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A literature review

Bachelor's thesis in Human Movement Science
Supervisor: Knut Skovereng
May 2022

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Abstract

Purpose: The purpose with this review was to investigate which determinants that are important for performance in an individual ski mountaineering race.

Methods: A literature search was carried out in the databases PubMed and SPORTdiscus on keywords related to performance, physiology and ski mountaineering. The search resulted in seven studies. All studies had to investigate how different factors affected race performance.

Results: VO^2_{max} (r = 0.71-0.87), VO^2 @ VT^1 (r = 0.607-0.90) and VO^2 @ VT^2 (r = 0.694-0.91) and body fat percentage (r = 0.72-0.782) correlated with race performance.

Conclusion: VO^2_{max}, VO^2 @ VT^1, VO^2 @ VT^2 and body fat percentage were all important determinants for race performance in an individual ski mountaineering race.

Abstrakt

Hensikt: Hensikten med denne rapporten var å undersøke hvilke bestemmende faktorer som er viktige for prestasjon i et individuelt randoneeløp.

Metode: Et litteratursøk ble gjennomført i databasene PubMed og SPORTdiscus på nøkkelord relatert til prestasjon, fysiologi og randonee. Dette søket resulterte i syv studier. Alle studiene måtte undersøke hvordan forskjellige faktorer påvirket løpsprestasjon.

Resultat: VO^2_{max} (r = 0.71-0.87), VO^2 @ VT^1 (r = 0.607-0.90) og VO^2 @ VT^2 (r = 0.694-0.91) og kroppsfettprosent (r = 0.72-0.782) korrelerte med løpsprestasjon.

Konklusjon: VO^2_{max}, VO^2 @ VT^1, VO^2 @ VT^2 og kroppsfettprosent var viktige bestemmende faktorer i et individuelt randoneeløp.

Introduction

Ski mountaineering is one of the most physically demanding endurance sports and is characterized by extensive work performed at high intensities at altitude (> 1500 m)[1–4]. The sport involves ascending mountains on skis with skins attached to the base followed by descending them with the skis locked into the heel piece of the binding, making the skis like traditional alpine skis. In professional ski mountaineering, there are several competition formats. The competitions are regulated by the ISMF (International Ski Mountaineering Federation), and the formats differ mainly in elevation gain, total distance covered and the balance between uphill and downhill sections. This literature review will limit its scope to the competition format individual race, characterized by both ascents and descents (table 1)[4]. In July 2021, the International Olympic Committee (IOC) approved the inclusion of ski mountaineering into the Olympic programme for the Milano Cortina Winter Olympics in 2026[5]. This decision will probably increase its popularity and hopefully attract interest from the field of exercise physiology and sports science.

Table 1. ISMF's official ski mountaineering race characteristics for individual races.

Format	**Categories**	**Vertical gain**	**Duration**	**Characteristics**
Individual	Men	1600-1900 m	1.5-2 h	• At least three ascents and descents in total
	Women	1300-1600 m	1.5-2 h	• The length of the longest ascent shall not exceed 50 per cent of the total ascent
				• At least 85 per cent must be covered on skis
				• At most 5 per cent shall be raced on foot
				• At most 10 per cent should be technical sections. Carrying skis on the backpack

The literature on physiological determinants in ski mountaineering is scarce, but the literature on other similar endurance sports such as cross-country skiing and trail running report that high VO^{2}_{max} and high ventilatory thresholds (VT^1 and VT^2) ratios to VO^{2}_{max} are important determinants for performance[6,7]. VO^{2}_{max} is the highest amount of oxygen an individual can inhale, transport and utilize to create ATP aerobically during exercise[8]. VO^{2}_{max} is a physiological determinant that is often measured in athletes and is a strong predictor of endurance performance[9]. In ski mountaineering, athletes carry their own body weight against gravitational forces which costs energy. Naturally, the more oxygen the athletes can utilize will result in a higher energy turnover. Ultimately, this facilitates for better performance due to increased energy availability. Ventilatory thresholds are points where the linear rise in minute ventilation breaks from linearity during exercise[8]. The first break point is called VT^1, and the second break point is called VT^2. VT^1 indicates the upper limit of moderate exercise and is the point where the exercise metabolism is primarily aerobic (i.e., where CO2 production does not exceed clearance). VT^2 indicates the intensity that separates heavy but sustainable from heavy, non-sustainable exercise, and above it is the point where exercise metabolism is primarily anaerobic (i.e., where CO2 production exceeds clearance)[8,9]. These thresholds are of practical value as they indicate the intensities a ski mountaineering athlete can sustain during an individual race**.**

