b}Difference between DIA and DP (P<0.05). ^{c}Difference between RUN and DP (P<0.05) (Holmberg et al., 2006).



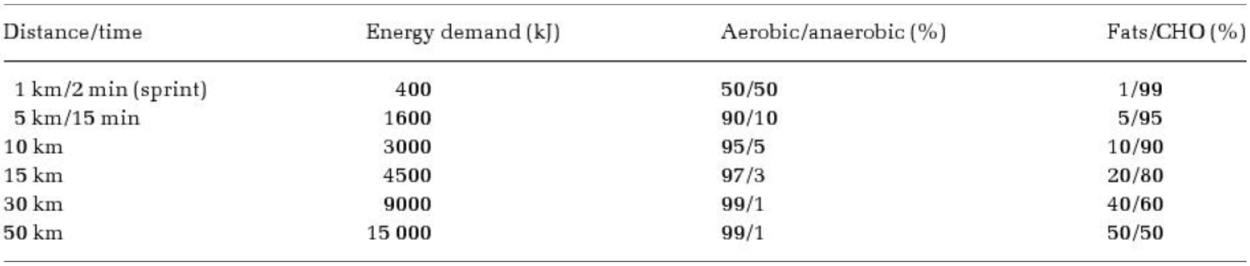
	VO_2 (L/min)	VCO_2 (L/min)	$\dot{V}_E$ (L/min)
Submaximal			
DIA_{SUB}	4.41 ± 0.32^{ab} (3.99–4.88)	4.08 ± 0.29^{ab} (3.67–4.45)	108.7 ± 7.6^{ab} (99.6–119.6)
RUN_{SUB}	3.86 ± 0.51^{ac} (3.20–4.59)	3.60 ± 0.52^{a} (2.91–4.32)	95.2 ± 17.2^{a} (77.0–120.4)
DP_{SUB}	3.66 ± 0.35^{bc} (3.17–4.10)	3.48 ± 0.35^{b} (3.04–3.89)	100.0 ± 11.2^{b} (89.6–116.4)
Maximal			
DIA_{MAX}	6.23 ± 0.47^{ab} (5.60–6.94)	7.28 ± 0.47^{ab} (6.69–7.94)	206.6 ± 24.8^{b} (163.3–239.0)
RUN_{MAX}	6.00 ± 0.42^{ac} (5.56–6.70)	6.83 ± 0.45^{ac} (6.23–7.51)	196.4 ± 22.2 (160.9–231.6)
DP_{MAX}	5.36 ± 0.28^{bc} (5.09–5.80)	6.06 ± 0.39^{bc} (5.71–6.89)	184.0 ± 20.0^{b} (155.9–209.0)

It is clear to see that there are many attributes and factors that need to be considered when explaining these differences. However, research concludes that despite similar peak HR and peak blood lactate measurements the DP technique results in lower peak oxygen uptake when compared to other techniques (Watts et al., 1993).

4.1.2 Energy expenditure

Energy expenditure is defined as the amount of energy required to move a specific distance. Similar to exercise economy, energy expenditure is an individualized value that can change depending on the technique, such as double poling, that is being utilized. As a result, energy expenditure can have a significant influence on XC skiing performance as well as other endurance sports. Table 3 shows the energy required for various XC skiing races and if the energy output is anaerobic or aerobic energy (Rusko, 2003, 5).

TABLE 3 Different energy demand and contribution of aerobic and anaerobic energy production for various common distances in cross country ski competitions. (Rusko, 2003, 5)



Distance/time	Energy demand (kJ)	Aerobic/anaerobic (%)	Fats/CHO (%)
1 km/2 min (sprint)	**400**	**50/50**	**1/99**
5 km/15 min	**1600**	**90/10**	**5/95**
10 km	**3000**	**95/5**	**10/90**
15 km	**4500**	**97/3**	**20/80**
30 km	**9000**	**99/1**	**40/60**
50 km	**15 000**	**99/1**	**50/50**

There are many studies that have analyzed and compared changes in energy cost. Pellegrini et al. (2011) compared the physiological responses to increase in speed and slope for three different classic techniques. They found that when skiing on flat terrain (0-1 degree) the cost of locomotion for DP was lower making it a more economical technique for that terrain. Arms only skiing requires 40% less energy than legs-only skiing when skiing on a flat terrain, which can be explained by the lower propulsive forces they generate and due to the body weight support the legs passively support (Bellizzi et al., 1998). However, the cost of locomotion for DP has a higher rate of increase and no economic advantage is found once the terrain has a slope of 3 degrees or more (Pellegrini et al., 2011). This higher rate of increase compared to other techniques can be explained by a lower work economy in arms compared to legs and a significant increase in the exerted force that is necessary to DP uphill. At a 4 degree incline, the poling force value is 3 times larger compared to flat terrain, whereas diagonal stride only requires 1.5 times the increase (Pellegrini et al., 2011). Therefore, the energy cost is dependent on the slope of the terrain and the DP technique is only more economical at flat or very low inclines. (Figure 10)

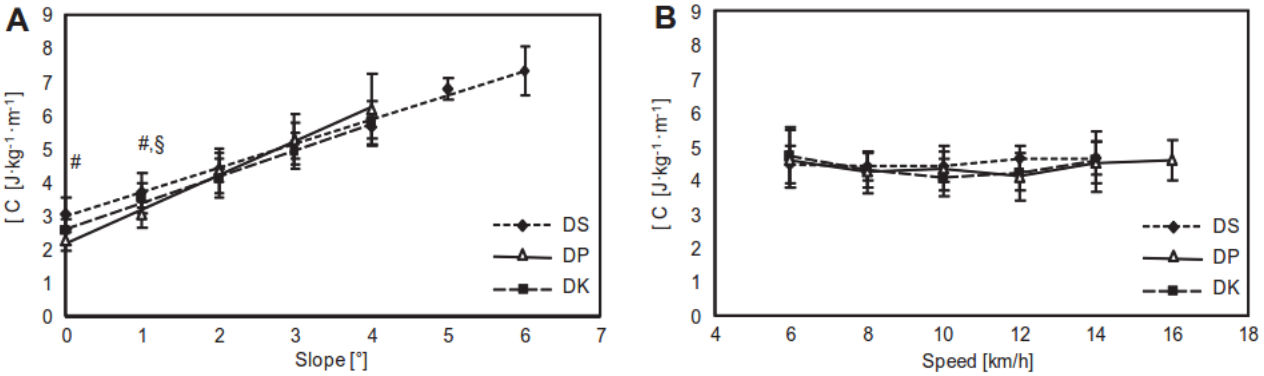


FIGURE 10. This shows the energy cost as a function of slope during a fixed speed of 10 km/h (graph A) and a speed at fixed slope of 2 degrees (graph B)(mean and standard deviation). Diagonal stride (DS), Double pole (DP), Double pole kick (DK). Significant differences between techniques ($p<0.05$) are indicated with symbol # for DS vs. DP, § for DP vs. DK and € for DS vs. DK. Modified from Pellegrini 2013. (Pellegrini et al., 2013).

Another study also investigated the muscle use during the double pole technique. This was done with positron emission tomography and studying the glucose uptake index levels at two different poling intensities (Bojsen-Møller et al., 2010). Similar to previous studies they found upper body to be the important contributor but also noted an increased whole body energy output with activation of the lower spine, hip and muscles of lower legs as the double poling intensity increased. There was a 27% increase of glucose index uptake in the knee flexors and 21% for the abdominal muscles when the intensity was increased 74% of peak VO_{2peak} values (Bojsen-Møller et al., 2010). This further supports the increasing importance of the lower legs during a propulsive double pole performance.

4.1.3 Blood lactate accumulation

One major producer of lactic acid during exercise is the skeletal muscles. An increase in the lactate level in muscle and blood is caused by a shift in the balance between the pyruvate production verses the consumption. An increase in pyruvate levels results in blood lactate accumulation (Åstrand et al., 2003). In XC skiing, it is helpful to know when a specific technique is an advantage over another, therefore, it is important to examine and compare blood lactate values in similar testing environments.

Van Hall et al.(2001) investigated this idea by comparing leg and arm lactate during exercise. Since the legs contain more muscle than the arms they expressed arm and leg data per kilogram of muscle. They discovered similar work and net glucose values but higher lactate uptake paired with a lower lactate release for the leg muscles suggesting that the arm muscles have a lower ability to utilize lactate paired with a higher ability to produce lactate (Van Hall et al., 2001). Additional literature supports this idea by finding the highest blood lactate concentrations when using the DP technique during submaximal exercise tests compared to running and diagonal stride (Holmberg et al., 2006).

4.2 Differences found among technique

In all sports, there is a recommended technique and specific way that is suggested in order to achieve optimal results. Years of coaching and research have worked together to find these answers but regardless of their discoveries differences will always exist. Every individual has different strengths and weaknesses they need consider when working to reach their highest level of performance. In addition to these differences, the specific way a technique is executed by an individual also varies. The following section will cover individual, physiological and biomechanical differences that can be found within the DP technique.

4.2.1 Individual differences

When analyzing the angular patter in DP, the body works as a chain of segments and the muscles engage in sequential order with the initial movement in the trunk and hip flexors, followed by shoulder extensors and the elbow extensors/triceps brachii. (Holmberg et al. 2005, Zory et al., 2008). How this movement is executed changes from one individual to the next. Individual differences as much as 22-33% were noticed in roller ski economy when testing skiers that were using the same pair of roller skis. This could be due to different body types, strength levels, flexibility and increased efficiency from high volumes of training. It has been shown that faster skiers begin their poling phase with their poles and trunks in a more vertical position and have a higher pole force and a shorter poling phase. Furthermore, they are also characterized by having a greater angular velocity in hip and elbow flexion with smaller minimum angles in the elbow, hip and knee. (Zory et al.,2008, Holmberg et al., 2005, Smith et al., 1996). These concepts will be further discussed in the biomechanics section.

Smith et al.(1996) used video analysis during the women's 30 kilometer race at the 1994 Winter Olympic games to investigate visible differences in DP technique. Movement patterns of 20 skiers were collected for analysis with 10 subjects from the top of the field and 10 additional subjects from the bottom third of the field. They highlighted that shoulder rotation was one main contributiors to the double pole technique with most top skiers displaying a large range of motion while others had a relatively small flexion-extension pattern. Even with elite skiers, few individuals displayed similar shoulder patterns but all utilized the stretch-shortening cycle for the triceps brachii muscle. (Figure 11) (Smith et al., 19996). When comparing faster and slower groups, the elbow angular velocites were significantly different between the faster and slower groups for both flexion and extension which is likely due to the faster groups improved ability to use the triceps preloading affects. (Smith et al., 1996).

