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Pacing Strategy and Exercise Intensity in Cross-country Skiing

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Abstract

Background: The pacing strategy employed by athletes have significant effect on their performance in endurance sports. Although several studies have investigated pacing in these kind of sports, little information exists with regard to and pacing strategies are applied in cross-country (XC) skiing. This paper presents a novel approach to investigate the relationship between pacing strategies and physiological demands in XC skiing. We estimate the skiers' O₂-demand by combining real-time positioning and physiological data from roller ski treadmill testing.

Methods: On separate days, eight male XC skiers (age: 23.0 ± 4.8 years, height: 183.8 ± 6.8 cm, weight: 77.1 ± 6.1 kg) completed a 15-km individual time trial in a World Cup XC ski course and a standardized treadmill protocol on roller skis. Differential global navigation satellite system data was used to determine position and speed. O₂-demand was estimated in seven sections of the time trial course by extrapolation of individual relationships between O₂-cost and external work rate for levelled and inclined skiing determined in the treadmill protocol.

Results: The skiers adopted a positive pacing strategy when comparing average speed between laps as a whole (6.84 ± 0.26 , 6.65 ± 0.39 and 6.69 ± 0.38 m·s⁻¹, $p = 0.044$). However, estimations of the O₂-demand imply that the skiers employed a variable pacing strategy. O₂-demand in the flat sections was less than 102% of VO_{2peak}, while in the inclined sections O₂-demand ranged from approximately 110 to 160% of VO_{2peak}. There was a significant interaction between section and average O₂-demand ($p < 0.001$).

Conclusion: XC skiers employ a variable pacing strategy when comparing the O₂-demand in flat and uphill terrain both within each lap and within the time trial as a whole. Furthermore, O₂-demand and pacing are dependent on the variations in the course profile.

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1. Introduction

Cross-country (XC) skiing is an endurance sport in which the goal is to cover the course distance in the shortest time. In the World Cup, World Championships and Olympics, athletes compete both in mass start races and individual time trials. In mass start races, the skiers are required to compete against each other in direct “head-to-head”, competitions, while in the individual time trials each skier competes against the clock (Hanley, 2015). When competing “head-to-head” pacing strategy is often influenced by the other competitors (Hanley, 2015). However, when competing in the individual time trial, the skier’s ability to distribute work and energy expenditure throughout the race, can have significant influence on the overall performance (Abiss & Laursen, 2008; Foster, Schragger, Snyder, & Thompson, 1994).

How an athlete chooses to distribute work output and energy reserves throughout an exercise task is recognized as the athlete’s “pacing strategy” (Abiss & Laursen, 2008). Pacing strategies have been studied in a variety of endurance sports such as running (Hanley, 2015; Tucker, Lambert, & Noakes, 2006), cycling (Liedl, Swain, & Branch, 1999; Swain, 1997), speed skating (van Ingen Schenau, de Koning, & de Groot, 1990), rowing (Garland, 2005) and XC skiing (Andersson et al., 2010; Bolger, Kocbach, Hegge, & Sandbakk, 2015; Losnegard, Kjeldsen, & Skattebo, 2017). In endurance sports events lasting >2 min, such as in running, swimming, speed skating, cycling, mountain biking and skiing, an even pacing strategy is regarded as “optimal” for the overall performance. However, studies of XC ski races indicate that XC skiers do not adopt an even pacing strategy (Andersson et al., 2010; Bolger et al., 2015; Formenti et al., 2015; Losnegard et al., 2017).

Traditionally, pacing has been studied by comparing average speed between laps. By utilizing global positioning system (GPS) technology, continuous measurements and comparisons can be made, to make a more detailed evaluation of pacing and adopted pacing strategies. This is especially interesting in endurance sports events where great variations in external conditions occur within a competition. One such endurance sport is XC ski race, which differs from other endurance sports, such as running, track cycling and speed skating, traditionally observed in studies on pacing strategy that all take place under relatively constant external conditions.

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Further, to completely understand the factors involved in XC skiing performance, the analysis of pacing or pacing strategy as speed (external load) need to be interpreted in relation to the exercise intensity (internal load). The traditional way of doing this is by using heart rate (HR) (Andersson, Holmberg, Ortenblad, & Bjorklund, 2016; Formenti et al., 2015; Larsson & Henriksson-Larsen, 2005). However, one of the unique aspects of XC skiing is the repeated periods of supramaximal intensities (Norman, Ounpuu, Fraser, & Mitchell, 1989; Sandbakk, Ettema, Leirdal, Jakobsen, & Holmberg, 2011). Therefore, since the HR ability to reflect supramaximal exercise intensities are limited (Buchheit & Laursen, 2013), it may not accurately reflect the exercise intensity.

A limited number of investigators have previously described exercise intensity in XC skiing as O₂-demand (Norman & Komi, 1987; Norman et al., 1989; Sandbakk et al., 2011; Sandbakk & Holmberg, 2017). Based on the fact of the considerable amount of supramaximal exercise intensities observed in XC skiing, this approach may give new and important insights into the physiological and regulatory processes involved in XC skiing performance.

1.1 Research questions

The aim of the present study was to utilize real-time positioning data from a self-paced individual time trial combined with physiological data from treadmill testing to estimate the O₂-demand in XC roller skiing. Further, we wanted to use these data to describe the pacing strategies adopted by and the physiological demands in XC skiing.

1.2 Hypothesis

We hypothesized that XC skier apply a variable pacing strategy based on the characteristic variations in the terrain of a XC ski course. Furthermore, we hypothesized that the intensity in XC skiing repeatedly exceeds the maximal aerobic power of the skiers.

2. Theory

2.1 Pacing

In XC ski racing completing the course in the shortest time possible is essential to performance. However, the athletes' ability to generate power is limited, hence they need to distribute the workload rationally during the race (Sundstrom, Carlsson, Stahl, & Tinnsten, 2013). How an athlete distributes the workload or energy reserves during exercise, is called the athlete's pacing or pacing strategy (Roelands, de Koning, Foster, Hettinga, & Meeusen, 2013). More specific, pacing is the distribution of speed, work rate or energy reserves during exercise, while the pacing strategy is the self-selected strategy that the athletes employ from the beginning to the end of a race (Roelands et al., 2013). An optimal pacing strategy yields that the energy resources are employed in such a way that all reserves are spent at the termination of exercise (Roelands et al., 2013). Even though the main purpose of pacing is to prevent potentially fatiguing homeostatic perturbations during exercise, the same mechanisms can be utilized to regulate performance (Tucker, 2009). The pacing strategy employed by an athlete may have a significant influence on the performance (Abbiss & Laursen, 2008; Foster et al., 1994).

2.2 Regulation of pacing

To describe how pacing is regulated, Tucker (2009) proposed the "anticipatory feedback" model. He suggested that the regulation of work rate during self-paced exercise is achieved by means of a combination of feedback integration and anticipatory forecasting, to protect the athlete from catastrophic failure and to regulate performance.

2.2.1 The anticipatory component

Before initializing exercise, the athlete uses previous experience, anticipation of exercise duration/distance and information about course profile, as well as knowledge of his/her current physiological and psychological state. The athlete then creates a "template" for the increase in the rating of perceived exertion (RPE) and to select the initial work rate expected to give the optimal performance. This "template" represents the RPE the exercising athlete considers acceptable or desired at any given stage of the imminent workload. The template is a theoretical construction and cannot be measured, but is continuously updated and modified throughout the

Theory

exercise bout based on remaining duration or distance and the current physiological and mental state of the athlete (Tucker, 2009) [Figure 2.1 and 2.2].

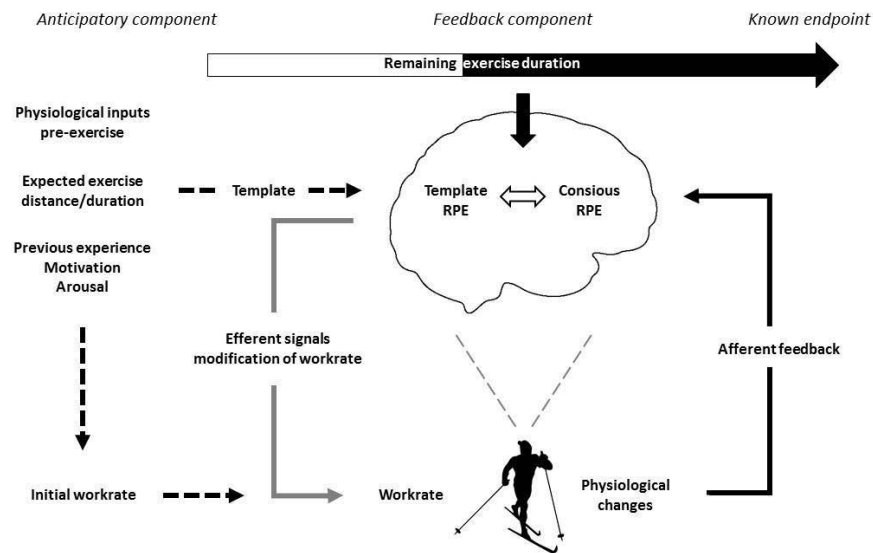


Figure 2.1: Schematic diagram showing the anticipatory regulation of exercise performance during self-paced exercise. The conscious RPE is continuously matched to the template RPE in the context of the remaining exercise duration. Work rate and RPE may be adjusted in order to match the conscious and the anticipated RPE. The template RPE and the initial work rate are determined based on previous experience and physiological and psychological status of the skier at the start of the exercise bout. Black arrows denote input to the brain, grey lines denote output from the brain and stapled arrows denote the anticipatory components. Modified from Tucker (2009).

2.2.2 The feedback component

Throughout the workload, the athlete has a conscious perception of effort. This “conscious” RPE is an integration of afferent information from the various physiological systems, such as body and skin temperature, metabolite storages levels, arterial oxygen saturation levels, respiratory rate, HR and mechanical afferents (Figure 2.1). The degree of afferent feedback is a function of the exercise work rate, and the “conscious” RPE is therefore strongly influenced by physiological changes. In contrast to the “template” RPE, the “conscious” RPE can be expressed verbally during exercise (Tucker, 2009).

Theory

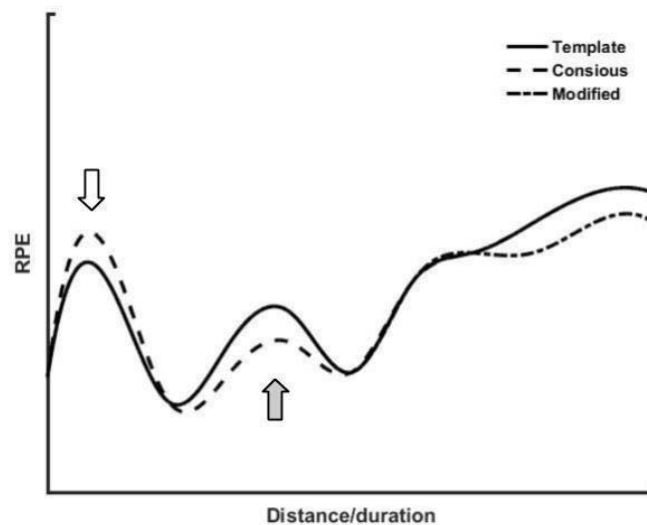


Figure 2.2: Prior to the start of the exercise bout the athlete constructs a template RPE regarded to be optimal for performance. The conscious RPE is matched to the template RPE throughout the exercise. This is achieved by altering work rate (illustrated by arrows). If the conscious RPE is regarded to high, work rate is reduced (white arrow) and a subsequent reduction in the conscious RPE will occur. On the other hand, if the conscious RPE is regarded to low, work rate can be increased (grey arrow) to match the template. The template can also be modified during the exercise (Tucker, 2009).

2.2.3 Regulation

Throughout the workload, the athlete matches the “conscious” RPE to the “template” RPE so that the physiological changes do not increase or decrease excessively thereby leading to premature exhaustion or underperformance. Thus, if the “conscious” RPE is regarded to high, work rate is reduced to an acceptable level. If, on the other hand, the “conscious” RPE is regarded to low, work rate can be increased (Tucker, 2009) [Figure 2.2].

There will always be some degree of uncertainty regarding the effort of the remaining distance or duration of a race, hence athletes maintain a physiological reserve. As the end of the race approaches the uncertainty is reduced, the physiological reserve is no longer needed and the reserve can be utilized to increase intensity (de Koning et al., 2011). This increase in intensity towards the end of an exercise bout has been named the “end-spurt” phenomenon (Tucker, 2009).

2.3 Pacing strategies

In a review of relevant literature Abbiss and Laursen (2008) identify six fundamental pacing strategies; negative, all-out, positive, even, parabolic and variable pacing strategies. A negative pacing strategy is characterized by an increase in speed over the duration of the event (Abbiss & Laursen, 2008). This is often observed in middle distance races (Foster et al., 2004; Sandals, Wood, Draper, & James, 2006). An all-out pacing strategy is characterized by a rapid increase in speed, followed by a gradual decrease in speed when maximal-speed is achieved (Abbiss & Laursen, 2008). This type of pacing strategy is often applied in sprint-like events (<60 s), where the cost associated with acceleration are of great importance. A positive pacing strategy is characterized by a gradual decrease in speed throughout a race (Abbiss & Laursen, 2005). A positive pacing strategy has been observed in 100 and 200 m swimming (Thompson, Haljand, & MacLaren, 2000), rowing (Garland, 2005), and XC skiing (Losnegard et al., 2017). An even pacing strategy is recognized by an even distribution of speed and work rate throughout the event and is widely recognized as the optimal pacing strategy in endurance sports events lasting >2 min (Abbiss & Laursen, 2005).

Parabolic pacing strategies are pacing strategies where the speed or work rate evolves in a consistent manner throughout an event (Abbiss & Laursen, 2008). Parabolic pacing strategies are often described as U-, J- or reversed J-shaped depending on how the speed evolves. Little research is available describing these strategies, but they have been observed in rowing (Garland, 2005) and in a 10 km simulated XC race (Formenti et al., 2015). Finally, a variable pacing strategy is recognized by continuous fluctuations in the speed or work rate throughout an event (Abbiss & Laursen, 2008). Swain (1997) has proposed that a variable pacing strategy is adopted in an attempt to maintain a constant pace or speed. The variable pacing strategy may be more relevant to actual race conditions in the field, because of variations in course geography and environmental conditions which is not present in the laboratory.

2.4 Characteristics of XC skiing

Cross country ski races are characterized by large variations in course length, from ~1.8 to 50 km. The competition rules of the International Ski Federation (FIS) ("The International Ski Competition Rules: Book II Cross-Country", 2015) claim that a World Cup XC ski course should consist of approximately one third ascending, one third flat and one third descending terrain.

Theory

This allows for great variations in the course profile of a race and XC skiers must therefore deal with large variations in both speed (5-70 km·h⁻¹) and terrain (-20 to 20% inclination) (Sandbakk, Ettema, & Holmberg, 2013). In addition, substantial variations in external factors such as temperature, wind, snow conditions and height above sea level may occur between, or even within, competitions.

In XC skiing there are two fundamental techniques, classical and skate. There are, however, a wide variety of subtechniques applied in each of the two main techniques. In the skate technique alone there are 7 different subtechniques or gears (Andersson et al., 2010). The skier controls the speed by changing between the different gears and by varying cycle length, frequency or both within each gear (Nilsson, Tveit, & Eikrehagen, 2004). It has been shown that XC skiers changes between subtechniques up to 30 times in a 1.5 km sprint, implying that several hundred changes between subtechniques might occur during a distance race (Andersson et al., 2010). The ability to choose the most appropriate technique in relation to speed and terrain may have great influence on efficiency of movement and performance (Pellegrini et al., 2013). The wide range of subtechniques and the frequency of changes between them makes XC skiing unique in aspect to other endurance sports.

Another hallmark of XC skiing is the considerable contribution from the arms to the propulsion of the skier (Sandbakk, Ettema, et al., 2013). During XC skiing, work is shared between the muscles of the arms, trunk and legs, and the relative contribution to propulsion from each muscle group depends on the chosen technique (Calbet et al., 2004; Rud, Secher, Nilsson, Smith, & Hallen, 2014) and the intensity of the work (Bojsen-Moller et al., 2010). Work capacity of the arms plays a crucial role to the performance in XC skiing. In fact, the lower work capacity of the arms compared to the legs may be one of the factors limiting performance in XC skiing (Calbet et al., 2005; Rud et al., 2014). This is also supported by the findings of Stadheim et al. (2013), who reported that athletes perceived a higher degree of pain in the arms compared to the legs at the same work intensity.