Literature on endurance sports similar to ski mountaineering also report that anthropometric variables (i.e. body mass, body fat percentage etc.) are linked to performance[7]. Clearly, this is logical considering general laws of physics. If athletes have to use muscle force to propulse their body forwards and uphill, the less excessive non-muscle tissue the athletes have, the less work must be done to create movement. Fat-free mass have no force-producing abilities. Ultimately, this saves energy and facilitates for a better performance. In races that last 1.5 to 2 hours, energy expenditure is very high[2]. Therefore, athletes must have the ability to tactically dispose their energy with efficient pacing strategies and choice of trajectory to be as vertically efficient as possible. Failure to do so, may result in a decrease in performance. Furthermore, downhill skiing is also a part of ski mountaineering. Literature on alpine skiing have reported that the ability to create torque through the leg muscles are important for performance[10]. Torque is a measure of the force that causes an object to rotate around an axis, i.e., what causes angular acceleration. In human biomechanics, this could translate to forces created from the quadriceps muscle that causes the lower leg to rotate at the knee joint in the sagittal plane.

This reviews main hypothesis is that VO^2_{max} and VO^2 @ VT^2 are the most important performance determinants in individual ski mountaineering races. In addition, the secondary hypothesis is that relative VO^2_{max} (ml/min/kg) is more important in individual ski mountaineering than in the similar endurance sports trail running and cross-country skiing due to more demanding trail profiles (i.e., higher vertical gain, fewer flat sections and more extensive work against gravitational forces). Therefore, the aim of this review was to investigate which performance determinants are most important in individual ski mountaineering, and whether relative VO^2_{max} is more important in individual ski mountaineering than in trail running and cross-country skiing.

Methods

The literature search was carried out using PubMed and SPORTdiscus as databases. The search was limited to studies which had abstract/titles with the following search phrases: "(Ski mountaineering AND performance) OR (ski-mountaineering AND performance) OR (ski mountaineering AND physiological parameters) or (ski-mountaineering AND physiological parameters)". The initial search resulted in 17 studies. All studies which were included in this review, had to perform performance tests (i.e., competitions, simulated competitions, time trials or treadmill tests either on skis, roller skis or by running, energy cost tests etc.) and investigate how these affected individual ski mountaineering performance. In addition, all studies had to be published in English and peer reviewed. All other studies who did not fulfill these demands, were excluded. In total, seven studies were used in this review. The magnitude thresholds for correlation coefficients used in this review are 0.1, 0.3, 0.5, 0.7 and 0.9 for small, moderate, large, very large and extremely large, respectively[11]. The term aerobic capacity will be used to describe the combination of VO^2_{max}, VO^2 @ VT^1 and VO^2 @ VT^2**.** For simplicity, VO^2 @ VT^1 and VO^2 @ VT^2 will be shortened to VT^1 and VT^2, respectively.

Results

VO^2_{max}

Lasshofer et al., Duc. et al. and Fornasiero et al. found very large correlations between VO^2_{max} (ml/min/kg) and race performance variables[1–3].

Table 2. Correlations between VO^2_{max} and race performance variables.

Study	Race performance variable	Correlation coefficient
Lasshofer et al.	Race time	-0.700**
Duc et al.	Race time	-0.87**
Fornasiero et al.	Mean power output	0.87**

$P \leq 0.01$ indicated by **.