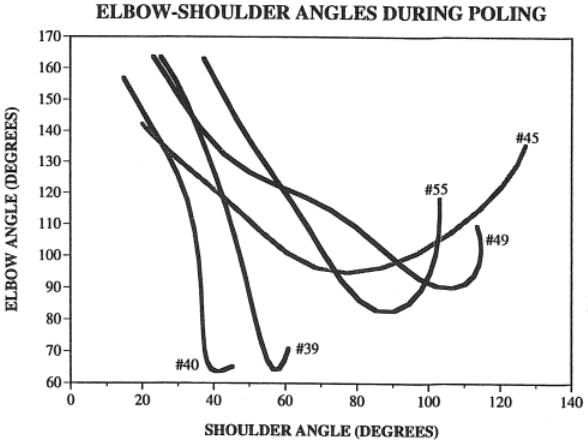


FIGURE 11. Shoulder angle verses elbow angle was plotted from measurements taken during the poling phase. Poling began at the right of each curve and proceeded to the left. 5 different skiers results are shown above that display two distinct patters of the shoulder involvement in double poling. Most skiers plant the pole with the elbow at a position of 100˚ or more and then allow the elbow to flex through 20-30˚. All results in this graph are taken from the fast group. (Smith et al., 1996)

Many individuals have their own specfic style or certain technique they prefer. Regardless of preferance, it is important to use the available scientific knowledge to help enhance and better performances.

4.2.2 Gender Differences

Men and women’s performance levels are compared in many different sports. Although they compete under similar environmental conditions, men have been found to have several physiological advantages. An average man has about 40-45% muscle mass, whereas 25-35% of body weight is muscle mass for females (Åstrand et al., 2003). When looking at the muscle fiber areas, the ratio is changes with females having larger type 1 areas while males typically have larger type 2 muscle fibers (Larsson et al., 2002). In addition, males' maximal anaerobic power is 15-30% superior to that of females. XC skiing involves both endurance and strength. In particular, the DP technique has an even greater emphasis on strength. Research has further confirmed this finding by showing the importance of ski-specific upper body strength in skiing. They had 13 male subjects and saw a clear relationship that having developed upper body strength was a prerequisite for successful performance (Manhood et al., 2001). As a result, gender differences are even greater in exercise modes where upper body is involved (Sandbakk et al., 2012). Therefore, it is important to consider these differences when analyzing and researching the sport.

Research has shown a 10-12% performance increase in elite male endurance athletes when compared to females. For most endurance sports, this is explained due to a higher VO_2max and lower body fat percentage found in men. Recently, Sandbakk et al., (2012) found a 17% gender difference when comparing uphill skating on roller skies. This more pronounced gender difference can be partially explained by men’s' more effective poling abilities. When the influence of poling was investigated, the DP technique had the greatest gender differences as 20% (Sandbakk et al., 2012). (Figure 13) The same subjects showed a 12% difference when performing running tests which was in agreement to previous endurance test comparing genders. Similar results were found during uphill skating technique with 17% greater speed in men and 21% longer cycle lengths at max speed which agrees with previous studies that men's increased speed is associated with a longer cycle length (Sandbakk et al., 2012 , Lindinger et al., 2009a).(Figure 12) This research concludes that when the contribution from upper-body propulsion increases, as seen in DP technique, gender differences are more pronounced.

Due to the many parameters in XC skiing, research has studied many different physiological factors during treadmill tests to see which presents the best correspondence in relation to performance. Larsson et al., (2002) found different parameters relative to performance correlations for men verses women. The best predictors of performance for males were the OBLA (onset of blood lactate accumulation) and TDMA (threshold of decompensated metabolic acidosis) whereas, with females, RER (respiratory exchange ratio) was a better predictor. This solidifies the importance of taking gender differences into consideration when interpreting and analyzing research results.

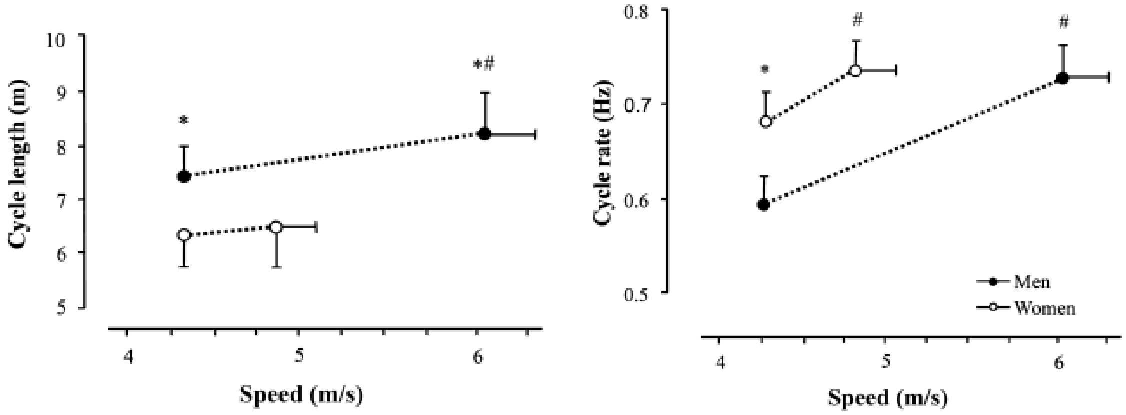


FIGURE 12. Differences in cycle length and rate for males and females during submaximal treadmill tests (4.4 m/s) and at maximal speed using the DP technique. Mean values are presented with ± standard deviation (vertical bars). # Indicates significant differences between genders and *significant differences between submaximal and peak speed within each group. (Sandbakk et al., 2012).

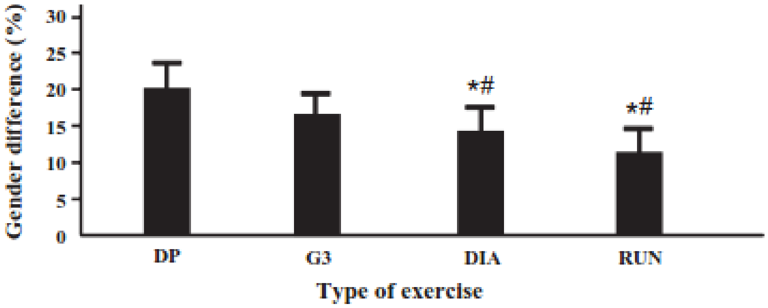


FIGURE 13. Contribution of poling on relative gender differences in speed for eight male and eight female performance matched sprint XC skiers in four different techniques. From high use of poling (left) to no use of poling (right): peak speed using double pole (DP), G3 skating, diagonal stride (DIA) and treadmill running (RUN). #Significantly different from DP and *significantly different from G3 (P<0.05). (Sandbakk et al., 2012)

5 BIOMECHANICS OF THE DOUBLE POLE TECHNIQUE

There has been numerous studies investigating the physiological aspects of DP but it is also necessary to look at the technique in further detail and from a biomechanical perspective. Successful XC skiing involves a combination of different techniques and these complex movements need to be smoothly linked together to generate maximum performance. This involves examining kinematics, the description of motion (such as speed, displacement and acceleration) and kinetics, the causes of motion (such as force, energy and torque). Although performance results are strongly related to an individual's physiology, this mechanical side of skiing cannot be ignored. (Moxnes et al., 2009, Rusko, 2003, 32) As a result, many studies have been performed on the DP technique investigating forces, cycle length/time and joint and pole kinematics.

5.1 Forces

The propulsive forces in DP are produced from upper body and trunk activity and are released through the ski poles. The poling force effectiveness is dependent on the trunk, shoulder, elbow and hand placement. A biomechanical analysis of DP was done by Holmberg et al. (2004) that showed the distinct impact forces throughout the DP movement with peak pole force occurring around the same time as the minimum elbow angle. (Figure 14) They found most successful skiers to use a DP strategy with specific characteristics that are directly correlated to DP velocity. This strategy consists of smaller joint angles, higher flexion velocities, and higher pole force applied during a shorter poling phase (Lindinger et al., 2011. Lindinger et al., 2009b, Holmberg et al., 2004).

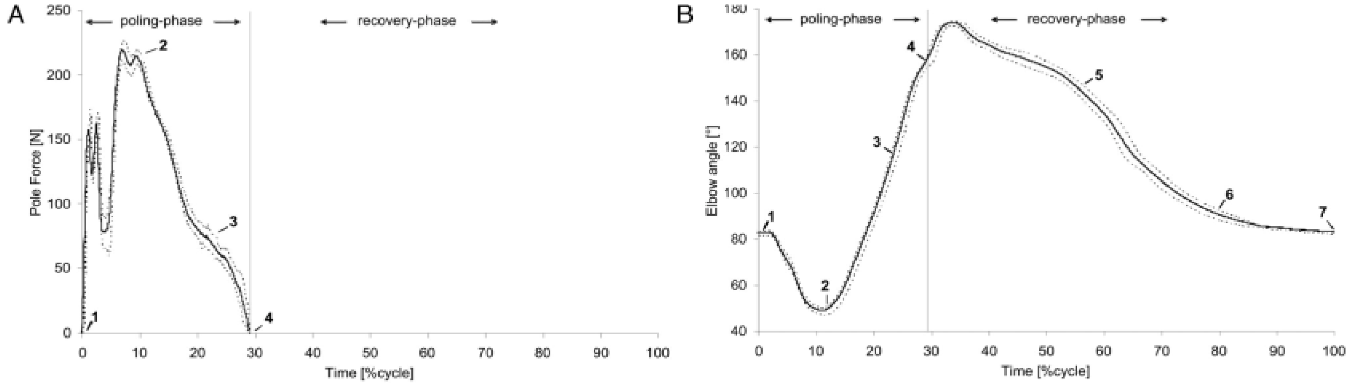


FIGURE 14. Pole Force (A) and elbow angles (B) verses time during a double pole cycle at 85% of Vmax. Poling and recovery phases both marked (Holmberg et al., 2004).

There is little a skier can do to change the gravitational force acting to slow or to propel him down the tracks. In contrast, frictional forces generated by skis on the snow and the body passing through air can be affected by technique and equipment (Holmberg et al., 2004, Rusko, 2003). A compiled study by Lindinger et al., (2009a) shows a comparison of poling frequency and the cycle length at submaximal and maximal DP velocities. (Figure 15) This shows that elite skiers are using a DP strategy that generates higher velocities by increasing both the poling frequency and the cycle length. A longer cycle length is attained by an increase in force production during a short poling phase. This DP method requires a well-developed ability to produce high pole force over a short time and stresses the necessary demands for specific explosive strength and highly developed motor skills (Lindinger et al., 2009a).

