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Skiing's Physiological Foundation

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ABSTRACT

Alpine ski racing is a challenging sport to examine because of the harsh cold, altitude, and plexity.This review includes 29 on-snow examinations of specific physiological aspects of the major ski racing disciplines, nine off-snow investigations of the physiological capacity of ski racers of different skill levels, four review papers, and 430 years of research. Alpine ski competitions appear to include the intricate integration of numerous physiological systems, none of which may be more crucial to performance than the others. Although technical skill seems to have the biggest impact on performance, the capacity to maintain technical proficiency over the course of a lengthy competition season necessitates excellent skills throughout all physiological systems. Sport scientists must figure out the best method and window of time to build these systems simultaneously. For the purpose of determining aerobic and anaerobic needs and abilities, additional research using portable, modern investigative instruments is needed, particularly in the areas of muscle function and relative energy system contribution during both single- and multi-runs over different terrain.

Keywords: physiologic capacities, energy systems, muscular weariness, and ski racing.

1. INTRODUCTION

Competence in both physical and technical areas is required for alpine skiing. The more we understand about the physiological and biomechanical settings of elite ski racers, the more effectively we can target our efforts to reproduce and advance these attributes in our own athletes. Understanding how the muscular forces and energy systems are used in ski racing is crucial for future performance improvement, injury avoidance, talent discovery, and training prescription. Two speed events and two technical events make up ski racing; each is distinguished by the location of the gates, the turning radius, the speed, and the length of the course. The fall line of the hill is followed by the Super Giant Slalom (SG) and Downhill (DH) speed races, which can reach speeds of up to 130 km/h. A DH race could take up to three minutes, whereas an SG race, which has a shorter track but more turns, typically lasts one to two minutes. Skiers can only attain speeds of 20 to 60 km/h in the technical Slalom (SL) and giant slalom (GS) events, which take place on steeper terrain. The GS normally lasts 60–90 seconds, while the SL lasts 45–60 seconds and features extremely sharp, quick twists (White & Johnson, 1993; Davidson &Laliotis, 1996; Szmedra et al., 2001). Skiing study must take into account the many disciplines as well as the degrees of athlete participation (Skilled vs. Unskilled, Club, Regional, National, International, and Elite). In order to draw conclusions about skiing as a whole, the majority of study has focused on GS, with the assumption that this event acts as a halfway point between SL and DH (Saibene et al., 1985). In the literature, there are some comparisons between the GS and SL (Veicsteinas et al., 1984) and the SL and DH (Bacharach &Duvillard, 1995), but nothing is known about the more recent hybrid SG. The more we learn about the nuances of ski racing, the more we start to doubt the distinctions between the various disciplines, and the more presumptions from the past seem doubtful.

No one characteristic can be used to assess an alpine ski racer's likelihood of success, claim Bacharach and Duvillard in 1995. Many have argued that when it comes to talent spotting and training, the sport's complexity is the most important aspect (Tesch et al., 1978; Veicsteinas et al., 1984; Saibene et al., 1985; White & Johnson, 1991, 1993; Tesch, 1995; Haman et al., 2002). The technical nature of ski racing makes "time on the snow" crucial for athlete development (Nygaard et al., 1978). It is crucial that the minimal technical and physical training that is done during times of severe competition is both efficient and pertinent (Laurent et al., 1993; Bacharach &Duvillard, 1995). To make this possible, it is crucial to have a solid grasp of certain physiological requirements and how they affect training, competition, and recuperation processes in order to guarantee accurate, high-quality training without wasting time or effort (Neumayr et al., 2003; Hartmann et al., 2005). In fact, the goal of this analysis is to draw attention to the distinctive environment and movement context of alpine ski racing in an effort to better understand where and how sports science may help and advance the sport of alpine skiing. Before reporting on the physiological components of ski racing, we will first talk about the environmental factors and scientific research considerations that need to be made.

Procedures for investigation

It is clear that the majority of skiing-related literature was published between the 1970s and 1990s. Such early study needs to be critically examined because some of the technology and investigative techniques have now been improved. Additionally, these earlier studies capture the demands of the sport as they were 420 years ago, prior to the introduction of contemporary gear and training methods (Karlsonn, 2005). For instance, breakaway poles have made slalom a faster and more aggressive straight-line race where the skier skis through the poles rather than around them. Due to altered posture and limb position, the carving ski has produced a sharper, decreased radius turn, inadvertently increasing the stresses on lower limb joints (Neumayr et al., 2003). A more athletic skier has emerged as a result of modern training techniques including riding portable bikes in hotel rooms during competitions and training camps and power training techniques that emphasise weightlifting exercises like the clean and jerk (Neumayr et al., 2003). The central circulation and gross energy output have received the majority of attention in historical accounts of the physiology of ski racing. The current focus has been on peripheral muscle physiology, specifically muscle energy output, oxygen transport, and fuel utilisation, due to the development of new investigative technologies as well as a more muscular and dynamic skiing style (Karlsonn, 2005).