Ventilatory thresholds

Lasshofer et al., Duc. et al. and Fornasiero et al. found large to extremely large correlations between VO^2 @ VT^1 and VO^2 @ VT^2 with race performance variables[1–3].

Table 3. Correlations between VO^2 @ VT^1 and race performance variables.

Study	Race performance variable	Correlation coefficient
Lasshofer et al.	Race time	-0.607**
Duc et al.	Race time	-0.82**
Fornasiero et al.	Mean power output	0.90**

$P \leq 0.01$ indicated by ******.

Table 4. Correlations between VO^2 @ VT^2 and race performance variables.

Study	Race performance variable	Correlation coefficient
Lasshofer et al.	Race time	-0.694**
Duc et al.	Race time	-0.85**
Fornasiero et al.	Mean power output	0.91**

$P \leq 0.01$ indicated by **.

Anthropometry

Lasshofer et al., Fornasiero et al., Schenk et al. and Gaston et al. found moderate to very large correlations between anthropometric variables and race performance variables[1,3,12,13].

Table 5. Correlations between anthropometric variables and race performance variables.

Study	Anthropometric variable	Race performance variable	Correlation coefficient
Lasshofer et al.	BMI	Race time	0.432*
Fornasiero et al.	BMI	Mean power output	-0.60*
Fornasiero et al.	Fat mass (kg)	Mean power output	-0.73*
Fornasiero et al.	Body fat (%)	Mean power output	-0.67*
Schenk et al.	Fat mass (%)	Partial race time above VT^2	0.782*
Gaston et al.	Fat mass (%)	Vertical race time	0.72*

$P \leq 0.05$ indicated by *.

Energy expenditure

Praz et al. investigated the effect of speed and slope gradient on energy cost (EC), vertical displacement (EC_{vert}) and mechanical efficiency (ME) during a laboratory test to identify the vertical speeds and slope gradients that minimizes energy expenditure[14].

Table 6. Effect of speed and slope gradient on EC, EC_{vert} and ME.

Slope gradient (%)	**Speed (km/h)**	**EC (J kg^{-1} m^{-1})**	**EC_{vert} (J kg^{-1} m^{-1} vert)**	**ME**
17	3	8.0 ± 0.7*	48 ± 4*	0.21 ± 0.02*
17	4	8.3 ± 0.5*	49 ± 4*	0.20 ± 0.01*
17	5	7.5 ± 0.6*	45 ± 4*	0.22 ± 0.02*
24	2	10.2 ± 0.8*	44 ± 4*	0.23 ± 0.02*
24	3	10.3 ± 0.7*	44 ± 3*	0.22 ± 0.02*
24	4	9.1 ± 0.9*	39 ± 4*	0.25 ± 0.03*

$P \leq 0.05$ indicated by *. Values are reported as mean ± SD.

Discussion

This reviews main results are 1) VO^2_{max} had very large correlations with race performance, and 2) VO^2 @ VT^1 and VO^2 @ VT^2 had very large to extremely large correlations with race performance. In addition, fat mass (kg) and body fat percentage had moderate to large correlations with race performance and skiing steep slope gradients were vertically more efficient than skiing less steep slope gradients.

VO^2_{max}

Lasshofer et al., Duc et al. and Fornasiero et al. all reported that a high VO^2_{max} were one of the most important physiological determinants for an individual ski mountaineering race performance[1–3]. This was highlighted further by Lasshofer et al. that compared elite level athletes (mean relative VO^2_{max} of 71.2 ± 6.8) with sub-elite level athletes (mean relative VO^2_{max} of 62.5 ± 4.7). Together with the very large correlations between VO^2_{max} and race performance variables (table 2), this comparison highlights that elite athletes differ substantially in VO^2_{max} measurements from sub-elite athletes and thereby have a higher potential to create ATP aerobically during individual ski mountaineering races.