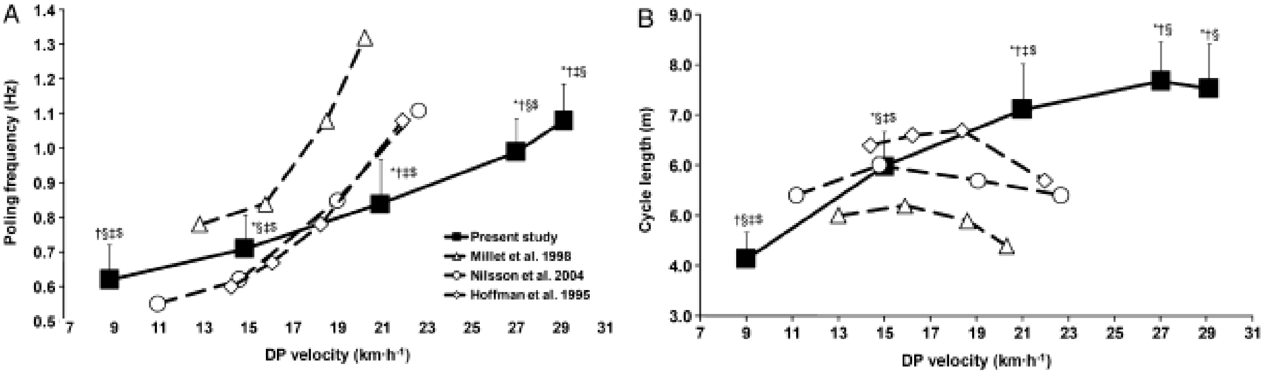


FIGURE 15. Submaximal and maximal DP velocities verses poling frequency (A) and cycle length (B). All data is mean values. *different to 9 km/h; † different to 15 km/h;§ different to 21 km/h; ‡ different to 27 km/h; $ different to Vmax (all P values < 0.05). (modified from Lindinger et al., 2009a).

When comparing the different classical techniques used in skiing, DP showed the highest force production. However, when skiing uphill, the force exerted through the pole increases greatly and the arms experience additional costs and it is no longer the most economical technique. Pellegrini et al. (2013) hypothesized that this could be due to a limit on the force. This finding is in agreement with additional research that found little change in the average pole force at various speeds (Vähäsoyrinki et al., 2008). (Figure 16) Before solid conclusions can be made, further studies will need to be conducted.

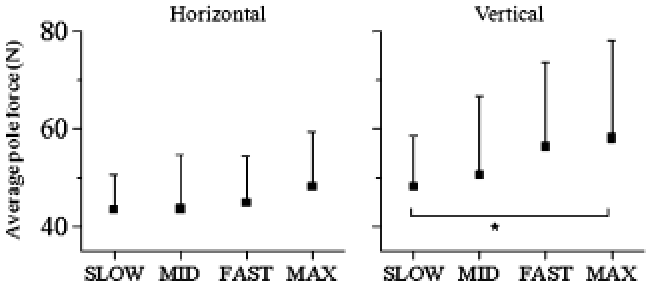


FIGURE 16. Averaged horizontal pole forces (left graph) and averaged vertical pole forces (right) during pole contact. Significantly different conditions at * P< 0.05 (Vähäsöyrinki et al., 2008).

5.2 Double pole cycle

The DP cycle can be separated into the propulsion phase and the recovery phase. The cycle time is defined as the time it takes from the start of one propulsion phase to the start of the subsequent one (Stöggl et al., 2006) and the cycle length is the distance covered per cycle. DP speed is regulated by the product of the cycle length and the poling frequencies (Lindinger et al, 2011). Previous research that studied cycle characteristics believed that increases in speed were primarily due to increases in the poling frequency and cycle length increases were not common (Lindinger and Holmberg, 2011, Hoffman et al., 1995). At present, high performance DP is now characterized as a more dynamic movement with shorter poling phases, longer recovery times, higher forces and greater force impulses that generate a more explosive push off. A recent study disapproves earlier research showing that elite skiers control their DP speed by increasing both the poling frequency and cycle length (Lindinger et al., 2009a). This increase in cycle length is achieved by increasing the pole force which could be a result of improved upper body strength and more focused upper body training but is also possibly due to new technical patterns in the DP technique that allow for a greater utilization of the lower body and different arm and shoulder patterns (Lindinger et al., 2009a). They found impulses of pole forces as much as 38% higher when the skiers used longer cycle lengths at lower poling frequencies. It is argued that greater force is generated during longer cycle lengths due to the skier's ability to recruit a larger amount of muscle fibers than during shorter cycles. However, it is also suggested that the poles are planted at greater angles which possible creates a better preloading of the upper-body, and a higher center of mass as well as a greater forward lean is the result of generating greater forces (Lindinger and Holmberg, 2011). Regardless of the cause, the most important factor is finding the optimal relationship between the cycle length, poling frequency and the force impulse in the given cycle time (Stöggl et al, 2009).

Lindinger et al., (2009b) further investigated DP at submax and maximal velocities on a treadmill by examining the neuromuscular activity and the use of the stretch shortening cycle in arm and shoulder extensor muscles. Their results showed that the poling phase was characterized a by flexion-extension pattern in the elbow joint which became more pronounced with increasing DP velocity and that a stretch-shortening cycle occured in the elbow joint and adapted to higher velocities with a faster elbow flexion and a more immediate transition between the flexion and extension phases. When looking at peak pole force, highest force was found at the smallest elbow angle. (Figure 17)

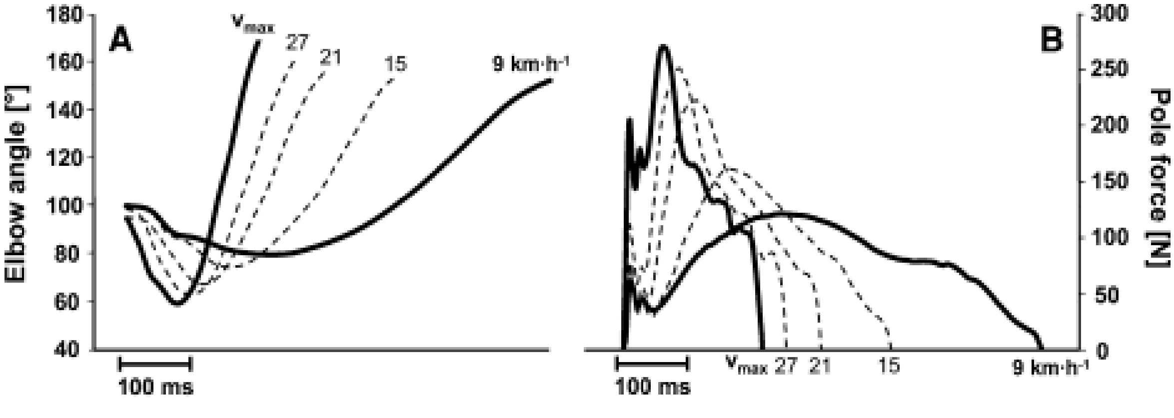


FIGURE 17. Graph A: Shows representation of the elbow angle at various DP velocities. Graph B: Shows representation of the pole force curves at various DP velocities. (Lindinger et al., 2009b)

5.3 Joint Kinematics

As previously mentioned, the joint angles and flexion-extension patterns are different from one individual to another. However, similar patterns and trends are found in successful and highly trained skiers. Elbow flexion and extension angular velocities are the highest at lower poling frequencies. This is often found in combination with high force values which allows the skier to cover a greater distance and therefore, increases the cycle length (Lindinger and Holmberg, 2011). Additional advantages to performing the DP techinque at a lower frequency is the more immediate transition from the flexion and extension and increased force production that enables an effective utilization of the stretch-shortening cycle (Lindinger et al., 2009a,b). Leg joints of the knee and hip also show greater flexion/extension at the lower poling frequencies and elite skiers have a better ability to adapt to changing speeds.

The contribution of the legs to the DP techinique was studied in further detail with a study comparing normal and locked knee joints (Holmberg et al., 2006). Locked knees showed many disadvantages such as a decrease in force, lower peak velocities, higher heart rate and lactate values and lower maximal DP velocities. This is due to the skiers increasing their poling frequencies because the poling phase was less efficient without active leg work. This finding supports highlights the importance of lower body and supports previous research that longer cycle lengths and lower poling frequencies create a more effective DP movement.

In conclusion, research has demonstrated a strong relationship between the level of maximal DP velocity, along with specific upper body strength, and DP performance. DP performance plays a crucial role in competitions and individual technique can result in significant gains or losses. Modern high performance DP has been shown to have shorter ground contacts and a more dynamic flexion-extension movements in the elbow joint, together these factors generate higher pole forces and more expolsive pole thrusts (Lindinger and Holmberg, 2010, Lindinger et al., 2009b, Holmberg et al., 2005, Smith et al., 1996). As advancements in equipment and technique continue to be introduced it is important for science to also advance and investigate and uncover the physiological and biomechnical advantages so skiers are able to reach their highest possible performance level.

6 PURPOSE OF THE STUDY AND RESEARCH QUESTIONS

The aim of this study was to compare the physiological differences and determine any possible advantages while performing the double pole technique while using curved verses straight cross-country ski poles. The study included a progressive treadmill test with three increasing speeds testing both curved and straight poles in a randomized order. The idea was to study and compare VO_2 values, blood lactate, ventilation values and gross efficiency to determine if there were any visible advantages or differences between the pole types being utilized. Three various speeds were tested to see if speed was a prevalent factor and if faster speed resulted in greater changes between the curved and straight ski poles. Research questions and hypotheses are as follows:

1. **Do curved ski poles result in an improved physiological response compared to straight traditional ski poles while performing the double pole technique?**

H1: Curved ski poles do not show improved physiological responses in the double pole technique when compared to straight poles.

No previous studies have been performed investigated the physiological response that occurs while using curved poles. When comparing the differences between the two poles identical angles of the elbows, back and knees are found suggesting the only difference with the curved poles is a more forward application of pole force due to the curved design. The curved design is only a small difference and as a result, no significant differences in the physiological responses will be found.

2. **Do curved ski poles result in an improved ski economy at low, easy or medium intensities compared to straight ski poles while performing the double pole technique?**

H2: Due to increased force production curved poles show a slightly higher ski economy when compared to straight ski poles while performing the double pole technique.

It has been suggested that the change in the pole plant due to the curved pole allows for an increase in the force applied.

7 METHODS

7.1 Subjects

Ten well-trained cross country skiers, 5 males (24.2 ± 6.83 years) and 5 females (21.8 ± 3.42 years), were recruited for this study (Table 4). A large number of the athletes were students at the Vuokatti-Ruka Sports Academy. The inclusion criterion was that all subjects were trained and familiar with the double pole technique. Data was analyzed separately for male and female subjects due to the different speeds used in the protocol to make sure that the subjects were testing at low, easy and medium intensities. All subjects had prior experience and familiarity of performing tests on a roller ski treadmill which made a training/familiarization phase unnecessary. Before participation, all subjects were fully informed and aware of the experimental protocol and possible risks of the study. Verbal and written instructions were given and all subjects provided a signed consent form. All subjects were able to complete the entire study protocol and no sickness or injuries occurred. As a result, all tests were included in the final analysis.

