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The effect of competition duration on oxygen demand and-uptake in cross-country skiing

Abstract

Abstract

Purpose: This study aimed to investigate changes in pacing patterns and energy system contributions in a short (~3.5 min), middle distance (~7.6 min) and long race (~15.8 min) in competitive XC skiers during roller skiing. We hypothesized that the relationship between average metabolic energy turnover (VO_2^{dem}) and race duration follows an approximately inverse curve in intermittent endurance exercise, similar to constant load endurance exercise. We additionally expected average VO2 uptake to not change with test duration.

Methods: 12 competitive XC-skiers (8 male and 4 female, VO_{2Max} 78. ± 2,5 and 63.5 ± 3.9 mL/kg/min) raced a 1.6 km course at 3 distinct tests for 1, 2 and 4 laps (~3.5, ~7.6 and ~15.8 min) in a randomized order with 35 min breaks in-between. VO_2 and GPS data was acquired to establish VO_2 uptake and demand. On an additional day, the athletes completed 6 submaximal loads of 5 min and a 1000m uphill maximal effort test to establish skiing economy, $VO_{2\text{-}}Max$ and maximal $\Sigma O2$-deficit (MAOD). Pulmonary VO_2 was measured using mixing chamber. $\Sigma O2$-def and VO_2 demand was calculated from an athlete-specific model of skiing economy.

Results: During the 1, 2 and 4 laps tests, average VO_2^{dem} including tucked position was 110 ± 8 %, 101 ± 7 % and 96 ± 7 % of VO_{2max} respectively. When excluding tucked position, corresponding VO_2^{dem} averaged 130 ± 9 %, 119 ± 9 % and 112 ± 8 % of VO_{2max}. Both peak and average VO_2^{dem} followed an inverse relationship with test duration irrespective of whether tucked position was included or not. The average VO_2 uptake was similar on all tests with 86 %, 86 % and 84 % of VO_{2max} on the 1, 2 and 4 laps respectively.

Conclusion: We established a relationship between energy demand and test duration in XC skiing which indicates similar duration-dependent energy demand changes in highly intermittent endurance exercise modalities compared to constant load endurance exercise.

Acknowledgements

Acronyms

P_c	Critical power
VO_2	Ventilatory oxygen uptake
VO_2^{dem}	Oxygen demand
$\sum O_2^{def}$	Accumulated oxygen deficit
VO_{2max}	Maximal oxygen uptake
VO_{2crit}	Critical oxygen uptake
P_{prop}	Propulsive power
F_{prop}	Propulsive force
PCr	Phosphocreatine
ATP	Adenosine triphosphate

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Introduction

Endurance sports are characterized by the sustained high metabolic energy demands during racing performance (Joyner & Coyle, 2008). Primarily the aerobic energy system has capacity to supply these energy demands, whereas anaerobic energy systems contributes inversely with increasing race duration given a constant load intensity (Gastin, 2001). This results in a hyperbolic propulsive power-duration relationship curve where propulsive power output falls abruptly, then levels off with increasing race duration. Eventually, a steady state threshold is reached when the anaerobic capacity becomes fatigued. This formulates a concept termed the 'critical power' (P_c), which practically describes a maximal sustainable metabolic steady state (Bishop et al., 1998; Monod, 2007; Noordhof et al., 2013; Poole et al., 2016; Skiba et al., 2012).

Compared to intermittent endurance sports, the P_c concept has demonstrated superior applicability to endurance sports with constant load intensity. Running is one such typical constant load modality where sustained propulsive power outputs above P_c leads to predictable time to exhaustion when applying the P_c concept (Poole et al., 2016). As these supra-P_c power outputs are connected to non-sustainable anaerobic energy contributions, energy system contributions are therefore also predictable as a function of competition duration (Gastin, 2001).

During intermittent endurance sports featuring varying terrain however, propulsive power is unevenly distributed through the undulating racecourse, with workloads exceeding P_c and even VO_{2max} during parts of the race (Gloersen et al., 2020; Granier et al., 2018; Losnegard, 2019). Downhill sections then presents temporary recovery opportunities when propulsive power falls beneath P_c, allowing athletes to repeatedly race at supramaximal intensities (above P_c) associated with O2-deficits and thus anaerobic energy contribution (Gloersen et al., 2020). Mechanical efficiency is therefore not constant, thus rendering P_c an inappropriate steady state metabolic boundary. The maximal sustainable aerobic rate (VO_{2crit}) however, corresponds with the power output at a maximal sustainable metabolic steady state, and therefore proves a more appropriate measurement of P_c in such intermittent endurance sports (Poole et al., 2016).

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XC skiing represents a compelling model for studying this intermittent phenomenon due to considerable variations in terrain and consequently also in propulsive power outputs, expressed here as oxygen demand (VO_2^{dem}) (Gloersen, Losnegard, et al., 2018). Specifically, VO_2^{dem} typically range between 110 % to 160 % of VO_{2max} during uphill in long distance skiing (>30 min) (Gloersen et al., 2020; Karlsson et al., 2018; Norman & Komi, 1987) and 120 % to 160 % during sprint skiing (2 min to 4 min) (Andersson et al., 2017; Andersson et al., 2016; Andersson et al., 2019; Sandbakk et al., 2011). These oxygen demands far exceeds VO_{2crit}, which in XC skiing races normally range between 80 % to 90 % of VO_{2max} (Gloersen et al., 2020; Welde et al., 2003), consequently implying substantial anaerobic energy contributions in uphill. This in turn creates a complex challenge of adjusting pacing patterns to the course profile to minimize finishing time.

Nevertheless, anaerobic capacity have displayed no correlation with FIS-points in distance skiing (Losnegard, 2019). And Gloersen et al. (2020) argued their intermittent O_2-deficits to rather challenge the rate of recovery from these deficits during downhill segments. An argument based on a continuously estimated VO_2^{dem} and VO_2 uptake through a treadmill simulated roller skiing distance race. To date, this is the only previous study to combine such measurements in simulated distance skiing.

During the sprint distance in XC skiing however, anaerobic capacity have been regarded as a performance limiting factor by Losnegard et al. (2012), a claim supported by a base of treadmill simulations (Andersson et al., 2016; Losnegard et al., 2015) Even the rate of which anaerobic capacity can be released (anaerobic power) has been suggested to limit sprint performance (Mikkola et al., 2010). Although neither of these claims build upon field tested research. Moreover, continuous estimations of VO_2^{dem} and VO_2 uptake have regardless of distance yet to be executed in field XC skiing.

The present study therefore continuously measured oxygen uptake and estimated oxygen demand throughout 3 field test races on roller skis ranging from sprint to distance skiing duration. The aim for which was to compare and describe the changes in pacing patterns and energy system contributions at this type of race durations. The basis for which was estimations of propulsive power from global navigational satellite systems (Gloersen, Losnegard, et al., 2018), laboratory measurements of skiing specific working economy (Gloersen, Losnegard, et al., 2018) and a treadmill test assessing maximal oxygen deficit

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(MAOD) and VO_{2max}. These tools allowed continuous oxygen demand estimates, which was combined with oxygen uptake measurements from a portable metabolic VO_2 analyzer to assess energy demand and pacing patterns.

We hypothesized that the relationship between average metabolic energy turnover (VO_2^{dem}) and race duration follows an approximately inverse curve in intermittent endurance exercise, similar to constant load endurance exercise. We additionally expected average VO_2 uptake to not change with test duration.

Theory

Physiological aspects of XC skiing

XC skiing is a sport characterized by its complex and varied nature. Competition duration ranges from <3 minutes to >4 hours and race course topography is highly varied (Losnegard, 2019). World cup course terrain includes uphill sections that normally range from 10 s to 35 s, and rarely above 70 s, (Losnegard, 2019) adding up to over 50 % of total race time (Bolger et al., 2015). Flat terrain amounts to 15 % to 20 % and downhills from 25 % to 30% (Bolger et al., 2015). Uphill sections evoke the highest opposing forces, and is consequently where athletes increase intensity and performance differentiate most severely (Bolger et al., 2015).

Metabolic energy requirements therefore fluctuates rapidly throughout XC skiing competitions, dictating an important physiological demand in the ability to sustain these changes repeatedly (Losnegard, 2019). Despite constant variations in energy demands, the main performance determining factor in XC skiing distance races is the ability to sustain a high aerobic turnover rate, illustrated by a high VO_{2max} displayed by XC distance skiers (Losnegard & Hallen, 2014). Sprint skiers likewise display high values of VO_{2max}, yet comparably lower than distance skiers (Losnegard & Hallen, 2014). Furthermore, sprint skiers have demonstrated comparably higher MAOD, a measurement of anaerobic energy capacity, and the size of which has been found to correlate with sprint skiing performance (Losnegard et al., 2012)

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Bioenergetic systems

The splitting of adenosine triphosphate (ATP) provides energy for muscle contractions enabling human locomotion (Gastin, 2001). This energy source is stored in amounts capable of maintaining only a few seconds of intensive muscle contractions (Glaister, 2005), demanding a near instant initiation of resynthesizing processes. The human bioenergetic systems can increase the metabolic rate 50-fold compared to resting levels to meet the increasing energy demands at the onset of intensive exercise (Gloersen, 2019). These bioenergetic systems coactivate in a complex interaction of 3 distinctive chemical pathways composing various abilities of storing and delivering energy to the working muscles (Gastin, 2001).

Two of these pathways composes the anaerobic energy systems, which utilizes different sources of energy. Providing the initial resynthesization of ATP to the muscle alongside the stored ATP is the splitting of the high energy phosphagen phosphocreatine (PCr). Short and explosive muscle work heavily relies upon this energy store, which makes elite weightlifters capable of producing maximal power outputs at 10-20 times maximal aerobic power (Gastin, 2001). However, the PCr energy turnover and degradation peaks immediately after exercise onset, and begins declining after about 1.3 s (Gastin, 2001). Within 10 s of intensive exercise the PCr store is practically depleted (Hultman & Sjoholm, 1983). The second anaerobic energy pathway uses carbohydrates, by breaking down muscle glycogen through glycolysis, producing both ATP and pyruvic acid, which without oxygen becomes lactic acid. This anaerobic energy pathway yields a slightly lower ATP turnover rate than the PCr system, and peaks after about 5 s of intensive exercise. (Hultman & Sjoholm, 1983). The lactic acid production or lack thereof is what terms these two components as alactic and lactic, respectively (Gastin, 2001).

The aerobic energy system has capacity of near infinite resupply of ATP, although at a substantially lower rate than the anaerobic system. This system relies on the presence of oxygen and converts pyruvic acid from glycolysis and lactate from anaerobic processes into a 16/18-fold greater net supply of ATP compared to the lactic pathway. Whereas the anaerobic processes heavily relies on intracellular and peripheral energy stores, the aerobic system is primarily limited by the central cardiovascular delivery of oxygenated blood (Bangsbo, 2000). Measuring cardiovascular oxygen delivery directly is a simpler process

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than assessing the complex peripheral interplay of anaerobic processes (Noordhof et al., 2013). Instantaneous estimates of energy contributions from the three systems is therefore a complex process for which we lack adequate measurement methods (Noordhof et al., 2013).

Energy system contribution as a function of exercise duration

The onset and accumulation of fatigue during exercise is dictated by intensity and duration of the exercise. This relationship is illustrated in **Feil! Fant ikke referansekilden.** from Gastin (2001). During high intensity exercise this process dynamically involves aerobic and anaerobic energy systems contribution through central and peripheral mechanisms (Poole et al., 2016). The contrasting mechanisms and capacities represented by the 3 energy systems allows for both sustained high and diverse energy demands, due to the smooth and efficient interplay of replenishing ATP to the working muscles during exercise (Gastin, 2001).
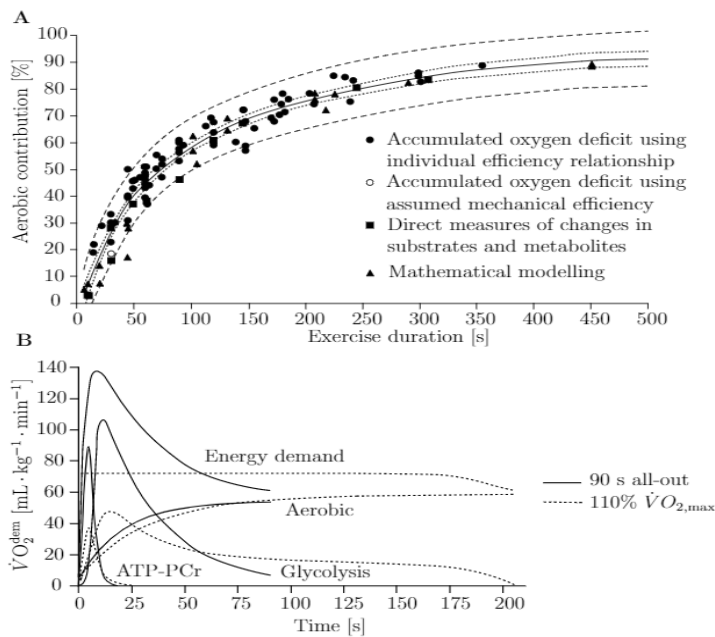
Figure 1: A depicts energy system contribution as a function of exercise duration from a collection of various sports. Different methods of estimating anaerobic contributions are including the accumulated oxygen method from both individual and assumed mechanical efficiency, measurements of substrates and metabolites and mathematical modeling. The inner band depicts 95 % confidence interval while the outer band depicts 95 % prediction intervals. B Depicts a 3-systems energy contribution from a 90s all out cycle exercise and a constant 110 % of VO_{2max} effort. The figure is adapted from Gastin (2001) and reprinted with permission from Sports medicine journal.

Maximal efforts of short duration demand a high power output, placing a greater demand at the anaerobic energy systems as these are capable of a high ATP supply rate. With increasing duration, the aerobic contribution to energy supply gradually becomes more influential, such that the anaerobic system contributes inversely with the maximal exercise duration.

Within 30s of a maximal effort, 80% of the anaerobic capacity has been depleted (Calbet et al., 1997; Medbo & Tabata, 1989). A further duration increase to 75 s yields an approximately equal contribution from anaerobic and anaerobic energy systems, corresponding to a running distance of about 600m. At 2-3 minutes of a constant maximal effort, the anaerobic capacity is practically depleted. When exceeding 10 minutes, the anaerobic contribution to performance becomes negligible at constant load exercise modalities (Gastin, 2001).

The aerobic system reacts comparably slower to increasing energy demands, which reflects the adjustment of oxygen transport on a system level and muscle metabolism (O'Brien et al., 1997). Aerobic rate may reach 90 % of VO_{2max} between 30 to 60 s of intensive exercise (Kavanagh & Jacobs, 1988), although a minimum of 2 min is normally required to reach VO_{2max} (Katch, 1973; Kavanagh & Jacobs, 1988).

Intermittent endurance exercise

In steady state endurance exercise where athletes race against the clock, peak power output is rarely attained, establishing an even energy demand through the race. Endurance sports involving movement through undulating terrain however, have the potential of becoming intermittent when downhills allow for downregulation or cessation of active propulsion (Whipp et al., 1998). This is the case for sports like cycling and skiing, and it leads to a variable pacing pattern where exercise intensity is increased in uphill at the cost of decreased intensity during downhill sections (Abbiss & Laursen, 2008; Swain, 1997). During some intermittent endurance sports like XC skiing and MTB cycling, propulsive power outputs may greatly exceed intensities capable of eliciting VO_{2max} and are thereby termed supramaximal. The magnitude of fluctuations these energy demands demonstrate depends on the course profile, where short steep uphill in XC skiing have demonstrated an apex of these power outputs with upwards of 160 % of VO_{2max} (Gloersen et al., 2020). The

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same study from Gloersen et al. (2020) additionally showed longer uphill length to effectively downregulate energy demands towards values close to VO_{2max}. These near continuous variations in metabolic energy demands greatly challenges athletes power distribution, known as pacing strategies. Adopting a variable pattern with increased power outputs during uphill have been showed to improve performance when comparing to even intensity pacing in both road cycling and XC skiing (Atkinson et al., 2007; Sundström et al., 2013; Swain, 1997).

Critical power

The critical power (P_c) concept was introduced to establish a threshold for metabolic steady state exercise and predict a tolerable duration of exercise above this threshold (Monod, 2007). Exercise intensities below P_c can be maintained for a long time, largely supplied by aerobic energy contributions. Above P_c, time to exhaustion becomes predictable with a hyperbolic relationship between exercise intensity and duration (Morton & Billat, 2004; Poole et al., 2016). With increased exercise duration, the maximal tolerable work output displays an inverse reduction (Poole et al., 2016), and converges towards P_c. This inverse curvature constant is defined as the W' parameter, predicting a finite work capacity above the P_c threshold.

As the name implies, power was the original defining variable of this intensity threshold, mostly applied in studies of cycling (Barker et al., 2006; Chidnok et al., 2012). Later, this threshold has been found to coincide with several other variables like locomotion speed in swimming and running as well as single joint torque (Jones & Vanhatalo, 2017; Poole et al., 2016). These findings support the notion of P_c being linearly related to a critical metabolic rate, which has been demonstrated by Keir et al. (2015) to correspond well with a critical VO_2 uptake (VO_{2crit}). Moreover, aerobic responses are more blunted and remains high during sub-P_c power outputs partially recovering the anaerobic capacity (Chidnok et al., 2012). VO_{2crit} may therefore demonstrate superior measurement stability and thus practicality, compared to power output and speed when these latter variables fluctuate, like in XC skiing.

The development of fatigue induced by exercising in the supra-P_c-domain is connected to reduced muscle efficiency reflected by a VO_2 slow component driving a steady increase

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from VO_{2crit} towards VO_{2max} (Jones et al., 2011). Reductions in muscle PCr and blood PH together with progressively accumulating blood lactate have also been demonstrated to coincide with supra-P_c workloads. These findings consistently show that P_c represents a metabolic threshold separating an both a whole body and intramuscular steady state from a non-steady state (Poole et al., 2016).

Fatigue onset have also in intermittent endurance exercise been shown to occur by attaining a similar muscle milieu as in constant load exercise, representing a critical level of homeostatic disturbance Poole et al. (2016). However, accurately predicting the P_c model in intermittent endurance exercise is associated with additional complexity in understanding recovery from supra-P_c exercise bouts. Key findings was obtained by Chidnok et al. (2013), who demonstrated that recovery of W' was only possible when power output fell below P_c. Moreover, the recovery rate approached zero when recovery bout intensity tended towards P_c. Additionally, when applying a ½ work/recovery relationship, a doubling of work period durations from 32 s to 64 s with equal mean power outputs was shown by Davies et al. (2017) to shift energy contributions from PCr towards increased anaerobic glycolysis. Considering an accumulation of lactate is associated with reduced time to fatigue, increased work period durations may therefore effectively downregulate power output to limit a reduction in the size of W'.

MAOD

Human performance is by Noordhof et al. (2013) described as a cooperation between aerobic and anaerobic energy systems, and mechanical efficiency (translated to working economy). Aerobic energy contribution is normally determined by varying measurement methods of pulmonary VO_2 that are validated to have a high precision. An estimation of working economy is often established by measuring oxygen uptake at various speeds or power outputs. Anaerobic energy contribution on the other hand, is a more peripheral and intracellular process with less relation to central processes compared to the aerobic energy system. Hence, there exists less scientific agreement on a universally accepted validation of these mechanisms (Gastin, 2001; Noordhof et al., 2013).