An individual ski mountaineering race is similar to a cross-country skiing race, especially in uphill terrain. Talsnes et al. reported a very large correlation between VO^2_{max} and skiing in uphill terrain in cross-country skiing[7]. The result from this review (table 2) and the result from Talsnes et al. is logical due to the nature of ascents on skis: the athletes are carrying their own weight against gravitational forces to a greater degree than in flat and intermediate terrain, and the steep slope gradient inhibits the athletes' advantages of good technique and energy return from efficient movement. The athletes must create concentric muscle forces to propulse uphill, and the increased muscle force needed to overcome stronger gravitational forces, elicits a higher oxygen demand. Therefore, a higher VO^2_{max} is more important in uphill terrain than in flat and intermediate terrain because it increases the athletes' potential to aerobically create ATP, and therefore have the energy availability to propulse in uphill terrain. This reviews' results on VO^2_{max} (table 2) are both scientifically and logically in compliance with the results from Talsnes et al., which more strongly emphasizes the fact that skiing in uphill terrain elicits a higher oxygen demand and despite if it is ski mountaineering or cross-country skiing.

In individual ski mountaineering, the vertical gain is much higher than in cross-country skiing. In addition, ski mountaineers ski uphill continuously to a greater degree than cross-country skiers. Trail running, however, has more similarities in race characteristics where cross-country skiing is lacking: longer continuous uphill sections. Ehström et al. reported that VO^2_{max} had a very large correlation with trail running performance in short distance races lasting approximately three hours[6]. Compared to this reviews results (table 2), VO^2_{max} seems to be more important in individual ski mountaineering than in trail running as well as cross-country skiing. Logically, this is likely true due to the extra equipment weight carried in ski mountaineering, steeper trajectory, and therefore more demanding uphill sections. Moreover, the effect from efficient movement is less in ski mountaineering than in trail running due to lower ground reaction forces and therefore a lower potential to absorb these forces and use them to move efficiently. All together, this strengthens the idea that a high VO^2_{max} is more important in individual ski mountaineering than in trail running and cross-country skiing.

Ventilatory thresholds

Lasshofer et al., Duc et al. and Fornasiero et al. all reported that high ventilatory thresholds relative to their VO^2_{max} were one of the most important physiological determinants in individual ski mountaineering races[1–3]. High ventilatory thresholds allows the athletes to average a higher velocity at a lower exercise intensity because of a greater ability to utilize oxygen and thereby inhibit lactate accumulation and improve race performance. However, the importance of VT^1 and VT^2 are most likely not equally important even though the correlations with race performance are very close to similar (table 3 and 4). Duc et al. reported that time spent at or below VT^1 was only 7.0 ± 4.8 per cent of total race time. The same authors reported that downhill race time was 9.7 ± 1.2 per cent[2]. The time spent at or below VT^1 and time spent downhill are close to each other, possibly indicating that the athletes may work at an exercise intensity corresponding to VT^1 primarily in the downhill sections of the race. As the downhill sections only constitutes approximately 10 per cent of total race time and the uphill sections constitutes 84 ± 1.3 per cent[2], the effect of VT^1 on race performance is most likely not crucial. Furthermore, the correlation between VT^1 and race time could be a result of VT^1 correlating with VO^2_{max} and VT^2 rather than race performance itself.

The speed that the athletes can sustain at or slightly above VT^2, is most likely more important than VT^1 for an overall performance in an individual ski mountaineering race. Duc et al. reported that 51.3 ± 4.7 per cent of total race time was spent at or slightly below VT^{22}. This equals approximately 45-60 minutes above this intensity threshold in a race lasting between 1.5 to 2 hours. Naturally, the fact that the athletes spend drastically more time around VT^2 than VT^1, indicates that athletes who seek to maximize performance should work on adaptations that allow for higher speeds around $VT^{2.}$ In addition to being logical, this is physiologically sound as well: the intensity at VT^2 is generally categorized as the intensity where there is an equilibrium between lactate production and lactate clearance; i.e., an intensity athletes can sustain for approximately 60 minutes[8]. The higher vertical speed that can be sustained around VT^2, the faster will the athletes advance without excessive lactate accumulation and thereby an increase in performance.