TABLE 4. Characteristics of the subjects during the study (mean ± SD).

	Women (n = 5)	Men (n = 5)
Age (yr.)	21.8 ± 3.4	24.2 ± 6.8
Height (cm)	167.6 ± 8.4	180.7 ± 3.3
Weight (kg)	60.2 ± 7.0	77.1 ± 2.4

7.2 Study Protocol

The study protocol included a treadmill test that was performed on roller skies while using both curved and straight ski poles. The testing protocol included three increasing speeds that were pre-determined to stimulate the double pole technique at a low, easy and medium intensity level. Speeds were adjusted based on gender with the males protocol at speeds of 13 km/h, 17 km/h and 21 km/h and females tested at speeds of 8 km/h, 12 km/h, and 16 km/h. Each intensity level was tested for a ten minute period with 5 minutes of each pole to make sure a steady state was reached. The order of straight or curved pole type being used was randomized for every subject. Blood lactate measurements were taken between the

5 minute periods when the pole type was changed. All subjects followed their own training plan throughout the testing period but they were asked to be recovered before the treadmill test. Because all subjects were familiar with the technique being used no prior training period was conducted.

7.3 Data Collection and Analysis

All tests were done in the laboratory at the Vuokatti Sports technology unit of the Department of Biology of Physical Activity, University of Jyvaskyla and Vuokatti Sports Institute (Snowpolis, Vuokatti, Finland). Before the study all subjects needed to be healthy and not under the influence of alcohol or any other substance that could have an impact on performance levels. The test protocol itself was safe and involved only small blood samples. There is only a small risk involved, such as falling, and the proper safety measures such as a harness and straps in addition to a proper warm-up and guidance throughout the test was implemented to minimize these risks.

Performance tests. The subjects were asked to be in a recovered state but training methods were not fully monitored before the tests were conducted. Before each treadmill test began, body weight (kg) and height were assessed and recorded. Also, each subject gave a written consent before the test and the testing protocol was thoroughly explained before the testing procedure began. Subjects were informed their rights to end the test by raising their hand if necessary. However, they were strongly encouraged to continue and complete the test if possible. All subjects were able to complete the testing protocol. Treadmill tests were conducted at 1 degree inclination and all subjects used the same Marwe roller skis (Classic 700 XC, Marwe Oy, Hyvinkää, Finland) that were provided to remove any difference in rolling resistances between treadmill tests. Subjects were able to use their own ski boots. EXEL ski poles were used with both curved (Figure 18b) and straight poles provided for the subjects. Before the initial treadmill test, a 5 minute warm-up was conducted to allow the subject to feel comfortable and warm up the roller ski wheels. The warm-up was performed at a low intensity and the same speed was used for the first tested speed. The starting speed for females was 8 km/h and males were 13 km/h and each stage increased by 4 km/h. The testing procedure included 5 minutes with one pair of poles followed by a short pole exchange and a small blood sample obtained using single use capillary blood sampling lancets (Unistik 2 Comfort) from the subject's fingertip were taken for blood lactate measurements (Arkray Lactate Pro Blood lactate test meter, Figure 18a). The treadmill was stopped for this short exchange period. An additional 5 minutes was then performed at the same intensity but with the opposite pole type followed by another blood lactate measurement. The pole type being used at the end of the initial stage was also used for the first part of the following stage at an increased speed, minimizing the pole exchange time needed and further randomizing the pole type throughout the treadmill test. Throughout the treadmill double pole test, breath-by-breath data of ventilation and respiratory gases (CORTEX Metamax 3B, Biophysik GmbH, Leipzig, Germany) and heart rate (Polar S410 heart rate monitor, Polar Electro Oy, Kempee, Finland), were continuously measured and monitored. The Metamax 3B transportable analyzer was calibrated before each test and resting values for heart rate and blood lactate were also obtained.

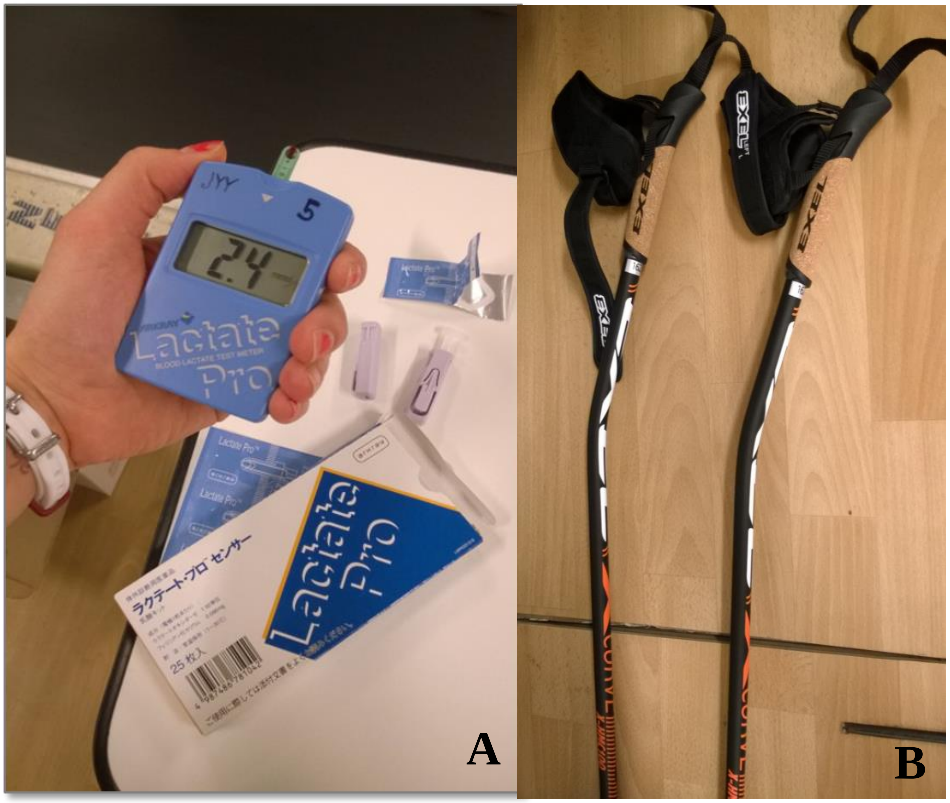


FIGURE 18. Measurements of capillary blood lactate concentrations from the fingertip were taken with the Lactate Pro blood lactate analyzer (A). EXEL curved poles (B) were the tested curved poles used during this investigation.

Gross efficiencies. Gross efficiencies were calculated as the external work rate divided by the metabolic rate (ME = WR/MR), in accordance with Sandbakk et al. (2010, 2013). The metabolic rate was calculated from the VO_2 and VCO_2 values during the steady state of each tested speed. This was obtained by averaging each value during the final two minutes of the 5 minute stages. The final metabolic rate value was calculated with the averaged oxygen consumption and the corresponding oxygen energetic equivalent (RER value) using the associated respiratory exchange ratio and standard conversion tables (Bellizare et al. 1998, Sandbakk et al., 2010, 2013). To determine more accurate metabolic rates, averaged blood lactate levels during each steady state were also viewed and when blood lactate levels exceeded (<2.0 mM) it's influence on the metabolic rate were taken into consideration and the energetic value of (change of blood lactate) was calculated on the basis of an equivalent of 60 J · kg-1· mM-1 (3 mL $0^2 \cdot kg^{-1} \cdot mM^{-1}$) (Prampero et al., 1993). The work rate was then calculated as the sum of power against gravity and friction [$P_f = m \cdot g \cdot \cos(\alpha) \cdot \mu \cdot v$]; where m is the mass of the skier, g is the gravitational acceleration (9.81 m s^{-2}, α is the angle of the treadmill incline (1 degree Celsius), v is the treadmill belt speed and μ was the frictional coefficient.

Frictional coefficient was measured with roller skis on the treadmill at 0 degrees while holding a pole which was connected to a force sensor (Figure 19). The coefficient of friction was then calculated by dividing the friction force with the weight of the skier and roller skis being tested. This test was conducted with two skiers (weights of 76 and 94 kg) and the friction value was the same. In addition, the effect of speed to friction was also investigated and there was no effect found.

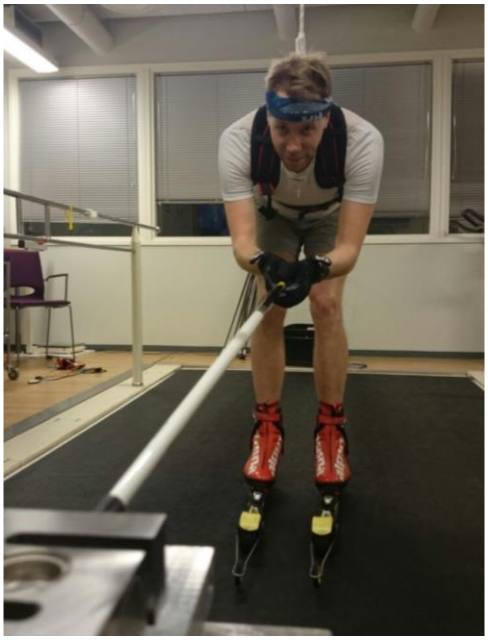


FIGURE 19. Determining the coefficient of friction value on the roller ski treadmill.

7.4 Statistical analysis

The results of physiological factors are expressed as means obtained from steady state of each tested parameter ± standard deviations (SD). Gross efficiencies are shown as percentages.

Results were analyzed separately for each gender due to changes in the protocol because faster speeds were needed for male subjects. To analyze differences between curved and straight pole mean values were calculated during the 2 minutes steady states for heartrate, blood lactate, VO_2, and VE. A paired t-test was used to compare the curved and straight poles for each of these factors. ANOVA for repeated measures was applied to the gross efficiency, heart rate, blood lactate, and oxygen uptake values to see if there were any significant differences between the straight and curved poles. All data was analyzed using Microsoft Excel 2013 for Windows. Probability level of $p \leq 0.05$ was applied as an indicator of statistical significance.

8 RESULTS

Technique comparison. When looking at the DP technique with the curved and straight poles there is no noticeable differences in the subjects' ankle, knee, back or elbow angles. The same pole heights were used for straight and curved poles, eliminating the length variable. The most noticeable difference between pole types is the angle of the pole plant with the curved pole having a slightly larger angle of ground contact. This also resulted in a pole plant that was further forward when using the curved poles (Figure 20). This was only a visual comparison and no statistical analysis was performed.