The O_2-deficit method popularized by Medbo et al. (1988) is amongst many considered the gold standard for estimating anaerobic capacity (Noordhof, de Koning, & Foster, 2010)

although protocol choice determines the degree to which different methods fit into the testing framework. Determining anaerobic capacity through this method of estimation is expressed by maximal accumulated oxygen deficiency (MAOD). The MAOD was originally estimated by Medbo et al. (1988) using a constant inclination protocol with increasing speed on a submaximal intensity to establish a linear relationship between O_2 uptake and running speed. A supramaximal load to exhaustion was then performed to establish a determine the difference between accumulated VO_2^{dem} and VO_2 uptake. In XC skiing, MAOD have been established from a maximal effort test where average propulsive force (F_{prop}) is measured. From extrapolating the relationship between F_{prop} and cost of transport (C) at submaximal intensities, the VO_2^{dem} through the maximal effort test is determined. Subtracting the VO_2 uptake measured through the test allows for determining the total amount of work performed without oxygen supply, which is the MAOD (Gloersen et al., 2020; Noordhof et al., 2013).

The anaerobic capacity is composed by energy reserves from local oxygen stores (5 % to 10 %), high energy phosphates mainly from PCr (20 % to 30 %) and anaerobic glycolysis (60 % to 70 %). At maximal intensity, the anaerobic capacity is rapidly depleted initially, where a 30s all out efforts have shown to elicit an 80 % accumulation of MAOD (Calbet et al., 1997; Medbo & Tabata, 1989). Further depletions demonstrate a slower rate, and accumulating O_2-deficits equivalent to 100 % of MAOD takes around 2 to 3 minutes (Medbo & Tabata, 1989).

Factors influencing MAOD

The reliability and validity of estimating MAOD depends upon several factors. Choice of test protocol should amongst other factors consider intensity and specificity. (Noordhof et al., 2013). Working economy determined by the submaximal protocol is influenced by the test intensity, where the working economy improves closer to anaerobic threshold intensity in a curvilinear matter (Noordhof, de Koning, van Erp, et al., 2010). But if the chosen intensity exceeds lactate threshold, the VO_2 slow component may affect the estimation of working economy (Ozyener et al., 2003). This occurs due to the reduction of contractile efficiency in skeletal muscle at a continuous high intensity, increasing the rate of VO_2 uptake in the muscles (Jones & Burnley, 2009).

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Specificity of movement pattern and hence the use of muscle groups may also affect measurements of working economy. This occurrence needs to be considered by including a similar incline when determining working economy as when having the maximal effort test of MAOD (Karlsson et al., 2018; Pringle et al., 2003). Karlsson et al. (2018) found a 25 % increase in MAOD at 8° compared to 1°. The amount of muscle mass activated during the activity likely affects the slow component of VO_2, which in turn may lead to an overestimation of MAOD at steeper inclines.

Recovery of anaerobic capacity

When exercise intensity falls below P_c after a supra- P_c exercise bout, some oxidative metabolic reserve is likely used for recovery processes. The replenishment of high energy phosphates (mainly PCr) have been shown an initial rapid boost with cessation or reduction of exercise intensity (Chidnok et al., 2013). However, this rate of recovery highly depends on the recovery duration and intensity (Ferguson et al., 2010; Margaria et al., 1969), where recovery bouts upwards of P_c intensity yields small amount of PCr replenishment (Chidnok et al., 2013). The lactic component of MAOD on the other hand, displays a substantially slower recovery process (Ferguson et al., 2010; McCully et al., 1994), and when exercise involves substantial lactic energy use, an inhibition of alactic recovery processes have been observed (Hoff et al., 2016; Jones et al., 2011).

Summary

Intermittent endurance exercise exhibits a rather complex modality in terms of energy contribution compared to constant load endurance exercise. Energy demands display fluctuating patterns, diverging from exercises like running but have yet to be thoroughly investigated and understood. XC skiing is a compelling study model with which to better understand intermittent endurance exercise due to substantial energy demand variations operating beyond the aerobic responsiveness (Gloersen et al., 2020; Gloersen, Losnegard, et al., 2018). To date, the only study to continuously estimate energy demand and measure oxygen uptake through a simulated distance race was performed by Gloersen et al. (2020) using a treadmill test. Sprint races are also an important XC skiing race format in which skiers specialize, exhibiting higher anaerobic capacity and body mass compared to distance skiing (Losnegard & Hallen, 2014). Both sprint and distance skiing remain uninvestigated in field by continuous assessments of energy demand and oxygen uptake, which renders

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this topic highly interesting and produces an attractive research problem for the present study.

Method

Subjects

Twelve competitive XC skiers participated in this study after giving informed consent to taking part in this experimental procedure. Inclusion criteria was previous experience in XC-skiing competitions at a national level and being over 18 years old. Subject characteristics are found in table 1. The study was conducted in line with the rules of the Helsinki-declaration and was approved by the ethical committee of the Norwegian School of Sport Sciences and in agreement with the Norwegian Center for Research Data.

Table 1 Subject characteristics (n=12, 8 men and 4 women)

	Men		**Women**	
	Mean ± SD	Range	Mean ± SD	Range
Age (yr)	21.4 ± 5.2	19 - 34	25.5 ± 3.7	23 - 31
Body mass (kg)	74.6 ± 4.6	67.4 - 80.2	65.1 ± 8.2	54.2 - 73.6
Height (cm)	183 ± 4.6	176 - 190	171 ± 2.6	167 - 173
VO2max (ml*min^{-1} *kg^{-1})	78.0 ± 2.5	75.7 - 82.1	63.5 ± 3.9	61.3 - 66.7

General design

The study consisted of 2 separate days of testing, separated by at least 48 hours and maximum 1 week. The first test day consisted of field testing on the national XC skiing arena's roller skiing course, Holmenkollen (**Feil! Fant ikke referansekilden.**), while the second test day took place in the biomechanics laboratory at the Norwegian School of

Sport Sciences. Field testing consisted of 3 maximal effort tests of different durations and in randomized order, where VO_2 uptake was measured. Skiing speed and propulsive power (P_{prop}) were calculated using a combination of GNSS receivers and inertial measurements as described in Gloersen, Losnegard, et al. (2018).

Lab testing consisted of a submaximal test with 6 different loads to establish skiing specific working economy. This data was used in an empirical model to predict VO_2^{dem} from skiing speed and propulsive power. Additionally, a maximal effort test to measure VO_{2max} and calculate maximal accumulated oxygen deficiency (MAOD) was performed on the lab test day. Men and women tested on the same course with equal number of laps on the field tests with minor adjustments to the laboratory tests as described below.

Field test day

The course

All field tests were performed on the course depicted in **Feil! Fant ikke referansekilden.**. This course measures 1560 m in length with an elevation gain of 65 meters over 1 lap. Subjects were all experienced on the course from previous training and competitions on both roller skis and on cross-country skis.

Segmentation

The course was split into 4 segments for a breakdown of the participants effort to a more detailed picture. The 3 first segments are uphill segments of various lengths and inclines, while S4 is a flat (Figure).
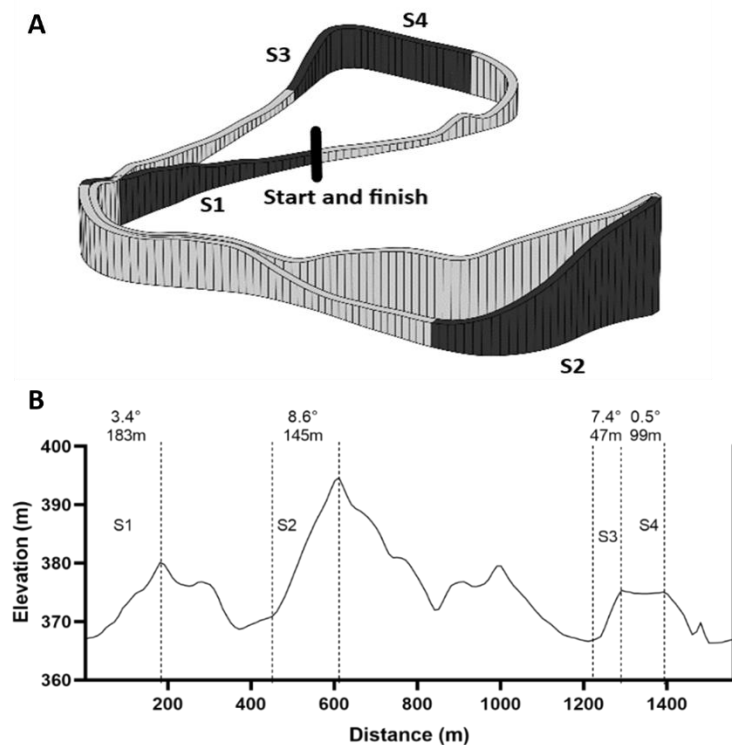
*Figure 2: **A** depicts Holmenkollen 3D course map depiction with individual segments marked black. Start, lap and finish at the same line. **B** shows elevation map featuring segment placement, average inclination and length.*

Field test day protocol

Field test day overview is provided in figure 3. The participants were weighed with and without equipment and informed about test order before warmup. The warmup consisted of 10 minutes easy activity where participants was asked to complete the course for the tests.
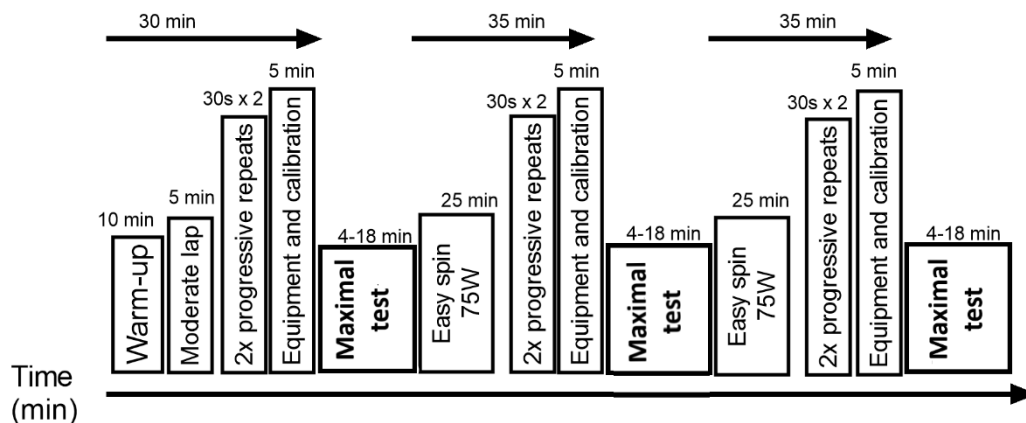
Figure 3: Field testing protocol overview. Participants were weighed and equipment was assembled prior to warm-up and 5 min before test start. Progressive repeats ended at test speed intensity. Test order was randomized.

Then a moderate lap followed, before the participants performed 2 progressive 30 seconds repeats ending at approximately 1 lap test intensity. This was followed by 3 minutes of light activity and 2 minutes standing still while the portable VO_2 analyzer was mounted, ensuring a similar starting metabolic rate directly prior to each test.

Participants was asked to complete the tests as if it was an XC skiing competition with regards to pacing and maximizing of the effort at each test. Upon completion of each test participants should maintain 75W of easy cycling on a bicycle ergometer for about 25 min of the 35 min break between each test. The remaining 10 min consisted of 2 progressive 30 seconds repeats on roller skis ending approximately at 1 lap intensity followed by a similar preparation to that of the first test for the last 5 min.

Equipment

The participants used the same pair of roller skis (Swenor skate long, wheel type 2). They were also equipped with two position tracking devices (Catapult Optimeye S5), which consists of a 10 Hz standalone GNSS-module and a 9-axis inertial measurement unit. This includes accelerometer, gyroscope and magnetic field measurements. Participants wore 1 receiver on the back in a tight-fitting breast vest. While the other was taped laterally on the thigh approximately in the mid-point from of the trochanter and the lateral condyle of the tibia. The aforementioned equipment is similar the setup used by Gloersen, Losnegard, et al. (2018).

Additionally, the participants were equipped with a Cosmed K5 portable pulmonary VO2-analyzer used in mixing chamber mode. The gas analyzer, which was worn in a harness, was positioned right below the upper GPS unit. With the K5 VO2-analyzer a Hans Rudolph mouthpiece was used (Two-Way Non-Rebreathing T-Shape, Hans Rudolph, Kansas City, MO, USA) along with a nose clip (NoseClip, Reusable Series 9015, Hans Rudolph, Kansas City, MO, USA). Preceding the first test, the pulmonary VO2 analyzer was calibrated using a certified calibration gas, while the volume was calibrated using a 3-liters calibration pump.

Figure 3: The setup with Cosmed K5 and the upper GPS-unit as used in the field tests.

Lab test day

Equipment

Submaximal lab tests were performed using Swenor skate long wheel type 2 (coefficient of rolling resistance; $C_{rr} = 0.018$), the same pair that was used on field tests. Maximal effort tests were performed using Swenor skate long wheel type 1 (coefficient of rolling resistance; $C_{rr} = 0.011$). Swix Triac 3.0 ski poles with customized treadmill ferrules (Swix sport Lillehamer Norway) was used on all lab tests. The tests were performed on a roller

skiing treadmill produced by Rodby Innovation AB, Hagby, Vänge, Sweden). Lactate was measured using Biosen C-line analyzer (EKF Diagnostic GmbH, Barleben, Germany). Pulmonary VO2 was measured with Cosmed K5 portable analyzer.

Submaximal protocol

The submaximal protocol was designed to test the skiing specific working economy of the subjects by applying 6 different workloads of 5 minutes at varying speed and incline with a rest period of 2.5 minutes (figure 4). A self-paced warm-up of 15 minutes including habituation to the maximal effort test preceded the submaximal loads. The intensity of these loads was aimed below, and close to the anaerobic threshold intensity.

Figure 4: Load intensity expressed in W/kg is calculated from F_{prop} and speed for each load. The male protocol figures on the left side, while the female protocol figures on the right. Incline and speed for all loads is summarized in the results. The order of load number 1-3 and 4-6 was randomized.

Therefore, a slightly different protocol was used for the two genders. For the females, speed was reduced by 10 %, using the same inclines as for the men. The protocol was repeated with speed adjustments on a separate day for 1 subject as the intensity exceeded anaerobic threshold intensity. Pulmonary VO2 measurements and HF data were collected during the workloads, while blood lactate and rate of perceived exertion (RPE) were collected at the end of each workload.
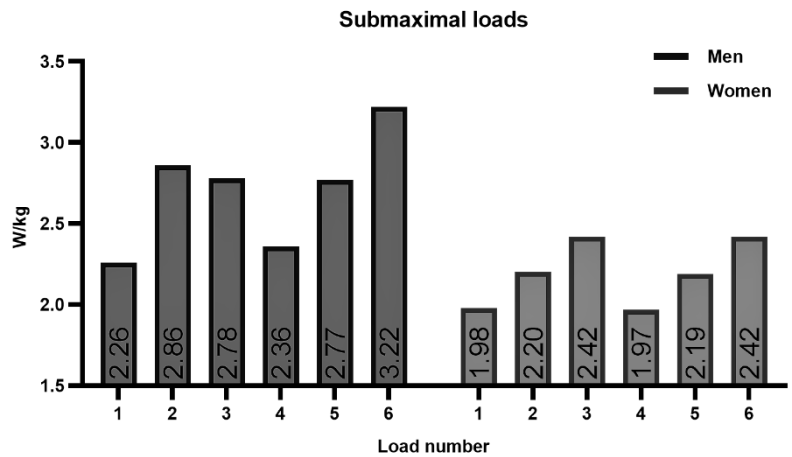
1000m maximal effort test protocol

For the maximal 1000m test the participants used Swenor skate long (wheel type 1). This test was performed after a 15 min rest period from the submaximal protocol at 6.0 and 4.5 degrees incline respectively for men and women, with a start speed of 3.25 m/s. Speed increased to 3.5 m/s at 100 meters, while at 200 meters participants could control speed by moving in front of (or behind) two laser lines with both front wheels. This gave an increase (or reduction) in speed by 0.25 m/s. Pulmonary VO2 measurements with Cosmed K5 in mixing chamber mode and HF data were collected during the test. Lactate and RPE were collected at the end of the test.

Figure 5: Picture from the lab test setup used on both submaximal and 1000m maximal tests.

Data analysis

Propulsive power

Propulsive power relies on the principle of power balance (van Ingen Schenau & Cavanagh, 1990) outlined by the following equation:

$$P_{prop} = \dot{E}_{mech} + \dot{w}_{env}$$

Where $\dot{E}_{mech}$ refers to the rate of change in mechanical energy and $\dot{w}_{env}$ is the rate of energy dissipation to the environment, which in theory sums up the total mechanical energy turnover. For XC skiing, it is customary to let $\dot{E}_{mech}$ represent the kinetic energy and gravitational potential energy of a point mass representing the skier and his or her equipment. While $\dot{w}_{env}$ refers to the energy loss due to friction (F_f) between the skis and the surface, as well as air drag (F_d). The accuracy of applying P_{prop} as a continuous measurement of intensity in roller skiing have been assessed by Gloersen, Losnegard, et al. (2018). They found that there was significant importance in vertical position measurement accuracy to calculate P_{prop} correctly.

$$P_{prop} = \frac{d}{dt}\left(\frac{1}{2}mv^2 + mgz\right) - \left(F_d + F_f\right)$$

Air drag

The calculation of air drag was conducted using the following equation:

$$F_D = -\frac{\rho}{2} \cdot v_f^2 \cdot A \cdot C_D \,(Re)$$

In this equation ρ denotes air density in kg/m^3. The air density is a product of temperature, air pressure and elevation above sea level expressed in the following way: $\rho = \frac{p}{R_{specific}\, T}$

Temperature (T) and air pressure (p) data was collected by the closest weather station and adjusted to the current elevation above sea level, as described by Karlsson et al. (2018). The $R_{specific}$ is 287.058 J kg^{-1} K^{-1} is derived from the universal gas constant divided by molar mass.

A in the air drag equation represents frontal area, a variable dependent on the size and posture of the athlete. Establishing a relationship between frontal area and posture data collected from IMU's as described in detail by Gloersen, Losnegard, et al. (2018) was applied. The difference to the current study is the lack of individual athlete frontal area images. Therefore, frontal area size in this study was estimated based allometric scaling of the relationship between body mass and frontal area. The allometric scaling was $A_0 = k \cdot m^{2/3}$, where the proportionality constant k was determined by least squares fitting to the data collected by Gloersen, Losnegard, et al. (2018). To calculate instantaneous frontal area with constantly changing body position throughout the tests, measurements of IMU angles from the accelerometers were applied as described by Gloersen, Losnegard, et al. (2018). The IMUs detected the angle of the torso and thigh as depicted in Figure 17: Positioning of the IMU's and basis for the above equation of body position. The upper IMU was placed approximately by the third thoracic vertebrae, while the other was placed approximately in the middle of trochanter and the lateral condyle of femur. To align the axes, in the mediolateral and anterior direction, the blue and red lines were used. The direction of gravity (green) was aligned when participants was standing still prior to start. The figure is taken from Gloersen, Losnegard, et al. (2018).

 to decide the body position of the athlete with the following equation:

$$\frac{A}{A_0} = \beta_0 + \beta_1 \cos\theta_{torso} + \beta_2 \cos\theta_{thigh}$$
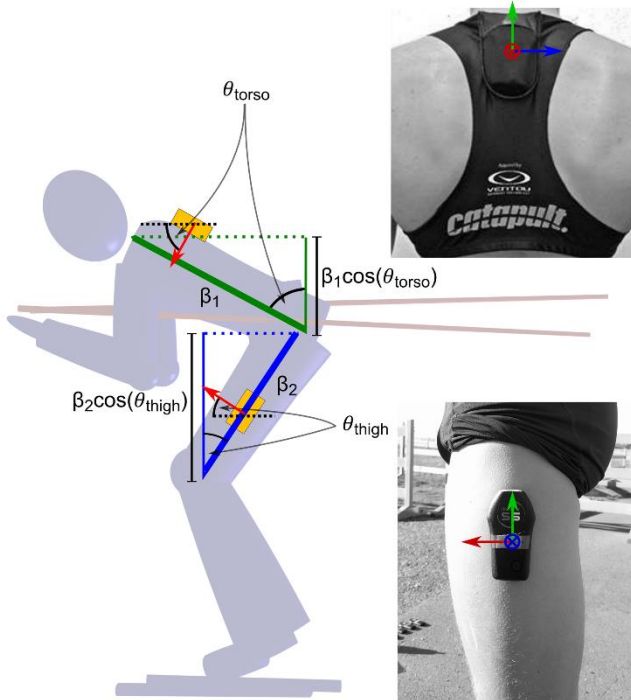
Figure 17: Positioning of the IMU's and basis for the above equation of body position. The upper IMU was placed approximately by the third thoracic vertebrae, while the other was placed approximately in the middle of trochanter and the lateral condyle of femur. To align the axes, in the mediolateral and anterior direction, the blue and red lines were used. The direction of gravity (green) was aligned when participants was standing still prior to start. The figure is taken from Gloersen, Losnegard, et al. (2018).