Environment for training

Skiing's training setting and movement context make it challenging to test for specificity, validity, and reliability. When stable states are reached, physiological testing is most accurate and enables precise performance prediction. The energy cost for a brief period would, in fact, be reflective of the entire length cost due to recurrent movements (Saibene et al., 1985). However, skiing requires unpredictable, erratic, short-duration, high-intensity efforts that take place in chilly mountain conditions. The ability to directly and precisely assess human physiology is also impacted by these behaviours and settings (Koutedakis et al., 1992; White & Johnson, 1993; Ferber et al., 2003; Neumayr et al., 2003; Seifert et al., 2005). It is obvious that scientists will have a difficult time estimating the actual demands of downhill skiing. It is challenging to determine an athlete's ability level in sporting events where the results are not measured against a standard. The sport's governing body, the Federation Internationale de' Ski (FIS), points, pre-determined but high-caliber racing successes, and participation or exclusion in national teams have all been used to define skiing talent (White & Johnson, 1993). Different nations may classify their national teams as "Elite," but this does not imply that they are competitive skiers on the world stage. For instance, despite the fact that "International/Elite" athletes were the subject of research by Koutedakis et al. (1992), Bosco et al. (1994), and Haymes and Dickinson (1980), Koutedakis et al. (1992) found that their Internationals were of a lower calibre than those in the other studies.

The use of various physical examinations and training methods has been prompted by debate regarding which energy systems are predominant during alpine skiing. Below is a list of the tests that are most frequently reported. According to various studies (Veicsteinas et al., 1984; Andersen & Montgomery, 1988; Andersen et al., 1990; White & Johnson, 1991, 1993; Bosco et al., 1994; Tesch, 1995; Neumayr et al., 2003), each has at some point been found to be significantly related to performance in one or all of the four ski events.

Tests of aerobic fitness

According to Brown & Wilkinson (1983) and White & Johnson (1991), the 20-m Multi Stage Fitness Test (MSFT) remains to be the industry-standard field test for assessing aerobic capacity in ski racing. Although no justification for the preference for the MSFT is provided, one hypothesises that it is more suitable to the overall aerobic environment of skiing because to its more constant nature and small turn phases than the previously employed 12-min straight run (Brown & Wilkinson, 1983). Treadmills have been used in the lab to determine VO2max directly, but because many skiers don't know how to run, they often report lower results than they may be biologically capable of (Brown & Wilkinson, 1983; Svensson, 2005). As an alternative to treadmill jogging, the cycle ergometer offers better recruitment and activation of the muscles used in skiing. Cycling assessment methods are preferred over treadmill assessment methods due to the prevalence of calf and knee injuries in ski racers (Koutedakis et al., 1992; Davidson &Laliotis, 1996; Neumayr et al., 2003; Noe&Paullard, 2005). Skiers have often been evaluated using incremental cycle step tests to determine the start of blood lactate buildup and VO2max (Karlsonn, 2005). Researchers have utilised a variety of approaches to estimate the on-snow VO2 needs due to the evident difficulties in directly measuring VO2 during on-snow skiing. For instance, Tesch et al. (1978) measured the blood lactate levels after a race. The premise behind blood lactate derivation of VO2 is that 1 mmol/L blood lactate correlates to 3.15 mL O2/kg. Heart rate (HR) has been employed by others (Andersen & Montgomery, 1988; Kahn et al., 1993) based on laboratory assessments of the HR-VO2 relationship. However, the impact of altitude, temperature, and intermittent exercise on physiological work load assessment, as well as competition anxiety, may impairthe capacity of HR to predict VO2. (Kuno et al., 1994; Koistinen et al., 1995; Haman et al., 2002; Glaister, 2005; Seifert et al., 2005) The difficulties of taking direct VO2 readings in the field were overcome in a few early studies. For the field-based direct measurement of VO2, Douglas bags of various sizes and shapes have been utilised in a number of investigations. To calculate VO2 during actual skiing, Veicsteinas et al. (1984) assessed post-exercise oxygen consumption. Small Douglas bags with a valve that opened and closed during a portion of the GS course were used by Saibene et al. (1985) to directly measure energy expenditure during that time. But more recently, the creation of tiny, portable breath-by-breath gas analyzers may have made it possible to examine people while they compete in ski races with more mobility. It is acknowledged that more investigation into the energy expenditure of skiing during competition and training opens up fascinating possibilities for comprehending the many ski racing disciplines (McLaughlin et al., 2001; Karlsonn, 2005).