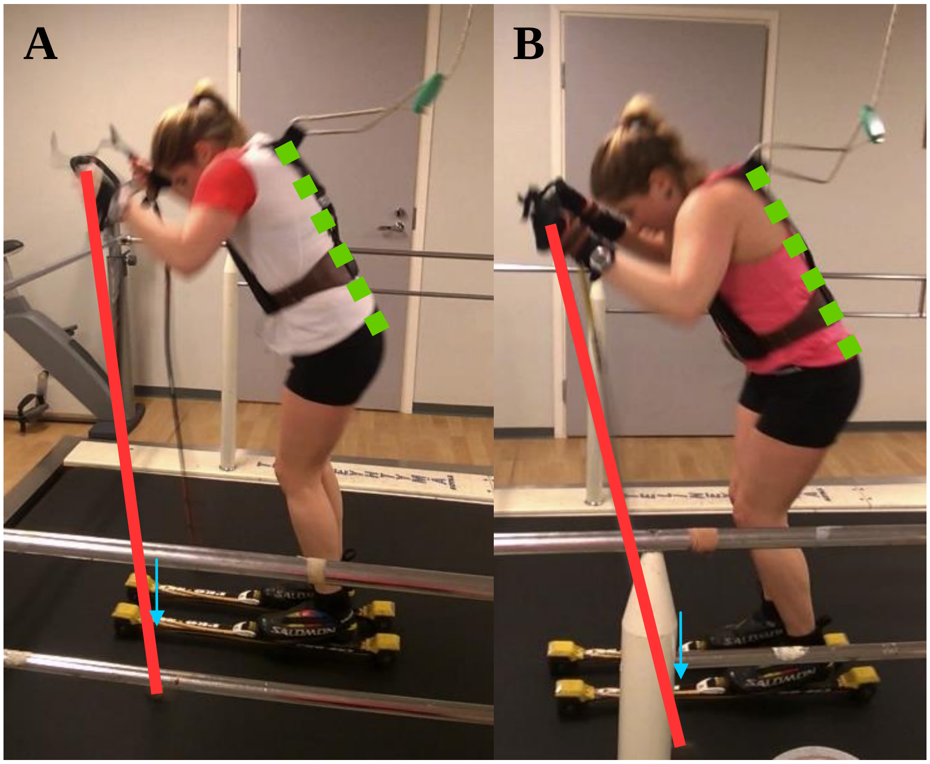


FIGURE 20. Comparison of pole plant ground contact, pole angle and angle of back and arm position with curved (A) and straight poles (B).

Oxygen uptake values. No significant differences were found in the oxygen uptake values at any of the tested submaximal speeds while performing the DP technique (Figure 21). As speed increased, oxygen consumption increased as predicted. For females while performing DP with straight ski poles, mean VO_2 values ($mL•kg^{-1}•min^{-1}$) were 21.4 ± 1.2 (speed 1), 28.0 ± 1.9 (speed 2) and 36.6 ± 4.1 (speed 3). Similar results were found with curved poles reaching mean values of 21.6 ± 0.9 (speed 1), 27.8 ± 2.5 (speed 2) and 37.1 ± 3.6 (speed 3). For males slightly higher values were obtained with the straight poles reaching mean values of 29.4 ± 1.9 (speed 1), 38.0 ± 1.7 (speed 2) and 49.3 ± 3.2 (speed 3) and the curved poles reaching mean values of 29.1 ± 1.6 (speed 1), 38.4 ± 1.8 (speed 2), and 50.2 ± 3.3 (speed 3).

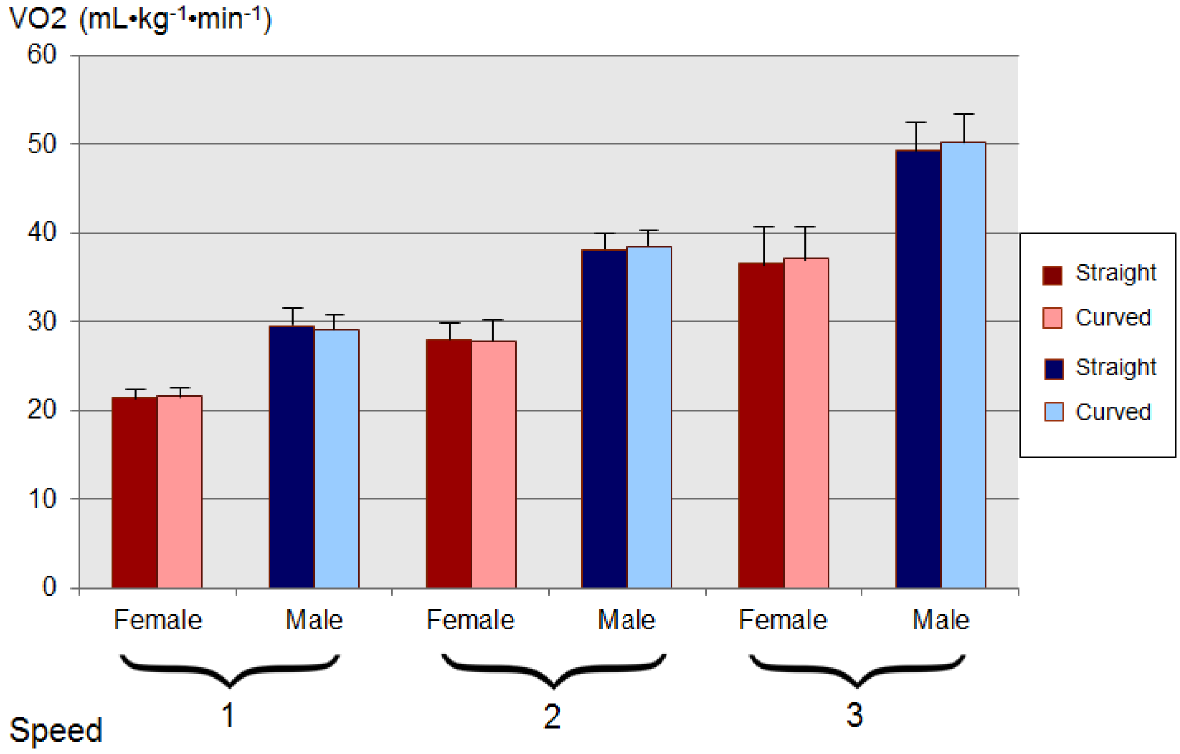


FIGURE 21. Oxygen uptake values for straight and curved poles at the three tested intensities. For females the following speeds were used: 8, 12, and 16 km/h and males performed the tests at: 13, 17, and 21 km/h. Bars represent the means and vertical lines standard deviations. (* $p < 0.05$)

Ventilation values. As Figure 22 shows, minute ventilation values showed similar values when comparing the straight and curved poles. However, for speed 1 (8km/h), female subjects shows a significant difference with slightly higher ventilation values with the curved poles (p = 0.042) and males had a similar response with higher ventilation values using the curved poles but during speed 3 (p = 0.047).

For females, mean V_E values (L/min) were 35.3 ± 4.6 (speed 1), 49.7 ± 3.6 (speed 2) and 68.9 ± 7.8 (speed 3). Similar results were found while using curved poles with mean values of 36.88 ± 4.18 (speed 1), 48.8 ± 4.3 (speed 2) and 71.2 ± 6.3 (speed 3). For males slightly higher values were obtained with the straight poles reaching mean values of 59.4 ± 4.1 (speed 1), 80.5 ± 6.3 (speed 2) and 112.7± 3.2 (speed 3) and the curved poles reaching mean values of 59.0 ± 4.6 (speed 1), 80.5 ± 6.3 (speed 2), and 116.9 ± 23.7 (speed 3).

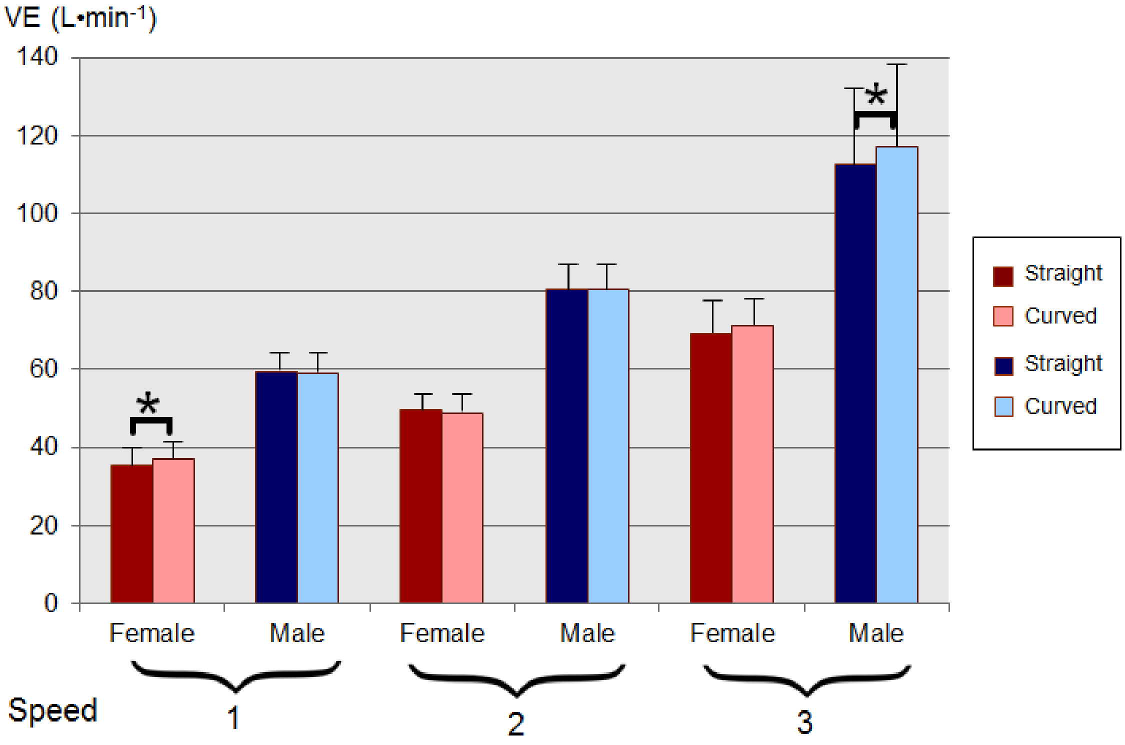


FIGURE 22. Ventilation values for the straight and curved poles at the three tested intensities. Significant differences were found during speed 1 for the females subjects (p=0.042) and during speed 3 for the male subjects (p=0.047). For females the following speeds were used: 8, 12, and 16 km/h and males performed the tests at: 13, 17, and 21 km/h. Bars represent the means and vertical lines standard deviations. (* p < 0.05)

Heart rate. No significant differences were found with heart rate values when comparing the two pole types (Figure 23). For females while performing DP with straight ski poles, mean heart rate values (bpm) were 126.8 ± 10.1 (speed 1), 146.2 ± 8.9 (speed 2) and 167.8 ± 7.3 (speed 3). Similar results were found with curved poles reaching mean values of 127 ± 10.3 (speed 1), 147 ± 11.3 (speed 2) and 169.6 ± 6.3 (speed 3). For males similar results were obtained with straight poles reaching mean values of 132.4 ± 14.0 (speed 1), 156.8 ± 9.0 (speed 2) and 175.2 ± 7.9 (speed 3) and the curved poles reaching mean values of 133.2 ± 10.5 (speed 1), 154.4 ± 9.0 (speed 2), and 179 ± 10.6 (speed 3).