Where A represents size of frontal area as previously described, and β_0, β_1 and β_2 are constants with the respective values of 0.27, 0.32 and 0.38 (Gloersen, Losnegard, et al., 2018).

The air drag coefficient C_D (Re) is based on the composition and speed of the object as well as the viscosity of the fluid (air) the object moves through, named Reynolds number (Re). Previous findings indicate that the drag coefficient as a function of Re is object to a higher level of uncertainty at Re numbers (1-2)x10^5 (Achenbach, 1968; Spurk & Aksel, 2008), equating about 5-10 m/s for XC skiers according to (Gloersen et al., 2020).

Lastly, v_f^2 represents wind speed. Estimations of wind speed and direction was based on collected data from Tryvann weather station approximately 2 km from the test course.

These data were measured 10 m above ground as an hourly average and corrected by an equation to 1 m above ground with an adjustment to the current surrounding vegetation.

Friction

F_f in the P_{prop} calculation denotes friction and was calculated using 4 pairs of photocells on a flat asphalt surface located directly by field test start. Entry and exit speed were measured by passively gliding onto a flat section to calculate deceleration and friction from a given rolling distance, ss described by Solli et al. (2018). This procedure was performed both rolling directions.

Oxygen demand

Oxygen demand (VO_2^{dem}) was applied as the primary estimate of metabolic rate in the present study. As outlined by Gloersen et al. (2020), VO_2^{dem} was predicted from an assumed linear relationship between cost of transport (C, expressed in mL/m) and propulsive force (F_{prop}) as depicted in the below figure 7.
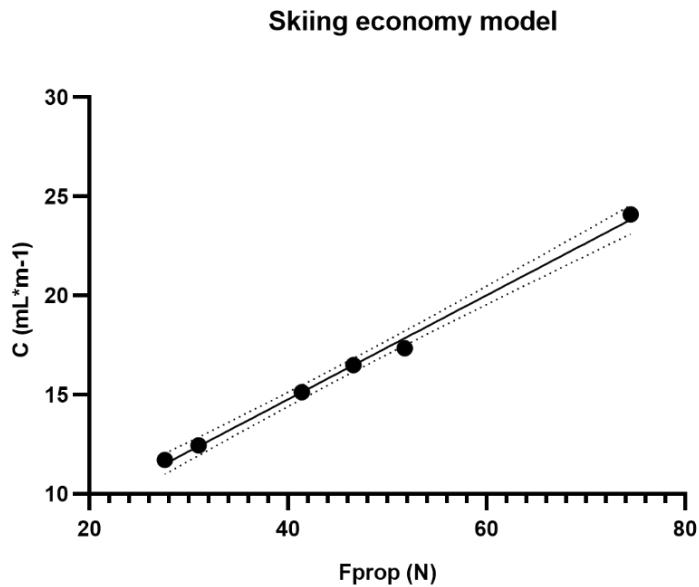
Figure 18: Linear regression of the individual relationship between cost of transport (C) and propulsive force (F_{prop}) for 1 athlete as tested on the submaximal test. C is presented as mL/m, while F_{prop} is presented in N.

Extrapolating this linear relationship allows a prediction of VO_2^{dem} at different workloads, a prediction found to be accurate for submaximal intensities on roller skiing using the skating technique by Gloersen et al. (2020).

The formulation used for prediction of VO_2^{dem} says that VO_2^{dem} increases linearly with *v* at a constant P_{prop}. This relationship has been validated by Gloersen et al. (2020) using the following calculation:

$$VO_2^{dem} - VO_2^{rest} = \beta_1 P_{prop} + \beta_2 v$$

Here VO_2^{rest} represents baseline metabolic rate, and was set to 5.1 mL/kg/min based on the findings of (Medbo et al., 1988). β_1 and β_2 denotes the x-variable and the constant respectively in the aforementioned linear regression of C and F_{prop}. During periods where participants generated no propulsion as detected by a threshold angle between torso and thigh, VO_2^{dem} was standardized to 20 mL/kg/min.

GPS measurements

Minimizing error in the measurements of the athletes' vertical position have demonstrated importance to accurately estimate P_{prop} (Gloersen, Losnegard, et al., 2018). The Catapult Optimeye S5 GPS falls short compared to the required vertical position accuracy, demanding additional calculations aside from the GPS tracking only. Therefore a common trajectory of the course in Holmenkollen has previously been manually mapped by Gloersen, Kocbach, et al. (2018). This common reference trajectory was then used along the standalone GPS position of the athlete, by mapping this position onto the reference trajectory, finding the shortest horizontal distance from the reference trajectory to the position of the GPS carried by the athlete. This position was then applied in the P_{prop} calculations.

Missing data

The collected data from Cosmed K5 was overseen and checked for outliers in VO_2 data, where the longest test for subjects 2, 3 and 10 were corrupted with erratic values. These values were most likely caused by saliva affecting the flow turbine, corrupting the measurements. Consequently, these tests were removed from the statistical analyzes.

The VO_2 uptake data from Cosmed K5 were delayed compared to other simultaneously recorded data from the K5. To standardize and calibrate the delay to match the remaining data, VO_2 uptake data was analyzed to find the average onset of a 2.5 mL/kg/min increase from the initial value. Linear interpolation of the 10 seconds measurement values was applied to determine the exact onset of this increase. A 26 ± 4 s delay was found, and consequently 26 s delay for all tests were set for both lab and field tests, as the lab data had similar delays compared to the data collected from the field.

Average VO_2 uptake was used to calculate fractional utilization of VO_{2max}. This was performed excluding the first 40 s of all tests to minimize the possibility of errors associated with VO_2 measurement delays. However, the first 40 s were included in calculations of O_2^{def}. VO_{2max} is derived from the highest 1 min average from the 1000m maximal effort test.

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References

Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Med*, *38*(3), 239-252. https://doi.org/10.2165/00007256-200838030-00004

Achenbach, E. (1968). Distribution of local pressure and skin friction around a circular cylinder in cross-flow up to Re = 5 × 106. *Journal of Fluid Mechanics*, *34*(4), 625-639. https://doi.org/10.1017/S0022112068002120

Atkinson, G., Peacock, O., & Passfield, L. (2007). Variable versus constant power strategies during cycling time-trials: prediction of time savings using an up-to-date mathematical model. *J Sports Sci*, *25*(9), 1001-1009. https://doi.org/10.1080/02640410600944709

Bangsbo, J. (2000). Muscle oxygen uptake in humans at onset of and during intense exercise. *Acta Physiol Scand*, *168*(4), 457-464. https://doi.org/10.1046/j.1365-201x.2000.00697.x

Barker, T., Poole, D. C., Noble, M. L., & Barstow, T. J. (2006). Human critical power–oxygen uptake relationship at different pedalling frequencies. *Experimental Physiology*, *91*(3), 621-632. https://doi.org/https://doi.org/10.1113/expphysiol.2005.032789

Bolger, C. M., Kocbach, J., Hegge, A. M., & Sandbakk, O. (2015). Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int J Sports Physiol Perform*, *10*(7), 873-880. https://doi.org/10.1123/ijspp.2014-0335

Calbet, J. A., Chavarren, J., & Dorado, C. (1997). Fractional use of anaerobic capacity during a 30- and a 45-s Wingate test. *Eur J Appl Physiol Occup Physiol*, *76*(4), 308-313. https://doi.org/10.1007/s004210050253

Chidnok, W., Dimenna, F. J., Bailey, S. J., Vanhatalo, A., Morton, R. H., Wilkerson, D. P., & Jones, A. M. (2012). Exercise tolerance in intermittent cycling: application of the critical power concept. *Med Sci Sports Exerc*, *44*(5), 966-976. https://doi.org/10.1249/MSS.0b013e31823ea28a

Chidnok, W., DiMenna, F. J., Fulford, J., Bailey, S. J., Skiba, P. F., Vanhatalo, A., & Jones, A. M. (2013). Muscle metabolic responses during high-intensity intermittent exercise measured by 31P-MRS: relationship to the critical power concept. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *305*(9), R1085-R1092. https://doi.org/10.1152/ajpregu.00406.2013

Davies, M. J., Benson, A. P., Cannon, D. T., Marwood, S., Kemp, G. J., Rossiter, H. B., & Ferguson, C. (2017). Dissociating external power from intramuscular exercise intensity during intermittent bilateral knee-extension in humans. *J Physiol*, *595*(21), 6673-6686. https://doi.org/10.1113/JP274589

Ferguson, C., Rossiter, H. B., Whipp, B. J., Cathcart, A. J., Murgatroyd, S. R., & Ward, S. A. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *J Appl Physiol (1985)*, *108*(4), 866-874. https://doi.org/10.1152/japplphysiol.91425.2008

Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med*, *31*(10), 725-741. https://doi.org/10.2165/00007256-200131100-00003

Glaister, M. (2005). Multiple sprint work : physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med*, *35*(9), 757-777. https://doi.org/10.2165/00007256-200535090-00003

Gloersen, O. (2019). *On the bioenergetics of cross-country skiing* University of Oslo]. University of Oslo.

Gloersen, O., Gilgien, M., Dysthe, D. K., Malthe, S. A., & Losnegard, T. (2020). Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc*, *52*(4), 983-992. https://doi.org/10.1249/MSS.0000000000002209

Gloersen, O., Kocbach, J., & Gilgien, M. (2018). Tracking Performance in Endurance Racing Sports: Evaluation of the Accuracy Offered by Three Commercial GNSS Receivers Aimed at the Sports Market. *Front Physiol*, *9*, 1425. https://doi.org/10.3389/fphys.2018.01425

Gloersen, O., Losnegard, T., Malthe-Sorenssen, A., Dysthe, D. K., & Gilgien, M. (2018). Propulsive Power in Cross-Country Skiing: Application and Limitations of a Novel Wearable Sensor-Based Method During Roller Skiing. *Front Physiol*, *9*, 1631. https://doi.org/10.3389/fphys.2018.01631

Hoff, J., Storen, O., Finstad, A., Wang, E., & Helgerud, J. (2016). Increased Blood Lactate Level Deteriorates Running Economy in World Class Endurance Athletes. *J Strength Cond Res*, *30*(5), 1373-1378. https://doi.org/10.1519/JSC.0000000000001349

Hultman, E., & Sjoholm, H. (1983). Energy metabolism and contraction force of human skeletal muscle in situ during electrical stimulation. *J Physiol*, *345*, 525-532. https://doi.org/10.1113/jphysiol.1983.sp014994

Jones, A. M., & Burnley, M. (2009). Oxygen uptake kinetics: an underappreciated determinant of exercise performance. *Int J Sports Physiol Perform*, *4*(4), 524-532. https://doi.org/10.1123/ijspp.4.4.524

Jones, A. M., Grassi, B., Christensen, P. M., Krustrup, P., Bangsbo, J., & Poole, D. C. (2011). Slow component of VO2 kinetics: mechanistic bases and practical applications. *Med Sci Sports Exerc*, *43*(11), 2046-2062. https://doi.org/10.1249/MSS.0b013e31821fcfc1

Jones, A. M., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Med*, *47*(Suppl 1), 65-78. https://doi.org/10.1007/s40279-017-0688-0

Karlsson, O., Gilgien, M., Gloersen, O. N., Rud, B., & Losnegard, T. (2018). Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front Physiol*, *9*, 846. https://doi.org/10.3389/fphys.2018.00846

Katch, V. L. (1973). Kinetics of oxygen uptake and recovery for supramaximal work of short duration. *Int Z Angew Physiol*, *31*(3), 197-207. https://doi.org/10.1007/BF00697599

Kavanagh, M. F., & Jacobs, I. (1988). Breath-by-breath oxygen consumption during performance of the Wingate Test. *Can J Sport Sci*, *13*(1), 91-93. https://www.ncbi.nlm.nih.gov/pubmed/3359368

Keir, D. A., Fontana, F. Y., Robertson, T. C., Murias, J. M., Paterson, D. H., Kowalchuk, J. M., & Pogliaghi, S. (2015). Exercise Intensity Thresholds: Identifying the Boundaries of Sustainable Performance. *Med Sci Sports Exerc*, *47*(9), 1932-1940. https://doi.org/10.1249/MSS.0000000000000613

Losnegard, T. (2019). Energy system contribution during competitive cross-country skiing. *European Journal of Applied Physiology*, *119*(8), 1675-1690. https://doi.org/10.1007/s00421-019-04158-x

Losnegard, T., & Hallen, J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *Int J Sports Physiol Perform*, *9*(1), 25-31. https://doi.org/10.1123/ijspp.2013-0066

Losnegard, T., Myklebust, H., & Hallen, J. (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*, *44*(4), 673-681. https://doi.org/10.1249/MSS.0b013e3182388684

Margaria, R., Oliva, R. D., Di Prampero, P. E., & Cerretelli, P. (1969). Energy utilization in intermittent exercise of supramaximal intensity. *J Appl Physiol*, *26*(6), 752-756. https://doi.org/10.1152/jappl.1969.26.6.752

McCully, K. K., Iotti, S., Kendrick, K., Wang, Z., Posner, J. D., Leigh, J., Jr., & Chance, B. (1994). Simultaneous in vivo measurements of HbO2 saturation and PCr kinetics after exercise in normal humans. *J Appl Physiol (1985)*, *77*(1), 5-10. https://doi.org/10.1152/jappl.1994.77.1.5

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O. M. (1988). Anaerobic capacity determined by maximal accumulated O2 deficit. *J Appl Physiol (1985)*, *64*(1), 50-60. https://doi.org/10.1152/jappl.1988.64.1.50

Medbo, J. I., & Tabata, I. (1989). Relative importance of aerobic and anaerobic energy release during short-lasting exhausting bicycle exercise. *J Appl Physiol (1985)*, *67*(5), 1881-1886. https://doi.org/10.1152/jappl.1989.67.5.1881

Monod, H. S., J. (2007, April 25). The work capacity of a synergic muscular group. *Ergonomics*, 329-338.

Morton, R. H., & Billat, L. V. (2004). The critical power model for intermittent exercise. *Eur J Appl Physiol*, *91*(2-3), 303-307. https://doi.org/10.1007/s00421-003-0987-z

Noordhof, D. A., de Koning, J. J., & Foster, C. (2010). The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity? *Sports Med*, *40*(4), 285-302. https://doi.org/10.2165/11530390-000000000-00000

Noordhof, D. A., de Koning, J. J., van Erp, T., van Keimpema, B., de Ridder, D., Otter, R., & Foster, C. (2010). The between and within day variation in gross efficiency. *Eur J Appl Physiol*, *109*(6), 1209-1218. https://doi.org/10.1007/s00421-010-1497-4

Noordhof, D. A., Skiba, P. F., & de Koning, J. J. (2013). Determining anaerobic capacity in sporting activities. *Int J Sports Physiol Perform*, *8*(5), 475-482. https://doi.org/10.1123/ijspp.8.5.475

O'Brien, B., Payne, W., Gastin, P., & Burge, C. (1997). A comparison of active and passive warm ups on energy system contribution and performance in moderate heat. *Aust J Sci Med Sport*, *29*(4), 106-109. https://www.ncbi.nlm.nih.gov/pubmed/9428991

Ozyener, F., Rossiter, H. B., Ward, S. A., & Whipp, B. J. (2003). Negative accumulated oxygen deficit during heavy and very heavy intensity cycle ergometry in humans. *Eur J Appl Physiol*, *90*(1-2), 185-190. https://doi.org/10.1007/s00421-003-0870-y

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sports Exerc*, *48*(11), 2320-2334. https://doi.org/10.1249/MSS.0000000000000939

Pringle, J. S., Doust, J. H., Carter, H., Tolfrey, K., & Jones, A. M. (2003). Effect of pedal rate on primary and slow-component oxygen uptake responses during heavy-cycle exercise. *J Appl Physiol (1985)*, *94*(4), 1501-1507. https://doi.org/10.1152/japplphysiol.00456.2002

Solli, G. S., Kocbach, J., Seeberg, T. M., Tjønnås, J., Rindal, O. M. H., Haugnes, P., Torvik, P. Ø., & Sandbakk, Ø. (2018). Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PloS one*, *13*(11), e0207195-e0207195. https://doi.org/10.1371/journal.pone.0207195

Spurk, H., & Aksel, N. (2008). Fluid Mechanics, 2 Edn. *Springer-Verlag*.

Sundström, D., Carlsson, P., Ståhl, F., & Tinnsten, M. (2013). Numerical optimization of pacing strategy in cross-country skiing. *Structural and Multidisciplinary Optimization*, *47*(6), 943-950. https://doi.org/10.1007/s00158-012-0856-7

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Med Sci Sports Exerc*, *29*(8), 1104-1108. https://doi.org/10.1097/00005768-199708000-00017

van Ingen Schenau, G. J., & Cavanagh, P. R. (1990). Power equations in endurance sports. *J Biomech*, *23*(9), 865-881. https://doi.org/10.1016/0021-9290(90)90352-4

Whipp, B. J., Ward, S. A., & Hassall, M. W. (1998). Paleo-bioenergetics: the metabolic rate of marching Roman legionaries. *Br J Sports Med*, *32*(3), 261-262. https://doi.org/10.1136/bjsm.32.3.261

Article

The effect of competition duration on oxygen demand and -uptake in cross-country skiing

Abstract

Purpose: This study aimed to investigate changes in pacing patterns and energy system contributions in a short (~3.5 min), middle distance (~7.6 min) and long race (~15.8 min) in competitive XC skiers during roller skiing. We hypothesized that the relationship between average metabolic energy turnover (VO_2^{dem}) and race duration follows an approximately inverse curve in intermittent endurance exercise, similar to constant load endurance exercise. We additionally expected average VO_2 uptake to not change with test duration.

Methods: 12 competitive XC-skiers (8 male and 4 female, VO_{2Max} 78. ± 2,5 and 63.5 ± 3.9 mL/kg/min) raced a 1.6 km course at 3 distinct tests for 1, 2 and 4 laps (~3.5, ~7.6 and ~15.8 min) in a randomized order with 35 min breaks in-between. VO_2 and GPS data was acquired to establish VO_2 uptake and demand. On an additional day, the athletes completed 6 submaximal loads of 5 min and a 1000m uphill maximal effort test to establish skiing economy, $VO_{2\text{-}Max}$ and maximal ΣO_2-deficit (MAOD). Pulmonary VO_2 was measured using mixing chamber. $\Sigma O2$-def and VO_2 demand was calculated from an athlete-specific model of skiing economy.