A high VT^2 is not only important in individual ski mountaineering races but is also acknowledged as an important physiological determinant in other endurance sports, as well. Farrell et al. reported that VT^2 had an extremely large correlation with marathon running performance[15]. Individual ski mountaineering definitely share similarities with flat marathon running: aerobic capacity is essential for performance; lower body muscles is responsible for propulsion; and the race time is not far from similar. However, individual ski mountaineering differs in one important aspect: slope gradient. Due to the steep slope gradient in ski mountaineering and thereby an increase oxygen demand, it is not surprising that Farrell et al. reports a larger correlation between marathon performance and VT^2 than this reviews results do between individual ski mountaineering performance and VT^2 (table 3 and 4). All together, the result from Farrell et al. still supports this reviews results on that VT^2 is an important physiological determinant for performance in individual ski mountaineering, even though the effect on performance is stronger in flat running.

Anthropometry

A body composition that allows the athletes to maximize work efficiency is critical in endurance sports, but especially in ski mountaineering due to the reason that the work is done in steep uphill terrain where the athletes work against gravity in a greater degree than in flatter terrain. If you compare two athletes with the same absolute VO^2_{max} (L/min), but one of the athletes weigh significantly less than the other, the athlete with the lowest weight will have a higher energy potential to do work and therefore most likely perform better during the uphill part of an individual ski mountaineering race. Therefore, relative VO^2_{max} (ml/kg/min) have larger correlations with individual ski mountaineering performance and endurance performance in general than absolute VO^2_{max} (L/min)[1–3].

Schenk et al. and Gaston et al. reported that a low body fat percentage (BFP) positively affected race time, while Lasshofer et al. reported how a low BMI positively affected race time (table 5). Even though all variables correlated with shorter race times and therefore better performance, the correlations were larger between BFP and race time than BMI and race time. While BMI takes the athletes' height into account, BFP does not and is therefore possibly a stronger performance predictor. According to general laws of physics, gravitation does not discriminate on the athletes' height, it only affects their center of mass (COM). In addition, movement of the athletes' COM is created by muscle contractions. The force output of a muscle is mostly dependent on the cross-sectional area of the muscle (M_{CSA}) and not the volume of the muscle[16]. Therefore, athletes with different heights and in general longer limbs, should have the same force output abilities. Shorter ski mountaineering athletes with low BFP and high M_{CSA} relative to total body weight will have an increased relative force-producing capacity if total muscle mass is not excessive, and therefore a greater potential for better performance.

Energy expenditure

Minimizing the energy cost when striding uphill allow the athletes to gain vertical meters with less exhaustion. This is both a tactical disposition and physiologically logical since the athletes must work within his or her physiological boundaries to avoid a fatigue-induced decrease in performance. Praz et al. demonstrated that EC_{vert} were significantly less when walking uphill in a 33 % gradient versus 11 % and 7 % (table 6). The goal of the uphill sections is naturally to cover as many vertical meters in as little time as possible. Based on the results from Praz et al., athletes should, if possible, choose the steepest trajectory to minimize EC_{vert}. However, skiing steep uphill sections is aerobically demanding, and it is therefore a necessity for the athlete to possess a sufficient aerobic capacity to sustain the steep uphill trajectory throughout the race and to avoid a decrease in performance.

Downhill performance

To our knowledge, there is no literature on performance determinants on downhill performance in individual ski mountaineering races. However, what characterizes the downhill sections in these races, are off-piste skiing on bumpy and uneven terrain in varying snow conditions. Previously in this review, we stated that only a small part of the race were downhill sections. Since the downhill sections only constitutes such a small amount of the race, it indicates that individual ski mountaineering races are won uphill, not downhill. However, there are situations where downhill performance could be the difference between success and failure. Individual ski mountaineering races consist of several uphill and downhill sections, and the last section to the finish is downhill. Consider the situation where one athlete has lacking downhill abilities and is followed closely by an athlete with strong downhill abilities up the last ascent. If the strong downhill athlete is able to follow all the way up, he could pass the other athlete on the last downhill section and secure the win. These cases do most likely seldom occur in individual ski mountaineering races, but it still indicates that downhill performance should not be completely overlooked for a strong overall race performance. Further on, Praz et al. and Duc et al. reported that athletes who perform better on uphill sections, also perform better on downhill sections[2,17]. One possible explanation that explains this phenomena is that strong uphill athletes have a high aerobic capacity. This allows for less metabolic strain accumulation during the uphill sections and thereby higher muscle force output during downhill sections. All together, this may result in a better downhill performance by athletes who are already strong in the uphill sections.