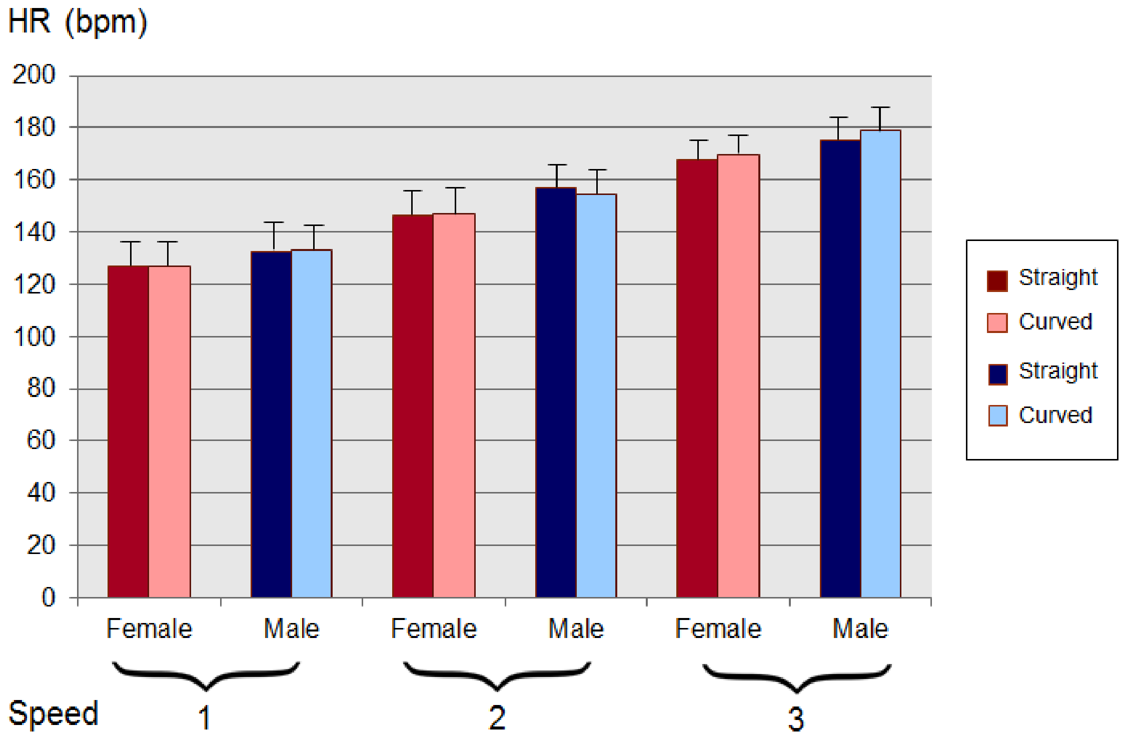


FIGURE 23. Heart rate values for straight and curved poles at the three tested intensities. For females the following speeds were used: 8, 12, and 16 km/h and males performed the tests at: 13, 17, and 21 km/h. Bars represent the means and vertical lines standard deviations. (* $p < 0.05$)

Blood lactate. No significant differences were found with blood lactate concentrations when comparing the two pole types. Although you will see slightly higher blood lactate values were found for the curved pole, differences were not significant (Figure 24). For females while performing DP with straight ski poles, mean blood lactate concentrations (mmol/L) were 1.3 ± 0.6 (speed 1), 1.6 ± 0.4 (speed 2) and 3.5 ± 1.4 (speed 3). Similar results were found with curved poles reaching mean values of 1.5 ± 0.7 (speed 1), 2.4 ± 0.7 (speed 2) and 3.6 ± 1.9 (speed 3). For males similar results were obtained with straight poles reaching mean values of 1.6 ± 0.5 (speed 1), 2.2 ± 1.0 (speed 2) and 5.7 ± 2.9 (speed 3) and the curved poles reaching mean values of 1.7 ± 0.6 (speed 1), 2.8 ± 1.0 (speed 2), and 6.0 ± 4.2 (speed 3).

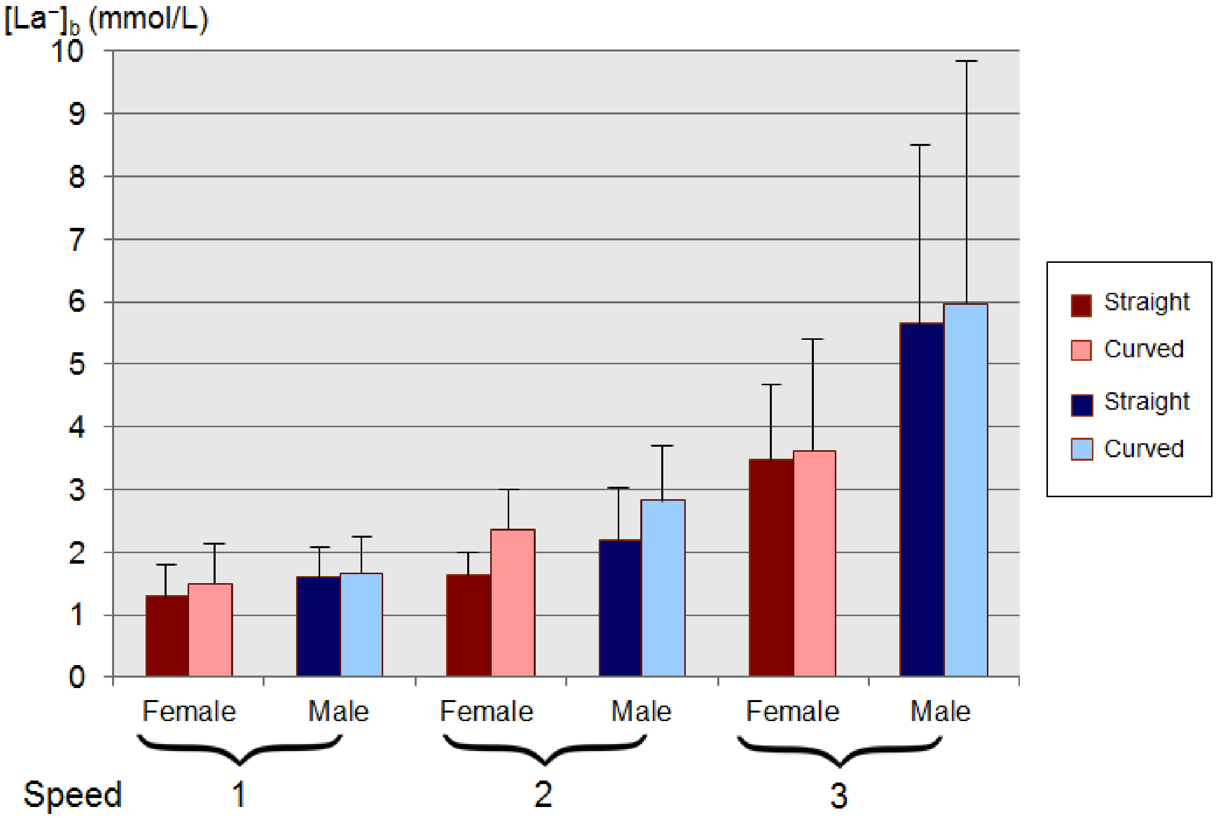


FIGURE 24. Blood lactate values are shown for straight and curved poles at the three tested intensities. For females the following speeds were used: 8, 12, and 16 km/h and males performed the tests at: 13, 17, and 21 km/h. Bars represent the means and vertical lines standard deviations. (* $p < 0.05$)

Gross Efficiency. Gross efficiency values showed similar values between the curved and straight poles. For females while performing DP with straight ski poles, mean GE (%) were 25.8% ± 1.3 (speed 1), 29.6% ± 2.1 (speed 2) and 30.2% ± 3.9 (speed 3). Similar results were found with curved poles reaching mean values of 25.4% ± 1.1 (speed 1), 29.8% ± 2.8 (speed 2) and 29.2% ± 3.0 (speed 3). For males similar results were obtained with straight poles reaching mean values of 30.2% ± 2.2 (speed 1), 30.4% ± 2.0 (speed 2) and 28.8 ± 1.64 (speed 3) and the curved poles reaching mean values of 30.6% ± 1.8 (speed 1), 29.6% ± 0.9 (speed 2), and 28% ± 2.2 (speed 3). No significant differences were found and mean values between straight and curved pole were differences within or less than 1 percent.