Results: During the 1, 2 and 4 laps tests, average VO_2^{dem} including tucked position was 110 ± 8 %, 101 ± 7 % and 96 ± 7 % of VO_{2max} respectively. When excluding tucked position, corresponding VO_2^{dem} averaged 130 ± 9 %, 119 ± 9 % and 112 ± 8 % of VO_{2max}. Both peak and average VO_2^{dem} followed an inverse relationship with test duration irrespective of whether tucked position was included or not. The average VO_2 uptake was similar on all tests with 86 %, 86 % and 84 % of VO_{2max} on the 1, 2 and 4 laps respectively.

Conclusion: We established a relationship between energy demand and test duration in XC skiing which indicates similar duration-dependent energy demand changes in highly intermittent endurance exercise modalities compared to constant load endurance exercise.

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Introduction

Endurance sports are characterized by the sustained high metabolic energy demands during racing performance (Joyner & Coyle, 2008). Primarily the aerobic energy system has capacity to supply these energy demands, whereas anaerobic energy systems contributes inversely with increasing race duration given a constant load intensity (Gastin, 2001). This results in a hyperbolic propulsive power-duration relationship curve where propulsive power output falls abruptly, then levels off with increasing race duration. Eventually, a steady state threshold is reached when the anaerobic capacity becomes fatigued. This formulates a concept termed the 'critical power' (P_c), which practically describes a maximal sustainable metabolic steady state (Bishop et al., 1998; Monod, 2007; Noordhof et al., 2013; Poole et al., 2016; Skiba et al., 2012).

Compared to intermittent endurance sports, the P_c concept has demonstrated superior applicability to endurance sports with constant load intensity. Running is one such typical constant load modality where sustained propulsive power outputs above P_c leads to predictable time to exhaustion when applying the P_c concept (Poole et al., 2016). As these supra-P_c power outputs are connected to non-sustainable anaerobic energy contributions, energy system contributions are therefore also predictable as a function of competition duration (Gastin, 2001).

During intermittent endurance sports featuring varying terrain however, propulsive power is unevenly distributed through the undulating racecourse, with workloads exceeding P_c and even maximal oxygen uptake (VO_{2max}) during parts of the race (Gloersen et al., 2020; Granier et al., 2018; Losnegard, 2019). Downhill sections then presents temporary recovery opportunities when propulsive power falls beneath P_c, allowing athletes to repeatedly race at supramaximal intensities (above P_c) associated with O_2-deficits and thus anaerobic energy contribution (Gloersen et al., 2020). Mechanical efficiency is therefore not constant, thus rendering P_c an inappropriate steady state metabolic boundary. The maximal sustainable aerobic rate (VO_{2crit}) however, corresponds with the power output at a maximal sustainable metabolic steady state, and therefore proves a more appropriate measurement of P_c in such intermittent endurance sports (Poole et al., 2016).

XC skiing represents a compelling model for studying this intermittent phenomenon due to considerable variations in terrain and consequently also in propulsive power outputs, expressed here as oxygen demand (VO_2^{dem}) (Gloersen, Losnegard, et al., 2018). Specifically, VO_2^{dem} typically range between 110 % to 160 % of VO_{2max} during uphill in long distance skiing (>30 min) (Gloersen et al., 2020; Karlsson et al., 2018; Norman & Komi, 1987) and 120 % to 160 % during sprint skiing (2-4 min) (Andersson et al., 2017; Andersson et al., 2016; Andersson et al., 2019; Sandbakk et al., 2011). These oxygen demands far exceeds VO_{2crit}, which in XC skiing races normally range between 80 % to 90 % of VO_{2max} (Gloersen et al., 2020; Welde et al., 2003), consequently implying substantial anaerobic energy contributions in uphill. This in turn creates a complex challenge of adjusting pacing patterns to the course profile to minimize finishing time.

Nevertheless, anaerobic capacity have displayed no correlation with FIS-points in distance skiing (Losnegard, 2019). And Gloersen et al. (2020) argued their intermittent O_2-deficits to rather challenge the rate of recovery from these deficits during downhill segments. An argument based on a continuously estimated VO_2^{dem} and VO_2 uptake through a treadmill simulated roller skiing distance race. The only previous study to combine such measurements in simulated distance skiing.

During the sprint distance in XC skiing however, anaerobic capacity have been regarded as a performance limiting factor by Losnegard et al. (2012), a claim supported by a base of treadmill simulations (Andersson et al., 2016; Losnegard et al., 2015) Even the rate of which anaerobic capacity can be released (anaerobic power) has been suggested to limit sprint performance (Mikkola et al., 2010). Although neither of these claims build upon field tested research. Moreover, continuous estimations of VO_2^{dem} and VO_2 uptake have regardless of distance yet to be executed in field XC skiing.

The present study therefore continuously measured oxygen uptake and estimated oxygen demand throughout 3 field test races on roller skis ranging from sprint to distance skiing duration. The aim for which was to compare and describe the changes in pacing patterns and energy system contributions at this type of race durations. The basis for which was estimations of propulsive power from global navigational satellite systems (Gloersen, Losnegard, et al., 2018), laboratory measurements of skiing specific working economy (Gloersen, Losnegard, et al., 2018) and a treadmill test assessing maximal oxygen deficit

(MAOD) and VO_{2max}. These tools allowed continuous oxygen demand estimates, which was combined with oxygen uptake measurements from a portable metabolic VO_2 analyzer to assess energy demand and pacing patterns.

We hypothesized that the relationship between average metabolic energy turnover (VO_2^{dem}) and race duration follows an approximately inverse curve in intermittent endurance exercise, similar to constant load endurance exercise. We additionally expected average VO2 uptake to not change with test duration.

Method

Subjects

Twelve competitive XC skiers participated in this study after giving informed consent to taking part in this experimental procedure. Inclusion criteria was previous experience in XC-skiing competitions at a national level and being over 18 years old. Subject characteristics are found in table 2.0. The study was conducted in line with the rules of the Helsinki-declaration and was approved by the ethical committee of the Norwegian School of Sport Sciences and in agreement with the Norwegian Center for Research Data.

Table 2.0: Subject characteristics (n=12, 8 men and 4 women)

	Men		Women	
	Mean ± SD	Range	Mean ± SD	Range
Age (yr)	21.4 ± 5.2	19 - 34	25.5 ± 3.7	23 - 31
Body mass (kg)	74.6 ± 4.6	67.4 - 80.2	65.1 ± 8.2	54.2 - 73.6
Height (cm)	183 ± 4.6	176 - 190	171 ± 2.6	167 - 173
VO2max (ml*min^{-1} *kg	78.0 ± 2.5	75.7 - 82.1	63.5 ± 3.9	61.3 - 66.7

General design

The study consisted of 2 separate days of testing, separated by at least 48 hours and maximum 1 week. The first test day consisted of field testing on the national XC skiing arena's roller skiing course, Holmenkollen, while the second test day took place in the lab. Field testing consisted of 3 maximal effort tests of different durations and in randomized order, where VO_2 uptake was measured. Skiing speed and propulsive power were calculated using a combination of GNSS receivers and inertial measurements as

Lab testing consisted of a submaximal test with 6 different loads to establish skiing specific working economy. This data was used in an empirical model to predict VO_2^{dem} from skiing speed and propulsive power. Additionally a maximal effort test to measure VO_{2max} and calculate maximal accumulated oxygen deficit (MAOD) was performed on the lab test day. Men and women tested on the same course with equal number of laps on the field tests with minor adjustments to the laboratory tests as described below.

Field test day

The course

All field tests were performed on the course depicted in figure 1.1. This course measures 1560m in length with an elevation gain of 65m over 1 lap. Subjects were all experienced on the course from previous training and competitions on both roller skis and on cross-country skis.

Segmentation

The course was split into 4 segments for a breakdown of the participants effort to a more detailed picture. The 3 first segments are uphill segments of various lengths and inclines, while *S4* is a flat (figure 1.1).
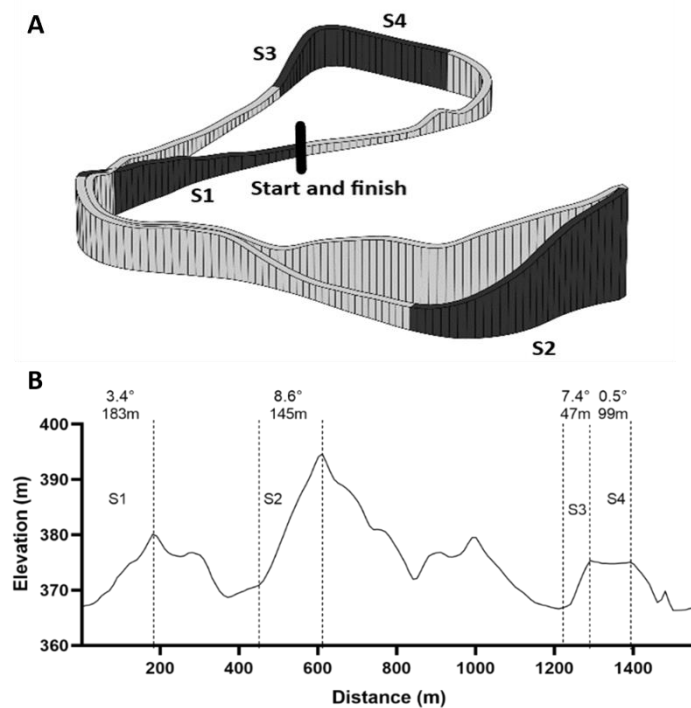

*Figure 1.1: **A** shows Holmenkollen 3D course map depiction with individual segments marked black. Start, lap and finish at the same line. **B** shows Elevation map featuring segment placement, (S1-S4) average inclination and length.*

Field test day overview

Field test day overview is provided in figure 1.2. The participants were weighed with and without equipment and informed about test order before warmup. The warmup consisted of 10 minutes easy activity where participants was asked to complete the course for the tests. Then a moderate lap followed, before the participants performed 2 progressive 30 s repeats ending at approximately 1 lap test intensity. This was followed by 3 min of light activity and 2 min standing still while the portable VO_2 analyzer was mounted, ensuring a similar starting metabolic rate before each test.
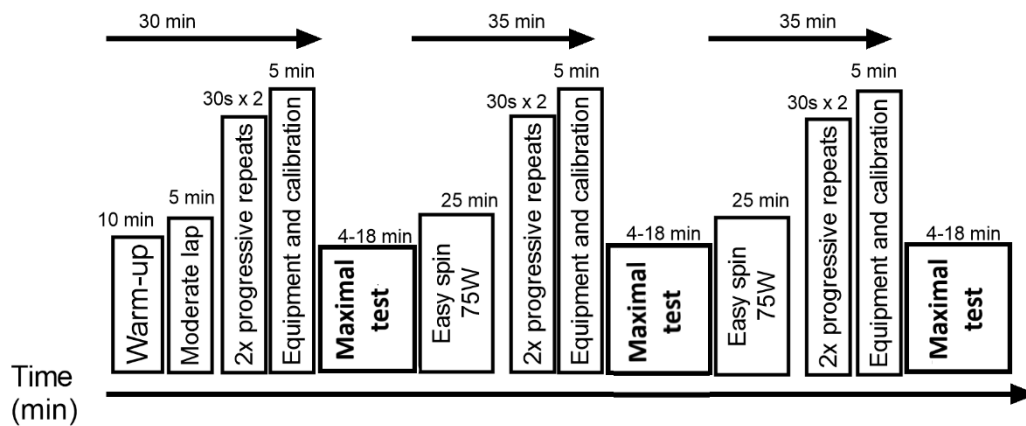
Figure 1.2: Field testing protocol overview. Participants were weighed and equipment was assembled prior to warm-up and 5 min before test start. Progressive repeats ended at test speed intensity. Test order was randomized.

Participants were asked to complete the tests as if it was an XC skiing competition with regards to pacing and maximizing of the effort at all tests. Upon completion of each test participants should maintain 75W of easy cycling on a bicycle ergometer for about 25 min of the 35 min break between each test. The remaining 10 min consisted of 2 progressive 30 s repeats on roller skis ending approximately at 1 lap intensity followed by a similar preparation to that of the first test for the last 5 min.

Equipment

The participants used the same pair of roller skis (Swenor skate long, wheel type 2). They were also equipped with two position tracking devices (Catapult Optimeye S5), which consists of a 10 Hz standalone GNSS-module and a 9-axis inertial measurement unit. This includes accelerometer, gyroscope and magnetic field measurements. Participants wore 1

receiver on the back in a tight-fitting breast vest. While the other was taped laterally on the thigh approximately in the mid-point between trochanter and the distal lateral condyle of the femur. The aforementioned equipment is similar the setup used by Gloersen, Losnegard, et al. (2018).

Additionally, the participants were equipped with a Cosmed K5 portable pulmonary VO_2-analyzer used in mixing chamber mode. The gas analyzer, which was worn in a harness, was positioned right below the upper GPS unit. With the K5 VO_2-analyzer a Hans Rudolph mouthpiece was used (Two-Way Non-Rebreathing T-Shape, Hans Rudolph, Kansas City, MO, USA) along with a nose clip (NoseClip, Reusable Series 9015, Hans Rudolph, Kansas City, MO, USA). Preceding the first test, the pulmonary VO2 analyzer was calibrated using a certified calibration gas, while the volume was calibrated using a 3-liters calibration pump.

Figure 1.3: The setup with Cosmed K5 and the upper GPS-unit as used in the field tests.

Lab test day

Submaximal protocol

The submaximal protocol was designed to test the skiing specific working economy of the subjects by applying 6 different workloads of 5 min at varying speed and incline with a rest period of 2.5 minutes (figure 1.4). A self-paced warmup of 15 min including habituation to the maximal effort test preceded the submaximal loads. The intensity of these loads was aimed below, and close to, the anaerobic threshold intensity. Therefore, a slightly different protocol was used for the two genders. Speed was reduced by 10 % for the females, using the same inclines as the men. The protocol was repeated with speed adjustments on a separate later day for 1 subject as the intensity exceeded anaerobic threshold intensity. Pulmonary VO_2 measurements and HF data were collected during the workloads, while

blood lactate and rate of perceived exertion (RPE) were collected at the end of each
workload.

Submaximal loads
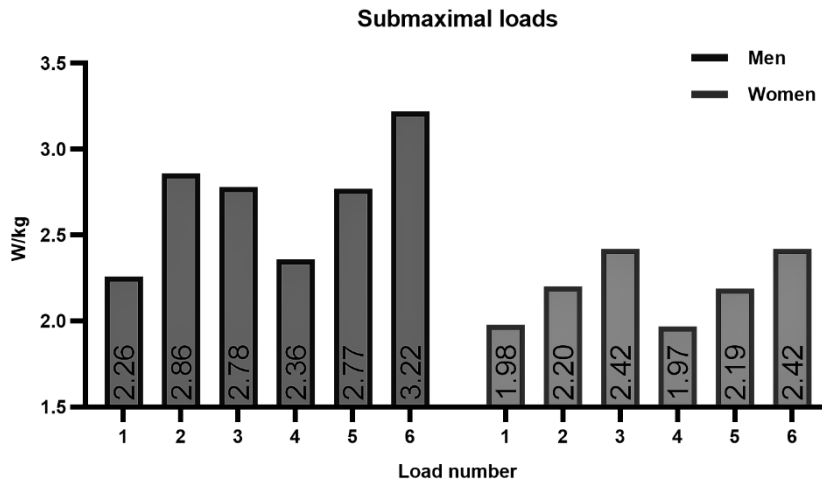
*Figure 1.4: Load intensity is expressed in watt per kilogram (W/kg) and is calculated from propulsive force
(F_{prop}) and speed for each load. Male and female protocols is depicted on the left and right respectively.
Incline and speed for all loads is summarized in the results. The order of load number 1-3 and 4-6 was
randomized.*

1000m maximal effort test protocol

For the maximal 1000m test the participants used Swenor skate long
(wheel type 1). This test was performed after a 15 min rest period
from the submaximal protocol at 6.0 and 4.5 degrees incline
respectively for men and women, with a start speed of 3.25 m/s.
Speed increased to 3.5 m/s at 100 meters, while at 200 meters
participants could control speed by moving in front of (or behind)
two laser lines with both front wheels. This gave an increase (or
reduction) in speed by 0.25 m/s. Pulmonary VO_2 measurements with
Cosmed K5 in mixing chamber mode and HF data were collected
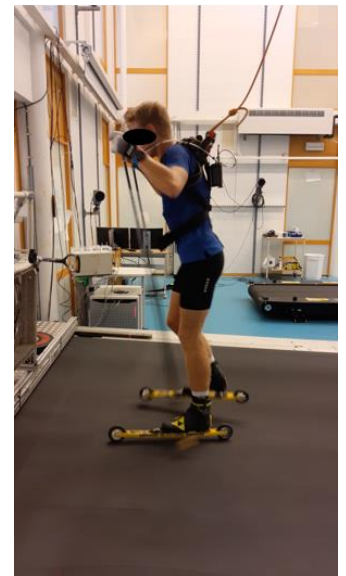during the test. Lactate and RPE were collected at the end of the test.

*Figure 1.5: Picture from the lab test
setup used on both submaximal and
1000m maximal tests.*

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Data analysis

The measure of intensity in this study is based on an estimate of propulsive power (P_{prop}) and its relation to individual skiing specific working economy. P_{prop} has been validated as an intensity measurement in XC skiing and described in detail by Gloersen, Losnegard, et al. (2018). The following equation describes the composition of P_{prop}:

$$P_{prop} = \dot{E}_{mech} + \dot{w}_{env}$$

Where E_{mech} is defined as the change in mechanical energy of a point mass (representing the skier with equipment) and W_{env} represents rate of energy dissipation to the environment. Our P_{prop} calculations largely followed the method from Gloersen, Losnegard, et al. (2018) with some deviations regarding W_{env}, specifically on air drag and friction estimates.

Estimating air drag, Gloersen, Losnegard, et al. (2018) used frontal area imaging to determine frontal area size. We instead applied allometric scaling of the relationship between body mass and frontal area using data from Gloersen, Losnegard, et al. (2018). The allometric scaling was $A_0 = k \cdot m^{2/3}$, where the proportionality constant $k=0.03251$ $m^2/kg^{(2/3)}$ was determined by least squares fitting to the data from Gloersen, Losnegard, et al. (2018).

Lastly, F_f denotes friction and was calculated using 4 pairs of photocells on a flat asphalt surface located directly by field test start. Entry and exit speed were measured by passively gliding onto a flat section to calculate deceleration and friction from a given rolling distance, as described by Solli et al. (2018). This procedure was performed in both rolling directions.

Oxygen demand

The primary estimate of metabolic rate in the present study is oxygen demand (VO_2^{dem}), which was predicted using a formulation stating that VO_2^{dem} increases linearly with speed (v) at a constant P_{prop}. Therefore, P_{prop} = Propulsive force (F_{prop})$*v$ (Gloersen, Losnegard, et

al., 2018). F_{prop} was used to establish a skiing specific working economy by predicting VO_2^{dem} from a linear relationship between F_{prop} and cost of transport (C) in mL VO_2/m on the submaximal test (Gloersen et al., 2020) as depicted in figure 1.6.

