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Abstract

Cross-country skiing is one of the most demanding of endurance sports, involving protracted competitions on varying terrain employing a variety of skiing techniques that require upper- and/or lower-body work to different extents. Through more effective training and extensive improvements in equipment and track preparation, the speed of cross-country ski races has increased more than that of any other winter Olympic sport and, in addition, new types of racing events have been introduced. To a certain extent this has altered the optimal physiological capacity required to win and the training routines of successful skiers have evolved accordingly. The longstanding tradition of researchers working closely with XC skiing coaches and athletes to monitor progress, improve training and refine skiing techniques has provided unique physiological insights revealing how these athletes are approaching the upper limits of human endurance. In the present review, we summarize current scientific knowledge concerning the demands involved in elite cross-country skiing, as well as the physiological capacity and training routines of the best athletes.

Keywords: aerobic capacity, anaerobic capacity, efficiency, maximal oxygen uptake, exercise performance, speed and strength.

Introduction

Cross-country (XC) skiing, one of the most demanding of endurance sports, involves competitions on varying terrain employing different sub-techniques of the classical and skating styles that require upper- and/or lower-body work to different extents. Accordingly, XC skiers design their training to improve a variety of physiological capacities, as well as technical and tactical expertise. Since XC skating is also employed in the biathlon and Nordic combined events, 27 gold medals (i.e., more than one fourth of the total number of medals) in the recent Winter Olympics were won utilizing XC skiing techniques.

The longstanding tradition of researchers working closely with XC skiing coaches and athletes to improve training, monitor progress, and refine techniques has provided unique insight into the physiological capacity and training of these skiers.[1] Both applied and more basic studies on XC skiing have been has been performed in recent decades, with the number of scientific publications in this field increasing from less than 80 in the 1980's to 100-150 in the 1990's and 2000's, and close to 200 in the last six years – more than on any other individual winter sport. In the present review, we summarize current scientific knowledge on the demands involved in competitive XC skiing, as well as the physiological capacities and training routines of these elite athletes.

The demands involved in competitive XC skiing

The average speed in XC ski races has almost doubled during the last 50 years, especially in the skating events introduced in the middle of the 1980's.[2] Thereafter a number of other major changes were introduced and in today's championships female and male XC skiers perform 10- or 15-km individual time-trials, 15- or 30-km pursuit races, 30- or 50-km mass-starts races, and 1.3-1.8-km sprint races, respectively, including a qualifying time-trial race and three subsequent knock-out heats. In addition, four skiers from each country each perform a 5- or 10-km section of a relay race and in addition there is a sprint relay with a qualifying race and a final heat with three 1.3-1.8 km sections each that two skiers on the team run. Finally, XC skiing contains long-distance mass-start races of 40-90 km. These are sparsely examined and not reviewed in the current paper.

Thus, XC skiing competitions extend from multiple ~3-min races in sprint skiing to a 50-km race lasting more than 2 hours. The race courses consist of approximately one-third uphill, one-third flat, and one-third downhill terrain, with ~50% of the total time spent racing uphill.[3-5] This requires the skier to master many different techniques and efficient transitions between these, at a wide range of speeds (5-70 km/h) and on terrains with inclines varying from -20 to 20%. At present, 10 of the 12 competitions in international championships involve mass-starts, where tactics are crucial and the outcome often decided during the final sprint.

While a relatively constant speed is generally optimal for prolonged endurance events on even terrain, speed during XC skiing competitions must be adapted to the track profile, snow conditions and altitude (0-1800 above sea level). In time-trials skiers generally utilize a positive pacing strategy, reducing their speed on comparable terrain throughout the race.[3,4,6] In addition, skiers exert more effort uphill, achieving more work for a given metabolic cost [7], and reduce their intensity on downhill sections (see a typical example for a male world class skier in Figure 1).[3,8,9] Thus, the highest rates of work and most pronounced differences in performance are also observed on uphill sections. Overall, the relative time spent on uphill, flat and downhill terrains contribute in that order to overall time-trial performance, although the best athletes are usually faster on all types of terrain.[4]

In comparison to time-trials, less is known about speed profiles, distribution of work and pacing strategies during mass-start races, in which the importance of both drafting behind other skiers and obtaining a position that allows optimal utilization of one's individual strengths are accentuated. Although, team tactics can sometimes provide an advantage in connection with mass-starts, these differ from those employed, for example, in road cycling competitions, due to the lower average speeds and thereby less drag involved in XC skiing. In addition, rapid changes in incline and work rate make changing position while XC skiing more difficult. These factors result in greater reliance on individual than team tactics in this sport.