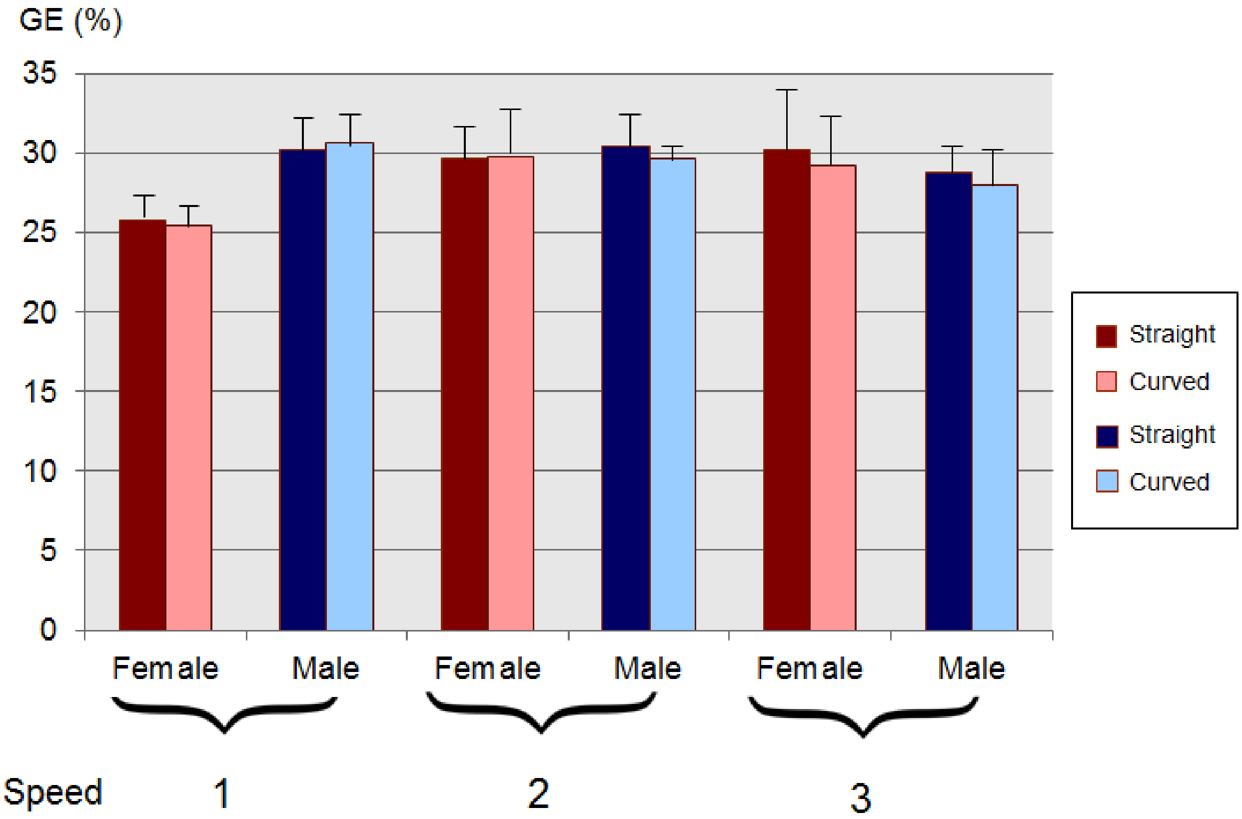


FIGURE 25. Gross efficiency values for straight and curved poles at the three tested intensities. For females the following speeds were used: 8, 12, and 16 km/h and males performed the tests at: 13, 17, and 21 km/h. Bars represent the means and vertical lines standard deviations. (* $p < 0.05$)

9 DISCUSSION

To our knowledge, this is the first study to investigate and compare the economy and physiological effects that occur during the double pole technique while using straight traditional ski poles verses curved poles (EXEL). The physiological factors investigated were heart rate, blood lactate, oxygen uptake and ventilation. In addition, exercise economy was determined and compared by using the gross efficiency values that were found for both curved and straight ski poles. The main findings of this study showed no significant differences between the two pole types at the three tested speeds of a low, easy and medium intensity. As expected, the physiological responses increased along with the increased speed but when comparing the two pole types the differences in heart rate, blood lactate and oxygen uptake were relatively small and did not reach statistical significant differences. In addition, no statistical differences were found when comparing the ski economy with curved versus straight poles.

Differences in poles tested. Cross country ski poles main requirements are that they are stiff and lightweight. They consist of a pole shaft, a handle with a wrist strap and a ski basket with a metal tip. Today, elite racing poles are constructed of carbon fibers in an epoxy resin. Research has tested and proven that this construction generates a high strength value while maintaining a minimum weight and high level of flexibility (Swaren et al., 2013). Unlike skis, pole structure and function does not depend on specific snow conditions so the same pair of poles is applicable in many different circumstances. So the question changes to what pole design is the most effective? The curved pole tested (EXEL) in this study was designed with the purpose to allow for increased power when double poling and improved biomechanical aspects, as well as muscle recruitment (FIS Skiing). Although the curved section contributes to an overall increased weight which is thought to be a disadvantage, the ergonomic advantage helps overcome the weight and strange feeling. It is thought to reduce lactate levels and our findings do not correspond to the previous suggestion with lactate levels slightly higher with the curved poles in all three intensities tested.

XC skiers normally use pole lengths of 83-85% of body height for classical skiing (Swaren et al., 2013) and the small range in height differences of our test subjects allowed for proper pole height to be utilized throughout our testing period. Therefore, no significant differences could be due to unfamiliar pole lengths while testing. It is possible that the curved poles have a training or learning curve before any positive advantages are shown. If that is the case, a short adaptability stage could be favorable so a "feeling" for the curved pole was present. A training period was not administrated so the acute affects of the curved pole were able to be examined and compared to the traditional straight pole. It is possible that allowing a training period would alter the overall results. In addition, any technique and equipment adjustments could be made before testing the subjects. This could have had a significant effect on the overall results. However, it is important to note that when tests are performed in a laboratory, the effects of possible uncertainties are minimized because all subjects are using the same technique and equipment and also performing the test at the same exact speed. This allows for an accurate and good comparison and enables work rates and metabolic rates to be measured (Watts et al., 1993). Therefore, this study shows that there are no advantages when double poling with curved or straight ski poles at the tested intensities.

Changes in Metabolic Rates. XC skiing allows individuals to travel faster and further than possible by foot alone. Elite skiers are able to sustain speeds for 10 kilometers that would exhaust world-class runners in one kilometer (Bellizzi et al., 1998). There is an equal amount of metabolic power available for both runners and skiers but the energetic cost of skiing is much lower, which further increases the stress and importance of the exercise economy. Gross efficiency or economy levels are important determinants of XC skiing performance and calculating these values allows for an easy comparison between different techniques at various speeds and on a wide variety of terrain. When we investigated the gross efficiency values we found no differences in the efficiency values for the two different poles. Therefore, our study does not support the idea that a curved pole allows for an increased economy level while performing the double pole technique at submaximal intensities. Losnegard et al. (2014) found that exercise economy did not change much regardless of the exercise mode examined. When testing different techniques the most economical subjects had the highest values in many difference exercise modes. Therefore, this agrees with the results found in the current study comparing the straight and curved poles. Regardless of the small changes of the pole shape, no changes in economy were shown. Losnegard et al. (2014) found that athletes tend to naturally select a cycle rate and length that is most economical for them and quickly adapt to changes. Curved poles are only a slight change in form, perhaps too small to cause an effect, and the DP technique is a technique XC skiers are very familiar with. It is possible no changes were found because the curved pole is not a high enough modification to the accustomed straight pole. The body quickly adapts and since minimal changes, if any, were needed in the individual movement patterns performed similar results were found when comparing the two pole types.

Force and cycle characteristics. It is possible that there were differences in cycle characteristics and force values between the two pole types. As previously mentioned, an increase in force would allow for greater speeds with equal energy costs and may also result in an increased cycle length. We have not analyzed the force values or cycle characteristics so at this time we cannot say whether these change are visible with the curved versus straight poles in the double pole technique.

Individual response. Individual differences are commonly found in the field of exercise physiology. No exceptions were made with this research study. As previously mentioned, XC skiers have a large range in body size and weight. Therefore, changes in poles can result in possible gains for certain individuals that show no advantage for others. The pole length utilized by elite skiers has varied throughout history. It has been shown that pole length affects elite XC skiers time to complete a short DP sprint (Hansen and Losnegard, 2010). They found longer poles resulted in an improved performance with seven out of eight of their subjects. Similar to this current study, no training period was used to the acute effect of changing the pole length could be examined. It is possible that if they allowed a training period with the longer poles that even better performance would have been found. It should also be noted that in this study one subject did not have an increase in performance which shows an individual response is also present. Similar to length, it is possible that the curved pole could work for some individuals. Hansen and Losnegard (2010) also stress that in increase in performance doesn't directly translate to an increase in race performance and it is important to consider the terrain of the entire course and that these gains may not be visible after an amount of intensive exercise was performed.

When analyzing the results based on the gender, no major differences were found between the male and female subjects. This shows that no gains were present with the curved poles regardless of the known strength advantages that males have. Overall, male subjects reached higher values in heart rate, blood lactate, VO_2 and ventilation which can be explained by the protocol that was used. Although both protocols were of submaximal intensities the protocol used for males was slightly more difficult resulting in these higher values. Despite this small difference, both protocols tested at comparable intensities so it did not alter the overall results.

Limitations of the study. There are a few limitations in this present study. First, a training/adaptability stage was not enforced prior to exercise testing. Although the DP technique used is familiar to all subjects when you are investigating a new product it is important to eliminate all variables and this unfamiliarity could have had an effect on the overall results. Although no training period was enforced to allow for the examination of acute changes, allowing this period may have shown greater differences. This training period was also not obtainable due to the limited availability of poles for all subjects involved. Even though there were only minimal differences between the two pole types, a performed test with even a slight unfamiliar feeling could have caused an addition mental stress and less relaxed and natural feeling.

Another limitation was that equipment adjustments may have needed to be performed to result in proper technique and pole plant. With a traditional straight pole, a slight turn in the wrist has no effect on the pole plant or applied forces. However, with a curve introduced to the pole, it is necessary that the subject’s wrist isn’t turned when planting the pole because this would result in the pole planting at the wrong place. A simple adjustment to the hand grip, where the pole is attached to the subject, could have fixed even slight error that may have occurred throughout the DP tests. Therefore, both of the above limitations could have been prevented with an adequate familiarization stage.

A third limitation to this study is that it only showed the clear effect of pole shape with the DP technique. Today, curved poles are used by some elite athletes in the World Cup Biathlon circuit which does not include the DP technique, but rather is performed with the skating technique. XC skiers encounter a wide variety of terrains and work demands so the DP technique is only a small part of their overall performance so this current study only investigates that one particular part.

Finally, the current protocol applied to this study was also a limitation. The testing protocol only investigated at submaximal speeds that were low, easy and medium intensities so it is possible different results could be obtained at maximal speeds.

Conclusions. The present study found that when comparing straight and curved ski poles during the DP technique at submaximal intensities there are no differences in the physiological responses or ski economy. However, there were significant differences with the female subjects in the low intensity (8 km/h) and for the male subjects during the medium intensity (21 km/h) in ventilation values with the curved poles showing higher ventilations. Blood lactate values were also higher with the curved poles but it was not a significant difference. In contrast, small if any differences were found between the pole types proving that curved poles do not result in any type of disadvantages. Therefore, it is possible that at faster speeds or with a familiarization period they result in a more economical double pole. As with all research, studies that show no significant results are also of importance. This study shows no acute affects, regarding physiological factors and economy, on submaximal double pole performance with curved poles but many other areas of importance that need to be explored. Further studies should investigate the force values, cycle rates and lengths to see if these factors show greater differences in performance levels.

Practical applications. Cross country skiing is a sport with very high physical demands so it is important to explore new ideas and determine any possible advantages they may provide. With small amounts of time, less than a second, often determining if an athlete wins or loses a competition, even very small improvements are of great importance. Poles with a curve or bend were explored in downhill skiing with the main gain to provide a more aerodynamic profile and today elite athletes' pole choice varies with some using curved and others preferring the straight poles. Therefore, it is necessary to investigate these ideas and to determine and provide scientific evidence to athletes and coaches, allowing them to decide what they believe will allow them to reach their highest performance level.