Skiing economy model
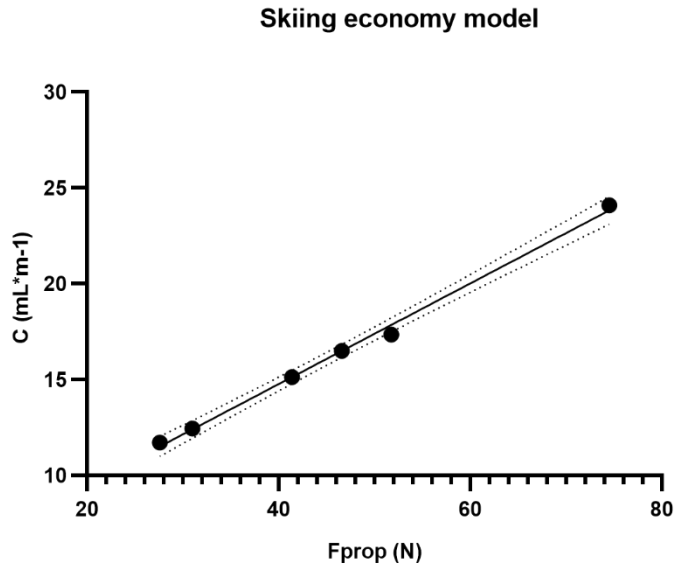
Figure 1.6: Linear regression of the individual relationship between cost of transport (C) and propulsive force (F_{prop}) for 1 athlete as tested on the submaximal test. C is presented as mL/m, while F_{prop} is presented in N.

This relationship has been validated by Gloersen et al. (2020), and field VO_2^{dem} estimations were therefore based on the following calculation:

$$VO_2^{dem} - VO_2^{rest} = \beta 1 P_{prop} + \beta 2 v$$

Here VO_2^{rest} represents baseline metabolic rate, and was set to 5.1 mL/kg/min based on the findings of Medbo et al. (1988). β_1 and β_2 denotes the x-variable and the constant respectively in the aforementioned linear regression of C and F_{prop}. During periods where participants generated no propulsion as detected by a threshold angle between torso and thigh, VO_2^{dem} was standardized to 20 mL/kg/min.

Accumulated oxygen deficit ($\sum O_2^{def}$) was calculated from the difference between accumulated VO_2^{dem} and accumulated VO_2 uptake during a set time interval. On the 1000m maximal effort test, $\sum O_2^{def}$ was defined as maximal accumulated oxygen deficiency (MAOD).

Equipment

Submaximal lab tests were performed using Swenor skate long wheel type 2 (coefficient of rolling resistance; $C_{rr} = 0.018$), the same pair that was used on field tests. Maximal effort tests were performed using Swenor skate long wheel type 1 (coefficient of rolling resistance; $C_{rr} = 0.011$). Swix Triac 3.0 ski poles with customized treadmill ferrules (Swix sport Lillehamer Norway) was used on all lab tests. The tests were performed on a roller skiing treadmill produced by Rodby Innovation AB, Hagby, Vänge, Sweden). Lactate was measured using Biosen C-line analyzer (EKF Diagnostic GmbH, Barleben, Germany). Pulmonary VO2 was measured with Cosmed K5 portable analyzer.

Missing data

The collected data from Cosmed K5 was overseen and checked for outliers in VO_2 data, where the longest test for subjects 2, 3 and 10 were corrupted with erratic values. These values were most likely caused by saliva affecting the flow turbine, corrupting the measurements. Consequently, these tests were removed from the statistical analyzes.

The VO_2 uptake data from Cosmed K5 were delayed compared to other simultaneously recorded data from the K5. To standardize and calibrate the delay to match the remaining data, VO_2 uptake data was analyzed to find the average onset of a 2.5 mL/kg/min increase from the initial value. Linear interpolation of the 10 s measurement values was applied to determine the exact onset of this increase. A 26 ± 4 s delay was found, and consequently 26 s delay for all tests were set for both lab and field tests, as the lab data had similar delays compared to the data collected from the field.

Average VO_2 uptake was used to calculate fractional utilization of VO_{2max}. This was performed excluding the first 40 s of all tests to minimize the possibility of errors associated with VO_2 measurement delays. However, the first 40 s were included in calculations of O_2^{def}. VO_{2max} is derived from the highest 1 min average from the 1000m maximal effort test.

Results

Submaximal test

Results from the submaximal and 1000m maximal effort, which were used as input data in the prediction of VO_2^{dem} test are presented in table 1.1.

Table 1.1: All values are presented as average ± standard deviation. Speed and incline were preset for all participants, where speed was reduced by 10% for the women compared to the men. Submaximal VO_2 is average over the last 2 min, while 1000m VO_2 is average over the last 1 min. RPE is scaled from 6 to 20. 1 participant was unable to complete the sub-maximal loads without exceeding her lactate threshold, and therefore reran the protocol with the following speeds: 5.1, 2.0, 4.9, 3.2, 3.2 and 3.1 m/s.

	Speed ($m \cdot s^{-1}$)	Incline (°)	VO2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	[La] ($mmol \cdot L^{-1}$)	RPE	MAOD ($mL \cdot kg^{-1}$)
			Men			
Submaximal loads	6.0	1.07	57 ± 3	2.3 ± 0.5	13.1 ± 0.8	
	2.5	4.65	50 ± 2	1.8 ± 1.0	12.4 ± 0.5	
	6.0	1.33	62 ± 3	3.1 ± 1.2	14.4 ± 1.1	
	4.0	2.12	52 ± 3	1.8 ± 0.5	11.9 ± 0.8	
	4.0	2.52	55 ± 3	2.0 ± 0.7	13.2 ± 0.7	
	4.0	2.91	59 ± 3	2.7 ± 0.7	14.6 ± 0.5	
1000m	3.8 ± 0.2	6.0	78 ± 2	10.3 ± 1.2		67 ± 21
			Women			
Submaximal loads	5.4	1.07	51 ± 4	2.8 ± 0.8	12.3 ± 0.5	
	2.3	4.65	45 ± 4	2.4 ± 0.8	12.5 ± 2.4	
	5.4	1.33	52 ± 2	3.3 ± 0.7	13.8 ± 1.3	
	3.6	2.12	45 ± 2	1.9 ± 0.6	12.3 ± 1.0	
	3.6	2.52	48 ± 1	2.2 ± 0.6	13.5 ± 1.3	
	3.6	2.91	51 ± 1	2.9 ± 0.7	14.8 ± 0.5	
1000m	3.7 ± 0.3	4.5	65 ± 7	9.2 ± 0.9		59 ± 9

Field tests

Participants finished the 1 lap test with an average time of 3:36 ± 0:18 [m:ss] while the 2 lap test was finished in 7:35 ± 0:37 [m:ss]. The 4 lap test was finished in 15:43 ± 1:26 [m:ss]. Participants spent 25.3 ± 5.9 %, 25.7 ± 6.2 % and 25.7 ± 7.4 % of their test in tucked position for the 1, 2 and 4 laps tests respectively.

Oxygen demand and uptake
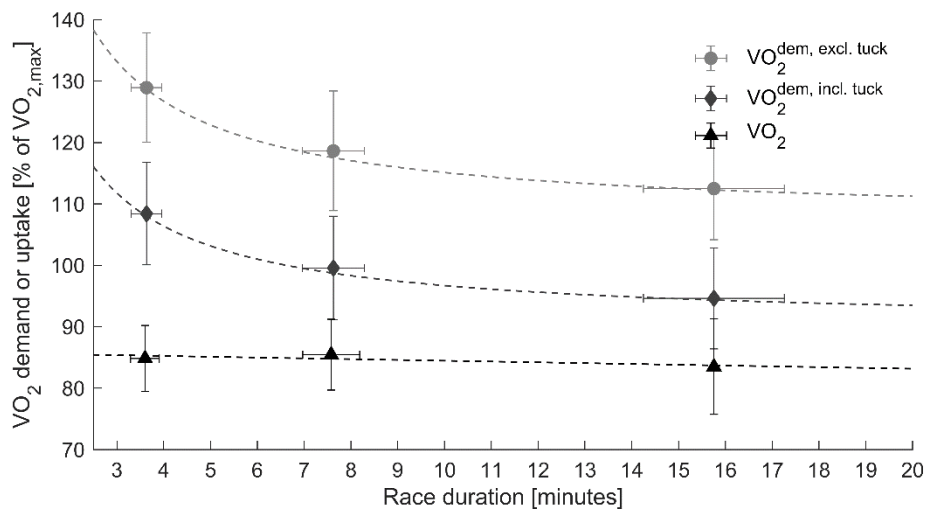
Figure 1.7: Average VO_2^{dem} and VO_2 uptake relative to VO_{2max} as a function of test race duration. All values are presented as average ± standard deviation relative to VO_{2max} in %. VO_2^{dem} estimates are included and excluded tucked position, where tucked position estimates were set to 20 mL/kg/min.

The VO_2^{dem} including periods in tucked position, depicted in figure 1.7, was on average 110 ± 8 %, 101 ± 7 % and 96 ± 7 % of the participants VO_{2max} for the 1, 2 and 4 laps tests respectively. Hence, from the 1 lap test VO_2^{dem} was reduced by 8.2 ± 2.6 percentage points (pp) and 12.7 ± 3.1 pp to the 2 and 4 laps tests respectively. When excluding tucked position from the calculations, thus summarizing periods of active propulsion, the corresponding VO_2^{dem} were 130 ± 9 %, 119 ± 9 % and 112 ± 8 % of VO_{2max}.

VO_2 uptake relative to the participants VO_{2max} (fractional utilization of VO_{2max}) for the 3 tests exhibited stable values of 86 ± 5 %, 87 ± 6 % and 85 ± 8 % for the 1, 2 and 4 laps tests respectively.

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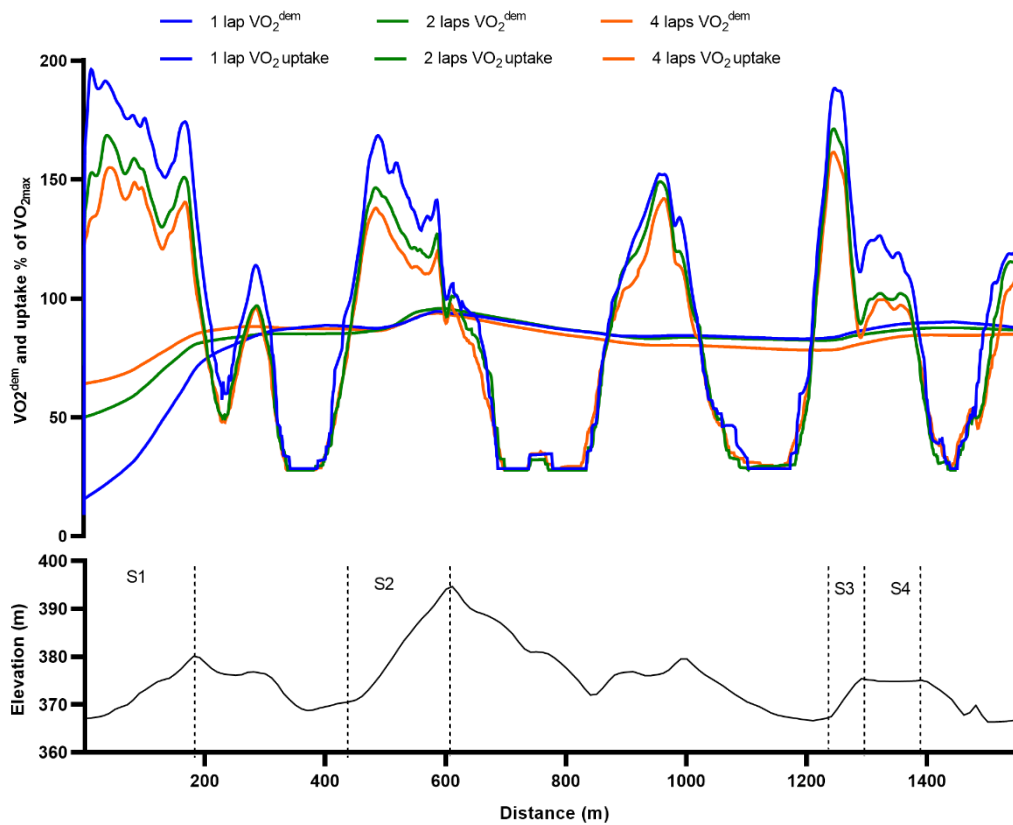
Figure 1.8: Instantaneous VO$_2^{dem}$ and VO$_2$ uptake relative to VO$_{2max}$ as a function of distance on the maximal field tests. The most variation occurs in VO$^2_{dem}$, while VO$_2$ uptake reaches a relatively steady state at approximately 40 seconds. 2 laps and 4 laps tests represent average values from all laps, which is the reason for the initial difference in VO$_2$ uptake. VO$_2^{dem}$ during periods of tucked position is set to 20 mL/kg/min.

The participants' instantaneous VO$_2^{dem}$ and VO$_2$ uptake as a function of race course position is plotted in figure 1.8. During uphill segments, participants race at a supramaximal VO$_2^{dem}$ averaging 120 % to 171 % of VO$_{2max}$ all tests and uphill segments considered. These uphill supramaximal VO$_2^{dem}$ leads to accumulation of O$_2^{def}$, alternating with a drop in VO$_2^{dem}$ going into the downhill, allowing participants to recover some of the $\sum$O$_2^{def}$. This recurring pattern differs approximately equally with test duration, although with less variation on shorter segments that directly follows a downhill.

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Accumulated O2 deficit

For the duration of the 1, 2 and 4 laps tests, the participants total $\sum O_2^{def}$ including tucked position were 104 ± 27 %, 125 ± 43 % and 180 ± 77 % of their MAOD. The equivalent $\sum O2^{def}$ when excluding tucked position were 141 ± 39 %, 202 ± 55 % and 350 ± 116 %. Overview of $\sum O_2^{def}$ on all tests is presented in figure 1.9, displaying that participants' $\sum O_2^{def}$ was gradually smaller relative to the test duration increase.
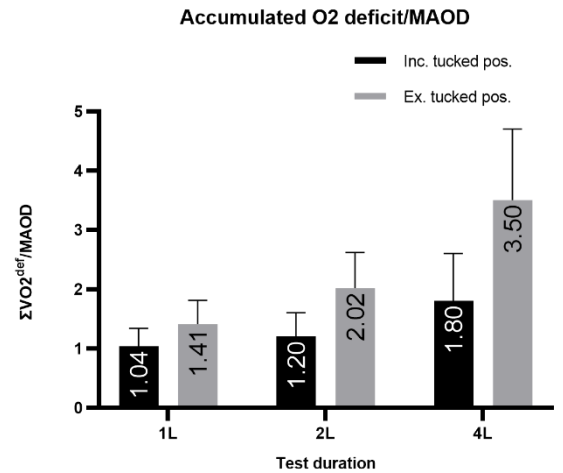

Figure 1.9: Average $\sum O_2^{def}$ with SD on all tests including and excluding tucked position.

Segmentation

The course was split into 4 individual segments as depicted in the below figure 2.0, where segment time, VO_2 uptake, VO_2^{dem} and $\sum O_2^{def}$ are presented for each segment. The average segment VO_2^{dem} decreased the most on the S1 segment with -13 ± 5 % and -20 ± 6 % from the 1 lap test to the 2 and 4 laps tests.

Adjusting for the delayed response in VO2, which is caused by both the inertia of oxidative metabolism and measurement delays due to the dynamic mixing chamber, S1 $\sum O_2^{def}$ is alternatively presented as S1 average VO_2^{dem} minus average test VO_2 uptake. This results in respective $\sum O_2^{def}$ values of 61 ± 18 %, 53 ± 15 % and 51 ± 18 % of MAOD. Even with this adjustment, participants accumulated over 50 % of their MAOD on S1 for all tests.

S2 was the steepest (8.6° average incline) and longest segment in completion time, and consequently demonstrated the largest relative increase in completion time, with 13 ± 5 % and 19 ± 11 % for 2 and 4 laps compared to 1 lap respectively. Thus, participants also exhibited reductions in $\sum O2^{def}$ of -23 ± 13 % and -28 ± 24 % on the 2 and 4 laps tests from the 1 lap on this segment. S3 showed the smallest reductions in $\sum O_2^{def}$ and VO_2^{dem} from 1 lap to 2 and 4 laps, partly explained by the segment's placement following a long downhill section, allowing participants sufficient recovery time to display high VO_2^{dem} on all tests. On the flat S4 segment, participants demonstrated lower VO_2^{dem} at an effort closer to VO_{2max} compared to uphill segments. Reductions in VO_2^{dem} of 12 ± 9 and 15 ± 6% from 1 lap to 2 laps and 4 laps occurred although completion time displayed similar reductions as

on S3 (8 ± 6 and $12 \pm 9\%$). Comparably therefore, similar increase in effort (VO_2^{dem}) yielded less time reductions on the flat (S4) compared to uphill (S3).
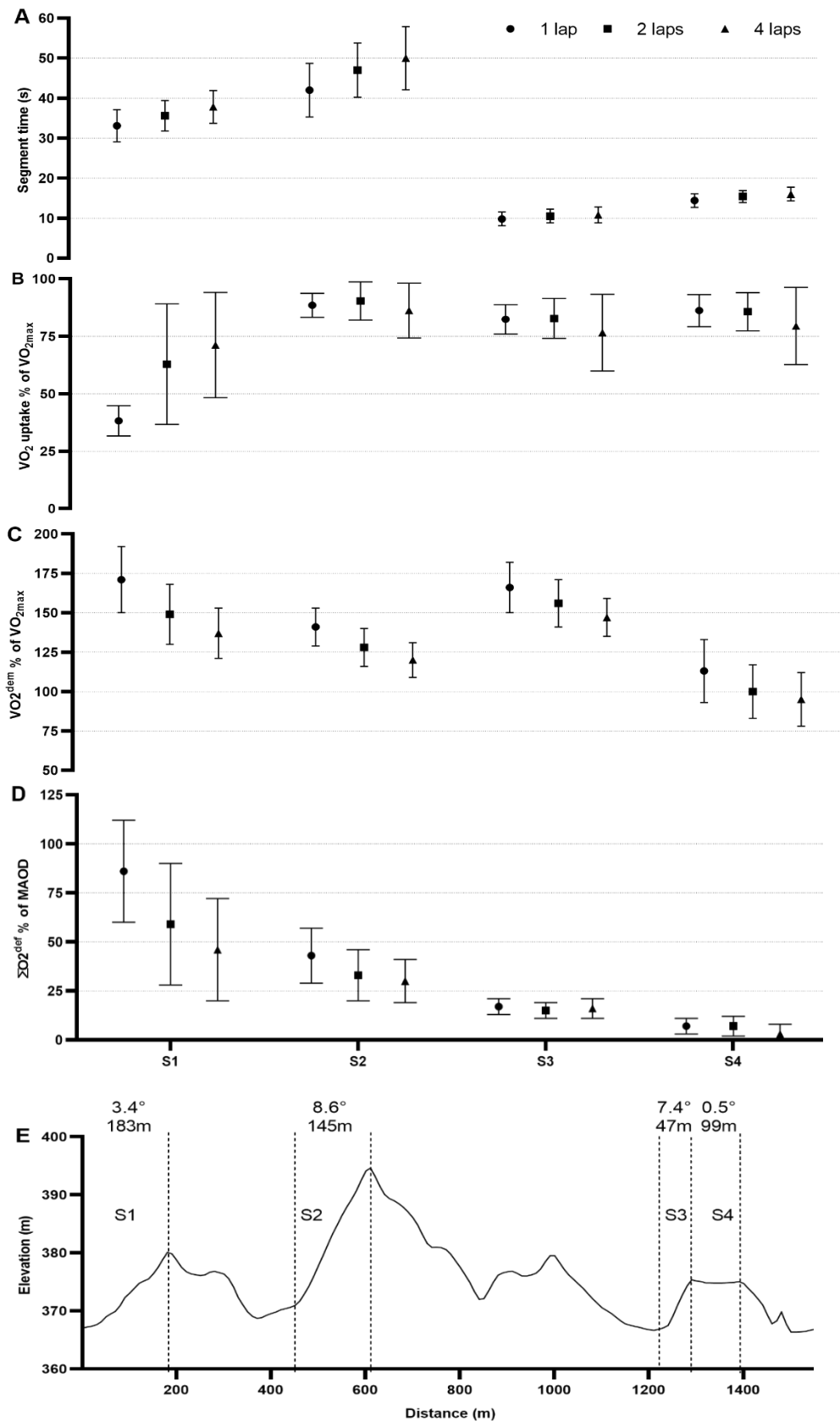
*Figure 2.0: Segmentation of the course where **A** depicts segment completion time on each test. 2 lap and 4 laps represent average from all test laps. **B** shows VO_2 uptake in % of VO_{2max}. **C** shows $VO2^{dem}$ as % of VO_{2max}. **D** shows $\sum O2^{def}$ as % of MAOD. **E** depicts the individual segments on an elevation profile, where they are found on the course, as well as length in meters and average incline in degrees.*

Energy system contribution

The overview of energy system contribution including and excluding tucked position is found in figure 2.1. Anaerobic energy release including tucked position was reduced by 40 ± 16 % and 57 ± 11 % from 1 lap to 2 and 4 laps respectively. While excluding tucked position, the corresponding reductions were 25 ± 11 % and 36 ± 8 %
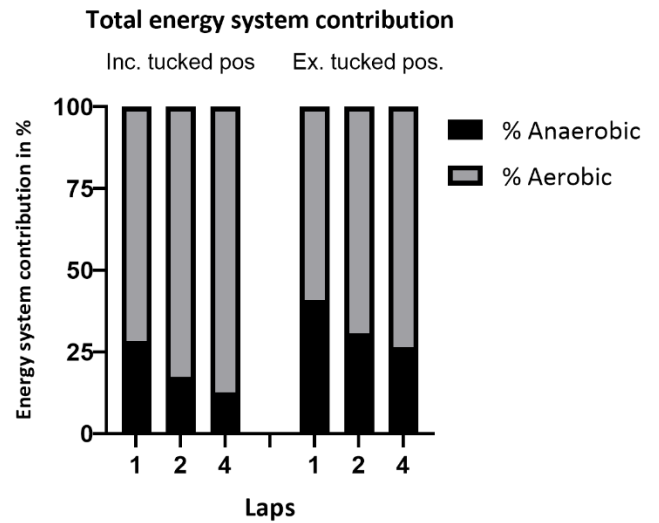
Figure 2.1: Total energy contribution for the 1, 2 and 4 laps tests calculated from the difference between $VO2^{dem}$ and VO2 uptake including and excluding periods of no propulsion. For periods of no propulsion, $VO2^{dem}$ was set to 20 mL/kg/min.