Distribution of the various techniques

XC skiers are continuously changing between and adapting the sub-techniques of classical (diagonal stride, double poling with a kick, double poling and herringbone) and skating skiing (G2, G3, G4 and G5) to the varying terrain. In addition, the downhill tuck position and a variety of turn techniques are employed with both styles.[10,11] During a 1.5-km sprint race, skiers change sub-technique approximately 30 times,[5] whereas over longer distances many hundreds of such transitions occur. This situation is unique among endurance sports and requires considerable technical skill and physical capacity. Clearly, this emphasizes the necessity of integrating physiological and biomechanical approaches in attempting to understand the demands made by XC skiing.

Biomechanics

With both the skating and classical techniques, attaining higher speed requires both the production of sufficient propulsive force to increase cycle length, as well as more rapid cycles.[12-14] Longer cycle length is particularly important at high speeds on flat terrain, whereas rapid cycles while minimizing the reduction in cycle length is mandatory for accelerating on steep hills, during the start and sprinting at the finish of races. To accomplish this, more explosive techniques, such as “running diagonal”, “jump skate”, “kangaroo” double poling and double-push skating, have been developed.[13,15,16] This allow the most explosive skiers to produce peak double poling forces as high as 430 N within 0.05 seconds, as well as forces greater than 1600 N during leg push-off when skating.[17,18] In addition, there is increasing focus on the downhill sections of a race, especially the challenging downhill turns, where faster skiers utilize the accelerating step-turn technique more extensively.[10,11]

Energetics

On average, the aerobic proportion of the total energy expended during XC skiing competitions (i.e., 70-75% in sprints and 85-95% across longer distances) is comparable to the corresponding values for other sports with similar racing times. However, application of higher intensity on uphill terrain, driving work rates considerably above that required to elicit maximal oxygen uptake, requires an additional anaerobic component.[8] In such situations skiers repeatedly approach oxygen uptake values close to their maximum, with additional production of anaerobic energy that can be as much as 40% and 15-20% greater than that achieved aerobically during sprint races and the longest distances, respectively (Figure 1).[8,19]

The physiological capacity of elite XC skiers

Maximal and peak oxygen uptake

World-class XC skiers exhibit some of the highest maximal oxygen uptake (VO_{2max}) values ever reported,[20-22] with values of 80-90 and 70-80 $mL \cdot kg^{-1} \cdot min^{-1}$ being common for men and women, respectively. Absolute values for male and female medal winners exceeding 6.5 and 4.5 L·min^{-1} have been observed. Thus, every aspect of oxygen transport is being challenged, sometimes at temperatures as low as -20° C. Exercise ventilation rates of >250 L·min^{-1}, blood volumes of >9 L, cardiac outputs >40 L·min^{-1} and stroke volumes exceeding 200 ml have all been reported for elite male skiers.[1] Corresponding information for female skiers are limited, although ventilation rates of 180 L·min^{-1} have been reported.[20] While the absolute VO_{2max} values exhibited by elite sprint and distance skiers are similar, when normalized to body mass the values for the former, who demonstrate higher anaerobic capacity and speed, are slightly lower.[23]

In addition to a high VO_{2max}, the development of and ability to utilize a high peak oxygen uptake (VO_{2peak}) are key determinants of performance in XC skiing. VO_{2max} is consistently attained with diagonal skiing,[20,21] but the corresponding values with other sub-techniques are often 5-15% lower.[24] Elite XC skiers attempt to elevate their VO_{2peak} to ≥95% of VO_{2max} when using all of the sub-techniques and this ability to achieve high VO_{2peak}/VO_{2max} ratios even when employing sub-techniques that involve relatively little muscle mass, a unique characteristic of these athletes, has improved dramatically over the past decades.[1] Table 1 summarizes the technique-specific physical capacity of Norwegian and Swedish sprint and distance XC skiers who have won gold medals during the past 10 years.

Fractional utilization of VO_{2max}

The fractional utilization of VO_{2max} during a race, which reflects the aerobic energy utilized (i.e., performance VO_2), is an additional determinant of performance. In many other sports, the anaerobic threshold is thought to influence the $\%VO_{2max}$ at which an athlete can perform, especially during longer endurance competitions. However, while this threshold is of interest as a reference value for monitoring training progress in XC skiers, it does not necessarily provide a reliable estimate of the fractional utilization of VO_{2max} during competitions, where the constantly varying terrain and intensity of skiing lead to variations in work rate and metabolic intensity. In addition, since this threshold differs between the different techniques, as well as between the upper and lower limbs, its definition for XC skiing is more complex than in the case of e.g., running or cycling.