REFRENCES

Ainegren, Mats, Peter Carlsson, Mats Tinnsten, and Marko S. Laaksonen. 2013. Skiing economy and efficiency in recreational and elite cross-country skiers. Journal of Strength and Conditioning Research. 27.5:1239-1252.

Åstrand, Per-Olof, Kaare Rodahl, Hans A. Dahl, and Sigmund B. Stromme. 2003. *Textbook of Work Physiology: Physiological Bases of Exercise*. 4th ed. Canada: Human Kinetics, 2003. Print.

Bassett, David R. and Edward T. Howley, 2000. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Medicine & Science in Sports & Exercise. 31.1:70-84.

Bellizzi, Matthew J., Kellin A. D. King, Sara K. and Peter G. Weyand. 1998. Does the application of ground force set the energetic cost of cross-country skiing? Journal of Applied Physiology. 85:1736-1743.

Bergh, U. and A. Foreberg. 1992. Influence of body mass on cross-country ski racing performance. Med Sci Sports Exerc. 24.9:1033-9.

Bojsen-Møller, Jens, Thomas Losnegard, Jukka Kemmpainen, Tapio Viljanen, Kari K. Kalliokoski and Jostein Hallén. 2010. Muscle use during double poling evaluated by positron emission tomography. Journal of Applied Physiology. 109:1895-1903.

Burtscher M, Nachbauer W, and Wilber R. 2011. The upper limit of aerobic power in humans. European Journal of Applied Physiology. 111:2625–2628.

Calbet, J. A. L., H.-C. Holmberg, H. Rosdahl, G. Van Hall, M. Jensen-Urstad and B. Saltin. 2005. Why do arms extract less oxygen than legs during exercise? Am J of Physiol Regul Intergr Comp Physiol 289:R1448-R1458.

Coast, J. Richard, Jennifer S. Blevins and Brian A. Wilson. 2004. Do gender differences in running performance disappear with distance? Canadian Journal of Applied Physiology. 29.2:139-145.

Formenti, Feferico, Luca P. Ardigo and Alberto E. Minetti. 2005. Human locomotion on snow: determinants of economy and speed of skiing across the ages. The Royal Society. 272:1561-1569.

Hansen, Ernst Albin and Thomas Losnegard. 2010. Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. Sports Engineering. 12:171-178.

Hoffman, Jay. 2002. Physiological Aspects of Sport Training and Performance. United States, 2002. Print.

Hoffman, Martin D, Philip S. Clifford, Phillip B. Watts, Kathleen P. O'Hagen and Scott W. Mittelstadt. 1995. Delta efficiency of uphill roller skiing with the double pole and diagonal stride techniques. Canadian Journal of Applied Physiology. 20.4:465-479.

Holmberg, Hans-Christer, H. Rosdahl and J. Svedenhag. 2007. Lung function, arterial saturation and oxygen uptake in elite cross country skiers: influence of exercise mode. 17:437-444.

Holmberg, Hans-Christer, Stefan Lindinger, Thomas Stöggl, Glenn Bjorklund, and Erich Muller. 2006. Contribution of the legs to double-pole performance in elite cross country skiers. American College of Sports Medicine. 38.10:1853-1860.

Holmberg, Hans-Christer, Stefan Lindinger, Thomas Stöggl, Glenn Bjorklund, and Erich Muller. 2004. Biomechanical analysis of double poling in elite cross-country skiers. Medicine & Science in Sports & Exercise. 37.5:807-818.

Jones, Andrew M. and Helen Carter. 2000. The effect of endurance training on parameters of aerobic fitness. Sports Medicine. 29.6:373-386.

Joyner, Michael J. and Edward F. Coyle. 2008. Endurance exercise performance: the physiology of champions. The Journal of Physiology. 586.1:35-44.

Larsson, P., P. Olofsson, E. Jakobsson, L. Burlin, K. Henriksson-Larsen. 2002. Physiological predictors of performance in cross-country skiing from treadmill tests in male and female subjects. Scandinavian Journal of Medicine and Science in Sports. 12:347-353.

Levine, Benjamin D. 2008. VO_{2max}: what do we know, and what do we still need to know? Journal of Physiology. 586.1:25-34.

Lindinger, Stefan Josef and Hans-Christer Holmberg. 2011. How do elite cross-country skiers adapt to different double poling frequencies at low to high speeds? European Journal of Applied Physiology. 111:1103-1119.

Lindinger, Stefan Josef, Thomas Stöggl, Erick Muller, and Hans-Christer Holmberg. 2009a. Control of speed during the double poling technique performed by elite cross-country skiers. Medicine & Science in Sports & Exercise. 41.1:210-2010.

Lindinger, Stefan J., H.-C. Holmberg, Erich Muller and Walter Rapp. 2009b. Changes in upper body muscle activity with increasing double pole velocities in elite cross-county skiing. European Journal of Applied Physiology. 106:353-363.

Losnegard, Thomas, Daniela Schäfer and Jostein Hallen. 2014. Exercise economy in skiing and running. Frontiers in Physiology. 5.5:1-6.

McArdle, W.D., Katch, F.I. & Katch, V.L. 2001; Exercise physiology: energy, nutrition and human performance. 5th ed. Williams & Wilkins.

Millet, Gregoire P., Denis Boissiere and Robin Candau. 2003. Energy cost of different skating techniques in cross-country skiing. Journal of Sports Sciences. 21:3-11.

Mognoni, Piero, Giulio Rossi, Franco Gastaldelli, Arrigo Canclini and Francesco Cotelli. 2001. Heart rate profiles and energy cost of locomotion during cross-country skiing races. European Journal of Applied Physiology. 85:62-67.

Moxnes, John F. and Kjell Hausken. 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.

Manhood, Nicholas, Robert W. Kenefick, Robert Kertzer and Timothy J. Quinn. 2001. Physiological determinants of cross-country ski racing performance. Medicine and Science in Sports and Exercise 33.8 1379-84.

Nilsson, Johnny, Per Tveit and Olav Eikrehagen. 2004. Effects of speed on temporal patterns in classical and freestyle cross-country skiing. Sports Biomechanics. 3.1:85-108.

Pellegrini, B., C. Zoppirolli, L. Bortolan, H.-C. Holmberg, P. Zamparo and F. Schena. 2013. Biomechanical and energetic determinants of technique selection in classical cross-country skiing. Human Movement Science. 32:1415-1429.

Pellegrini, B., L. Borotolan and F. Schena. 2011. Poling force analysis in diagonal stride at different grades in cross-country skiers. Scandinavian Journal of Medicine and Science in Sports. 21:589-597.

Prampero, P. E, C. Capelli, P. Pagliaro, G. Antonutto, M. Girardis, P. Zamparo and R. G. A Soule. 1993. Energetics of best performances in middle-distance running. The American Physiological Society. 74.5:2318-2324.

Rusko, Heikki. 2003. Cross Country Skiing: Olympic Handbook of Sports Medicine. Chichester, GBR: John Wiley & Sons. Print.

Saltin, Bengt and Per-Olof Åstrand. 1967. Maximal oxygen uptake in athletes. Journal of Applied Physiology. 23.3:353-358.

Sandbakk, Oyving, G. Ettema, and H.-C. Holmberg. 2014. Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. Scandinavian Journal of Medicine and Science in Sports. 24:28-33.

Sandbakk, Oyvind, Ann Magdalen Hegge and Gertjan Ettema.2013. The role of incline, performance level, and gender on the gross mechanical efficiency of roller ski skating. Frontiers in Physiology. 4.293:1-5.

Sandbakk, Oyving, Gertjan Ettema, Stig Leirdal and Hans-Christer Holmberg. 2012. Gender differences in the physiological responses and kinematic behavior of elite sprint cross-country skiers. European Journal of Applied Physiology. 112:1087-1094.

Sandbakk, Oyvind, Boye Welde and Hans-Christer Holmberg. 2011. Endurance training and sprint performance in elite junior cross-country skiers. Journal of Strength and Conditioning. 25.5:1299-1305.

Sandbakk O., H.-C. Holmberg, S. Leirdal and G. Ettema. 2010. The physiology of world-class sprinters. Scandinavia Journal of Medicine and Sports Science. 21:e9-e16.

Saunders, Philo U., David B. Pyne, Richard D. Telford and John A. Hawley. 2004. Factors affecting running economy in trained distance runners. Sports Medicine. 37.7:465-485.

Sidossis L.S., J.F. Horowitz and E.F. Coyle. 1992. Load and velocity of contraction influence gross and delta mechanical efficiency. International Journal of Sports Medicine. 13.5:407-411.

Stöggl Thomas L. and Erich Muller 2009. Kinematic determinants and physiological response of cross-country skiing at maximal speed. Medicine and Science in Sports and Exercise. 41: 1476–1487.

Stöggl, Thomas, Stefan Lindinger and Erich Muller. 2006. Biomechanical validation of specific upper body training and testing drill in cross-country skiing. Sports Biomechanics. 5.1:23-46.

Smith, Gerald A., Jon. B. Fewster and Steven M. Braudt. 1996. Double poling kinematics and performance in cross-country skiing. Journal of Applied Biomechanics. 12:88-103.

Swaren, Mikael, Mikael Therell, Anders Eriksson and Hans-Christer Holmberg. 2013. Testing method for objective evaluation of cross-country ski poles. Sports Engineering. 12:255-264

Vähäsöyrinki, Pekka, Paavo V. Komi, Seppo Seppälä, Masaki Ishikawa, Veli Kolehmainen, Jukka A. Salmi and Vesa Linnamo. 2008. Effect of skiing speed on ski and pole forces in cross-country skiing. Medicine of Science and Sports Exercise. 40.6:1111-1116.

Van Hall, G., M. Jensen-Urstad, H. Rosdahl, H.-C. Holmberg, B. Saltin and J. A. L. Calbet. 2003. Leg and arm lactate and substrate kinetics during exercise. American Journal of Physiological Metabolics. 284:E193-E205.

Watts, Phillip B., Martin D. Hoffman, Jon Eric Sulentic, Kip M. Drobish, Timothy P. Gibbons, Victoria S. Newbury, Scott W. Mittelstadt, Kathleen P. O'Hagen and Philip S. Clifford. 1993. Physiological responses to specific exercise tests for cross-country skiing. Canadian Journal of Applied Physiology. 18.4:359-365.

Zory, Raphael, Nicolas Vuillerme, Barbara Pellegrini, Frederico Schena and Annie Rouard. 2008. Effect of fatigue on double pole kinematics in sprint cross-country skiing. Human Movement Science. 28:85-98.