Theory

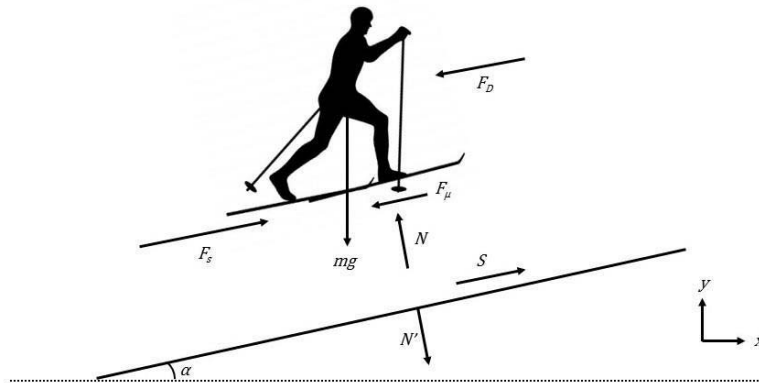


Figure 2.3: Forces acting on the skier in an arbitrary section of the course. F_D : air drag resistance, F_μ : friction force, F_s : propulsive force, N : normal force, S : resultant propulsive force. m : mass, g : gravitational acceleration and α : inclination angle. Modified from Sundström et al., 2013.

2.5 What determines performance in XC skiing.

Moving through the course, the XC skiers continuously counteracts the external forces acting upon them. These external forces are the gravitational force, the frictional force between the skis and the snow, and the air drag resistance (Figure 2.3). The specific amount of work each skier has to perform to overcome the external forces vary with weight, speed, inclination, friction and body position (Moxnes & Hausken, 2008; van Ingen Schenau & Cavanagh, 1990). The ultimate goal is to achieve the highest average speed. The average speed ($\text{m} \cdot \text{s}^{-1}$) obtained over a certain distance is primarily determined by energy turnover ($\text{J} \cdot \text{s}^{-1}$) balanced by work economy ($\text{J} \cdot \text{m}^{-1}$) (di Prampero, 2003; Joyner & Coyle, 2008):

$$\text{Speed } (\text{m} \cdot \text{s}^{-1}) = \frac{\text{Energy turnover } (\text{J} \cdot \text{s}^{-1})}{\text{Work economy } (\text{J} \cdot \text{m}^{-1})} \quad (1)$$

Thus, by increasing energy turnover and/or alter work economy, speed can be adjusted during a workload. Further, the equation can be elaborated to explain how speed is regulated by physiological factors (di Prampero, 2003)

$$\text{Performance (speed)} = \frac{VO_{2\max} \cdot \text{fractional utilization of } VO_{2\max} + \text{anaerobic power}}{O_2\text{cost}} \quad (2)$$

2.5.1 Maximal oxygen uptake

Performance in endurance sports demand a very high VO_{2max} (Bassett & Howley, 1997, 2000; Saltin & Astrand, 1967). Several investigations have demonstrated that male world-class skiers are among the athletes with the highest VO_{2max} , with values frequently above $80 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ or $6.0 \text{ L}\cdot\text{min}^{-1}$ (Holmberg, 2015; Losnegard & Hallen, 2014b). Considering the number of subtechniques in XC skiing, the athletes' ability to utilize a high peak oxygen uptake in each of the different subtechniques are important to performance (Sandbakk & Holmberg, 2017). VO_{2max} attained in running is constantly attained in the diagonal stride, while in other subtechniques mode specific VO_{2peak} are often limited to 85-95% of VO_{2max} in running (Losnegard & Hallen, 2014a). The ability to attain a high VO_{2peak} and to achieve high VO_{2peak}/VO_{2max} values even when employing subtechniques that involve muscles and muscle groups of different masses, is a unique characteristic of elite XC skiers (Sandbakk & Holmberg, 2017) .

Furthermore, VO_{2max} is dependent on the amount of active muscle mass (Secher, Ruberg-Larsen, Binkhorst, & Bonde-Petersen, 1974). Sandbakk, Ettema, et al. (2013) observed that the mode specific VO_{2peak} was 10% higher with poling than without in the V2 technique. Hence, the distribution of work between the upper and lower body may affect the VO_{2peak} obtained in the different subtechniques and in the same subtechnique across slopes (Kvamme, Jakobsen, Hetland, & Smith, 2005).

2.5.2 The fractional utilization of VO_2

The fractional utilization of VO_{2max} , defined as the average percentage of VO_{2max} that can be utilized over a distance or period, reflects the aerobic energy utilized during a race (Bassett & Howley, 2000). The aerobic proportion of the total energy expended during XC skiing average 70-75% and 85-95% in sprint and distance races respectively, and is comparable to other endurance sports with similar racing times (Sandbakk & Holmberg, 2017). The metabolic demands on the working muscles are high during a XC ski race. Supplying enough blood and oxygen to all the working muscles while maintaining blood pressure and physiologic homeostasis, is challenging, especially when changing between intensities and subtechniques as frequent as in XC skiing (Holmberg, 2015). Continuous measurements of VO_2 in simulated competitions show an average VO_2 of approximately 70 to 90 % of VO_{2max} (technique specific) (Larsson & Henriksson-Larsen, 2005; Welde, Evertsen, Von Heimburg, & Medbo, 2003).

2.5.3 Anaerobic capacity

The anaerobic capacity of sprint- and distance-specialized skiers, determined by the maximal accumulated ΣO_2 -deficit method, has been reported to be 6.8 ± 0.9 L and 4.7 ± 0.7 L respectively (Losnegard & Hallen, 2014b). In sprint skiing, anaerobic energy supply is correlated to performance, and account for approximately 26% of the total energy turnover (Losnegard, Myklebust, & Hallen, 2012a). The relative contribution from anaerobic energy systems decrease with duration of the exercise, and is therefore of less importance when distance increases and speed is constant (Gastin, 2001). However, the characteristics of a XC ski race emphasizes the importance of the ability to reproduce high workloads, thus having the ability to repeatedly utilize and recover the anaerobic capacity.

2.5.4 Skiing efficiency

In XC skiing the ability to efficiently transform metabolic energy into mechanical work is of great importance. Efficiency of movement is often described as gross efficiency (GE), the ratio of external work rate to whole body energy expenditure, and reflects the performance level of XC skiers (Sandbakk, Hegge, & Ettema, 2013; Sandbakk, Holmberg, Leirdal, & Ettema, 2010).

Gross efficiency in world-class skiers measured when treadmill roller skiing, is typically 15-17% depending on speed, inclination and technique (Losnegard, 2013; Losnegard, Schafer, & Hallen, 2014b; Sandbakk et al., 2010). Further, GE seems to increase when inclination increases (Sandbakk, Hegge, et al., 2013). The higher efficiency at steeper inclines may be related to the more continuous force generation and shorter passive phases associated with the lower speeds at the steeper inclines (Sandbakk, Hegge, et al., 2013). Skiing efficiency however, has not been measured in actual competitions, and can be attributed to the lack of valid measurements of VO_2 and the external work load.

Because of the high intensities obtained and the duration of XC distance skiing an increase in VO_2 for a given external work load would be expected, as the exercise bout progresses. This increase is known as the “ VO_2 slow component” ($\text{VO}_{2\text{sc}}$), and is evident for workloads in the heavy to extreme domain (Jones et al., 2011). The $\text{VO}_{2\text{sc}}$ may arise from a reduced mechanical efficiency due to gradual development of fatigue, which results in recruitment of less efficient

fibers higher in the recruitment hierarchy (Jones et al., 2011). This would ultimately lead to a reduction in GE.

2.6 Exercise intensity in competitive XC skiing

Average HR has consistently been reported to be >90% of HR_{max} during XC ski competitions (Formenti et al., 2015; Larsson & Henriksson-Larsen, 2005; Mognoni, Rossi, Gastaldelli, Canclini, & Cotelli, 2001). Furthermore, both (Larsson & Henriksson-Larsen, 2005; Welde et al., 2003) have shown that XC skiers have an average VO₂ of approximately 70 to 90% of the technique specific VO_{2max} during simulated competitions. In their studies the athletes did not, however, reach their VO_{2max} during the simulated competitions. The intensities observed corresponded to the VO₂ at the onset of blood lactate accumulation ($100 \pm 3\%$ of VO₂ at OBLA) (Welde et al., 2003).

Norman et al. (1989) estimated VO₂ in an Olympic 30 km race based on the mechanical power output, using kinematic data obtained from video recordings in an uphill part of the course. The estimated power output was 656 ± 153 W and estimated VO₂ ranged from 53-112 mL·kg⁻¹·min⁻¹. Even though individual measurements of mechanical power were made, the estimations of VO₂ were based on the assumption of an average metabolic cost and efficiency. Sandbakk et al. (2011) estimated mean work rate with a modified power balance model to be 476 ± 42 W in uphill terrain (mean incline 6%, length 270 m) during a simulated sprint ski time trial. This corresponded to a work rate 60% greater than the peak aerobic power measured. Furthermore, Sandbakk and Holmberg (2017) estimated that uphill (3-8%) work rate was approximately 450 and 350 W in sprint and distance races respectively. These values correspond to an O₂-demand of approximately 130% and 110% of VO_{2max}. Estimated work rate on flat terrain ($\pm 3\%$) was approximately 360 and 300 W in sprint and distance races respectively, corresponding to an O₂-demand of approximately 115% and 95% of VO_{2max}.

The above-mentioned investigations demonstrate that there are great variations in intensity throughout an XC ski race. Intensities well above the peak aerobic power were repeatedly applied, implying that the skiers obtained a substantial oxygen debt during parts of the race. It seems to be agreement that the high intensities are due to an increase in anaerobic energy production (Andersson et al., 2016; Sandbakk et al., 2011; Sandbakk & Holmberg, 2017).

2.7 Pacing strategies in cross-country skiing

Even though there is an extensive body of literature concerning pacing and pacing strategies in endurance sports events, a limited number of studies have been conducted on XC skiing. In table 2.1 an overview of studies that have reported pacing strategies applied in XC skiing, is presented. The most common approach to describe pacing strategies, are lap-to-lap comparisons of average lap speed (Table 2.1). The studies based on average lap speed consistently show that XC skiers apply a positive pacing strategy independent of race distance and level of the skier (Andersson et al., 2016; Andersson et al., 2010; Bilodeau, Rundell, Roy, & Boulay, 1996; Bolger et al., 2015; Formenti et al., 2015; Larsson & Henriksson-Larsen, 2005; Losnegard et al., 2017).

However, when comparing pacing strategies in different types of terrain, it becomes apparent that skiers chooses different strategies dependent on the terrain (Andersson et al., 2010; Larsson & Henriksson-Larsen, 2005). Andersson et al. (2010) observed that XC skiers adopted a positive pacing strategy in uphill and downhill sections, while in levelled terrain, they adopted a negative pacing strategy, even though their general pacing strategy was positive when average speed was compared between the laps. There is also some evidence that the pacing strategy applied, depends on the level of the skier (Bilodeau et al., 1996; Losnegard et al., 2017). Higher ranked skier seem to apply a more even pacing strategy than lower ranked skiers, as indicated by a lower reduction in speed throughout the race (Losnegard et al., 2017).

Numerical optimization of a XC ski race has shown that major time savings can be achieved by employing a variable pacing strategy when compared to an even pacing strategy (Sundstrom et al., 2013). This is in accordance with models and observations from cycling (Liedl et al., 1999; Swain, 1997). Furthermore, the optimization routine strived at increasing the propulsive power in the uphill sections and decreasing the propulsive power in the downhill sections of the course. An advantage of mathematical modeling is the possibility to study how various factors influence performance in an objective way.

Table 2.1: Overview of literature on pacing strategies applied in XC skiing.

Study	Subjects	Level	Distance	Method	Measure	Pacing strategy
Bilodeau et al. (1996)	34/27	National	30/50	LtL	avg. speed	POS
Larsson and Henriksson-Larsen (2005)	10	Elite Jr.	5.6 km	LtL	avg. speed	POS
Andersson et al. (2010)	9	Elite	1425 m	LtL	avg. speed	POS
Sundstrom et al. (2013)	-	-	1425 m	SIM	power	VAR
Bolger et al. (2015)	9	Elite	15/10 km	LtL	avg. speed	POS
Formenti et al. (2015)	11	National	10 km	LtL	avg. speed	POS/PAR
Andersson et al. (2016)	10	well-trained	1300 m	LtL, TM	time	POS
Losnegard et al. (2017)	22*	Elite	15 km	LtL	avg. speed	POS

*: number of races

LtL = lap-to-lap comparison; **TM** = tread mill **SIM** = computer simulation; **POS** = positive; **VAR** = variable; **PAR** = parabolic

2.8 Variability in performance of elite XC skiers

Performance differences between world-class XC skiers in the same competition often seem marginal, thus an improvement of as little as 0.3% in performance, may have a significant impact on the result (Spencer, Losnegard, Hallen, & Hopkins, 2014). In a typical distance event (30 min), an improvement of 0.3% equates to a 5.4 s faster race time. It is widely recognized that the athletes' choice of pacing or pacing strategy, may have significant impact on their performance (Abbiss & Laursen, 2008; Foster et al., 1994; Roelands et al., 2013). The effect of adopting an optimal pacing strategy is comparable to the effect of other performance enhancing interventions such as altitude training, weight reduction, nutrition and equipment alterations (Atkinson, Peacock, & Passfield, 2007b; Jeukendrup & Martin, 2001). Based on numerical optimization, Sundstrom et al. (2013) suggested that the time saved by adopting a variable pacing strategy could be as much as 13.0 s or 6.5% when compared to adopting an even pacing strategy in a XC sprint prologue. This equals the time difference between the winner and the skier being number 51 in the 2010 Olympics sprint qualification (Sundstrom et al., 2013). Optimization of the pacing strategy may therefore have a great impact on the final result.

2.9 Constant versus variable intensity

Most investigations of pacing and pacing strategies have focused on endurance sports, such as track running, track cycling and speed skating, where external conditions and work intensity is relatively constant. In XC skiing, however, there are great variations in intensity throughout a competition, separating XC skiing from these types of investigations.

Liedl et al. (1999) suggested two reasons why greater physiological stress might be expected during exercise with a variable work rate compared to exercise with a constant work rate. Firstly, the lactate concentration increases exponentially at exercise intensities above the lactate threshold. The quantity of lactate accumulated when increasing work rate above this threshold, might therefore be greater than that which can be eliminated when work rate is reduced. Secondly, because VO_2 increases monoexponentially when work rate is increased, an accumulated O_2 -deficit is generated. When work rate is reduced, VO_2 again responds in a nonlinear manner, remaining elevated for some time before returning to a steady state. However, the excess VO_2 in the periods with a low work rate may not be sufficient to compensate for the O_2 -deficit accumulated in periods with a high work rate, thus resulting in a greater total O_2 -consumption. These considerations may be of special importance in XC skiing where great changes in intensity occur both rapid and frequent.

Several investigators have compared the effects of exercise with constant and variable intensity on fatigue and physiological parameters in cycling (Lepers, Theurel, Hausswirth, & Bernard, 2008; Liedl et al., 1999; Palmer, Borghouts, Noakes, & Hawley, 1999; Theurel & Lepers, 2008). When average intensity is submaximal ($<90\%$ of $\text{VO}_{2\text{max}}$) and the variations are relatively small ($\pm 5\text{-}20\%$), there are no differences in the induced fatigue, neither are there any differences in average physiological perturbations (VO_2 , HR, $[\text{La}^-]$ and RPE) between the different protocols (Lepers et al., 2008; Palmer et al., 1999). However, significant differences in physiological parameters were observed at timepoints during the different protocols (Lepers et al., 2008; Liedl et al., 1999). Furthermore, Palmer et al. (1999) observed an increase in plasma $[\text{La}^-]$ and increased reliance on glucose oxidation towards the end of variable exercise protocols. Despite the dissimilarities there were no difference in RPE or in the subsequent performance tests (Palmer et al., 1999).