The constantly changing workload during XC skiing may provide skiers who can alter their O_2 kinetics rapidly with a major advantage, particularly with respect to the fractional utilization of O_2 uptake. While humans learn relatively quickly how to perform and change between the various XC skiing techniques, the metabolic demands on working muscles and supporting organs (e.g., the lungs and cardiovascular system) are high.[1] Supplying blood and oxygen to all of these muscles while maintaining blood pressure and the homeostasis of the muscle environment is challenging, in particular in connection with changes between different work intensities and different techniques that require major physiological adaptations.[1] Rapid delivery of O_2 to the active muscles in combination with extensive O_2 extraction requires considerable perfusion pressure accompanied by commensurate vascular conductance.[25] For example, both the leg and arm muscles of most elite XC skiers extract O_2 to a remarkable extent (i.e., 93-95% in the leg muscles, and only 10-12% less in the arms).[26]

Energy availability

Energy availability may also limit XC skiing performance, not only during long races (>30 km), but even when approaching the finish after 3 hours of sprint skiing competition. Carbohydrate is the primary substrate utilized during intense exercise and the muscles of well-trained XC skiers contain as much as twice the level of muscle glycogen as those of untrained individuals. This is of special interest, since depletion of glycogen during prolonged, exhausting exercise appears to contribute to muscle fatigue by impairing Ca^{2+} regulation inside the muscle.[27] Recently, the functional significance of glycogen has been shown to be dependent on its subcellular location and strong experimental evidence indicates that reduction of the depot of glycogen within the myofibrils plays a direct role in the reduction in release of Ca^{2+} from the sarcoplasmic reticulum during fatigue.[27] Furthermore, this specific pool of glycogen is elevated in trained muscle and used preferentially during exercise. In addition, the muscles of well-trained athletes contain higher levels of intramyocellular triglyceride stores, although, the importance of this energy source during exercise requires further elucidation.[28]

Anaerobic power

The anaerobic power, often measured as the accumulated oxygen ($\sum O_2$) deficit, of sprint and distance skiers differs, and is correlated to sprint performance.[29] This important capacity of sprint XC skiers appears to improve during the preparatory training period to become higher during the competitive period.[30] World -class female and male XC skiers demonstrate $\sum O_2$ deficits as high as 55 and above 70 $mL \cdot kg^{-1}$, respectively.[20,23] This gender difference is somewhat greater than corresponding difference in aerobic power, probably because the men have a larger muscle mass and specialize more in sprint skiing. However, the relative contribution from anaerobic energy decreases as by competition proceeds, thus becoming less important at longer distances, although the athletes with both high aerobic and anaerobic power may be most successful.

Skiing efficiency

In the case of both sprint and distance XC skiing, the ability to transform metabolic energy efficiently into speed is a key determinant of performance. Gross efficiency while roller skiing with various techniques, which is the ratio of external work rate to energy expenditure, reflects the performance levels of XC skiers.[7,31,32] This observation probably reflects the technical complexity involved, with the numerous degrees of freedom with respect to the timing of force generation by the arms and legs. However, certain techniques are more challenging and/or make a greater contribution to performance, and in particular, efficient skating techniques are correlated to performance in both sprint and distance XC skiing.[31] Notably, the efficiency of certain techniques are easier to assess on roller skis than on snow, e.g., when diagonal skiing skiers have complete grip with roller skis.

Speed and strength

In connection with sprint skiing, speed over a short distance and maximal strength in connection with movement-specific exercises correlate with performance.[5,18] At the same time, speed is important in mass-start races as well, especially during changes in speed and in the final sprint, where most races are decided. In addition to increasing movement-specific strength and power, maximal skiing speed can be enhanced considerably by improving technique. In addition, the ability to obtain and maintain high speed even when fatigued is of particular importance for racing performance.