Discussion

This study is the first to measure oxygen uptake and estimate oxygen demand continuously throughout maximal tests of durations ranging from sprint (~3.5 min), to distance (~15.8 min) roller skiing in the field. We found that both peak and average VO_2^{dem} followed an inverse relationship with test duration while the average VO_2 uptake was similar on all tests. Thus, anaerobic energy turnover explains the substantial difference in speed between sprint and distance skiing and confirm anaerobic capacity as an important determinant for performance in sprint skiing.

Energy demand and contribution at sprint duration

We found that the average VO_2^{dem} during a sprint distance of ~3 min was 109 % of VO_{2max} including tucked position, agreeing with treadmill simulated findings from Losnegard et al. (2012) and (Losnegard et al., 2015; Losnegard et al., 2013). Compared to running, an 800m (113 % VO_2^{dem}) displays more similarity to the 1 lap distance than a 1500m (103 % VO_2^{dem}) (Gastin, 2001; Spencer & Gastin, 2001). Previously, this energy demand difference have been attributed to elevated activation of muscle mass volume, considering the upper body involvement in XC skiing (Losnegard, 2019).

The energy demands amounted to 28 % anaerobic contribution, agreeing with collected findings from maximal efforts of similar duration (figure 2.2) (Gastin, 2001; Spencer & Gastin, 2001). This estimation was also in compliance with treadmill simulations by Losnegard et al. (2012) and Andersson and McGawley (2018). However, other treadmill simulated sprint distances have estimated a lower (~20 %) anaerobic energy contribution (Andersson et al., 2017; Andersson et al., 2016; McGawley & Holmberg, 2014), likely explained by increased test duration. Additionally, considering participants accumulated 104% of MAOD even including tucked position on the 1 lap test, our findings therefore add field tested evidence confirming anaerobic capacity is a determining factor for XC skiing sprint performance.

Anaerobic power, i.e. the maximal rate of energy release has been proposed as a possible performance limiting factor on the sprint distance by Mikkola et al. (2010). Our data showed that participants averaged VO_2^{dem} at 170 % of VO_{2max} during the first 30 s (S1) and accumulated an O_2^{def} equal to 100% of MAOD from an average of 47 s of active propulsion. This time window was interspersed with 1 downhill segment, allowing a partial recovery, resulting in participants accumulating their MAOD within a shorter time frame. Findings from Calbet et al. (1997); Medbo and Tabata (1989) of all out constant exercise indicate that a 30 s effort elicits 80 % of MAOD, arguably showing that participants were either very close to, or at their maximal anaerobic power during the early stage of the 1 lap test.
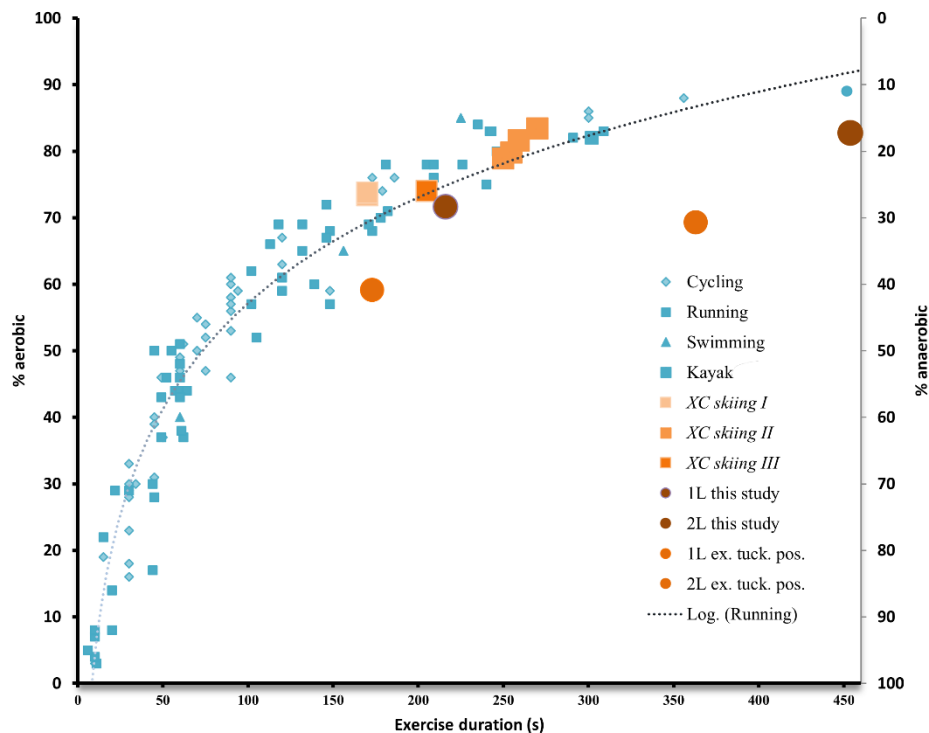
Figure 2.2: Aerobic and anaerobic energy contributions as a function of exercise duration in various sports. The trendline is based on the running studies. Data plots from Gastin (2001), with plots from the 1 and 2 laps tests including and excluding tucked position. Additional data plots of XC skiing from Losnegard et al. (2012) and Losnegard et al. (2013) (XC skiing I and II). XC skiing III is unpublished data from Losnegard and Hallen (2014) and Losnegard et al. (2015)s. The figure is an adaption from Losnegard (2013).

Energy demand and contribution with increasing duration

Energy demand as a function of test duration displayed an inverse relationship curve with test duration. We additionally measured a similar average VO_2 uptake on all tests, agreeing with the expected VO_{2crit} observed in well trained endurance athletes (Poole et al., 2016; Welde et al., 2003). Average VO_2^{dem} values converged towards VO_{2crit} as test duration increased, corresponding well within the critical power framework, which implies that ability to sustain work is reduced more abruptly at higher compared to lower exercise intensity (Poole et al., 2016). Available work capacity above VO_{2crit} is thereby rendered predictable in intermittent endurance exercise. Additionally, $\sum O_2^{def}$ is connected to the prediction of work available above VO_{2crit}, displaying an inverse disproportional

relationship to VO_2^{dem} with ~17 % and ~42 % increases from the 1 lap test to the 2 and 4 laps tests respectively.

Energy systems contribution in constant load endurance sports of durations above ~10 minutes have not received comparable attention to durations below, likely due to the negligible role of anaerobic energy contributions. Intermittent endurance exercise however, are characterized by substantial energy demand variations, which separates work requirements from constant load exercise. The size of these variations are illustrated by intermittently accumulated O_2 deficits, which we estimated to 350 % of MAOD excluding tucked position on the 4 laps test. Gloersen et al. (2020) found a 380 % $\sum O_2^{def}$ over double the distance on their treadmill simulation, implying a flattening of the $\sum O_2^{def}$ curve plotted against test duration. These estimates likely differentiates partly due to course variations, whereas Gloersen et al. (2020)'s course featured longer uphill segments (~2 min as opposed to ~50 s) with VO_2^{dem} closer to VO_{2max}. Furthermore, time in tucked position was 6 % less, where both factors are likely to affect active energy demands.

The above $\sum O_2^{def}$ estimates composed 27 % of the energy contribution on the 4 laps test, while the corresponding anaerobic energy contribution including tucked position was 12 %. Consequently, anaerobic energy stores were partly recovered aerobically during downhills. A similar alternating energy demand pattern likely occurs in related intermittent endurance exercise, raising the question of what implications this has for training applications with respect to the principle of specificity.

The effect of course profile and test duration on pacing patterns

The course profile and pacing patterns have been argued to stronger regulate uphill work rates compared to variations in test durations by Losnegard (2019). This argument was partly based on equal VO_2^{dem} (160 % of VO_{2peak}) observed both on short uphill segments in distance skiing (15 s (Gloersen et al., 2020)) and long uphill segments in sprint skiing (51 s (Sandbakk et al., 2011)). We found that increase in test duration from ~3.5 min to ~7.6 and ~15.8 min elicited a ~10 and ~15% average reduction in VO_2^{dem} on all segments. The course profile on the other hand brought about a maximal difference in VO_2^{dem} ranging from ~18 % to 19 % comparing long (~50 s) and short (~11 s) uphill segments of all tests. Consequently, our study showed that pacing patterns, and specifically uphill work

rates was almost equally regulated by test duration compared to the course profile. Test durations could potentially be increased upwards of 5 times (30 km), and still range within normal world cup distances, whereas uphill segments typically range between 10 s to 35 s (Losnegard, 2019), matching our course profile. Hence, test duration could hypothetically dictate uphill work rates to a significantly stronger degree, possibly exceeding the effect of course profile.

Bioenergetics

The bioenergetic framework of intermittent endurance exercise depends on both total work performed over a given race duration and the duration of work and recovery periods. On an equal supramaximal power output, short work periods of (<30 s) have been shown to put a greater reliance on high energy phosphates from the PCr system (the alactic component), whereas longer work periods put greater demands on anaerobic glycolysis (Davies et al., 2017). The work periods in the present study ranged from ~9 s to ∼50 s with a ~27 s average, combined with substantially higher work rates than the study of Davies et al. (2017), ranging from 120 % to 171 % as opposed to 110 % VO_2^{dem}. This likely implies a considerable contribution from both systems, even on shorter segments (<30 s).

Recovery of the alactic component of MAOD is a faster process than the lactic component recovery (Ferguson et al., 2010; McCully et al., 1994). Moreover, there are evidence that suggests an inhibition of the alactic component recovery and reduction of working economy associated with substantial lactic energy use (Hoff et al., 2016; Jones et al., 2011). These mechanisms may partly explain the difference in uphill work rates on short (S3) and long (S2) uphill segments (~18 % to19 %). Anaerobic recovery kinetics was argued to explain work rate reductions during long uphill segments observed by Gloersen et al. (2020) considering O2 deficits ranged within the expected alactic component of MAOD. Average $\sum O_2^{def}$ during individual segments O2 deficits in the present study was comparably higher than Gloersen et al. (2020) (14 % vs 33 % on the 4 laps test), thus a bigger contribution from lactic sources likely occurred. Findings from repeated sprint exercise strengthens this argument, by displaying a significant initial contribution from anaerobic glycolysis, followed by a downregulation partly replaced by aerobic energy contribution (Girard et al., 2011).

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Methodological considerations

The estimations of VO_2^{dem} assumes a linear relationship between VO_2 cost and external workload. However, predicting VO_2^{dem} at supramaximal intensities involves assumptions whose validity is hard to accurately assess. The linear VO_2^{dem} prediction relies on a skiing specific working economy for submaximal efforts with far less speed and accumulating fatigue affecting the technique, and whether the linearity of this relationship applies to supramaximal workloads is unknown (Noordhof, de Koning, & Foster, 2010). The VO_2 slow component has neither been adjusted for in the calculations, even though test duration and intensity are expected to elicit a reduction in gross efficiency and an increase in VO_2^{dem} at the last part of the tests (Jones et al., 2011). This may lead to an underestimation of VO_2^{dem} towards the end of the tests.

A significant difference in propulsive power outputs and thereby VO_2^{dem} between flat and uphill is evident in XC skiing, and have received a thorough explanation in Losnegard (2019). Physiological and biomechanical factors affects both measurements and actual pacing differences on different inclinations. I.e. MAOD have been estimated to 25 % higher at an 8° incline compared to a 1° incline, implying maximal potential energy turnover rate is higher in uphill and that VO_2^{dem} estimates are more reliable at specific inclinations (Karlsson et al., 2018). MAOD was estimated at 6° incline in this study, so VO_2^{dem} estimates above this inclination may be overestimated, and vice versa.

The VO_2^{dem} estimates includes calculations of air drag from the participants' speed, weather station wind measurements, athlete weight and continuous body position. Some of these calculations build upon data with associated uncertainty, and makes the accuracy of the VO_2^{dem} estimates less precise with increasing athlete speed (Gloersen, Losnegard, et al., 2018). All things considered, between test comparisons have been weighted in the present study, downgrading the importance of pin-point accuracy and emphasizing reliability in VO_2^{dem} estimates.

The Cosmed K5 used in mixing chamber mode to measure pulmonary VO_2 uptake in this study was validated against a Jaeger Oxycon Pro pulmonary VO_2 analyzer and was found to systematically overestimate VO_2 by 371 ± 154 mL/min at all intensities using mixing chamber mode. This overestimation is in line with another study investigating K5 validity

in a similar manner (I. Perez-Suarez et al., 2018). Cosmed K5 mixing chamber measurements was still chosen in favor of breath by breath measurements due to the superior accuracy it has demonstrated at high intensities (Winkert et al., 2020). As we exclusively apply relative VO_2^{dem} compared to the participants VO_{2max}, the measurements' reliability was emphasized over validity.

The use of mixing chamber mode is associated with delay in the measurements (Hughson et al., 1980), which affects $\sum O_2^{def}$. To adjust for this delay to match the remaining data, VO_2 uptake data was analyzed to determine the average onset of a 2.5 mL/kg/min increase from the initial value. Linear interpolation of the 10 seconds measurement values was applied to determine the exact onset of this increase, which occurred at 26 s. Consequently, 26 s delay was adjusted for on all tests.

Lastly, the mental aspect of having 3 consecutive maximal performance tests within a short time frame is likely to affect athlete motivation, inducing a more conservative approach to save energy. Additionally, the lack of a physical competitor have been shown to inhibit performance via motivational factors (Wilmore, 1968). These factors should be considered when interpreting the results, and especially the pacing aspect was likely affected by the multitude of maximal efforts.

Practical implications

Based on our results, we consider aerobic capacity, anaerobic capacity and may also maximal anaerobic power to be performance limiting factors on the sprint distance. Aerobic energy contribution becomes more important on the longer distances, although with heavily fluctuating demands following terrain changes and pacing patterns.

This is supported by the findings of Losnegard and Hallen (2014), demonstrating that distance skiers had lower anaerobic capacity and body mass, and a higher VO_{2max} relative to body mass. With increasing duration, the rate of recovery from supramaximal energy demands become a stronger performance determining factor in distance XC skiing (Gloersen et al., 2020), a factor primarily limited by oxygen availability, which is the main adaptation produced by endurance training on a broad intensity spectrum (Hughes et al.,

2018). However, endurance trainings effect on the rate of recovery from supramaximal energy demands have yet to prove decisively positive (Glaister, 2005). Making decisive training recommendations based on experimentally tested protocols is therefore complex and would in our case be reserved for future studies. On sprint distances however, aerobic capacity is accompanied by anaerobic capacity and possibly anaerobic power, where the latter two is most efficiently trained by high intensity ($\geq P_c$) interval-based exercise (Girard et al., 2011; Stoggl & Bjorklund, 2017; Ziemann et al., 2011). Low intensity training has shown little to no effect on anaerobic abilities (Stoggl & Bjorklund, 2017). Integrating the principle of specificity, our findings could suggest an interval modality involving short work period durations which varies between <2 min and >15 s with ¼ recovery periods is recommendable.

Conclusion

We showed that both peak and average VO_2^{dem} followed an inverse relationship with test duration, while the average VO_2 uptake was similar on all tests, providing novel insight into shifting working requirements in field XC skiing from sprint to distance duration. These findings may have implications for the understanding of energy demand and race durations in relatable intermittent endurance exercise.