On the other hand, when the variations in the power output include efforts above the maximal average power (MAP), neuromuscular and cardiovascular responses are exaggerated when compared to constant power cycling (Theurel & Lepers, 2008). A significantly greater reduction in maximal voluntary contraction torque and voluntary activation level has been observed following a variable power protocol including work rates >100% of MAP when compared to a constant power protocol (70% of MAP) with the same average power (Theurel & Lepers, 2008). Further, significant differences in HR during, and blood [La⁻] after, the variable protocol were observed. RPE also tended to be greater during the variable protocol, but the differences were only significant towards the end of the protocols. The authors concluded that the greater reduction in maximal voluntary contraction torque and voluntary activation levels following the variable protocol resulted from both greater central and peripheral fatigue (Theurel & Lepers, 2008).

2.10 Global navigational satellite system

The current study is based on data from both the American Global Positioning System (GPS, 31 satellites) and the Russian global navigational system (GLONASS, 24 satellites). Global navigational satellite systems (GNSS) is used as a common term for both systems. With the use of GNSS, position can be determined trigonometrically by calculating the distance from a given point to at least four satellites. By utilizing data from two GNSS units, the accuracy of a moving object can be improved by correcting the position with data from a stationary unit, this is called a differential GNSS (dGNSS) solution.

The application of dGNSS to describe XC skiing performance are sparse. Only two published studies have utilized this technology to date (Andersson et al., 2010; Larsson & Henriksson-Larsen, 2005). The dGNSS is potentially a useful tool when investigating pacing and pacing strategies in XC skiing, because it gives an accurate description of an athlete's position throughout a race in situ, without affecting the athlete's performance. The dGNSS also make it possible to obtain continuous data from the course as opposed to the average lap-to-lap comparisons which has frequently been used in former studies.

2.11 Summary

In endurance sports the pacing strategy employed by the athletes have significant effect on their performance. Although pacing strategies in general has been extensively studied, specific information on pacing strategies in endurance sports characterized by great variations in external conditions such as XC skiing, are scarce. Considering the unique nature of XC skiing, this may significantly influence how pacing and pacing strategies are employed. Furthermore, these characteristics may affect how the skiers utilize their physiological capacities. Traditional methods used to describe pacing strategies, are inadequate to describe pacing strategies in events where substantial variations in exercise intensity and/or external conditions occur. Hence, new methods to describe pacing strategy and exercise intensity as well as the effect of changing external conditions, are therefore necessary to fully understand the factors that influence performance in endurance sports such as XC skiing.

3. Methods

3.1 Subjects

Eight well-trained male XC skiers volunteered to participate in the study. The skiers were either active or former competitors on a national level in Norway. All had previous experience with roller ski treadmill testing. Their personal characteristics are presented in Table 3.1. All skiers gave their written informed consent before participating. When the participant was less than 18 years old, the consent form was also signed by the participant's parents. The study was conducted according to the Declaration of Helsinki and reviewed by the Regional Ethics Committee of Southern Norway prior to the start of the study (ref. nr.: 2016/1448).

3.1.1 General design

The study consisted of two sessions, one performed outdoors and one performed indoors. In the outdoor session, the skiers completed a self-paced 15-kilometer free style individual time trial on roller skis, to simulate an actual XC competition. The second, indoor session was performed on a separate day within 20 days of the time trial. The skiers then performed six submaximal workloads and two performance tests, to estimate intensity and physiological demands in levelled and inclined terrain. Individual real-time positioning data from the time trial and data from the indoor tests were used to estimate the O₂-demand in seven sections in the time trial course. The study was carried out in the period between medio August and medio October 2016, in a period considered as a pre-competition phase for the XC skiers.

3.1.2 Outdoor time trial

The individual time trials were carried out in the roller ski course in Holmenkollen (Oslo, Norway) on two separate days (Figure 3.1). Six of the skiers completed the time trial during the first day, and two of the skiers during the second day. The course resembles an actual profile of a cross-country skiing competition used in the FIS World Cup. In addition, all the athletes were familiar to the course from previous training and competition.

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Table 3.1: Subject characteristics ($n = 8$).

Variable	Mean \pm SD	Range
Age (yr.)	23.0 \pm 4.8	17.2 - 30.3
Height (cm)	183.8 \pm 6.8	173.0 - 193.0
Body-mass (kg)	77.1 \pm 6.1	69.1 - 84.7
Weight incl. equip. (kg)*	80.7 \pm 6.6	73.2 - 89.2

*: excl. dGNSS system

The time trial consisted of three identical laps (4.5 km) with a total length of 13.5 km. Prior to the time trial the skiers performed 2 x 10 min of individual warm up, separated by the time it took to fit the dGNSS system (~5 min). During the first 10 min of warm up, the skiers used their own equipment. During the second 10 min of warm up they used the assigned test skis and wore the dGNSS system so that the equipment would be familiar when the time trial started. After completing the warm up procedure, athletes set out with a 2 min interval. They were instructed to complete the time trial as fast as they could. No further information was given prior to the start. During the time trial the skiers' positions were continuously recorded with the dGNSS system, and their heart rates were recorded with a separate HR monitor. In two preselected sections of the course, one inclined (S4) and one levelled (S7), video recordings was made to document the subtechnique applied by each skier. In addition, the skiers verbally reported their RPE in these sections. Total duration of the time trial session was approximately 1.5 hours for each skier.

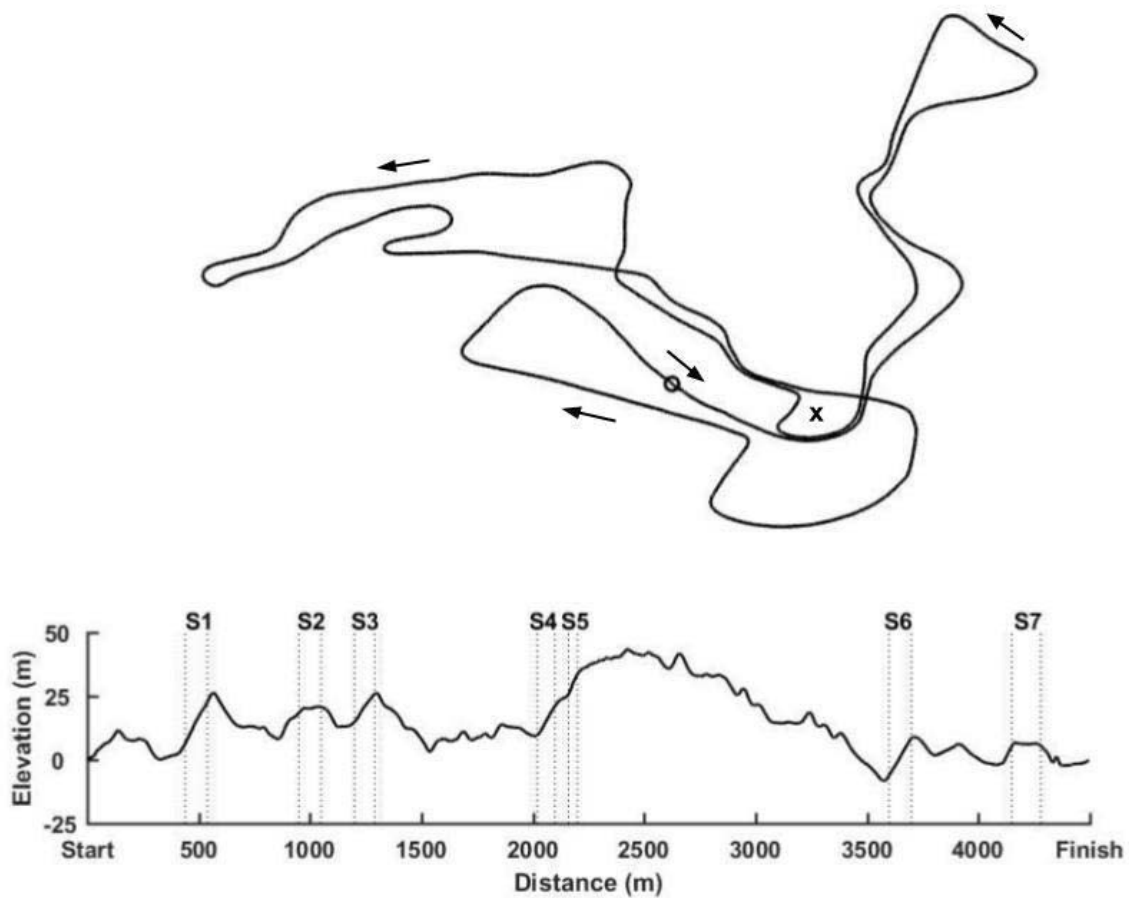


Figure 3.1: Graphic representation of the time trial course profile. The time trial consisted of 3 identical laps (4500 m), total 13500 m. O₂-demand was estimated in eight different sections (S1, ..., S7). Arrows indicate direction of travel. o: start and finish line. X: placement of static GNSS antenna.

3.1.3 Submaximal workloads and performance tests

The submaximal workloads and performance tests were carried out on a roller ski treadmill at the Norwegian School of Sport Sciences (Oslo, Norway). Prior to the submaximal workloads, the skiers performed a standardized 15 min warm up at an inclination of 3° and a speed of 3.0 m·s⁻¹ (approximately 60–75% of peak HR).

3.1.4 Submaximal workloads

To determine the individual relationship between external work rate and VO₂, each skier performed a total of six submaximal workloads divided into two subsets of three (Figure 3.2). Three workloads were meant to resemble the inclined section S4 of the outdoor course, and were

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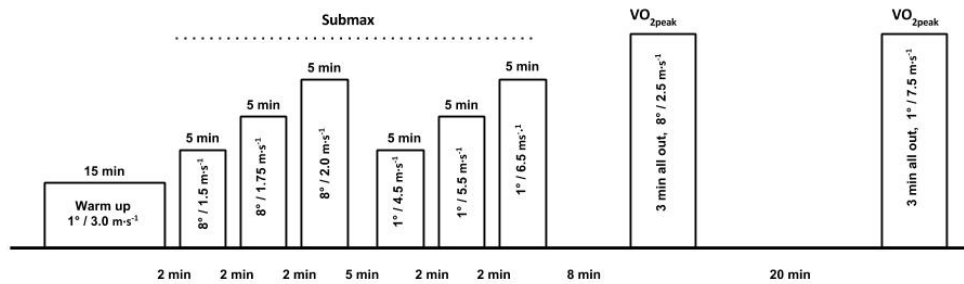


Figure 3.2: Test protocol for the treadmill submaximal workloads and performance tests. The skiers completed one subset consisting of three workloads in the V1 technique at 8° inclination and a speed of 1.5, 1.75 and 2.0 m·s⁻¹, and one subset consisting of three workloads in the V2 technique at 1° inclination and a speed of 4.5, 5.5 and 6.5 m·s⁻¹. The order in which the inclined and level subsets were performed was counter balanced between athletes. Thereafter the skiers completed two 3 min maximal performance tests at inclinations of 8° and 1° respectively. The performance tests were performed in the same order as the submaximal workloads.

carried out at the speeds 1.5, 1.75 and 2.0 m·s⁻¹ with an inclination of 8° in the V1 technique (one pole plant for two ski pushes).

The other three workloads were meant to resemble the levelled section S7 of the outdoor course, and were carried out at the speeds 4.5, 5.5 and 6.5 m·s⁻¹ at 1° inclination in the V2 technique (two pole plants for two ski pushes). The duration of each submaximal workload was 5 min. Each workload was separated by a 2 min break, while the inclined and levelled subsets were separated by a 5 min brake. The order in which the levelled and inclined subsets were executed were counter balanced between the skiers.

To assess submaximal workload, measurement of external power (as described below), steady state VO₂, HR, blood [La⁻] and RPE. VO₂, respiratory exchange ratio (RER), ventilation (VE) and breathing rate (BR) was measured continuously during the workloads. HR and RPE were registered and blood lactate concentration measured immediately after completion of each workload. Oxygen cost for each workload was defined as the average oxygen consumption in the period from 3 to 4.5 min into each workload.

3.1.5 Performance tests

After the submaximal workloads were completed, the athletes had 8 min of rest, with the possibility of active recovery at their own wish. Subsequently the performance tests were carried

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out. Two 3 min all-out protocols were executed, one at 8° inclination with the V1 technique, and one at 1° inclination with the V2 technique. The two performance tests were separated by 20 min of rest and the athletes were allowed 10 min of active recovery at low intensity (60-70% of HR_{peak}) at their own wish.

During the first 30 s of the two performance tests, the speed was set to 2.5 and 7.5 $m \cdot s^{-1}$, respectively, to avoid overpacing. Thereafter the skiers controlled the speed by adjusting their position relative to two laser beams projected in front of and behind the skiers on the tread mill belt (Figure 3.3). When both front wheels passed the laser beam in front of the skier in one cycle, the speed was increased. Accordingly, when both front wheels passed the laser beam behind the skier in the same cycle, the speed was reduced. Passing the beam resulted in a 0.25 $m \cdot s^{-1}$ or a 0.5 $m \cdot s^{-1}$ alteration in speed in the inclined and the levelled test, respectively. A new, separate passing of the laser beam was required to cause another increase or decrease of the speed. All speed changes were conducted manually by the test leader. Throughout the performance tests a separate monitor gave the skiers visual feedback on remaining time. The aim of the tests was to cover the greatest distance possible in 3 min. Continuous measurements of VO_2 , RER, VE and BR were conducted. Immediately after each performance test HR and RPE were registered and blood lactate concentration measured. VO_{2peak} in inclined and levelled terrain were defined as the highest average value measured in any 30-s period during each of the performance tests. Accordingly, HR_{peak} in the respective terrains were defined as the highest value measured in each test. HR_{max} was defined as the maximal HR measured during all tests. The performance tests were performed in the same order as the submaximal workloads. Total duration of the indoor session was approximately 1.5 hours.

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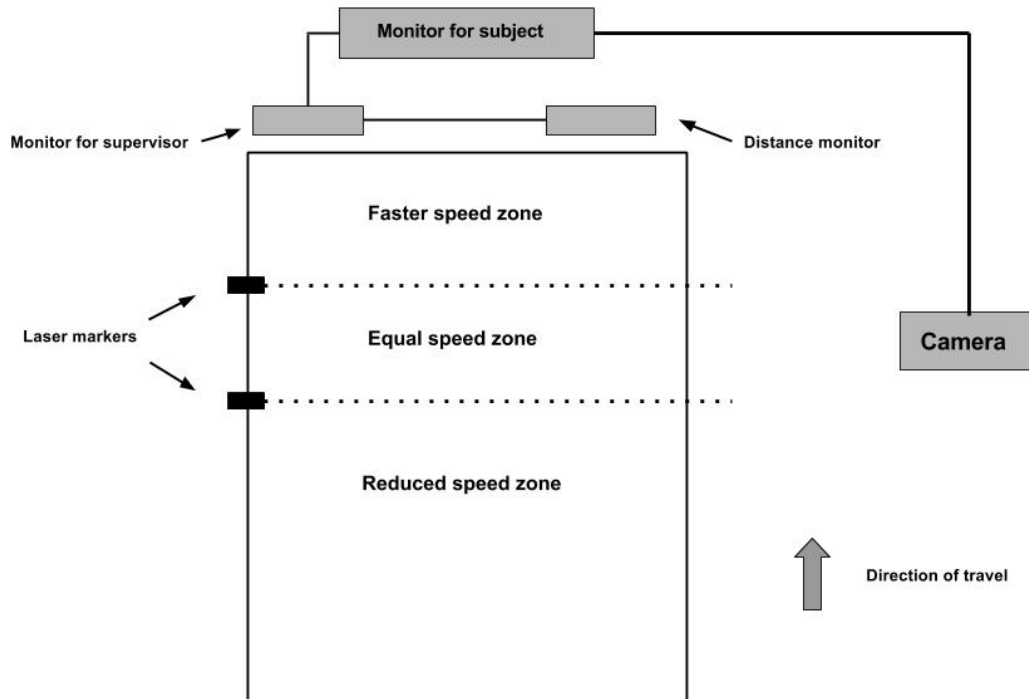


Figure 3.3: Instrumental settings for the treadmill 3 min performance tests. Modified from Losnegard (2013).