Upper-body strength and power have become a major interest for both researchers and competitors in XC skiing. Both are important determinants of performance, for example, upper-body power and double-poling performance have often been shown to be related.[33]

Gender differences

Most studies to date have focused on male XC skiers and there is a dearth of information concerning the physiological demands faced by elite female skiers, who are generally shorter and lighter, with less muscle mass, a higher percentage of body fat, a smaller cardiac capacity and lower levels of hemoglobin. When normalized for body mass, VO_{2max} values for female XC skiers, are approximately 10-15% lower than for men,[34] as also expected for other sports.[35] Among the world's best female XC skiers, the highest individual oxygen uptakes observed are ~75 $mL \cdot min^{-1} \cdot kg^{-1}$.[20] In comparison, the best female skiers utilize ~90% of their VO_2max when double poling, a value only somewhat below findings on elite male skiers.[20] However, since gender differences in power production by the upper-body are more pronounced than for the legs[36] the corresponding differences in XC skiing performance are enhanced as the contribution by the upper body increases.[37] Overall, observations to date indicate that female XC skiers should be able to improve their upper-body power considerably.

Training by XC skiers

Endurance training has always been the major component of an elite XC skier's training. The 750-950 hours of annual training (including 700-850 hours of endurance) by the best skiers include approximately 80% at low-intensity, 4-5% moderate- and 5-8% high-intensity endurance training, and 10% training strength and speed.[2] Approximately 60% of this training is performed between May and October and the remaining 40% during the competition period from November to April. A typical distribution of training sessions within these categories throughout the annual cycle for a Norwegian world-class skier is shown in Table 2. Uniquely, certain elite skiers perform well both in sprint and distance races. while others specialize in one of these disciplines. While most of the training by skiers specializing in distance or sprint is similar, the latter appear to train slightly less, with more speed and strength training. In all cases, roller skiing, running on varying terrain and cycling are the predominant modes of endurance exercise from May to October, with only 5-10 days of training on snow per month. In recent years more training is being performed with roller skis on special tracks with competition-specific terrain and techniques. From November on, most training involves skiing on snow. Table 3 illustrates training programs typical for the preparation and competition periods.

Distribution of the intensity of training

Endurance training involves low, moderate, and high levels of intensity (defined in Table 2). Apparently, low-intensity training provides an important foundation for the more intense period of XC skiing competition, with world-class skiers performing more of such training than national-class XC skiers.[20,38] Alternating between sport-specific and cross-training may help XC skiers to tolerate large amounts of low-intensity training, with a low risk of injury. Low-intensity training has been proposed to enhance overall aerobic capacity and exercise efficiency, as well as to improve "tolerance" for high training loads by facilitating more rapid recovery.[39] With all of its sub-techniques performed on varying terrains and under changing external conditions, XC skiing requires a wide range of motor skills. Low-intensity training can be performed for many hours at an acceptable level of stress.

Moderate-intensity training, performed by definition immediately below the anaerobic threshold, allows prolonged exercise with a sufficient supply of aerobic energy. In practice, such sessions are commonly long with short breaks or continuous for 30-60 min. To control the intensity, it is preferable to carry out this type of training on relatively unvarying terrain. However, in practice moderate-intensity training also takes place on XC skiing tracks, where the intensity is intermittent since it changes with the varying terrain and the relative contribution of the arms and legs depending on both the technique and intensity, allowing competition-specific training at average moderate intensity. Moderate-intensity training is performed once or twice a week in the preparation period (May to October) and less often during the competition period (November to March).[20] In addition, moderate-intensity training is part of the warm-up for high-intensity sessions and competitions, as well as utilized to a certain extent on uphill terrain during low-intensity sessions.

Despite the focus of the best athletes on large amounts of low-intensity training, the positive effects of high-intensity training on endurance performance have been demonstrated repeatedly.[40-42] At the same time, it can be speculated that many highly trained athletes should focus more on improving the quality of each high-intensity session (i.e., optimization of physical, technical, and mental aspects) rather than increasing the number of such sessions. Furthermore, the period of preparation with extensive low-intensity training is followed by the competition season, with more high-intensity training (i.e., including competitions) and numerous competitions, a pattern that might be beneficial for the long-term development of elite endurance athletes, i.e., in terms of optimizing adaptive signaling.

Exercise mode

While their high-intensity training is primarily ski-specific, skiers vary their low-intensity training considerably. During the six months of endurance training during their preparation period, 50-60% of the time a gold medal-winning male or female skiers' devotes to training is sport-specific (i.e., roller skiing and skiing), while most of the remainder involves running/walking with or without poles and cycling.[20,39] During the competitive season, most endurance training is skiing, although some recovery sessions involve running or cycling. Although different modes of training clearly evoke different physiological adaptations,[43] much remains to be determined in this respect.