Downhill skiing in individual ski mountaineering races is similar to alpine skiing. Research on alpine skiing performance show that peak torque production (T_{peak}) through the leg muscles are an important performance determinant[10]. Due to the similarity between the two sports, it is reasonable to assume that ski mountaineering athletes will benefit from T_{peak} abilities to technically navigate the downhill race sections and to absorb the ground reaction forces and thus minimize the muscle damage and metabolic strain. Minimization of metabolic strain during downhill sections will be of great importance in individual ski mountaineering races because it allows the athlete to move faster during the uphill sections. As previously mentioned, uphill sections are where the races are won. However, athletes should be careful of increasing T_{peak} too much. Increases in T_{peak} will most likely result in an increase in M_{csa}, and therefore an increase in body weight. As previously emphasized, VO^2_{max} are of utter importance to perform in individual ski mountaineering races. This physiological determinant is relative phenomena, i.e., it is strongly affected by the athletes' body weight. Ultimately, a too high body weight increase caused by muscle hypertrophy could hinder performance. Therefore, athletes who seek to maximize overall performance and not only downhill performance, should strongly consider if an increase in T_{peak} and therefore M_{csa} is necessary for overall performance due to the risk of lowering their VO^2_{max}.

Limitations

The literature on performance determinants in individual ski mountaineering is scarce. In this reviews' case, it has led to little research available and therefore little data which leads to weaker strength of evidence. In addition, the studies on ski mountaineering are done on high-level or elite athletes which leads to a low number of subjects. This may lead to statistically insignificant results even though the results observed are in fact true.

The studies included in this review were not split by gender in their statistical analysis. This could affect the results due to obvious physical differences between genders. However, there are small differences in the competition formats between male and female athletes in individual ski mountaineering races (table 1). It is therefore reasonable to suggest that the effects of not splitting by gender had minimal impact in discovering which performance determinants are important in individual ski mountaineering races.

The main studies used in this review do mainly investigate on the individual race format. However, the study from Gaston et al. is done on vertical races (i.e., no alternating downhill and uphill sections, but only one uphill race between 500-700 vertical meters for men and 400-500 for women[4]), not individual races. This may have affected the results, but it is reasonable to assume that the results are still relevant due to the fact that vertical races are quite similar in the uphill sections as individual races. Furthermore, due to the fact that uphill sections constitute above 80 per cent of total race time, this further strengthens the claim that the results are relevant for individual ski mountaineering races.

Conclusion

A high VO^2_{max} relative to body weight and a high VO^2 @ VT^2 are the most important performance determinants for an individual ski mountaineering race performance. The differences observed in this review on the importance of relative VO^2_{max} between individual ski mountaineering, trail running and cross-country skiing, are not large. However, it is reasonable to assume that the importance is higher in individual ski mountaineering than in cross-country skiing due to higher vertical gain, fewer flat sections and more extensive work against gravitational forces. The same applies to the difference between individual ski mountaineering and trail running, but the difference between these two are more likely a result of more weight carried and more concentric work in individual ski mountaineering. Furthermore, low BFP and fat mass are important performance determinants as well. In addition, the ability to produce adequate levels of torque through the leg muscles to efficiently absorb forces from downhill sections to minimize muscle damage and metabolic strain is most likely an important determinant. Athletes should, if possible, choose the steepest trajectory uphill to be as vertically efficient as possible if they have the aerobic capacity to do so.

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