References

Andersson, E., Bjorklund, G., Holmberg, H. C., & Ortenblad, N. (2017). Energy system contributions and determinants of performance in sprint cross-country skiing. *Scand J Med Sci Sports*, *27*(4), 385-398. https://doi.org/10.1111/sms.12666

Andersson, E., Holmberg, H. C., Ortenblad, N., & Bjorklund, G. (2016). Metabolic Responses and Pacing Strategies during Successive Sprint Skiing Time Trials. *Med Sci Sports Exerc*, *48*(12), 2544-2554. https://doi.org/10.1249/MSS.0000000000001037

Andersson, E. P., Govus, A., Shannon, O. M., & McGawley, K. (2019). Sex Differences in Performance and Pacing Strategies During Sprint Skiing. *Front Physiol*, *10*, 295. https://doi.org/10.3389/fphys.2019.00295

Andersson, E. P., & McGawley, K. (2018). A Comparison between Different Methods of Estimating Anaerobic Energy Production. *Front Physiol*, *9*, 82. https://doi.org/10.3389/fphys.2018.00082

Bishop, D., Jenkins, D. G., & Howard, A. (1998). The critical power function is dependent on the duration of the predictive exercise tests chosen. *Int J Sports Med*, *19*(2), 125-129. https://doi.org/10.1055/s-2007-971894

Calbet, J. A., Chavarren, J., & Dorado, C. (1997). Fractional use of anaerobic capacity during a 30- and a 45-s Wingate test. *Eur J Appl Physiol Occup Physiol*, *76*(4), 308-313. https://doi.org/10.1007/s004210050253

Davies, M. J., Benson, A. P., Cannon, D. T., Marwood, S., Kemp, G. J., Rossiter, H. B., & Ferguson, C. (2017). Dissociating external power from intramuscular exercise intensity during intermittent bilateral knee-extension in humans. *J Physiol*, *595*(21), 6673-6686. https://doi.org/10.1113/JP274589

Ferguson, C., Rossiter, H. B., Whipp, B. J., Cathcart, A. J., Murgatroyd, S. R., & Ward, S. A. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *J Appl Physiol (1985)*, *108*(4), 866-874. https://doi.org/10.1152/japplphysiol.91425.2008

Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med*, *31*(10), 725-741. https://doi.org/10.2165/00007256-200131100-00003

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability - part I: factors contributing to fatigue. *Sports Med*, *41*(8), 673-694. https://doi.org/10.2165/11590550-000000000-00000

Gloersen, O., Gilgien, M., Dysthe, D. K., Malthe, S. A., & Losnegard, T. (2020). Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc*, *52*(4), 983-992. https://doi.org/10.1249/MSS.0000000000002209

Gloersen, O., Losnegard, T., Malthe-Sorenssen, A., Dysthe, D. K., & Gilgien, M. (2018). Propulsive Power in Cross-Country Skiing: Application and Limitations of a Novel Wearable Sensor-Based Method During Roller Skiing. *Front Physiol*, *9*, 1631. https://doi.org/10.3389/fphys.2018.01631

Granier, C., Abbiss, C. R., Aubry, A., Vauchez, Y., Dorel, S., Hausswirth, C., & Le Meur, Y. (2018). Power Output and Pacing During International Cross-Country Mountain Bike Cycling. *Int J Sports Physiol Perform*, *13*(9), 1243-1249. https://doi.org/10.1123/ijspp.2017-0516

59

Hoff, J., Storen, O., Finstad, A., Wang, E., & Helgerud, J. (2016). Increased Blood Lactate Level Deteriorates Running Economy in World Class Endurance Athletes. *J Strength Cond Res*, *30*(5), 1373-1378. https://doi.org/10.1519/JSC.0000000000001349

Hughson, R. L., Kowalchuk, J. M., Prime, W. M., & Green, H. J. (1980). Open-circuit gas exchange analysis in the non-steady-state. *Can J Appl Sport Sci*, *5*(1), 15-18. https://www.ncbi.nlm.nih.gov/pubmed/7389042

Jones, A. M., Grassi, B., Christensen, P. M., Krustrup, P., Bangsbo, J., & Poole, D. C. (2011). Slow component of VO2 kinetics: mechanistic bases and practical applications. *Med Sci Sports Exerc*, *43*(11), 2046-2062. https://doi.org/10.1249/MSS.0b013e31821fcfc1

Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: the physiology of champions. *J Physiol*, *586*(1), 35-44. https://doi.org/10.1113/jphysiol.2007.143834

Karlsson, O., Gilgien, M., Gloersen, O. N., Rud, B., & Losnegard, T. (2018). Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front Physiol*, *9*, 846. https://doi.org/10.3389/fphys.2018.00846

Losnegard, T. (2013). *Physiological determinants of performance in modern elite cross-country skiing*

Losnegard, T. (2019). Energy system contribution during competitive cross-country skiing. *European Journal of Applied Physiology*, *119*(8), 1675-1690. https://doi.org/10.1007/s00421-019-04158-x

Losnegard, T., Andersen, M., Spencer, M., & Hallen, J. (2015). Effects of active versus passive recovery in sprint cross-country skiing. *Int J Sports Physiol Perform*, *10*(5), 630-635. https://doi.org/10.1123/ijspp.2014-0218

Losnegard, T., & Hallen, J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *Int J Sports Physiol Perform*, *9*(1), 25-31. https://doi.org/10.1123/ijspp.2013-0066

Losnegard, T., Myklebust, H., & Hallen, J. (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*, *44*(4), 673-681. https://doi.org/10.1249/MSS.0b013e3182388684

Losnegard, T., Myklebust, H., Spencer, M., & Hallen, J. (2013). Seasonal variations in VO2max, O2-cost, O2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res*, *27*(7), 1780-1790. https://doi.org/10.1519/JSC.0b013e31827368f6

McCully, K. K., Iotti, S., Kendrick, K., Wang, Z., Posner, J. D., Leigh, J., Jr., & Chance, B. (1994). Simultaneous in vivo measurements of HbO2 saturation and PCr kinetics after exercise in normal humans. *J Appl Physiol (1985)*, *77*(1), 5-10. https://doi.org/10.1152/jappl.1994.77.1.5

McGawley, K., & Holmberg, H. C. (2014). Aerobic and anaerobic contributions to energy production among junior male and female cross-country skiers during diagonal skiing. *Int J Sports Physiol Perform*, *9*(1), 32-40. https://doi.org/10.1123/ijspp.2013-0239

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O. M. (1988). Anaerobic capacity determined by maximal accumulated O2 deficit. *J Appl Physiol (1985)*, *64*(1), 50-60. https://doi.org/10.1152/jappl.1988.64.1.50

Medbo, J. I., & Tabata, I. (1989). Relative importance of aerobic and anaerobic energy release during short-lasting exhausting bicycle exercise. *J Appl Physiol (1985)*, *67*(5), 1881-1886. https://doi.org/10.1152/jappl.1989.67.5.1881

Mikkola, J., Laaksonen, M., Holmberg, H. C., Vesterinen, V., & Nummela, A. (2010). Determinants of a simulated cross-country skiing sprint competition using V2 skating technique on roller skis. *J Strength Cond Res*, *24*(4), 920-928. https://doi.org/10.1519/JSC.0b013e3181cbaaaf

Monod, H. S., J. (2007, April 25). The work capacity of a synergic muscular group. *Ergonomics*, 329-338.

Noordhof, D. A., de Koning, J. J., & Foster, C. (2010). The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity? *Sports Med*, *40*(4), 285-302. https://doi.org/10.2165/11530390-000000000-00000

Noordhof, D. A., Skiba, P. F., & de Koning, J. J. (2013). Determining anaerobic capacity in sporting activities. *Int J Sports Physiol Perform*, *8*(5), 475-482. https://doi.org/10.1123/ijspp.8.5.475

Norman, R. W., & Komi, P. V. (1987). Mechanical Energetics of World Class Cross-Country Skiing *International journal of Sport Biomechanics*, 353-369.

Perez-Suarez, I., Martin-Rincon, M., Gonzalez-Henriquez, J. J., Fezzardi, C., Perez-Regalado, S., Galvan-Alvarez, V., Juan-Habib, J. W., Morales-Alamo, D., & Calbet, J. A. L. (2018). Accuracy and Precision of the COSMED K5 Portable Analyser. *Front Physiol*, *9*, 1764. https://doi.org/10.3389/fphys.2018.01764

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sports Exerc*, *48*(11), 2320-2334. https://doi.org/10.1249/MSS.0000000000000939

Sandbakk, O., Ettema, G., Leirdal, S., Jakobsen, V., & Holmberg, H. C. (2011). Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur J Appl Physiol*, *111*(6), 947-957. https://doi.org/10.1007/s00421-010-1719-9

Skiba, P. F., Chidnok, W., Vanhatalo, A., & Jones, A. M. (2012). Modeling the expenditure and reconstitution of work capacity above critical power. *Med Sci Sports Exerc*, *44*(8), 1526-1532. https://doi.org/10.1249/MSS.0b013e3182517a80

Solli, G. S., Kocbach, J., Seeberg, T. M., Tjønnås, J., Rindal, O. M. H., Haugnes, P., Torvik, P. Ø., & Sandbakk, Ø. (2018). Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PloS one*, *13*(11), e0207195-e0207195. https://doi.org/10.1371/journal.pone.0207195

Spencer, M. R., & Gastin, P. B. (2001). Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med Sci Sports Exerc*, *33*(1), 157-162. https://doi.org/10.1097/00005768-200101000-00024

Stoggl, T. L., & Bjorklund, G. (2017). High Intensity Interval Training Leads to Greater Improvements in Acute Heart Rate Recovery and Anaerobic Power as High Volume Low Intensity Training. *Front Physiol*, *8*, 562. https://doi.org/10.3389/fphys.2017.00562

Welde, B., Evertsen, F., Von Heimburg, E., & Ingulf Medbo, J. (2003). Energy cost of free technique and classical cross-country skiing at racing speeds. *Med Sci Sports Exerc*, *35*(5), 818-825. https://doi.org/10.1249/01.MSS.0000064936.04725.FD

Wilmore, J. H. (1968). Influence of motivation on physical work capacity and performance. *J Appl Physiol*, *24*(4), 459-463. https://doi.org/10.1152/jappl.1968.24.4.459

Winkert, K., Kirsten, J., Dreyhaupt, J., Steinacker, J. M., & Treff, G. (2020). The COSMED K5 in Breath-by-Breath and Mixing Chamber Mode at Low to High Intensities. *Med Sci Sports Exerc*, *52*(5), 1153-1162. https://doi.org/10.1249/MSS.0000000000002241

Ziemann, E., Grzywacz, T., Luszczyk, M., Laskowski, R., Olek, R. A., & Gibson, A. L. (2011). Aerobic and anaerobic changes with high-intensity interval training in active college-aged men. *J Strength Cond Res*, *25*(4), 1104-1112. https://doi.org/10.1519/JSC.0b013e3181d09ec9

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Appendix 1

Within-lap and between-test pacing patterns

We calculated two pacing aspects from instant speed GPS data, which was within lap pacing on the 4 laps test and between test pacing for all tests.

Within test pacing on the 4 laps tests was relatively even, exhibiting a change in time from 1st to last lap of 0.5 ± 4.1 % and -0.3 ± 4.4 % respectively. The middle laps (2 and 3) were the slowest with a 1.0 ± 2.2 % and 1.7 ± 3.9 % time increase compared to lap 1. Despite an almost equal lap time, a major pacing difference occurred at the 1st and 4th lap of the 4 laps test as shown in figure 3.0. At the 1st lap, participants raced at a faster pace from start, averaging a 4.6 ± 6.6 % faster time over the S1 segment. Pacing evens out from the S2 segment start. From S3 and till lap finish, the 4th lap is faster, displaying an end spurt. An important difference is evident on the flat S4 segment with a 4.9 ± 6.1% faster time on the 4th lap. Moreover, the 1st and last hilltops seem to be key segments where the most substantial pacing difference occurs.

Another pacing aspect is comparing the different tests to each other. This comparison is depicted in figure 3.0. To shortly summarize, uphill and hilltops are the key segments where pacing difference become most significant as test duration increases.

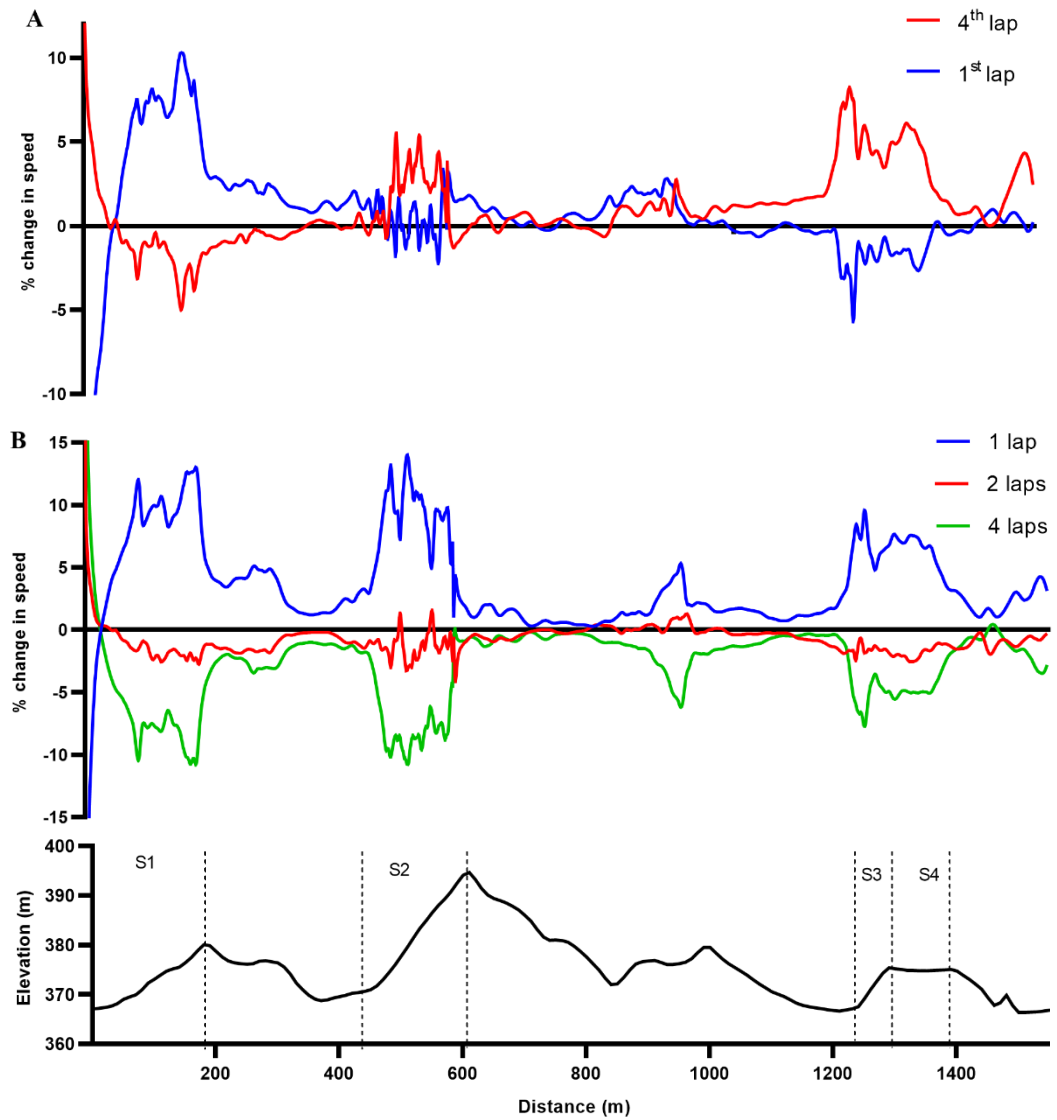*Figure 3.0: **A** shows within lap pacing of the 4 laps test expressed as speed change in % compared to the average instant speed of the 4 laps test. Lap time changed -0.3 % from 1st to 4th lap. **B** shows test by test pacing compared to the average instant pace from all tests. 2 and 4 laps display average speed over all laps. The compared average pace from all tests is derived from 3 different averages, 1 for each test.*

Appendix 2

Cosmed K5 validation

The process of validating the portable VO2 analyzer Cosmed K5 was conducted with both submaximal and maximal loads running on a treadmill while comparing measurements to Oxycon pro. 3 distinct subjects performed a submaximal protocol consisting of 6 progressive repetitions aiming to finish the last 2 at anaerobic threshold intensity. These 3 also performed 2 VO_{2max}-tests following the submaximal protocol with a 20-minute break in between. Additionally, 1 subject performed 2 VO_{2max} tests without the submaximal loads, making the total count of validation subjects at 4.

The tests were performed with varying speeds and inclinations adjusted to each subject, although nearly all tests were performed at 10,5 % inclination. Furthermore, the speed always increased 1 km/h when the load increased at both submaximal and maximal tests. Common for all the tests was the use of mixing chamber mode at both apparatuses and having the Cosmed K5 attached to a harness on the back. The K5 unit was then replaced with a 1kg weight to equalize the loads when Oxycon pro measured VO2.

We conducted the tests using Hans Rudolph mouthpieces on both the K5-unit and Oxycon Pro with the exception of subject 3, which used the multi-use silicone V2 face mask with the K5-unit on all the K5 tests.

Overview of the submaximal (table 2.0) and VO_{2max} (table 2.1) validation protocols are presented below.

Table 2.0: Submaximal validation protocol with 2 min break in-between each workload with apparatus change. The aim intensity was lactate threshold (RPE 15 and/or lactate >2,5<4) at the last 2 workloads.

Duration (min)	Speed (km/h)	Apparatus and measurement mode
5	9	Cosmed K5 Mixing chamber mode
5	9	Oxycon Pro mixing chamber mode
5	10	Cosmed K5 Mixing chamber mode
5	10	Oxycon Pro mixing chamber mode
5	11	Cosmed K5 Mixing chamber mode
5	11	Oxycon Pro mixing chamber mode

Table 2.1: VO_{2max} validation protocol. Tests were performed increasing speed by 1 km/h each minute aiming at approximately 6 minutes total test duration applying 20 min break in-between tests.

Duration	Speed (km/h) and incline (deg)	Apparatus and measurement mode
6 approx.	10-15 and 6	Cosmed K5 Mixing chamber mode
6 approx.	10-15 and 6	Oxycon Pro mixing chamber mode

Validation results

Our validation results are presented in the figure below, and shows that Cosmed K5 mixing chamber mode overestimated VO_2 by 371±154 mL/min at all intensities compared to the Oxycon Pro. This relationship was similar on both submaximal and maximal loads (figure 3.0)
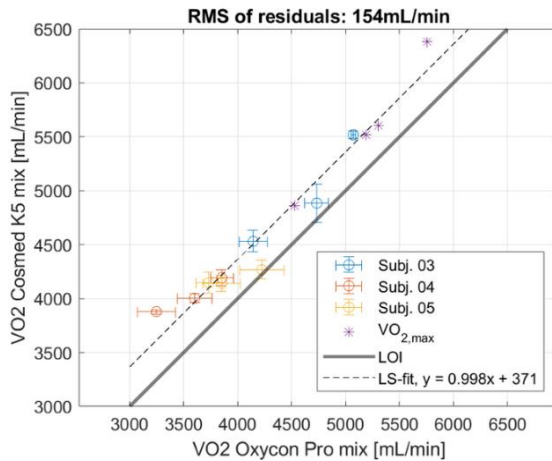

Figure 3.0: VO_2 in mL/min average of last 60 seconds of each load from all submaximal and maximal validation tests performed. Blue, orange and yellow dots represent submaximal test results for the individual subjects with accompanying root mean square error (RMS). Purple dots represent VO_{2max} test results.

The tests were conducted with varying speeds and inclines between individuals, although all followed the general outline above with respect to number of loads and their durations. The subject always wore the Cosmed K5 harness while running. When measuring with the K5, the K5-unit was attached to the harness; when measuring with Oxycon Pro, the Cosmed K5-unit was removed from the harness and replaced by a 1kg weight. With the Cosmed K5 we used mixing chamber mode and a Hans Rudolph mouthpiece. With the Oxycon Pro we used mixing chamber mode, a Hans Rudolph mouthpiece

Both the K5 and Oxycon Pro were calibrated directly prior to the measurement for each participant. Calibration of Oxycon Pro: Volume was calibrated with a 3L syringe using the manufacturer's software. Gas transduces were calibrated using a their respective nitrogen-based calibration gases.

Previous Cosmed K5 validations

The Cosmed K5 has been validated against Oxycon Pro metabolic cart in present studies somewhat similar to the methods that have been used in this study. However, the difference in measurement methods regarding the use of either mixing chamber and breath by breath (BxB) regularly occurs, and has to be addressed. In the literature covering earlier validation, BxB is more widely covered for the Cosmed K5, while the mixing chamber method is lacking in validation studies. Partly this is due to the fact that Cosmed K5 is the first model that has a mixing chamber mode, unlike its predecessor, K4b2(I Perez-Suarez et al., 2018).