In addition, skiers need to develop their performance of the specific sub-techniques that load the upper- and lower body to different extents. The technique chosen is influenced by speed and external conditions (e.g., the profile of the terrain, snow conditions, waxing of skis, altitude, etc.), as well as individual performance level and physical characteristics. Accordingly, skiers must choose the terrain they train on and thereby the extent to which they train the different sub-techniques purposefully. For example, since 50% of racing time is spent uphill, training of uphill techniques is especially important. In addition, the ability to double pole with the classical technique throughout an entire race has become increasingly important and often the choice between using grip wax, that enables skiers all the major classical techniques to be employed or double poling without grip wax exerts a decisive influence on the outcome. Accordingly, XC skiers develop not only their upper-body capacity, but also the use of their whole body for poling in several gears appropriate for different terrains.[16,17] Overall, XC skiers must be aware of not only of the mode and intensity of their exercise, but also how they load the whole body, upper and/or lower limbs while training.

Altitude training

Scandinavian world-class skiers perform 10-20% of their training at moderate altitude (living at ~1800-2000 m and training between 1500-3000 m), where low- and moderate-intensity training receive highest priority.[20] Such training usually involves natural, rather than simulated altitudes and in some countries the latter method has been abandoned entirely. When important competitions are performed at an elevated altitude, an appropriate period of acclimatization (>5 days, depending on the altitude) is recommended and employed by most XC skiers. However, altitude training increases red blood cell mass and evokes nonhematological adaptation that also improve endurance at lower altitudes.[44] For the latter, at least three ~3 weeks camps each year, with many (>18) hours spent daily at the elevated altitude and good general health are required to obtain significant effects. Furthermore, in the opinion of many coaches such altitude training is primarily beneficial for elite athletes performing at a high level, who require additional stimulus and can ski fast enough with good technique even on snow on glaciers. However, individual responses to altitude training on elite endurance athletes remains largely unexplored.

As mentioned above, during altitude camps, high-intensity training is often performed less extensively than otherwise, as well as at altitudes lower than where the skiers sleep,[44] in contrast to low-intensity training, which has higher priority and is performed at the same or higher altitudes. Thus, the variation between training at elevated altitude and at sea-level may be beneficial for many elite endurance athletes. In addition, in the summer skiing on snow outdoors is only possible at elevated altitude and many skiers use altitude training for this reason as well.

Periodization

Many elite skiers periodize their training relatively constantly from week to week during the 6-month preparation period from May to October, training mostly around 20-25 hours per week, with some less arduous weeks involving <15 hours following extensive periods of training.[20] In addition, the number of moderate- to high-intensity sessions is normally constant at 2 or 3 per week during all phases of training (except at higher altitude; see above). Notably, skiers with a relatively "flat" periodization during the preparation period place greater emphasis on high-intensity training and periodize such training in blocks to a greater extent during the period of competition.

Certain athletes also alternate between high- and low-volume weeks, without changing the distribution of training intensity, while others focus on developing specific capacities over shorter periods (so-called blocks). However, the manner in which each athlete optimizes periodization with respect to the type (endurance, strength and speed) and mode of training (i.e., loading of the whole-, upper- and/or lower-body), the terrain, and intensity of endurance training, strategies that differentiate XC skiing from most other endurance sports, require further examination. Table 2 illustrates typical training programs and sessions of successful XC skiers during the different phases of the year.

Speed and strength training

The focus on developing speed and strength has been enhanced by the introduction of novel events and further development of equipment and tracks. Thus, both male and female world-class skiers perform more speed training than national-class skiers, [20,38] often as ski-specific sessions involving 10-15 maximal sprints (i.e., 10 to 20 seconds depending on technique and terrain, with 2-3 min of recovery between sprints), or integrated into other types of endurance training. The single investigation to date on the impact of speed training on the performance and physiological characteristics of XC skiers documented positive effects of 20-s intervals of DP on both sprint and endurance performance.[45]

However, reports on the effects of strength training on XC skiing performance vary, with a few studies demonstrating that movement-specific maximal upper-body strength training is beneficial in particular for double poling [46,47] and others finding no effects.[48] Overall, available findings allow us to speculate that in the case of for athletes who perform extensive endurance training, additional strength and speed training could help develop and maintain muscle mass and power, particularly in the upper-body of women. However, the potential effects of combined speed and endurance training require considerably more evaluation.