3.2 Data analysis

3.2.1 Calculation of external power indoors

For the submaximal workloads performed on the treadmill, external power (P_{ext}) was calculated as the sum of power against gravity (P_g) and the power against rolling friction (P_f) in a coordinated system moving with the treadmill belt at constant speed.

$$P_{ext} = \sum P = P_g + P_f \quad (3)$$

Power against gravity was calculated as the increase in potential energy per time

$$P_g = m \cdot g \cdot \sin \alpha \cdot v \quad (4)$$

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where m represents the total mass of the skier and equipment, g the gravitational acceleration, v the belt speed, and α the inclination of the treadmill measured in degrees.

Power against friction (P_f) was calculated as work against Columb frictional forces at a given tangential speed

$$P_f = \mu \cdot m \cdot g \cdot \cos \alpha \cdot v \quad (5)$$

where μ represent the coefficient of friction, m the total mass of the skier and equipment, g the gravitational acceleration, v the belt speed, and α the inclination of the treadmill measures in degrees (Losnegard, Myklebust, Spencer, & Hallen, 2013).

The rolling friction force (F_f) of the roller skis was determined by a towing test previously described by Hoffman, Clifford, Bota, Mandli, and Jones (1990) and the coefficient of friction (μ) was calculated as

$$\mu = \frac{F_f}{N} \quad (6)$$

where F_f is the friction force and N the normal force. The measured coefficient of friction ($\mu = 0.024$) was incorporated in the calculations of external workload. Deformation of treadmill belt was ignored since the treadmill surface was very compact.

3.2.2 Calculation of external power outdoors

For estimation of O₂-demand outdoors, power against external forces (P_{ext}) was calculated as the sum of power against gravity (P_g), the power against rolling friction (P_f) and the power against air drag friction (P_d) in a coordinated system moving in the direction of the skier's center of mass:

$$P_{ext} = \sum P = P_g + P_f + P_d \quad (7)$$

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Power against air drag resistance (P_d) was estimated as follows:

$$P_d = F_d \cdot v \quad (8)$$

F_d represents the force from the air drag acting on the skier, and v is the speed of the skier in the direction of the course. F_d was estimated assuming a turbulent air flow and no environmental wind (Sundstrom et al., 2013):

$$F_d = 0.5 \cdot C_D A \cdot \rho \cdot v^2 \quad (9)$$

C_D represents the drag coefficient, A is the projected frontal area of the skier, ρ the air density and v the speed of the skier relative to the air. The drag area ($C_D A$) was determined by scaling, as described by Sundstrom et al. (2013), using the reference value for an 80 kg athlete of 0.65 m² in an upright posture (Spring, Savolainen, Erkkila, Hamalainen, & Pihkala, 1988):

$$\frac{C_D A}{C_D A_{ref}} = \left(\frac{m_b}{m_{bref}} \right)^{\frac{2}{3}} \quad (10)$$

$C_D A_{ref}$ represents the reference drag area, m_b the actual skier's body mass and m_{bref} the reference skier's body mass.

Air density (ρ) was calculated from ambient temperature measurements on site the test day. Air pressure (p) was obtained from the meteorological station at Blindern (Oslo, Norway, eklima.net). Assuming dry air, air density ρ was calculated from the following equation:

$$\rho = \frac{p}{R \cdot T} \quad (11)$$

where R is the specific gas constant and T the ambient temperature.

Methods

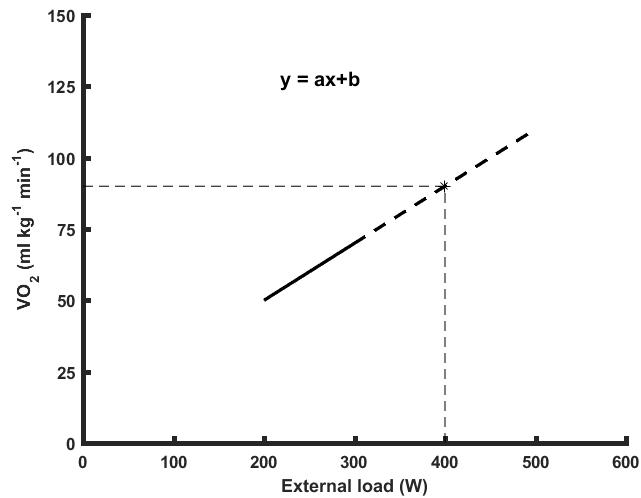


Figure 3.4: Linear regression and extrapolation of VO_2 -demand, based on indoor external power, VO_2 and calculation of external power outdoors. Solid line: regression line. Staped line: extrapolated line. *: extrapolated value.

3.2.3 Estimation of O_2 -demand

Individual O_2 -demands were calculated in seven sections (S1 through S7, Figure 3.1) of the time trial course. Oxygen demands were estimated from linear extrapolation of each athlete's external power and VO_2 values from the submaximal workloads performed indoors (Figure 3.4).

Assuming a linear relationship between external power and O_2 -demand, two regression equations were computed for each athlete, one for levelled and for inclined skiing.

Positional data from each section S1 through S7, was standardized according to section length (100 points for each section) and an estimation of external power was made at each point. The individual regression equations were applied to make an estimation of O_2 -demand for each skier at each sample point. Section O_2 -demand was defined as the average O_2 -demand of the 100 sample points of one section. Separate calculations were made for each section on each lap.

3.2.4 Gross efficiency

Gross efficiency in the submaximal workloads was defined as the ratio between external power output (W) and aerobic energy turnover rate (W) and expressed in percentage units (Losnegard, Schafer, & Hallen, 2014a). External power was calculated as the sum of the power against gravity and the power against rolling friction (Eq. 1 and 2). The aerobic energy turnover rate was determined from VO_2 and VCO_2 , by calculating the product of VO_2 and the oxygen energetic

equivalent using the associated measurements of RER and standard conversion tables (Peronnet & Massicotte, 1991).

3.2.5 Estimation of the accumulated O₂-deficite

The accumulated O₂-deficite (ΣO_2 -deficite) was calculated by a method modified from Medbo et al. (1988). A linear relationship was determined for each athlete at each inclination by linear regression of steady state VO₂ and exercise intensity (treadmill speed). Individual O₂-demand at supramaximal intensities was estimated by extrapolation, using the mean speed from the respective performance tests and the corresponding regression equation. The calculations assumed that the ratio of O₂-cost to external power is constant with increasing speed. The ΣO_2 -deficit was estimated from the difference between the ΣO_2 -demand and the average ΣO_2 -uptake during the performance test.

3.3 Equipment

All tests were performed on Swenor Skate Long roller skis (length: 630 mm, weight incl. binding: 795 g·ski⁻¹, Swenor, Sarpsborg, Norge) equipped with wheel type 2 ($\mu = 0.024$) and Rottefella NNN bindings (Rottefella, Klokke, Norge). The skiers used the same pair of roller skis and their personal ski boots and ski poles in both test sessions. Indoor tests were performed on a roller ski treadmill with belt dimension 3 x 4.5 m (Rodby, Södertälje, Sverige). Athletes wore a safety harness connected to an emergency stop. Their personal ski poles were mounted with customized ferrules for treadmill roller skiing. The skiers used the same pair of roller skis during the outdoor time trial and the indoor tests.

The dGNSS system used in the present study was originally developed for use in alpine skiing (Gilgien et al., 2015; Gilgien, Sporri, Chardonens, Kroll, & Muller, 2013), but was modified to work in cross-country skiing for the purpose of this study. The dGNSS system consisted of an antenna mounted on the skier's helmet (G5Ant-2AT1, Antcom, USA) connected to a GPS/GLONASS dual frequency (L1/L2) receiver (Alpha-G3T, Javed, USA) placed in a small backpack (Figure 3.5). Recording frequency for positional data was 50 Hz. Total weight of the dGNSS system was 940g (receiver 430 g, backpack 350 g, antenna 160 g). To facilitate differential positioning, a base station was placed on a fixed position relative to the course

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Figure 3.5: Athlete equipped with GNSS equipment. The receiver is placed in a small backpack worn under the number vest. The receiver is connected through cable to a GNSS antenna mounted on the athlete's helmet.

(Figure 3.1). The base station consisted of an antenna (GrAnt-G3T, Javad, USA) and a receiver (Alpha-G3T, Javad, USA). The antenna was mounted to a tripod and raised approximately 2 m above ground. The dGNSS measurements were determined in the global coordinate system WGS84 (Universal Transverse Mercator zone 32, northern Hemisphere). The position of the head was used to represent the position of the center of mass. Accuracy of positional data was <5 cm (Gilgien, Sporri, Limpach, Geiger, & Muller, 2014)

Oxygen consumption was measured with an automated ergospirometry system (Oxycon Pro, Jaeger Instrument, Hoechberg, Tyskland). The skiers breathed through a rubber mouth piece connected to a Hans Rudolph 2700 series large two-way non-rebreathing valve (Hans Rudolph, Inc., Kansas City, USA). Expired air was led through a corrugated flexible hose to the mixing chamber of the Oxycon Pro and further through a flow turbine (Triple V; Erich Jaeger GmbH, Hoechberg, Tyskland). The athletes wore nose clips to prevent nasal breathing. The Oxycon Pro was calibrated according to the instruction manual before each test session. The gas analyzer was

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calibrated with room air and certified calibration gasses at 180 kPa (5.55% CO₂ and 94.45% N₂). The flow turbine was manually calibrated with a 3 L calibrating syringe (Calibration Syringe, series 5530; Hans Rudolph Inc., Kansas City, Missouri, USA).

Blood lactate concentration was measured in unhemolyzed blood, from capillary fingertip samples (YSI 1500 Sport; Yellow Springs Instruments, Yellow Springs, OH, USA). The blood lactate analyzer was calibrated according to the instruction manual before each test session with a standard 5.0 mmol·L⁻¹ solution. Rating of perceived exhaustion was registered using a Borg CR10 scale (Borg, 1998), 0 representing rest and 10 representing maximum effort. This scale is regarded as a valid method to quantify exercise intensity and is consistent with objective physiological measures of exercise intensity (Foster et al., 2001). Heart rate was registered with the athlete's personal training computers. Athlete height, body weight and weight inclusive full equipment (roller skis, ski boots, poles, helmet and dGNSS system) were measured with a Seca Model 708 (Voegel & Halke, Hamburg, Germany). Measurements were made prior to both indoor and outdoor tests. Video was recorded with two Canon HF100 video cameras (frame rate = 25 Hz, Canon Inc, Tokyo, Japan).

3.4 Environmental conditions

Indoor testing was performed at approximately 20°C with no circulation of air. Air temperature during the outdoor time trials was between 8-16°C and air pressure approximately 1005 hPa. Local wind direction was NE and SE on the first and second day of outdoor testing, respectively. The asphalt was completely dry on both days. Weather data was retrieved from the weather stations at Besserud (air temperature), Blindern (air pressure) and Tryvannshøgda (wind direction and speed) (met.eklima.no, Meteorologisk institutt, Oslo, Norway).

3.5 Statistics

Data are presented as mean ± standard deviation (SD), unless otherwise stated. Normality of the data was assessed using the Shapiro-Wilks test of normality ($\alpha = 0.05$). Outliers in the data were assessed by inspection of boxplot and by examination of studentized residuals for values greater than ±3. Paired sample T-tests were used to determine whether there were statistically significant differences between physiological parameters, average speed and total distance during the 3 min performance tests and between average speeds and lap times during the simulated time trial. One-

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way repeated measures ANOVAs, with Bonferroni correction for multiple comparisons, were conducted to determine whether there were statistically significant differences in section O₂-demand (% VO_{2max}), average HR (% HR_{max}) and speed between laps. Pairwise comparison of average O₂-demand (% VO_{2max}) between sections and of average RPE between laps and sections were performed with a related samples Friedman's test two-way analysis of variance by ranks with Bonferroni correction for multiple comparisons. Pearson's Product Moment Correlation Analysis was applied to detect relations between parameters. The strength of correlation (r) between the measures were interpreted as follows: correlation coefficient < 0.1 was interpreted as no correlation, 0.1-0.3 as small, 0.3-0.5 as moderate, 0.5-0.7 as large and 0.7-0.9 as very large correlation, while a correlation coefficient of 0.9-1.0 was interpreted as almost perfect correlation (Hopkins, 2004). Statistical significance was set at an alpha level of $p < 0.05$. A statistical tendency was defined as $0.05 < p < 0.1$. Data was registered using Microsoft Office Excel 2016 (Microsoft, Redmond, USA). All calculations and modelling were performed in MATLAB R2016a (The MathWorks, Inc., Natick, Massachusetts, USA). Statistical analyses were performed in SPSS Statistics (IBM Corp., Armonk, NY).

One skier was excluded from the outdoor time trial because he experienced pain in his lower legs leading to unreliable data. Heart rate data was only complete for six out of eight skiers in the individual time trial. The two skiers from which only incomplete HR data existed, were excluded from the HR analysis of the time trial.

4. Results

4.1 Pacing

The mean finishing time of the time trial was $33:26 \pm 1:38$ min. Average lap time was 657 ± 24 s, 677 ± 39 s and 672 ± 37 s, respectively. There was a significant interaction between lap x average speed ($\text{m}\cdot\text{s}^{-1}$) during the 15-km individual time trial ($F(2,12) = 7.371$, $p < 0.008$).

Average lap speed between lap 1 and lap 2 was reduced, with a mean reduction of $0.19 \text{ m}\cdot\text{s}^{-1}$ (95% CI [0.006, 0.374], $p = 0.044$) (Figure 4.1). No differences in average lap speed was observed between the first and the third and the second and the third lap.

There were no differences in average speeds in S1, S2, S3, S5, S6 or S7 between laps (Table 4.1). In S4 there was a reduction in average speed from lap 1 to lap 2 and lap 3, with a significant mean difference of $0.191 \text{ m}\cdot\text{s}^{-1}$ (95% CI [0.002, 0.380], $p < 0.048$) and $0.215 \text{ m}\cdot\text{s}^{-1}$ (95% CI [0.093, 0.336], $p < 0.003$) respectively. In S7 there was an increase in average speed from lap 2 ($6.57 \pm 0.34 \text{ m}\cdot\text{s}^{-1}$) to lap 3 to ($6.90 \pm 0.40 \text{ m}\cdot\text{s}^{-1}$), with a significant mean difference of $0.33 \text{ m}\cdot\text{s}^{-1}$ (95% CI [0.027, 0.639], $p < 0.035$).

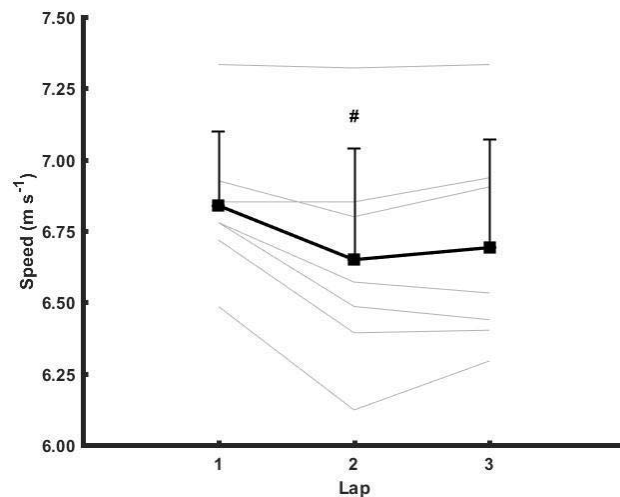


Figure 4.1: Average lap speeds of the 15-km individual time trial. Solid line: average data. Error bars indicate SD. Stapled lines: individual data. #: significantly different from lap 1 ($p \leq 0.05$), $n = 7$.

Results

Table 4.1: Pacing shown as average lap speed and average section speed ($m \cdot s^{-1}$) from each lap in the time trial.