One study that partly covers both methods is a validation study conducted by Perez-Suarez, et al., (2018). They aimed to compare the Cosmed K5 with Vyntus CPX (the next generation of Oxycon pro) at low and moderate intensities using BxB and mixing chamber measurements. Additionally they compared BxB to mixing chamber mode. These tests were performed at a cycle ergometer where the chosen intensities aimed to imitate brisk walking (low intensity) and RER values close to 1,0 (moderate intensity). What they found was that at the lowest intensity, Cosmed K5 mix mode overestimated VO2 by 5,8 %. At the moderate intensity Cosmed K5 overestimated VO2 4,8 %. This was accompanied by an equivalent underestimation of RER values (I Perez-Suarez et al., 2018). Although exercise intensity may differ between Perez-Suarez, et al., (2018) and our validation study, these results are somewhat similar to our results where the difference between ranged between 9.27 and 7.42 % (RMS at 4000 and 5000 ml respectively) overestimation of VO_2 in Cosmed K5 mixing chamber mode. This study concludes with mixing chamber mode being the preferable option at high exercise intensity, and they suggest the explanation being that F_IO_2 is a fixed number that is more accurate at higher intensities with less dead space in the face mask. (I Perez-Suarez et al., 2018)

Cosmed K5 has also been validated against the Douglas Bag method (DB) using cycling at different intensities fixed by watts (Crouter et al., 2019). This study looked at both measuring modes and didn't find any statistically significant difference between Cosmed K5 and DB on either VE, VO_2 or V_{CO2} at the different intensities of cycling.

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Another study aimed to compare Cosmed K5 against a Vacuumed metabolic simulator (Guidetti et al., 2018). This kind of simulator produces accurate gas exchange ratios and ventilation volumes that the K5 measures. Guidetti, et al., (2018) found a high agreement between the two. Mean percentage difference on VE, VO_2 and V_{CO2} in BXB mode was within 1.03, making them conclude with the apparatus being valid and reliable for these measurements.

References

Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Med*, *38*(3), 239-252. https://doi.org/10.2165/00007256-200838030-00004

Achenbach, E. (1968). Distribution of local pressure and skin friction around a circular cylinder in cross-flow up to Re = 5 × 106. *Journal of Fluid Mechanics*, *34*(4), 625-639. https://doi.org/10.1017/S0022112068002120

Andersson, E., Bjorklund, G., Holmberg, H. C., & Ortenblad, N. (2017). Energy system contributions and determinants of performance in sprint cross-country skiing. *Scand J Med Sci Sports*, *27*(4), 385-398. https://doi.org/10.1111/sms.12666

Andersson, E., Holmberg, H. C., Ortenblad, N., & Bjorklund, G. (2016). Metabolic Responses and Pacing Strategies during Successive Sprint Skiing Time Trials. *Med Sci Sports Exerc*, *48*(12), 2544-2554. https://doi.org/10.1249/MSS.0000000000001037

Andersson, E. P., Govus, A., Shannon, O. M., & McGawley, K. (2019). Sex Differences in Performance and Pacing Strategies During Sprint Skiing. *Front Physiol*, *10*, 295. https://doi.org/10.3389/fphys.2019.00295

Andersson, E. P., & McGawley, K. (2018). A Comparison between Different Methods of Estimating Anaerobic Energy Production. *Front Physiol*, *9*, 82. https://doi.org/10.3389/fphys.2018.00082

Atkinson, G., Peacock, O., & Passfield, L. (2007). Variable versus constant power strategies during cycling time-trials: prediction of time savings using an up-to-date mathematical model. *J Sports Sci*, *25*(9), 1001-1009. https://doi.org/10.1080/02640410600944709

Bangsbo, J. (2000). Muscle oxygen uptake in humans at onset of and during intense exercise. *Acta Physiol Scand*, *168*(4), 457-464. https://doi.org/10.1046/j.1365-201x.2000.00697.x

Barker, T., Poole, D. C., Noble, M. L., & Barstow, T. J. (2006). Human critical power–oxygen uptake relationship at different pedalling frequencies. *Experimental Physiology*, *91*(3), 621-632. https://doi.org/https://doi.org/10.1113/expphysiol.2005.032789

Bishop, D., Jenkins, D. G., & Howard, A. (1998). The critical power function is dependent on the duration of the predictive exercise tests chosen. *Int J Sports Med*, *19*(2), 125-129. https://doi.org/10.1055/s-2007-971894

Bolger, C. M., Kocbach, J., Hegge, A. M., & Sandbakk, O. (2015). Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int J Sports Physiol Perform*, *10*(7), 873-880. https://doi.org/10.1123/ijspp.2014-0335

Calbet, J. A., Chavarren, J., & Dorado, C. (1997). Fractional use of anaerobic capacity during a 30- and a 45-s Wingate test. *Eur J Appl Physiol Occup Physiol*, *76*(4), 308-313. https://doi.org/10.1007/s004210050253

Chidnok, W., Dimenna, F. J., Bailey, S. J., Vanhatalo, A., Morton, R. H., Wilkerson, D. P., & Jones, A. M. (2012). Exercise tolerance in intermittent cycling: application of the critical power concept. *Med Sci Sports Exerc*, *44*(5), 966-976. https://doi.org/10.1249/MSS.0b013e31823ea28a

Chidnok, W., DiMenna, F. J., Fulford, J., Bailey, S. J., Skiba, P. F., Vanhatalo, A., & Jones, A. M. (2013). Muscle metabolic responses during high-intensity intermittent exercise measured

by 31P-MRS: relationship to the critical power concept. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *305*(9), R1085-R1092. https://doi.org/10.1152/ajpregu.00406.2013

Crouter, S. E., LaMunion, S. R., Hibbing, P. R., S, A., & David, K. (2019, desember 16). Accuracy of the Cosmed K5 portable calorimeter. *PLOS ONE*.

Davies, M. J., Benson, A. P., Cannon, D. T., Marwood, S., Kemp, G. J., Rossiter, H. B., & Ferguson, C. (2017). Dissociating external power from intramuscular exercise intensity during intermittent bilateral knee-extension in humans. *J Physiol*, *595*(21), 6673-6686. https://doi.org/10.1113/JP274589

Ferguson, C., Rossiter, H. B., Whipp, B. J., Cathcart, A. J., Murgatroyd, S. R., & Ward, S. A. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *J Appl Physiol (1985)*, *108*(4), 866-874. https://doi.org/10.1152/japplphysiol.91425.2008

Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med*, *31*(10), 725-741. https://doi.org/10.2165/00007256-200131100-00003

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability - part I: factors contributing to fatigue. *Sports Med*, *41*(8), 673-694. https://doi.org/10.2165/11590550-000000000-00000

Glaister, M. (2005). Multiple sprint work : physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med*, *35*(9), 757-777. https://doi.org/10.2165/00007256-200535090-00003

Gloersen, O. (2019). *On the bioenergetics of cross-country skiing* University of Oslo]. University of Oslo.

Gloersen, O., Gilgien, M., Dysthe, D. K., Malthe, S. A., & Losnegard, T. (2020). Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc*, *52*(4), 983-992. https://doi.org/10.1249/MSS.0000000000002209

Gloersen, O., Kocbach, J., & Gilgien, M. (2018). Tracking Performance in Endurance Racing Sports: Evaluation of the Accuracy Offered by Three Commercial GNSS Receivers Aimed at the Sports Market. *Front Physiol*, *9*, 1425. https://doi.org/10.3389/fphys.2018.01425

Gloersen, O., Losnegard, T., Malthe-Sorenssen, A., Dysthe, D. K., & Gilgien, M. (2018). Propulsive Power in Cross-Country Skiing: Application and Limitations of a Novel Wearable Sensor-Based Method During Roller Skiing. *Front Physiol*, *9*, 1631. https://doi.org/10.3389/fphys.2018.01631

Granier, C., Abbiss, C. R., Aubry, A., Vauchez, Y., Dorel, S., Hausswirth, C., & Le Meur, Y. (2018). Power Output and Pacing During International Cross-Country Mountain Bike Cycling. *Int J Sports Physiol Perform*, *13*(9), 1243-1249. https://doi.org/10.1123/ijspp.2017-0516

Guidetti, L., Meucci, M., Bolletta, F., Emerenziani, G. P., 3, G., M. C, & Baldari, C. (2018, desember 31). Validity, reliability and minimum detectable change of COSMED K5 portable gas exchange system in breath-by-breath mode. *PLOS ONE*.

Hoff, J., Storen, O., Finstad, A., Wang, E., & Helgerud, J. (2016). Increased Blood Lactate Level Deteriorates Running Economy in World Class Endurance Athletes. *J Strength Cond Res*, *30*(5), 1373-1378. https://doi.org/10.1519/JSC.0000000000001349

Hughson, R. L., Kowalchuk, J. M., Prime, W. M., & Green, H. J. (1980). Open-circuit gas exchange analysis in the non-steady-state. *Can J Appl Sport Sci*, *5*(1), 15-18. https://www.ncbi.nlm.nih.gov/pubmed/7389042

Hultman, E., & Sjoholm, H. (1983). Energy metabolism and contraction force of human skeletal muscle in situ during electrical stimulation. *J Physiol*, *345*, 525-532. https://doi.org/10.1113/jphysiol.1983.sp014994

Jones, A. M., & Burnley, M. (2009). Oxygen uptake kinetics: an underappreciated determinant of exercise performance. *Int J Sports Physiol Perform*, *4*(4), 524-532. https://doi.org/10.1123/ijspp.4.4.524

Jones, A. M., Grassi, B., Christensen, P. M., Krustrup, P., Bangsbo, J., & Poole, D. C. (2011). Slow component of VO2 kinetics: mechanistic bases and practical applications. *Med Sci Sports Exerc*, *43*(11), 2046-2062. https://doi.org/10.1249/MSS.0b013e31821fcfc1

Jones, A. M., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Med*, *47*(Suppl 1), 65-78. https://doi.org/10.1007/s40279-017-0688-0

Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: the physiology of champions. *J Physiol*, *586*(1), 35-44. https://doi.org/10.1113/jphysiol.2007.143834

Karlsson, O., Gilgien, M., Gloersen, O. N., Rud, B., & Losnegard, T. (2018). Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front Physiol*, *9*, 846. https://doi.org/10.3389/fphys.2018.00846

Katch, V. L. (1973). Kinetics of oxygen uptake and recovery for supramaximal work of short duration. *Int Z Angew Physiol*, *31*(3), 197-207. https://doi.org/10.1007/BF00697599

Kavanagh, M. F., & Jacobs, I. (1988). Breath-by-breath oxygen consumption during performance of the Wingate Test. *Can J Sport Sci*, *13*(1), 91-93. https://www.ncbi.nlm.nih.gov/pubmed/3359368

Keir, D. A., Fontana, F. Y., Robertson, T. C., Murias, J. M., Paterson, D. H., Kowalchuk, J. M., & Pogliaghi, S. (2015). Exercise Intensity Thresholds: Identifying the Boundaries of Sustainable Performance. *Med Sci Sports Exerc*, *47*(9), 1932-1940. https://doi.org/10.1249/MSS.0000000000000613

Losnegard, T. (2013). *Physiological determinants of performance in modern elite cross-country skiing*

Losnegard, T. (2019). Energy system contribution during competitive cross-country skiing. *European Journal of Applied Physiology*, *119*(8), 1675-1690. https://doi.org/10.1007/s00421-019-04158-x

Losnegard, T., Andersen, M., Spencer, M., & Hallen, J. (2015). Effects of active versus passive recovery in sprint cross-country skiing. *Int J Sports Physiol Perform*, *10*(5), 630-635. https://doi.org/10.1123/ijspp.2014-0218

Losnegard, T., & Hallen, J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *Int J Sports Physiol Perform*, *9*(1), 25-31. https://doi.org/10.1123/ijspp.2013-0066

Losnegard, T., Myklebust, H., & Hallen, J. (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*, *44*(4), 673-681. https://doi.org/10.1249/MSS.0b013e3182388684

Losnegard, T., Myklebust, H., Spencer, M., & Hallen, J. (2013). Seasonal variations in VO2max, O2-cost, O2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res*, *27*(7), 1780-1790. https://doi.org/10.1519/JSC.0b013e31827368f6

Margaria, R., Oliva, R. D., Di Prampero, P. E., & Cerretelli, P. (1969). Energy utilization in intermittent exercise of supramaximal intensity. *J Appl Physiol*, *26*(6), 752-756. https://doi.org/10.1152/jappl.1969.26.6.752

McCully, K. K., Iotti, S., Kendrick, K., Wang, Z., Posner, J. D., Leigh, J., Jr., & Chance, B. (1994). Simultaneous in vivo measurements of HbO2 saturation and PCr kinetics after exercise in normal humans. *J Appl Physiol (1985)*, *77*(1), 5-10. https://doi.org/10.1152/jappl.1994.77.1.5

McGawley, K., & Holmberg, H. C. (2014). Aerobic and anaerobic contributions to energy production among junior male and female cross-country skiers during diagonal skiing. *Int J Sports Physiol Perform*, *9*(1), 32-40. https://doi.org/10.1123/ijspp.2013-0239

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O. M. (1988). Anaerobic capacity determined by maximal accumulated O2 deficit. *J Appl Physiol (1985)*, *64*(1), 50-60. https://doi.org/10.1152/jappl.1988.64.1.50

Medbo, J. I., & Tabata, I. (1989). Relative importance of aerobic and anaerobic energy release during short-lasting exhausting bicycle exercise. *J Appl Physiol (1985)*, *67*(5), 1881-1886. https://doi.org/10.1152/jappl.1989.67.5.1881

Mikkola, J., Laaksonen, M., Holmberg, H. C., Vesterinen, V., & Nummela, A. (2010). Determinants of a simulated cross-country skiing sprint competition using V2 skating technique on roller skis. *J Strength Cond Res*, *24*(4), 920-928. https://doi.org/10.1519/JSC.0b013e3181cbaaaf

Monod, H. S., J. (2007, April 25). The work capacity of a synergic muscular group. *Ergonomics*, 329-338.

Morton, R. H., & Billat, L. V. (2004). The critical power model for intermittent exercise. *Eur J Appl Physiol*, *91*(2-3), 303-307. https://doi.org/10.1007/s00421-003-0987-z

Noordhof, D. A., de Koning, J. J., & Foster, C. (2010). The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity? *Sports Med*, *40*(4), 285-302. https://doi.org/10.2165/11530390-000000000-00000

Noordhof, D. A., de Koning, J. J., van Erp, T., van Keimpema, B., de Ridder, D., Otter, R., & Foster, C. (2010). The between and within day variation in gross efficiency. *Eur J Appl Physiol*, *109*(6), 1209-1218. https://doi.org/10.1007/s00421-010-1497-4

Noordhof, D. A., Skiba, P. F., & de Koning, J. J. (2013). Determining anaerobic capacity in sporting activities. *Int J Sports Physiol Perform*, *8*(5), 475-482. https://doi.org/10.1123/ijspp.8.5.475

Norman, R. W., & Komi, P. V. (1987). Mechanical Energetics of World Class Cross-Country Skiing *International journal of Sport Biomechanics*, 353-369.

O'Brien, B., Payne, W., Gastin, P., & Burge, C. (1997). A comparison of active and passive warm ups on energy system contribution and performance in moderate heat. *Aust J Sci Med Sport*, *29*(4), 106-109. https://www.ncbi.nlm.nih.gov/pubmed/9428991

Ozyener, F., Rossiter, H. B., Ward, S. A., & Whipp, B. J. (2003). Negative accumulated oxygen deficit during heavy and very heavy intensity cycle ergometry in humans. *Eur J Appl Physiol*, *90*(1-2), 185-190. https://doi.org/10.1007/s00421-003-0870-y

Perez-Suarez, I., Martin-Rincon, M., Gonzalez-Henriquez, J. J., Fezzardi, C., Perez-Regalado, S., Galvan-Alvarez, V., Juan-Habib, J. W., Morales-Alamo, D., & Calbet, J. A. L. (2018). Accuracy and Precision of the COSMED K5 Portable Analyser. *Front Physiol*, *9*, 1764. https://doi.org/10.3389/fphys.2018.01764

Perez-Suarez, I., Martin-Rincon, M., Gonzalez-Henriquez, J. J., Fezzardi, C., Perez-Regalado, S., Galvan-Alvarez, V., Juan-Habib, J. W., Morales-Alamo, D., & Calbet, J. A. L. (2018, Desember 21). Accuracy and Precision of the COSMED K5 Portable Analyser. *Frontiers in physiology*.

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sports Exerc*, *48*(11), 2320-2334. https://doi.org/10.1249/MSS.0000000000000939

Pringle, J. S., Doust, J. H., Carter, H., Tolfrey, K., & Jones, A. M. (2003). Effect of pedal rate on primary and slow-component oxygen uptake responses during heavy-cycle exercise. *J Appl Physiol (1985)*, *94*(4), 1501-1507. https://doi.org/10.1152/japplphysiol.00456.2002

Sandbakk, O., Ettema, G., Leirdal, S., Jakobsen, V., & Holmberg, H. C. (2011). Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur J Appl Physiol*, *111*(6), 947-957. https://doi.org/10.1007/s00421-010-1719-9

Skiba, P. F., Chidnok, W., Vanhatalo, A., & Jones, A. M. (2012). Modeling the expenditure and reconstitution of work capacity above critical power. *Med Sci Sports Exerc*, *44*(8), 1526-1532. https://doi.org/10.1249/MSS.0b013e3182517a80

Solli, G. S., Kocbach, J., Seeberg, T. M., Tjønnås, J., Rindal, O. M. H., Haugnes, P., Torvik, P. Ø., & Sandbakk, Ø. (2018). Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PloS one*, *13*(11), e0207195-e0207195. https://doi.org/10.1371/journal.pone.0207195

Spencer, M. R., & Gastin, P. B. (2001). Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med Sci Sports Exerc*, *33*(1), 157-162. https://doi.org/10.1097/00005768-200101000-00024

Spurk, H., & Aksel, N. (2008). Fluid Mechanics, 2 Edn. *Springer-Verlag*.

Stoggl, T. L., & Bjorklund, G. (2017). High Intensity Interval Training Leads to Greater Improvements in Acute Heart Rate Recovery and Anaerobic Power as High Volume Low Intensity Training. *Front Physiol*, *8*, 562. https://doi.org/10.3389/fphys.2017.00562

Sundström, D., Carlsson, P., Ståhl, F., & Tinnsten, M. (2013). Numerical optimization of pacing strategy in cross-country skiing. *Structural and Multidisciplinary Optimization*, *47*(6), 943-950. https://doi.org/10.1007/s00158-012-0856-7

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Med Sci Sports Exerc*, *29*(8), 1104-1108. https://doi.org/10.1097/00005768-199708000-00017

van Ingen Schenau, G. J., & Cavanagh, P. R. (1990). Power equations in endurance sports. *J Biomech*, *23*(9), 865-881. https://doi.org/10.1016/0021-9290(90)90352-4

Welde, B., Evertsen, F., Von Heimburg, E., & Ingulf Medbo, J. (2003). Energy cost of free technique and classical cross-country skiing at racing speeds. *Med Sci Sports Exerc*, *35*(5), 818-825. https://doi.org/10.1249/01.MSS.0000064936.04725.FD

Whipp, B. J., Ward, S. A., & Hassall, M. W. (1998). Paleo-bioenergetics: the metabolic rate of marching Roman legionaries. *Br J Sports Med*, *32*(3), 261-262. https://doi.org/10.1136/bjsm.32.3.261

Wilmore, J. H. (1968). Influence of motivation on physical work capacity and performance. *J Appl Physiol*, *24*(4), 459-463. https://doi.org/10.1152/jappl.1968.24.4.459

Winkert, K., Kirsten, J., Dreyhaupt, J., Steinacker, J. M., & Treff, G. (2020). The COSMED K5 in Breath-by-Breath and Mixing Chamber Mode at Low to High Intensities. *Med Sci Sports Exerc*, *52*(5), 1153-1162. https://doi.org/10.1249/MSS.0000000000002241

Ziemann, E., Grzywacz, T., Luszczyk, M., Laskowski, R., Olek, R. A., & Gibson, A. L. (2011). Aerobic and anaerobic changes with high-intensity interval training in active college-aged men. *J Strength Cond Res*, *25*(4), 1104-1112. https://doi.org/10.1519/JSC.0b013e3181d09ec9