Training quality

In addition to the volume and distribution of training, the quality is also obviously an important factor. Here is how some of the world's best XC skiers describe their effort to increase this quality: *Athlete 1: "Before key sessions I prepare physically, technically and mentally in the same way I would before a competition. I choose the training environment to simulate important competitions to ensure that I train all of the relevant specific factors that contribute to performance while at the same time developing my mental capacity." Athlete 2: "I perform competition-specific sessions on a roller ski treadmill regularly in order to assess my present physical condition. This helps me design my training to ensure maximal quality."*

Doping in connection with XC skiing

As with other endurance sports, XC skiing has had problems with doping, in particular with respect to manipulation of red blood cells for better transport of oxygen.[49] For example, 50% of medal winners at the World championship in Lahti 2001, had highly abnormal hematological profiles and many medal-winning skiers have also been found guilty of doping.[49] However, it appears that in general hemoglobin levels in XC skiers are falling due to better antidoping programs, including more tests, better test methods and the introduction of blood passes by Professor Bengt Saltin.[50] However, new manipulations are being developed and today's regulations will need to evolve accordingly.

Another aspect being discussed recently, is whether and to what extent the utilization of e.g., various asthma medicines, ergogenic aids, oxygen supplementation and artificial altitude should be allowed. While the World Antidoping Agency (WADA) has formulated regulations in this context, new scientific information leads to changes in the rules. Therefore, sport associations should repeatedly monitor not only the use of banned substances, but also of medicines that are presently legal.

Future perspectives

The International Ski Federation has decided to continue using the current racing program for XC skiing during the coming international championships and the demands will probably not change to any great extent in the near future. However, more detailed analyses of competitions and training, employing advanced sensor technology to monitor the position, speed, kinematics and kinetics of XC skiers, are required. Such information will enhance our understanding of the demands of competitions and provide better guidelines for the training specificity and quality of future champions. Although XC skiers have been analyzed in great detail in the laboratory in recent decades, relatively little concerning longitudinal changes in physiological and biomechanical parameters and their influence on training and competitive success is yet known. The increasing physiological and technical demands made on modern XC skiers have already changed and possibly enhanced individual variation in their training.

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Figure legends

Figure 1. Estimated speed, work rate, metabolic rate and O_2 demand in different inclines during a sprint (dark grey) and distance (light grey) competition employing the skating technique for a world-class male cross-country skier.

Table 1. Peak oxygen uptake (VO_2peak), absolute and relative to VO_2max, for world-class sprint and distance cross-country skiers while skiing on flat and uphill terrain employing the classical and skating techniques.

	Men		**Women**	
	Sprint	Distance	Sprint	Distance
Uphill skating (G2/G3)				
VO_2peak ($L \cdot min^{-1}$)	5.8-6.6	5.5-6.4	4.1-4.4	4.0-4.4
VO_2peak ($mL \cdot min^{-1} \cdot kg^{-1}$)	70-78	80-85	63-68	65-72
$\%VO_2$max	≈97%	≈98%	≈97%	≈98%
"Flat" skating (G4)				
VO_2peak ($L \cdot min^{-1}$)	5.6-6.5	5.3-6.2	3.9-4.3	3.8-4.3
VO_2peak ($mL \cdot min^{-1} \cdot kg^{-1}$)	68-75	76-82	64-68	66-72
$\%VO_2$max	≈95%	≈94%	≈94%	≈94%
Uphill classical (diagonal)				
VO_2peak ($L \cdot min^{-1}$)	6.0-6.8	5.6-6.5	4.2-4.5	4.1-4.5
VO_2peak ($mL \cdot min^{-1} \cdot kg^{-1}$)	70-80	80-88	65-70	68-75
$\%VO_2$max	≈100%	≈100%	≈100%	≈100%
"Flat" classical (double poling)				
VO_2peak ($L \cdot min^{-1}$)	5.4-6.2	5.0-6.0	3.8-4.1	3.7-4.1
VO_2peak ($mL \cdot min^{-1} \cdot kg^{-1}$)	65-73	75-80	62-65	65-70
$\%VO_2$max	≈92%	≈91%	≈90%	≈90%

Table 2. An annual training plan of a world-class cross-country skier competing both in sprint and distance races. The table illustrates weeks of testing and training camps, as well as monthly training hours, number of competitions and training sessions.