	Angle (°)	Speed ($m \cdot s^{-1}$)			
		Lap 1	Lap 2	Lap 3	Average
Lap		6.84 ± 0.26	6.65 ± 0.39 [#]	6.69 ± 0.38	6.72 ± 0.34
Section					
S1	9.3	2.69 ± 0.28	2.59 ± 0.34	2.55 ± 0.33	2.61 ± 0.31
S2	1.0	6.09 ± 0.42	6.00 ± 0.47	5.80 ± 0.58	5.96 ± 0.47
S3	7.3	4.06 ± 0.23	3.91 ± 0.38	3.82 ± 0.47	3.93 ± 0.33
S4	8.2	3.12 ± 0.36	2.93 ± 0.28 [#]	2.90 ± 0.32 [#]	2.98 ± 0.32
S5	11.3	2.29 ± 0.22	2.26 ± 0.35	2.31 ± 0.38	2.29 ± 0.31
S6	8.2	3.83 ± 0.26	3.79 ± 0.27	4.19 ± 0.38	3.93 ± 0.23
S7	0.0	6.76 ± 0.36	6.57 ± 0.34	6.90 ± 0.40 [*]	6.74 ± 0.33

(mean ± SD), n = 7

[#]: significantly different from lap 1 ($p \leq 0.05$)

^{*}: significantly different from lap 2 ($p \leq 0.05$)

The preferred subtechniques in S4 and S7 was V1 and V2 respectively. Table 4.2 shows the individual choices of subtechniques in S4 and S7 on each separate lap.

Table 4.2: Subtechnique applied by skiers in S4 (8.2°) and S7 (0.0°) on each lap assessed by video recordings. (n = 7).

Subject	S4			S7		
	Lap 1	Lap 2	Lap 3	Lap 1	Lap 2	Lap 3
1	V1	V1	V1	V2	V2	V2
2	V2 - V1	V1	V1	V2a - V2 - V2a	V2	V2
3	V1	V1	V1	V2 - V2a	V2	V2
4	V1	V1	V1	V2 - V2a	V2	V2
5	V2 - V1	V2 - V1	V1	V2	V2	V2
7	V2	V2	V1	V2	V2	V2
8	V2	V2	V1	V2 - V2a	V2 - V2a	V2

V1: asymmetrically one pole push every second leg stroke (also named G2)

V2: one pole push for every leg stroke (also named G3)

V2a: one pole push for two leg strokes (also named G4)

Results

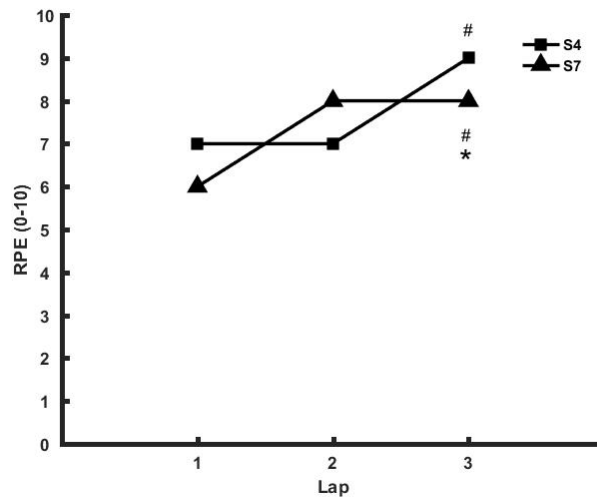


Figure 4.2: RPE reported on each lap in section S4 (inclined) and S7 (level). #: significantly different from S1 lap 1 ($p < 0.05$). *: significantly different from S2 lap 1 ($p \leq 0.05$). $n = 7$.

There was a significant two-way interaction between lap x section on RPE ($\chi^2 = 26.393$, $p < .001$) (Figure 4.2). There were significant differences in RPE between S4 lap 1 (Mdn = 6.0, IQR = 3.0) and S4 lap 3 (Mdn = 8.0, IQR = 1.0) ($p < .009$), between S4 lap 1 (Mdn = 6.0, IQR = 3.0) and S7 lap 3 (Mdn = 9.0, IQR = 1.5) ($p < .002$) and between S7 lap 1 (Mdn = 7.0, IQR = 2.0) and S7 lap 3 (Mdn = 9.0, IQR = 1.5) ($p < .015$).

4.2 Treadmill performance tests

Data from the leveled and inclined treadmill performance test are presented in Table 4.3. ΣO_2 -deficit was significantly greater in the inclined performance test compared to the level test, with a median difference of 1188.9 ml ($z = 2.521$, $p < .012$). BF was greater in the level performance test compared to the inclined test, with a significant mean difference of 11.13 BPM (95% CI [3.61, 18.64], $t(7) = 3.5$, $p < .01$). VE was significantly greater in the inclined performance test compared to the level test, with a significant mean difference of 11.9 L \cdot min $^{-1}$ (95% CI [0.9, 22.9], $t(7) = 2.561$, $p < .037$). No significant mean differences were observed in VO_{2peak} , HR, $[La^-]$, RER or RPE.

Results

Table 4.3: Performance (time and speed) and physiological responses during the level and inclined 3 min performance tests on the roller ski treadmill.

Variable	Level		Incline		p
	Mean ± SD	Range	Mean ± SD	Range	
Distance (m)	1446.7 ± 65.5	1363.7 - 1551.5	525.2 ± 50.3	463.1 - 606.2	> 0.001
Average speed (m·s ⁻¹)	8.04 ± 0.36	7.58 - 8.62	2.92 ± 0.28	2.57 - 3.37	> 0.001
VO _{2peak} (ml·min ⁻¹)	5560 ± 191	5296 - 5924	5521 ± 129	5322 - 5689	0.347
VO _{2peak} (ml·kg ⁻¹ ·min ⁻¹)	72.7 ± 5.3	64.9 - 81.5	72.3 ± 6.2	64.2 - 82.7	0.411
ΣO ₂ -deficit (ml)*	4634, 1101	3780 - 5277	6375, 1008	5263-6955	0.012
HR _{peak} (BPM) ^a	182 ± 5	174 - 188	183 ± 6	173 - 190	0.365
[La ⁻] (mmol·L) ^b	7.58 ± 1.02	6.1 - 8.9	6.87 ± 1.58	4.9 - 9.6	0.138
BF (breaths·min ⁻¹)	70.4 ± 7.0	56.0 - 76.0	59.3 ± 7.7	52 - 73	0.01
VE (L·min ⁻¹)	200.5 ± 10.8	175.1 - 210.7	188.6 ± 14.1	169.0 - 211.3	0.037
RER*	1.09, 0.04	1.05 - 1.15	1.05, 0.08	0.99 - 1.05	0.161
RPE (0-10)	9.2 ± 0.8	8 - 10	9.4 ± 1.1	7 - 10	0.504

*: Mdn, IQR
n = 8, ^a: n = 6, ^b: n = 7

4.3 Submaximal tests

VO₂ in the level and inclined submaximal workloads were 56.7 ± 5.3, 66.3 ± 5.8 and 78.2 ± 6.1% of VO_{2peak} and 62.3 ± 9.3, 68.7 ± 7.6 and 75.8 ± 8.0% of VO_{2peak} respectively. Heart rate in the level and inclined submaximal workloads was 76.3 ± 6.7, 82.9 ± 6.6 and 90.6 ± 5.15% of HR_{peak} and 79.8 ± 7.4, 86.0 ± 7.3 and 90.5 ± 6.2% of HR_{peak} respectively. Absolute VO₂, HR, RPE and external power from the submaximal workloads are presented in Figure 4.3.

Results

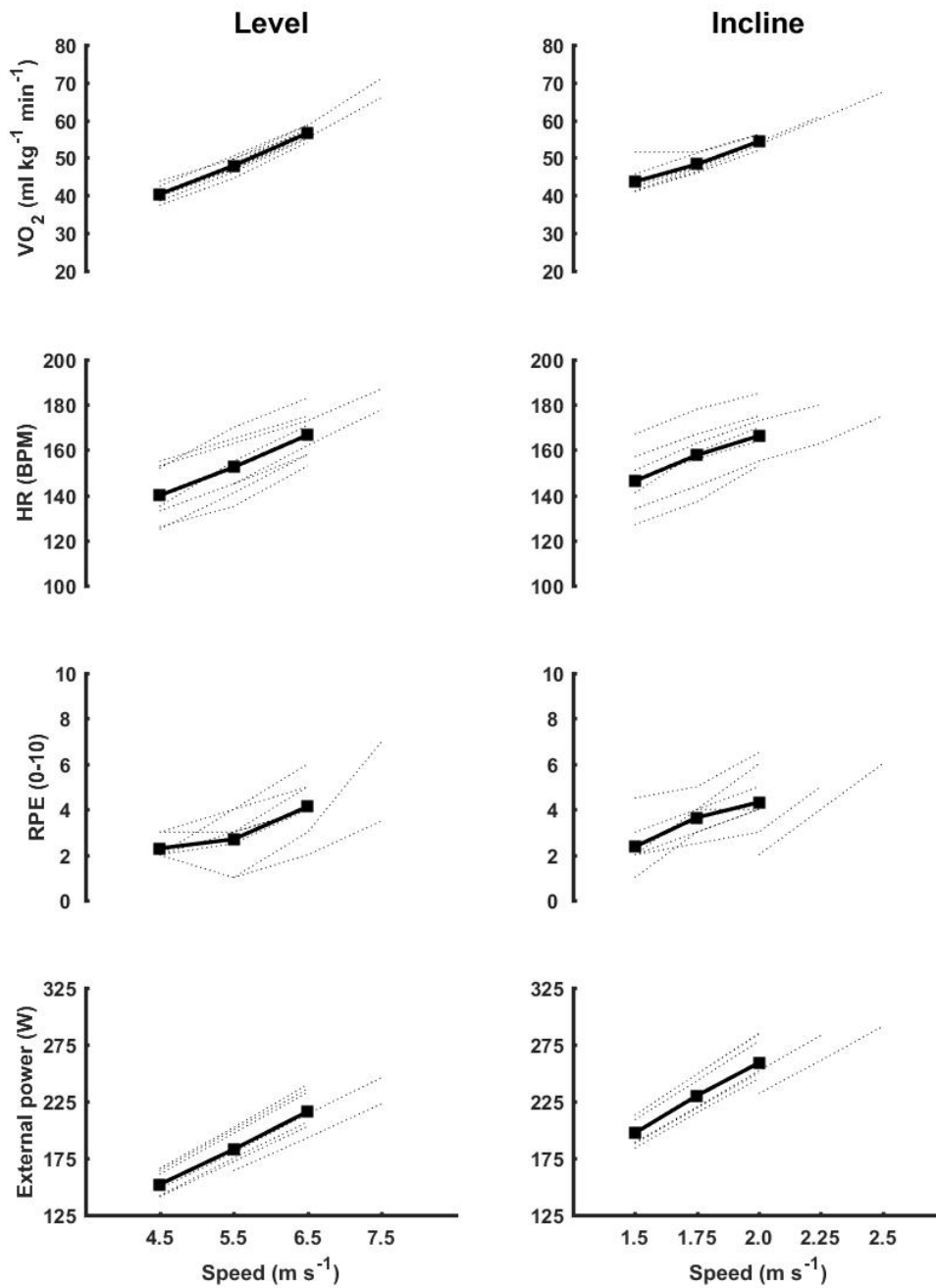


Figure 4.3: VO_2 , HR, RPE and external power during the submaximal level and inclined workloads on the roller ski treadmill. Square and solid line: average data. Dotted lines: individual data. ($n = 8$). Subject 2 completed one extra work load at $7.5 \text{ m}\cdot\text{s}^{-1}$ (total number of level workloads: 4) and one extra work load at $2.25 \text{ m}\cdot\text{s}^{-1}$ (total number of inclined workloads: 4). Subject 8 started the level submaximal workloads at $5.5 \text{ m}\cdot\text{s}^{-1}$ and the inclined submaximal workloads at $2.0 \text{ m}\cdot\text{s}^{-1}$.

Results

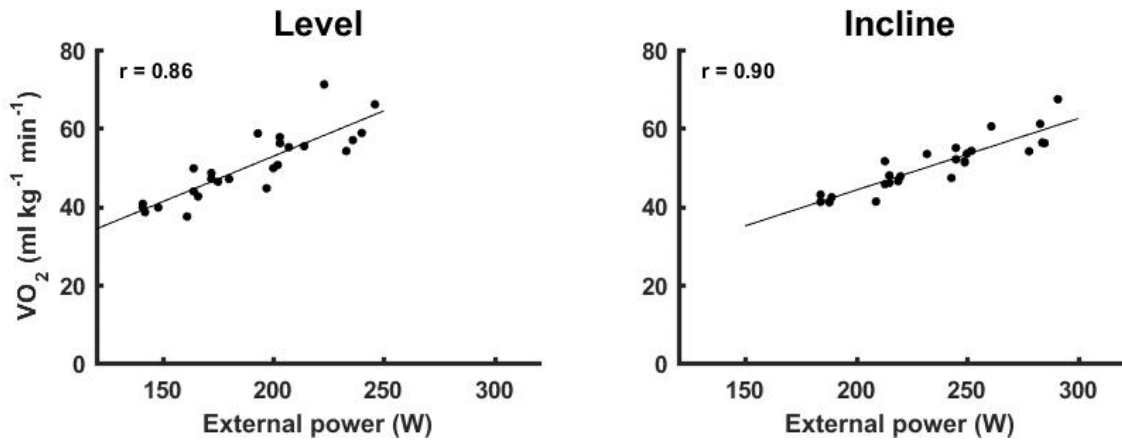


Figure 4.4: Relationship between external power and relative VO₂ during level (1°, 4.5, 5.5 and 6.5 m·s⁻¹) and inclined (8°, 1.5, 2.5 and 3.5 m·s⁻¹) submaximal workloads (n = 8).

Linear regression analysis of individual external power and individual O₂-uptake revealed strong correlations in the level ($r(25) = .856$, $p < 0.001$) and inclined ($r(25) = .897$, $p < 0.001$) submaximal workloads (Figure 4.4).

There were no significant differences in GE between workloads at the same inclination, but GE was significantly different between level (Mdn = 14.4%, IQR = 0.9%) and inclined (Mdn = 17.8%, IQR = 0.9%) treadmill roller skiing, with a median difference of 3.4% IQR = 1.0% ($z = 4.372$, $p < .001$) (Figure 4.5).

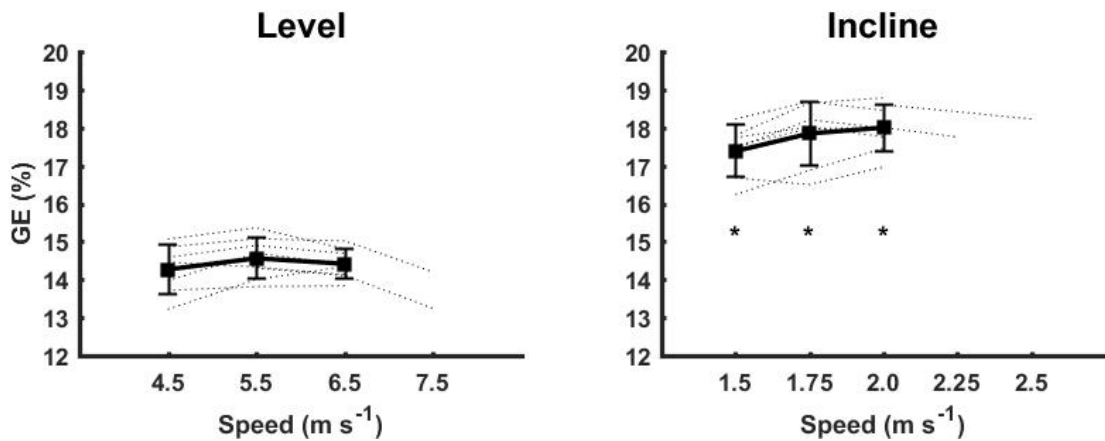


Figure 4.5: Gross efficiency at level (1°) and inclined (8°) submaximal workloads. *: significant difference between inclinations ($p \leq 0.05$) (n = 8).

4.4 Estimated O₂-demand

4.4.1 Comparison of lap to lap section O₂-demand

There was a reduction in estimated O₂-demand (% VO_{2peak}) in S4 between lap 1 (120.6 ± 8.8%) and lap 3 (112.3 ± 5.7%), with a significant mean difference of 8.3% (95% CI [3.4, 13.3], p < .005). Further, there was an increase in estimated O₂-demand (% VO_{2peak}) in S7 between lap 2 (83.9 ± 5.0%) and lap 3 (92.8 ± 9.8%), with a significant mean increase of 8.9% (95% CI [0.8, 17.1], p < .034). There was also a tendency to a reduction in estimated O₂-demand (% VO_{2peak}) in S4 between lap 1 (120.6 ± 8.8%) and lap 2 (113.2 ± 4.0%), with a mean difference of 7.4% (95% CI [0.02, 14.8], p < .051). The reduction in section O₂-demands were related to reductions in average section speeds (Table 4.1). No significant differences in estimated O₂-demand (% VO_{2peak}) between laps was observed in S1, S2, S3, S5 and S6 (Figure 4.6).

4.4.2 Comparison of average section O₂-demand

The average section O₂-demands ranged from 88.5 to 156.9% of VO_{2peak} (Figure 4.7). The O₂-demand in the level sections were below ~100% of VO_{2peak}, while in the inclined sections O₂-demand ranged from ~110 to 160% of VO_{2peak}. There was a significant interaction between section x average O₂-demand in the time trial (F(6,36) = 65.816, p < 0.001). Statistical differences in O₂-demand between the sections are indicated in Figure 4.7 (p < 0.05).

Results

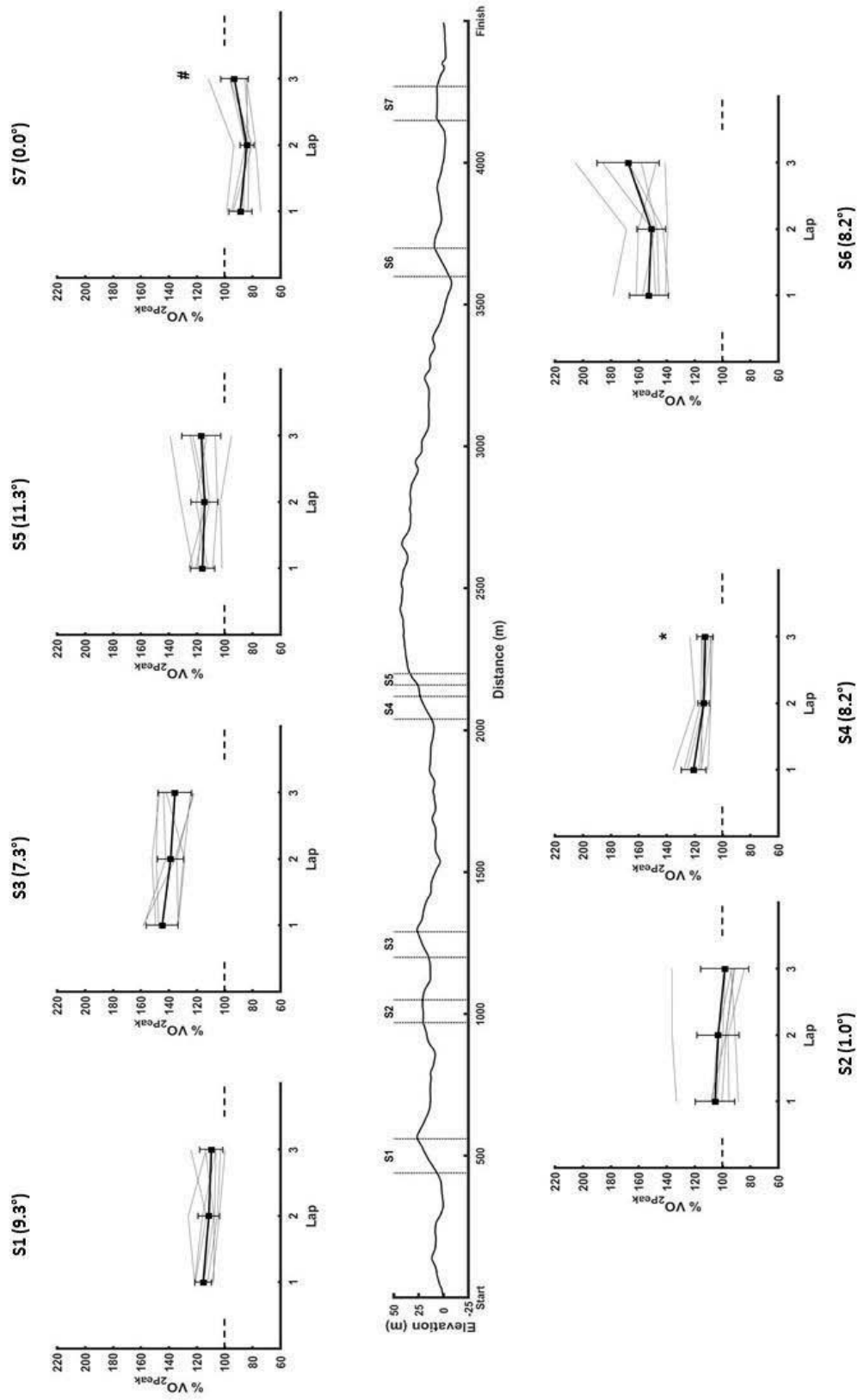


Figure 4.6: Intensity presented as estimated O_2 -demand ($\% VO_{2peak}$) from each lap in each of the seven sections of the 15-kilometer individual time trial. Solid squares and line: mean data \pm SD. Dotted line: individual data. #: significantly different from lap 1. *: significantly different from lap 2. ($n = 7$).

Results

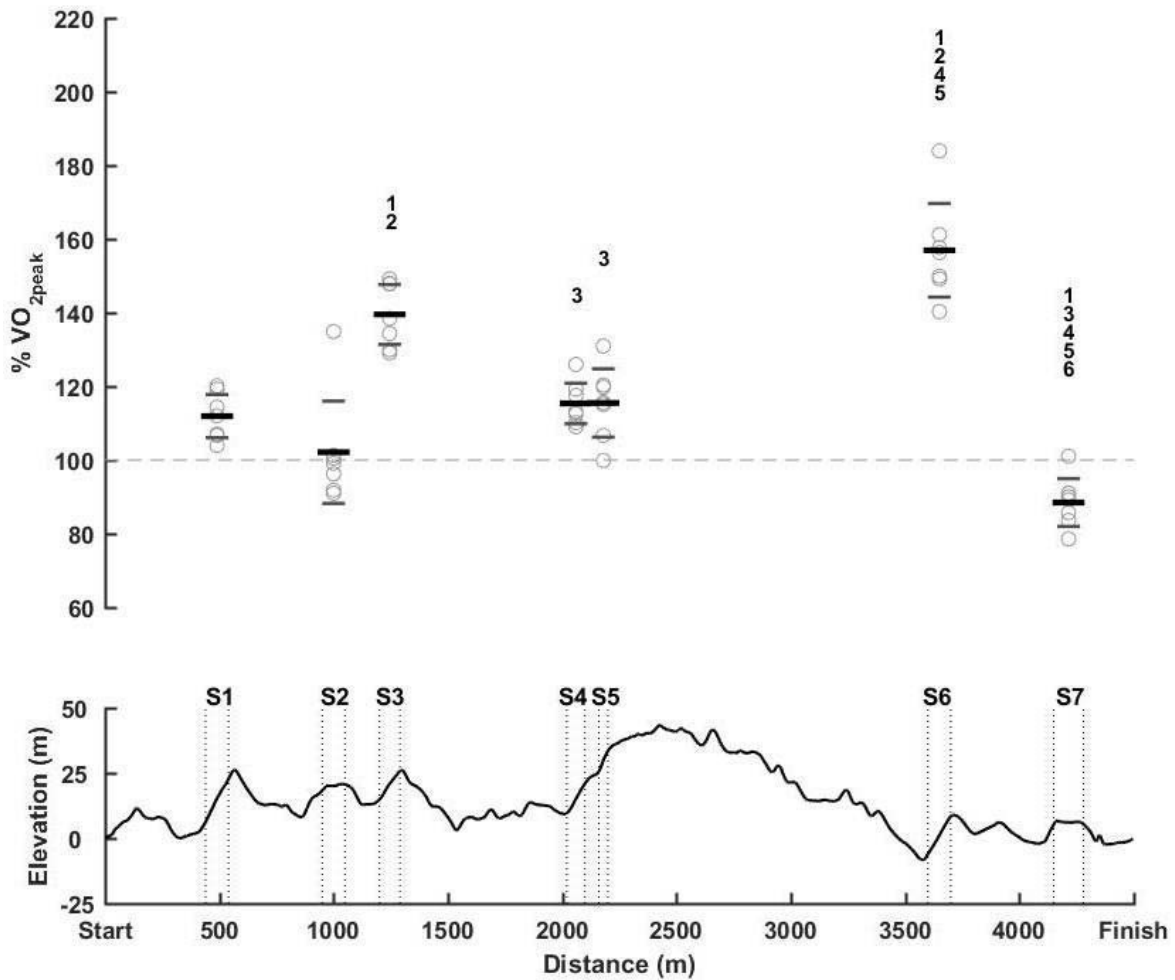


Figure 4.7: Estimated O_2 -demand ($\% \text{VO}_{2\text{peak}}$) in each section as the average of all subjects. Open symbols: individual data. Closed symbol: section average, $Q1$ and $Q4$. 1: significantly different from S1. 2: significantly different from S2. 3: significantly different from S3. 4: significantly different from S4. 5: significantly different from S5. 6: significantly different from S6. ($n = 7$, $p \leq 0.05$)

Results

4.5 Heart rate

Average HR in the time trial was $94.0 \pm 2.5\%$ of HR_{max} . Continuous HR data from the time trial is presented in Figure 4.8. There was a significant interaction between laps x average HR ($\% HR_{peak}$) in the 15-km individual time trial ($\chi^2(2) = 8.3, p < 0.016$). There was a significant increase in HR from lap 1 (Mdn = 91.9% HR_{peak} , IQR = 3.9%) to lap 3 (Mdn = 95.3% HR_{peak} , IQR = 2.1%) ($p < 0.12$). Average section HR are presented in Table 4.4.

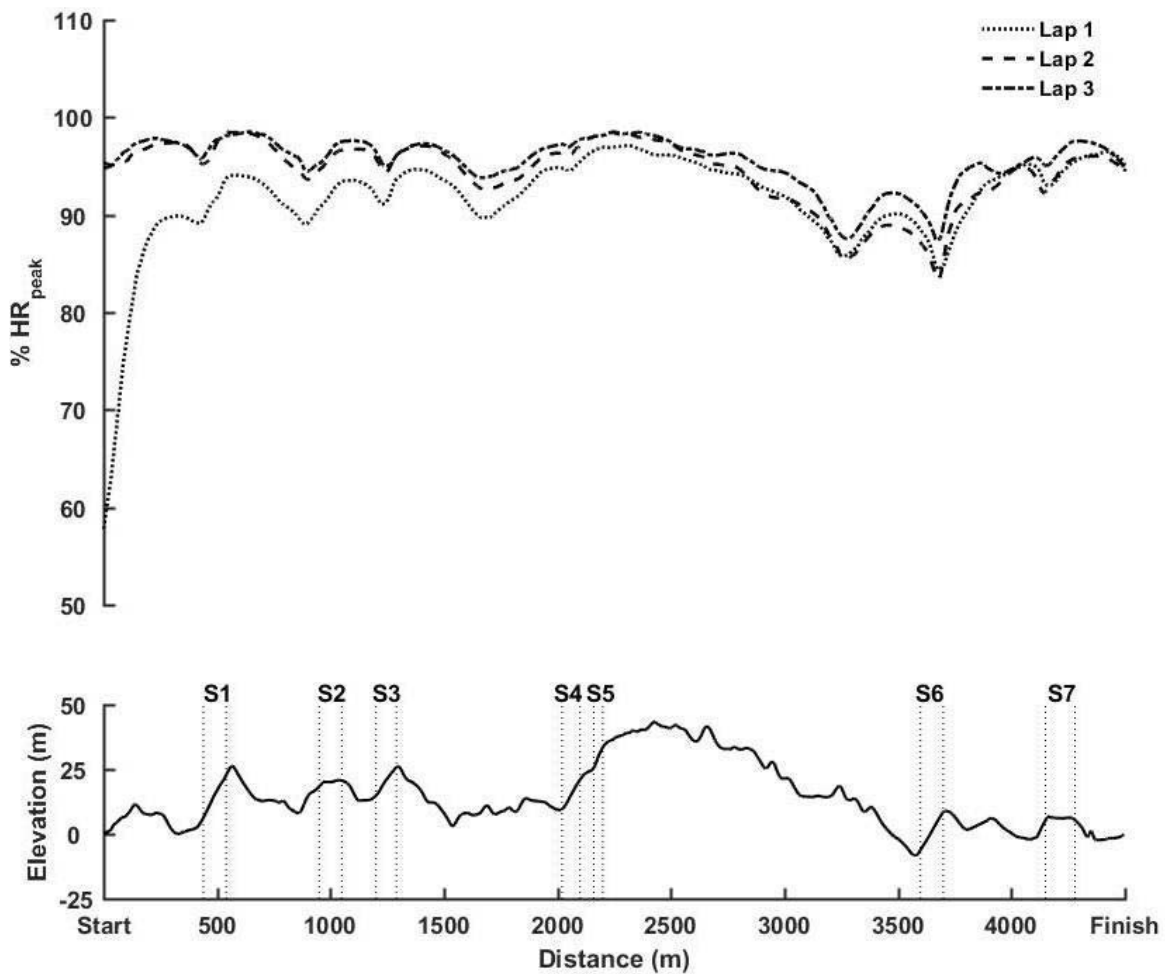


Figure 4.8: Continuous HR data ($\% HR_{peak}$) from each lap of the 15-km individual time trial. Dotted line: lap 1. Staped line: lap 2. Solid line: lap 3. ($n = 6$)

Results

Table 4.4: Section HR (%HR_{max}) from each lap in each section of the time trial.

Section	Section HR (% HR _{max})			
	Lap 1	Lap 2	Lap 3	Average
S1	92.3, 7.8	97.5, 2.7	97.1, 1.6	95.7, 3.9
S2	94.1, 6.2	96.7, 4.2	97.0, 2.3	95.6, 3.9
S3	93.1, 5.7	94.9, 4.4	95.0, 6.0	94.5, 4.0
S4	96.1, 4.8	96.6, 2.8	97.0, 3.1	96.9, 4.4
S5	98.0, 4.5	98.1, 2.6	91.4, 1.6	97.7, 2.4 ³
S6	85.5, 6.1	89.3, 11.3	90.5, 9.4	88.9, 7.9 ^{4,5}
S7	96.0, 5.8	95.5, 4.3	97.0, 2.3	96.4, 3.8

Mdn, IQR, n = 6

³: section average significantly different from S3 ($p \leq 0.05$)

⁴: section average significantly different from S5 ($p \leq 0.05$)

⁵: section average significantly different from S5 ($p \leq 0.05$)

5. Discussion

In this paper, we present a novel approach to estimate O₂-demand during XC skiing by combining real-time positioning data and physiological data from roller ski treadmill testing to investigate physiological demands and pacing strategies adopted in XC skiing. The main findings of the current study were (I) although XC skiers employ a general positive pacing on a lap-to-lap basis, our data suggest that a variable pacing strategy occur both within each lap and within the time trial as a whole. (II) The O₂-demand repeatedly exceeded the individual VO_{2peak} of the skiers. (III) Pacing in the different sections of the course were dependent on the characteristics of the preceding and subsequent terrain. The variations in the terrain, allows the skiers to recover in the flat and downhill parts of the course, enabling them to apply supramaximal intensities in the uphill parts.

5.1.1 Average speed

Comparing the average speed between laps shows that skiers adopt a general positive pacing strategy. This is in accordance with earlier observations during individual time trials in XC skiing (Andersson et al., 2010; Bolger et al., 2015; Formenti et al., 2015; Losnegard et al., 2017), but in contradiction to the even pacing strategy generally considered as optimal in endurance sports events lasting >2 min (Abbiss & Laursen, 2008). One unique aspect of on- snow skiing is that glide friction between the skis and the snow seems to increase during a race (Kuzmin & Tinnsten, 2006). This increases the O₂-cost for the skiers, and may explain some of the reduction in speed (positive pacing) observed in XC skiing. The present study was, however, performed on roller skis, where the friction coefficient seems to be constant, at least when enough time to warm-up of the skis are allowed (Ainegren, Carlsson, & Tinnsten, 2008). In XC skiing, fatigue influences technique (Asan Grasaas, Ettema, Hegge, Skovereng, & Sandbakk, 2014; Zory, Vuillerme, Pellegrini, Schena, & Rouard, 2009), leading to increased strain to coordinate the limbs, and reduces the ability to produce force and power (Zory, Millet, Schena, Bortolan, & Rouard, 2006). This may increase both the O₂-cost of maintaining a given external workload, and the perception of effort for a given external workload during a race. Hence, the reduction in speed observed when roller skiing, may be related to fatigue and not to alterations in friction properties of the skis.