Period	1. preparation period			2. preparation period			Competition period					Recovery	
Testing	T		T	T	T	T	T			T	T		
Training camps	L	L L	L	L H H	H L	H H H	L	H H		H H			
	May	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Des**	**Jan**	**Feb**	**March**	**April**	**SUM**
Training hours	70	75	80	85	85	85	70	60	60	50	45	35	**800**
# Sessions/month													
Sprint races		1		1			2	3	3	3	2	2	**17**
Distance races	1	1		3	1		3	4	5	5	4	4	**31**
HIT	2	3	3	2	3	4	2	2	1	1	2		**25**
MIT	4	4	5	4	5	5	1	1	1	1	1	1	**33**
LIT >2.5 hrs	4	6	8	8	8	8	5	4	3	2	2	5	**63**
LIT 1.5-2.5 hrs	10	9	10	11	11	12	11	12	12	11	8	5	**122**
LIT <1.5 hrs	6	6	6	8	8	8	10	10	11	12	11	2	**98**
Speed	3	4	4	4	5	5	4	4	3	3	2		**41**
Plyometrics	2	3	3	2	2	2	2	1	1	1	1		**20**
Strength	8	7	7	5	5	4	3	2	2	2	2	2	**49**
SUM	**40**	**44**	**46**	**48**	**48**	**48**	**43**	**43**	**43**	**41**	**35**	**21**	**500**

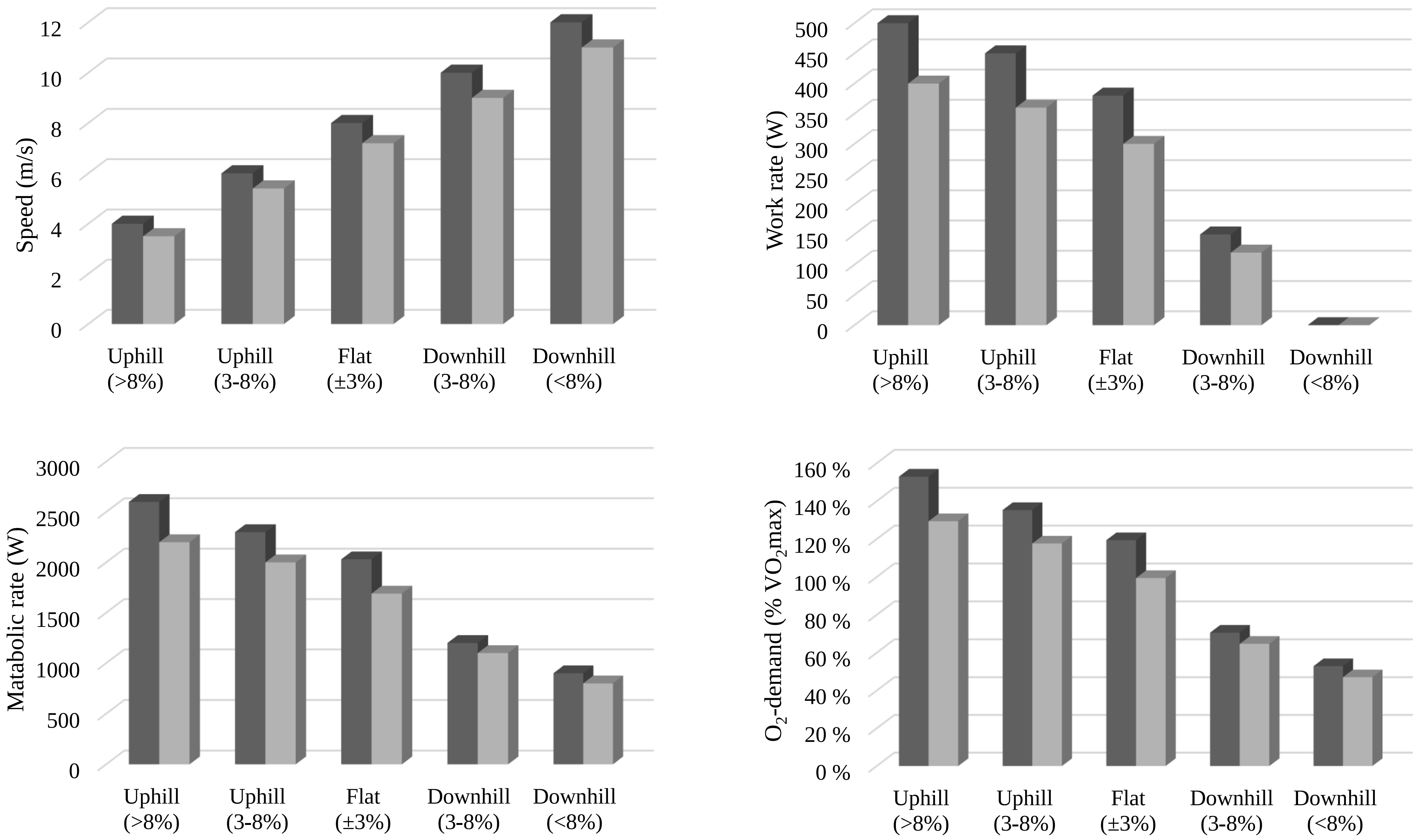
LIT = low-intensity training: blood lactate concentration < 2.5 mmol/L, heart rate < 81% HRmax.
MIT = moderate-intensity training: blood lactate concentration 2.5-4.0 mmol/L, heart rate 81-87% HRmax.
HIT = high-intensity training: blood lactate concentration 4.0-10.0 mmol/L, heart rate > 87% HRmax.
T = laboratory testing
L = training camp at low-land altitude
H = training camp at high altitude