5.1.2 Intensity

Even though the skiers adopted a positive pacing strategy when comparing the average speed between individual laps, our estimations of the O₂-demand implies that the skiers employed a variable pacing strategy within each lap and within the time trial as a whole. This is in accordance with earlier findings in XC skiing, suggesting that the O₂-demand repeatedly exceeds the individual skiers' VO_{2peak} ($\leq 160\%$ of VO_{2peak}) during competition (Norman & Komi, 1987; Norman et al., 1989; Sandbakk et al., 2011; Sandbakk & Holmberg, 2017). Furthermore, our results also suggest that the pacing adopted in XC skiing is highly dependent on the fluctuations in the terrain. When comparing intensity in S1 and S6, two sections of approximately the same length and inclination, the average intensity (% of VO_{2peak}) was approximately 50% higher in S6. The difference in intensity could mainly be attributed to the difference in speed, and may be explained by the fact that prior to S6, the skiers ran through approximately 1 km of downhill terrain which allowed the skiers to recover. Furthermore, S6 was followed by relatively flat terrain when compared to S1. Thus, the skiers knew that they had a less strenuous part of the course ahead of them when they skied the S6 section. On the other hand, both the terrain prior to and following S1 was undulating and may therefore have been regarded as tougher than the terrain before and after S6 (Sundstrom et al., 2013). Further, when the length and slope of the uphill section increased (S4 and S5), the skiers seemed to employ a lower work intensity ($\sim 115\%$ of VO_{2peak}) than during the shorter and less steep sections (S3 and S6, 140-160% of VO_{2peak}). Based on the individual data in S4 and S5 it could be speculated that skiers choose different pacing strategies in different parts of long uphill sections. In S4, skiers adopted a positive pacing strategy, while in S5 they adopted a negative pacing. This implies that skiers modify the intensity and hence the pacing strategy according to the terrain to avoid intolerable increases in the “conscious” RPE. Consequently, they may have to reduce intensity and apply a suboptimal pacing in the subsequent terrain.

When comparing section speed data, only one section (S4) showed a significant reduction in lap speed throughout the time trial, indicating that the skiers adopted a positive pacing strategy. In two sections, S6 and S7, an increase in lap speed on the last lap was observed. Speed data from the remaining sections indicated that the skiers adopted an even pacing strategy. Hence, even the section speed data imply that the skiers adopt a variable pacing both within the same lap and

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within the time trial as a whole. This is also supported by the findings of Andersson et al. (2010) who observed that the skiers adopted different pacing strategies in different parts of a course.

The rationale for adopting a variable pacing strategy in XC skiing is mainly attributed to two factors; (I) the large variations in the course profile of a XC ski race and (II) the exponential behavior of the air drag resistance. The repeated periods of supramaximal work intensities observed are made possible by the passive nature of the downhill sections of the course in which the skier apply little or no force to generate propulsion. To cover the O₂-demand in the supramaximal periods, skiers rely on both aerobic and anaerobic metabolism. While the capacity of the aerobic system is almost unlimited, the anaerobic system is not (Gastin, 2001). Therefore, following a period of supramaximal work rates either cessation of work or a reduction in work rate to a level that can be met by aerobic metabolism has to occur if the exercise is to continue (Gastin, 2001). Thus, skiers can attain a considerable O₂-debt in some parts of the course, knowing that they will have time to recover this debt in subsequent downhill parts of the course. This is in contrast to other endurance sports, such as running, track cycling and speed skating, where there are no periods of rest. Implying that in these sports the athletes can only maintain an intensity relying on a high contribution of anaerobic metabolism for a limited period. (Gastin, 2001; Poole, Ward, Gardner, & Whipp, 1988).

Although we found that the intensity exceeded the individuals' VO_{2peak} repeatedly in the uphill terrain, the average intensity throughout the time trial may not exceed the intensity at VO_{2peak}. In the present study, we did not measure the VO₂ or estimate the O₂-demand in the downhill sections. However, the O₂-demand was at- or below 100% of VO_{2peak} in the two flat sections observed (S2 and S7). According to Welde et al. (2003) VO₂ falls to approximately 65% of VO_{2max} in the downhill sections of a race. Athletes seem to be able to maintain an intensity (usually described by speed) corresponding to the minimal intensity to elicit VO_{2max} for approximately 6 to 9 min (Billat & Koralsztein, 1996). When intensity is reduced to approximately 90% of VO_{2max}, time to exhaustion increases to >15 min in well trained runners (Billat & Koralsztein, 1996). This implies that the skiers are able to apply supramaximal intensities during parts of the race because they get the necessary recovery periods in between the high intensity parts of the course. It has been suggested that a variable pacing strategy is adopted in an attempt to maintain an even pacing (Swain, 1997), hence to maintain the same

Discussion

work rate athletes need to vary the speed depending on the terrain. However, our results suggest that this is not the case. Even though the skiers reduce the speed in the uphill parts of the course, work rate is considerably higher than compared to the flat parts.

The exponential behavior of the air drag resistance, implies that a relatively large increase in work rate is needed to accelerate in the levelled parts of the course, because most of the work will be used to overcome the increasing air drag resistance and not to generate propulsion. On the other hand, since the speed is relatively low when skiing uphill, less work is needed to overcome the air drag resistance, and a larger part of an increase in work rate will result in propulsion. The ability to maintain a high intensity in uphill terrain is crucial in XC skiing. In a XC ski race >50% of the total time is spent moving uphill, and these sections are the major determinants for the overall performance (Andersson et al., 2010; Bergh & Forsberg, 1992; Sandbakk et al., 2011). Hence, the athlete which can maintain the highest speed in the uphill parts of the course, will ultimately perform the best. Thus, to optimize performance, the most rational choice for the XC skier is to increase work rate in the uphill parts of the course. This notion is supported by numerical simulations of XC skiing (Sundstrom et al., 2013) as well as by studies conducted in road cycling (Atkinson, Peacock, & Passfield, 2007a; Swain, 1997; Wells & Marwood, 2016) suggesting that increasing work rate in uphill terrain is optimal for overall performance in endurance sports events carried out under variable external conditions.

In the present study, the skiers VO_{2peak} and ΣO_2 -deficite were determined for both levelled (1°) and inclined (8°) terrain. We observed no differences in VO_{2peak} , which is in accordance with earlier observations in XC skiing. (Losnegard, Myklebust, & Hallen, 2012b). The ΣO_2 -deficite was, however, greater in the inclined performance test compared to the levelled performance test. This discrepancy has previously been reported in treadmill running and has mainly been attributed to the amount of active muscle mass (Olesen, 1992). The smaller anaerobic capacity on levelled compared to inclined terrain, may have implications for the maximal work rate that can be obtained by the skiers in different kinds of terrain. Since the maximal aerobic power in both levelled and inclined terrain is similar, the metabolic power attainable is differentiated by the anaerobic capacity. Thus, the maximal work rate applicable on flat terrain consequently will be lower than in uphill terrain.

5.1.3 Perception of effort

There was a significant increase in RPE in both S4 and S7 on the final lap when compared to RPE on the first lap. The increase in RPE coincides with a significant decrease in O₂-demand in section S4 and a significant increase in O₂-demand in S7. The increase in RPE observed in S7 on the final lap is as expected. The median RPE reported was 9 out of 10, which seems reasonable, since S7 is close to the finish line. According to Tucker (2009) exercise is terminated when the RPE reaches levels that are intolerably high or uncomfortable to the athlete. Therefore, exhaustion should occur when the skier passes the finish line in order to optimize the pacing (Roelands et al., 2013). In contrast to in S7, RPE increased in S4 even though there was a reduction in speed. This can be explained by the fact that fatigue affects the perception of effort for a given work rate during the race, and therefore the skiers reported the same RPE even though the speed was lower.

On the final lap the intensity increased in both S6 (not statistically significant) and S7 (significant), indicating that the skiers employed a negative pacing strategy. This phenomenon, in which the power output increase significantly at the end of self-paced exercise, has been named the “endspurt” phenomenon (Tucker, 2009). We did not investigate this, but Tucker (2009) suggests that as the skiers approaches the end of the time trial, the uncertainty regarding the duration of the effort is reduced. Therefore, their motor unit and metabolic reserve can be utilized, resulting in the higher intensities observed.

5.1.4 Heart rate

HR remained high for most of the race ($94.0 \pm 2.5\%$ of HR_{max}). This is in accordance with earlier observations in XC skiing (Formenti et al., 2015; Mognoni et al., 2001). Our results support the notion that variations in HR is mainly attributed to the changing slope of the course (Formenti et al., 2015). To some extent HR therefore reflects the intensity applied by the skiers in various parts of the course. Accurate determination of intensity is of key interest when investigating pacing and pacing strategies. HR has become the most commonly used tool to monitor exercise intensity in a variety of sports (Achten & Jeukendrup, 2003) including XC skiing. It's ability to reflect supramaximal exercise intensities are, however, limited due to the temporal dissociation between HR, VO₂ and work rate during high intensity exercise (Buchheit & Laursen, 2013). This is supported by the current observations, when comparing the section HR to section O₂-demands.

While there were great variations in the O₂-demand, the HR was relatively constant and remained high in most sections. Further support can also be found in the observations of Bolger et al. (2015), who showed that there were no correlation between speed and HR in different sections of XC race. Hence, HR is not suitable to describe exercise intensity in a XC competition, and other methods, such as the one applied in the present study should be employed.

5.2 Methodological considerations

5.2.1 Air drag resistance

The air drag resistance acting upon a XC skier is a complex mechanism. Our estimations of the air drag resistance are in the same range as previously reported, approximately 20 N for the average skier at 7 m·s⁻¹ (Leirdal et al., 2006; Svensson, 1994). The change in body position that occurs during one cycle, affects both the frontal area and the drag coefficient (Spring et al., 1988; Svensson, 1994). Further it seems that the sideways movement that occur during ski skating further increases the air drag resistance (Leirdal et al., 2006). In the present study we assumed that the upright position, as shown by Spring et al. (1988), represented the average position of the skiers throughout one cycle. Because of the exponential behavior of the air drag resistance, the position of the skier may have great influence on the estimations of external power when speeds are high, such as in the flat sections studied ($n_{\text{flat}} = 2$). On levelled terrain, air drag resistance accounts for approximately 50% of the external work. However, most of the sections studied were uphill sections ($n_{\text{uphill}} = 5$). Thus, the speeds were low and the relative contribution from air drag resistance was small at approximately 3%.

Furthermore, environmental wind conditions may influence the air drag resistance by altering the air flow relative to the skier. In the present study, no environmental wind was assumed in the calculations of the external work rate. Wind conditions on both test occasions were calm, and would have had little influence on the results. The literature concerning air drag resistance in XC skiing is scarce, and further research is needed to fully understand the effects of air drag resistance in this sport.

5.2.2 Friction

When poling, skiers apply their body mass to the poles, thereby reducing the mean normal force and the power against friction in each cycle (Sandbakk, Ettema, et al., 2013). Further, when skating, skiers angle their skis outwards. Thus, the resultant speed of the roller ski is greater than the average speed in the direction of travel. Using the average speed in the direction of travel would therefore lead to an underestimation of the power against friction (Sandbakk et al., 2010). This implies that the O₂-demand in the present study may have been underestimated.

The friction coefficient was not quantified outdoors, however, Myklebust (2016) has shown that the coefficient of friction measured on the roller ski treadmill and in the roller ski course used in the present study, are comparable. The environmental conditions in their study were also comparable to those of the present study. Therefore, it seems reasonable to assume that the coefficient of friction measured indoors in the present study, are applicable to the outdoors estimations of external work rate. Further, Ainegren, Carlsson, and Tinnsten (2009) observed a nonsignificant difference in maximal power when altering rolling friction. The authors reported that the difference in power against rolling resistance was almost fully compensated by a change in power from elevating the mass against gravity, indicating that the total external power does not change even if there is a change in rolling friction. Hence, no changes in the O₂-cost are induced.

5.2.3 Efficiency of movement

Taking in to account the duration of the time trial and the intensity applied, a VO_{2 SC} must be expected (Jones et al., 2011). This would consequently result in a reduction in GE and an increase in the energy cost of maintaining the same external workload throughout the time trial. We did not try to quantify alterations in the GE during the time trial. This could potentially have led to an underestimation of the actual O₂-demand in our study, at least in the later parts of the time trial.

Furthermore, GE was calculated for only two inclinations, levelled (1°) and inclined (8°). As described above, the GE increases when the inclination increases. The steepest section in the outdoor time trial (S5: 11.3°) was considerably steeper than the incline tested indoors. This could potentially have led to an overestimation of the O₂-demand in section S5. Considering the small

difference in O₂-demand between S4 (115.4 ± 2.3%) and S5 (115.5 ± 3.8%), a true difference may have been concealed.

5.2.4 Assumption of linear relationship between power and VO₂

When estimating O₂-demands outdoors, we assumed a linear relationship between the external power the skiers had to overcome and the O₂-cost. This is true when workloads are below the lactate threshold (LT) (Bassett & Howley, 2000; Noordhof, de Koning, & Foster, 2010).

However, it is debated whether this linearity also applies to workloads above the LT (Noordhof et al., 2010). When exercising at workloads above the LT, the steady state is delayed and for severe exercise no steady state is evident but the VO₂ projects to VO_{2max} (Jones et al., 2011).

This makes it difficult to quantify the O₂-cost for workloads in the heavy to severe exercise domain. Our results imply that the intensity in a XC ski race for the most parts are in the heavy to severe domain, hence using the linear relationship from the submaximal measurements does not reflect the relationship between external work rate and O₂-cost outdoors.

5.2.5 Roller skiing versus on snow skiing

Treadmill roller skiing and overground (asphalt) roller skiing are directly comparable, while roller skiing and on-snow skiing show some minor differences (Myklebust, 2016). These differences can be attributed to different properties of roller skis and on-snow skis (length, flexibility and weight of the skis and placement of binding hinge on the skis) and to differences in the ground/surface properties when on snow (Myklebust, 2016). Hence, the estimations in the present study may not directly compare to on-snow skiing. However, roller skiing has the advantage of eliminating some of the differences associated with ski properties, which has the potential to influence the pacing strategy employed, through increased cost of movement.

5.3 Perspectives

We have estimated the O₂-demand in seven separate sections of a XC ski course. In future investigations, our approach could be used to estimate continuous O₂-demand throughout a whole course. Continuous modelling of the O₂-deficite and reports of RPE will further increase our understanding of pacing and physiological demands in XC skiing. Future investigations should also validate the present model by comparing the estimated O₂-demand with physiological measurements. Considering the relatively large variations in anthropometry and

physiology between elite XC skiers, studying XC skiing offers a unique opportunity to investigate how these factors affect pacing and physiological demands. Including skiers of different specializations should therefore also be of interest in future investigators.

5.4 Practical application

The results of the present study challenge the traditional assumption that an even pacing strategy is optimal in endurance sports events lasting >2 min. According to our findings this is not true when external conditions vary throughout the event. Only small differences separate the top contenders in an elite XC ski competition, thus it is of utmost importance for the individual skiers to select the optimal pacing strategy to succeed. Athletes should therefore focus on pacing and pacing strategy in training.

Even though the duration of XC distance races are relatively long (>15 min), and the relative contribution from anaerobic metabolism is low, our results suggests that the ability to repeatedly utilize the anaerobic capacity is of great importance to XC skiers. Consequently, this should be taken in to consideration by coaches and athletes when planning their training.

Heart rate is commonly used as a measure of, and as an aid to control, exercise intensity (Achten & Jeukendrup, 2003). Heart rate may reflect exercise intensities during constant low to moderate intensity exercise, but fails to accurately describe exercise intensity during variable and/or high intensity exercise (Buchheit & Laursen, 2013). This should be take into consideration by athletes and coaches in the planning and evaluation of training.

The average speed in the present study ($\sim 6.7 \text{ m}\cdot\text{s}^{-1}$) is comparable to the speeds ($\sim 6.6 \text{ m}\cdot\text{s}^{-1}$) observed in 15 km individual time trials in international competitions (Losnegard et al., 2017) Further, our study was conducted on a WC track with inclinations and speeds used in such races. This implies that the results of this study are of relevance to the performance in international races. However, the level of the skiers in the present study must be taken into consideration when transferring the results to such competitions.

The dGNSS used in the current study provides researchers with a valuable tool for detailed analysis of performance, but is not convenient for practical use by athletes and coaches in the

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field. It is relatively heavy, expensive and requires considerable preparations with a setup time of >20 min. Modern training computers offering GPS tracking is, however, commercially available. These computers are a practical and economical alternative that can be used in every day training and in competitions, bearing in mind the accuracy limitations associated with the devices.

6. Conclusion

This paper presents a novel approach to estimate the O₂-demand during XC skiing by combining real-time positioning data from a self-paced time trial in a World Cup ski course and individual physiological measurements from treadmill roller skiing. Our findings show that XC skiers employ a variable pacing strategy, with great variations in exercise intensity during a race. The skiers repeatedly apply intensities exceeding their individual VO_{2peak}. This is possible because of the variations in the terrain, which allows the skiers to recover in flat and downhill parts of the course. Thus, the pacing strategy applied by XC skiers are highly dependent on the terrain. The estimations applied are crude, but have still made in depth analysis of the physiological demands and the pacing strategies employed by XC skiers, possible.

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Nomenclature

XC	Cross-country
GPS	Global positioning system
HR	Heart rate
O ₂	Oxygen
RPE	Rating of perceived exhaustion
VO ₂	Oxygen uptake
F _D	Air drag resistance
F _μ	Friction force
F _s	Propulsive force
N	Normal force
VO _{2max}	Maximal oxygen uptake
VO _{2peak}	Peak oxygen uptake
ΣO ₂	Accumulated oxygen
OBLA	Onset of blood lactate accumulation
GE	Gross efficiency
VO _{2 SC}	VO ₂ slow component
HR _{peak}	Peak heart rate
HR _{max}	Maximal heart rate
[La ⁻]	Lactate concentration
MAP	Maximal average power
VE	Ventilation
BR	Breathing rate
GNSS	Global navigational system
dGNSS	Differential global navigational system

Appendix

I Forespørsel om deltakelse i masterprosjektet: «*Pacing og intensitetstyring i langrenn*»

Appendix I



Forespørsel om deltakelse i masterprosjektet:

«Pacing og intensitetsstyring i langrenn»

Bakgrunn og hensikt

Langrenn er en vinteridrett hvor utøverens evne til å tilbakelegge konkurranse distansen på kortest mulig tid er vesentlig for prestasjonen. Siden utøverens evne til å generere effekt er begrenset, må arbeidet fordeles på en rasjonell måte. Hvordan en utøver velger å fordele arbeidet beskrives som utøverens pacing eller pacingstrategi. Hvilken pacingstrategi en utøver velger kan ha potensielt store konsekvenser for prestasjonen.

I utholdenhetsidretter med varighet på over 2 minutter, som løping, sykling, svømming, skøyter og langrenn, har en jevn pacing blitt ansett som det optimale for prestasjonen. Samtidig har mye av forskningen som er blitt gjort på pacing og pacingstrategier gjennomført under kontrollerte og simulerte forhold. Langrenn skiller seg også vesentlig fra mange av de andre idrettene som har blitt studert, da det er store variasjoner i konkurranse lengde, terreng og føreforhold. Et annet aspekt som gjør langrenn unikt er antallet teknikker som benyttes og byttene mellom disse teknikkene. I tillegg er det store forskjeller mellom utøvernes fysiske og fysiologiske egenskaper.

Hensikten med denne studien er derfor å undersøke valg av pacingstrategi i et distanserenn i langrenn. Samt å undersøke om utøvernes fysiske og fysiologiske egenskaper påvirker denne strategien.

Hva innebærer studien?

Studien innebærer at du som forsøksperson må være tilgjengelig 2 dager i perioden medio august til medio oktober for gjennomføring av tester. Dag I vil det gjennomføres 6 drag på submaksimale belastninger, med varighet på 5 minutter og 3 minutters pause, i skate på rullskimølle. Dette for å beregne effektiviteten i to ulike terrengtyper. Deretter vil det gjennomføres prestasjonstester for å bestemme det maksimale oksygenopptaket i det samme terrenget. Dag II vil det gjennomføres en simulert 15 kilometer i skate på rullski i Holmenkollen. Der vil posisjons og hastighetsdata samles inn ved hjelp av et bærbart GPS-system. I tillegg vil det bli gjort videoopptak for kinematiske analyser. Begge testdagene vil bli gjennomført inne 7 dager.

Mulige fordeler og ulemper

Fordeler

Deltakere i studien får under testing målt maksimalt oksygenopptak i 2 ulike terreng typer (flatt og motbakke), arbeidsøkonomi og effektivitet i to typer terreng ved tre ulike hastigheter. Deltakere vil også få detaljert informasjon om pacing og hastigheter under simulerte konkurranseforhold.

Ulemper

Deltakelse i studien vil kreve tid. Det må påberegnes å møte til testing totalt 2 dager. Det er forbundet en viss risiko for skade ved testing på tredemølle. Ved maksimale tester vil det benyttes sikkerhetssele som forhindrer deg i å falle ned på mølla mens den kjøres og som automatisk vil stoppe båndet. Ved oksygenmålinger benyttes det et munnstykke som kan oppleves noe ubehagelig, samt kan du oppleve å bli tørr i halsen. Dette er ikke skadelig og utstyr desinfiseres mellom bruk. Testene kan oppleves som meget anstrengende

Hva skjer med målingene og informasjonen om deg?

Prøvene tatt av deg og informasjonen som registreres om deg skal kun benyttes slik som beskrevet i hensikten med studien ovenfor. Alle opplysningene og resultater om deg vil bli anonymisert. En kode knytter deg til dine opplysninger og resultater gjennom en navneliste. Dette betyr at denne informasjonen er aidentifisert. Det er kun autorisert personell knyttet til prosjektet som har adgang til navnelisten og som kan finne tilbake til deg. Det vil ikke være mulig å identifisere deg i resultatene av studien når disse publiseres.

Frivillig deltakelse

Det er frivillig å delta i studien. Du kan når som helst og uten å oppgi noen grunn trekke ditt samtykke til å delta i studien. Dette vil ikke få konsekvenser for din videre behandling. Dersom du ønsker å delta, undertegner du samtykkeerklæringen på siste side. Om du nå sier ja til å delta, kan du senere trekke tilbake ditt samtykke uten at det påvirker din øvrige behandling. Dersom du senere ønsker å trekke deg eller har spørsmål til studien, kan du kontakte en av følgende:

Prosjektmedarbeider: Øyvind Karlsson på telefon 984 93 351 eller e-post: oyvind.karlsson@gmail.com

Eller

Prosjektleder: Thomas Losnegard på telefon 997 34 184 eller e-post: thomas.losnegard@nih.no

Ytterligere informasjon om studien finnes i kapittel A.

- Utdypende forklaring av hva studien innebærer

Ytterligere informasjon om personvern, biobank og forsikring finnes i kapittel B.

Samtykkeerklæring følger etter kapittel B.

Kapittel A – utdypende forklaring av hva studien innebærer

Kriterier for deltakelse

Du må være mann, frisk og eliteutøver på høyt nasjonalt/internasjonalt nivå (Scandinavisk/World cup: distanse eller sprint, eller langløp). Du må ha et høyt teknisk nivå i skate. Det legges ingen begrensninger i forhold til trening.

Bakgrunn

Langrenn er en vinteridrett hvor utøverens evne til å tilbakelegge konkurranse distansen på kortest mulig tid er vesentlig for prestasjonen. Siden utøverens evne til å generere effekt er begrenset, må arbeidet fordeles på en rasjonell måte. Hvordan en utøver velger å fordele arbeidet beskrives som utøverens pacing eller pacingstrategi. Hvilken pacingstrategi en utøver velger kan ha potensielt store konsekvenser for prestasjonen.

I utholdenhetsidretter med varighet på over 2 minutter, som løping, sykling, svømming, skøyter og langrenn, har en jevn pacing blitt ansett som det optimale for prestasjonen. Samtidig har mye av forskningen som er blitt gjort på pacing og pacingstrategier gjennomført under kontrollerte og simulerte forhold. Langrenn skiller seg også vesentlig fra mange av de andre idrettene som har blitt studert, da det er store variasjoner i konkurranse lengde, terreng og føreforhold. Et annet aspekt som gjør langrenn unikt er antallet teknikker som benyttes og byttene mellom disse teknikkene. I tillegg er det store forskjeller mellom utøvernes fysiske og fysiologiske egenskaper.

Hensikt

Hensikten med denne studien er derfor å undersøke valg av pacingstrategi i et distanserenn i langrenn. Samt å undersøke om utøvernes fysiske og fysiologiske egenskaper påvirker denne strategien.

Undersøkelser, tester og målinger

Som forsøksperson skal du gjennomgå 2 dager med testing. Testprotokollen vil inkludere måling av oksygenopptak (VO_{2peak}), arbeidsøkonomi (VO_2), effektivitet (gross efficiency), hjertefrekvens (HF), opplevd anstrengelse (RPE). I tillegg vil du gjennomføre en simulert 15 kilometer på rullski. Alle fysiologiske målinger og tester vil bli foretatt på fysiologisk laboratorium ved Norges idrettshøgskole. Den simulerte 15 kilometeren vil bli gjennomført i Holmenkollen.

Submaksimale tester

Før de submaksimale testene gjennomføres en standardisert oppvarming. Oppvarmingen består av 15 minutter rolig gange med en stigning på 1° og en hastighet på $3 - 4 \text{ m}\cdot\text{s}^{-1}$ ($\sim 60-75\%$ av HF_{maks}). Deretter gjennomføres det til sammen 6 drag av 5 minutter med to minutters pauser. De første tre dragene vil gjennomføres med en stigning på 1° og på hastighetene $4,5$, $5,5$ og $6,5 \text{ m}\cdot\text{s}^{-1}$. De tre neste dragene vil gjennomføres med en stigning på 8° og på hastighetene $1,5$, $1,75$ og $2 \text{ m}\cdot\text{s}^{-1}$. Direkte etter hvert drag registreres opplevd anstrengelse ved hjelp av subjektiv anstrengesskala (1-10) samt laktat. Mål på effektivitet blir bestemt med gross efficiency (GE). Rekkefølgen på dragene vil randomiseres.

Maksimale tester

De maksimale testene vil gjennomføres 8 minutter etter de submaksimale testene. Forsøkspersonene gjennomføre to self-paced prestasjonstester på 3 minutter for å bestemme VO_{2peak} og HF_{peak} . Målet for

testen er å gå lengst mulig på 3 minutter. Den ene testen gjennomføres med en stigning på 8°. Den andre testen gjennomføres etter 20 minutters pause. Den andre testen gjennomføres med en stigning på 1°. Hastigheten vil være konstant de første 30 sekundene for å unngå overpacing. Etter de første 30 sekundene kontrollerer forsøkspersonene selv hastigheten ($0,5 \text{ m}\cdot\text{s}^{-1}$ økning eller reduksjon) ved å justere sin posisjon på tredemøllen i forhold til to lasere plassert foran og bak forsøkspersonen. Visuell tilbakemelding i forhold til distanse tilbakelagt vil være tilgjengelig for forsøkspersonen. Rekkefølgen på testene vil randomiseres.

Simulert 15 kilometer

Den simulerte 15 kilometeren vil gjennomføres i skate-teknikk og med individuell start. Løypa vil bestå av tre identiske runder av 5 km. Løypa vil deles i ulike seksjoner basert på terrenntype for kartlegging av hastighetsutvikling. Forsøkspersonen gjennomfører egen oppvarming som før normal konkurranse. Målet er fullføre distansen på kortest mulig tid og du velger selv pacing/pacingstrategi. Under hele den simulerte 15 kilometeren vil posisjon og hastighetsdata registreres kontinuerlig med et differensielt GNSS system. I tillegg vil hjerterefrekvens bli registrert.

Tidsplan

Gjennomføring av tester er lagt til perioden medio august til medio oktober. Oppmøte og nøyaktig tidspunkt for tester vil bli avtalt nærmere med den enkelte deltager.

Økonomi og honorarer

Det gis ikke økonomisk honorar for å delta i prosjektet. Eventuelle ekstrautgifter i forbindelse med reise til og fra Norges idrettshøgskole eller Holmenkollen dekkes ikke.

Studiedeltakerens ansvar

- Følge anvisninger som gis fra prosjektleder/prosjektmedarbeidere.
- Møte opp til avtalt tid. Er du forhindret fra å komme, si i fra i god tid før.

Kapittel B – Personvern, biobank, økonomi og forsikring

Personvern

Opplysninger som registreres om deg som forsøksperson vil bli behandlet konfidensielt etter gjeldende regler for anonymitet. Opplysninger som registreres er alder, kjønn, høyde, vekt og resultater fra aktuelle tester.

Utlevering av materiale og opplysninger til andre

Hvis du sier ja til å delta i studien, gir du også ditt samtykke til at prøver og aidentifiserte opplysninger utleveres til bruk i vitenskapelige publikasjoner.

Rett til innsyn og sletting av opplysninger om deg og sletting av prøver

Dersom du takker ja til å delta i studien, har du rett til å få innsyn i hvilke opplysninger som er registrert om deg. Du har videre rett til å få korrigert eventuelle feil i de opplysningene som har blitt registrert. Dersom du trekker deg fra studien, kan du kreve å få slettet innsamlede data og opplysninger om deg, med mindre opplysningene allerede har inngått i analyser eller blitt brukt i vitenskapelige publikasjoner.

Økonomi

Kostnader knyttet til prosjektet vil støttes gjennom forskningsmidler fra Seksjonen for fysisk prestasjonsevne ved Norges Idrettshøgskole. Det er ingen interessekonflikter knyttet til finansieringen av prosjektet.

Forsikring

NIH er en statlig institusjon og er dermed selvassurandør. Eventuelle skader på deltakere i forbindelse med prosjektet vil bli dekket av NIH.

Informasjon om utfallet av studien

Utfallet av prosjektet vil bli offentliggjort gjennom undertegnende sin masteroppgave våren 2017. Etter at prosjektet er avsluttet har du rett til at få tilgang til egne resultater fra forsøket. Du får tak i disse ved at kontakte undertegnede.

Frivillig deltagelse

Deltagelse i studien er frivillig og du kan når som helst trekke deg fra studien uten begrunnelse. Dersom du skulle ønske å trekke tilbake samtykke om deltagelse i studien kan du kreve at det biologiske materialet blir destruert, og at innsamlet helse- og personopplysninger blir slettet eller utlevert. Muligheten til å tilbakekalle samtykket eller kreve destruksjon, sletting eller utlevering gjelder ikke dersom opplysningene alt har gått inn vitenskapelige arbeid, jfr. biobankloven § 14 tredje ledd. Dersom du ønsker flere opplysninger angående prosjektet kan du kontakte prosjektmedarbeidere:

Prosjektmedarbeider: Øyvind Karlsson på telefon 984 93 351 eller e-post: oyvind.karlsson@gmail.com

Eller

Prosjektleder: Thomas Losnegard på telefon 997 34 184 eller e-post:
thomas.losnegard@nih.no

Samtykke til deltakelse i studien:

Pacing og intensitetsstyring i langrenn

En sammenligning av intensitet og valg av pacingstrategi mellom utøvere på ulikt nivå

Jeg er villig til å delta i studien

(Signert av prosjektdeltaker, dato)

Stedfortredende samtykke når berettiget, enten i tillegg til personen selv eller istedenfor

(Signert av nærstående, dato)

Jeg bekrefter å ha gitt informasjon om studien

(Signert, rolle i studien, dato)