Table 3. Typical training weeks for a world-class cross-country skier at low altitude (<800 m above sea level) during the preparation and competition periods.

Day	Preparation	Competition
Monday	AM: 7 x 5-min HIT, uphill running/walking with poles PM: 1.5 hrs LIT, classical roller skiing with double poling on easy terrain	AM: 2 hrs LIT, classical skiing on easy terrain PM: Warm-up + 30 min strength training
Tuesday	AM: 1.5 hrs, LIT roller ski skating on easy/moderate terrain PM: 2 hrs LIT, running on easy/moderate terrain	AM: 6 x 4-min HIT*, classical skiing and skating on varied terrain PM: 0.5 hrs LIT, running on easy terrain
Wednesday	AM: Strength training[#] PM: 1.5 hrs LIT, roller ski skating on varied terrain, including 10 x 12-s sprints	AM: 1.5 hrs LIT, ski skating on relatively flat terrain PM: Rest
Thursday	AM: 2.5 hrs LIT, classical roller skiing on varied terrain PM: Rest	AM: Travel PM: 1.5 hrs LIT, skating on moderate terrain
Friday	AM: 45-min continuous MIT/HIT*, roller ski skating on a roller ski track PM: 1.5 hrs LIT, running on hilly terrain with a soft surface	AM: 45 min LIT on the competition track followed by 3 x 6-min MIT/HIT*. Classical skiing PM: Rest
Saturday	AM: 10 x 10 maximal jumps + strength training[#] PM: 1.5 hrs LIT, classical roller skiing on easy/moderate terrain, including 8 x 10-15-s double poling sprints	MO: Morning jog 30 min, 3-4 strides AM: 15-km classic competition * PM: Easy skiing 45 min, stretching/massage
Sunday	AM: 3.5 hrs LIT, running on terrain of moderate incline with a soft surface PM: Rest	AM: 30-km Skiathlon competition * PM: Travel

LIT = low-intensity training: blood lactate concentration < 2.5 mmol/L, heart rate < 81% HRmax.
MIT = moderate-intensity training: blood lactate concentration 2.5-4.0 mmol/L, heart rate 81-87% HRmax.
HIT = high-intensity training: blood lactate concentration 4.0-10.0 mmol/L, heart rate > 87% HRmax.

* Competitions and HIT sessions routinely included approximately 30-45 min of LIT, followed by 10-15 min of MIT/HIT. Cool-down involves 15 min of LIT.
[#] Strength sessions typically consist of a 30-minute warm-up (running/cycling at LIT) followed by 15-30 min maximal movement-specific strength exercises for the upper-body and thereafter 30-45 min of more general core/stabilization exercises


Speed (m/s)
0
2
4
6
8
10
12
Uphill (>8%)
Uphill (3-8%)
Flat (±3%)
Downhill (3-8%)
Downhill (<8%)
Work rate (W)
0
50
100
150
200
250
300
350
400
450
500
Uphill (>8%)
Uphill (3-8%)
Flat (±3%)
Downhill (3-8%)
Downhill (<8%)
Matabolic rate (W)
0
500
1000
1500
2000
2500
3000
Uphill (>8%)
Uphill (3-8%)
Flat (±3%)
Downhill (3-8%)
Downhill (<8%)
O2-demand (% VO2max)
0 %
20 %
40 %
60 %
80 %
100 %
120 %
140 %
160 %
Uphill (>8%)
Uphill (3-8%)
Flat (±3%)
Downhill (3-8%)
Downhill (<8%)