Anaerobic testing

Although it seems that the 30-s Wingate test is the most frequently utilised, the 60-s and 90-s tests have gained popularity and may be more applicable to the time scales and energy systems involved in ski racing. Although there are some correlations between 40-s and 2-min maximal tests, testing lasting longer than 30 s exhibit considerable power losses (Bacharach &Duvillard, 1995). According to Bacharach and Duvillard (1995), there is a crossover between SL and DH skiers. In other words, although DH racers were able to maintain higher average power outputs for longer but showed lower maximal powers, SL racers had higher maximal power outputs but were unable to sustain them. Anaerobic testing should go longer than 30 s to deplete the anaerobic energy supply, according to the crossover that took place after 30 s. Skiers have previously been subjected to field-based anaerobic tests like the repeated box jump (constant jumps over a 40 cm box) and the Hex test (revolving around a hexagonal perimeter) (Andersen et al., 1990). The USA "Medals Test" for ski fitness included the 40 and 400 m sprints, despite the fact that neither test has garnered much support or attention in the literature (Andersen et al., 1990; White & Johnson, 1991, 1993). A vertical jump, multiple vertical jumps, or double- and single-leg bounding have nearly always been used in explosive power tests (Andersen et al., 1990; White & Johnson, 1991, 1993). Blood lactate is a simple way to measure metabolic acidity and how much the body's energy systems are assisting with the exercise session. Muscle attributes, such as glycogen depletion patterns and muscle fibre type, have been identified more invasively using muscle biopsy procedures and muscle fibre dying (Nygaard et al., 1978; Tesch et al., 1978). Szmedra et al. (2001) used markers of muscle damage (myoglobin, creatine kinase, and cortisol) to quantify the work performed and fatigue induced during skiing, in their investigation of nutrition and skiing, and Laurent et al. (1993; Karlsonn, 2005) used MRI to identify individual muscle metabolism.

Muscle power

Since it can precisely distinguish concentric, isometric, and eccentric torque at different joint velocities, isokinetic dynamometry—using leg extension (and occasionally leg flexion)—has become the industry-standard laboratory tool for evaluating leg strength in skiers. Along with lifting exercises like the squat and leg press, field tests like the static wall sit, prone hold, and other sit-up tests have also been used to gauge strength. Due to technical and athlete condition considerations, these tests must be used cautiously (Hoff, 2005; Blazevich& Gill, 2006). Information on muscular activity, the percentage of maximum voluntary contraction (% MVC), and force distribution while skiing has been collected using portable EMG and in-boot force plates (Berg &Eiken, 1999; Karlsonn, 2005; Kroll et al., 2005). The vastuslateralis muscle group has been the subject of most research, with information on the abdominal, erector spinae, and tibialis groups also being available. The use of the gluteal and upper body muscles during skiing has received less consideration (Berg &Eiken, 1999). Due to the complexity of the environment and the dominance of talent in ski racing, testing batteries that cover a wide range of topics are frequently used (Brown & Wilkinson, 1983; White & Johnson, 1991, 1993). Physiological parameters alone are not enough to predict or develop a good ski racer, but they do provide a way to measure the impact of different training stimuli. While the specificity of different tests to ski racing alone is debatable, the existence of such a battery and the results of these tests unquestionably identify this (Bacharach &Duvillard, 1995).In conclusion, many testing techniques have been employed to evaluate skiers' physical prowess both on and off the snow. In the face of difficult environmental conditions, the continual development of new measurement methods has the potential to improve our understanding; yet, few such investigations have been carried out to date. The context, as well as a discussion of specific measurement and apparent demands within ski racing as they have been described in the literature, will be provided in the section that follows.

Alpine skiing's physiological requirements and key elements of fitness

Contribution of the energy system

VO2 needs of 120% VO2max were reported for GS skiing by Saibene et al. in 1985. Early studies (Tesch et al., 1978) noted even lower values: 80–90% VO2max for expert skiers and about 60% VO2max for novice skiers. GS skiing has been viewed as a submaximal sport because maximum cycle tests of identical time frequently elicit results of up to 175% VO2max (Saibene et al., 1985). Among contrast to the findings of these investigations, Veicsteinas et al. (1984) discovered that even in novice skiers, VO2 was 130% VO2max, whereas expert skiers' VO2 was over 200% and 160% VO2max in SL and GS, respectively. Each participant in this study reportedly reached their maximum heart rate (HRmax) before the end of the course and maintained this level for 30 seconds after course completion before starting to decrease, indicating strong aerobic input. Studies that have reported very low VO2 contributions have only measured O2 consumption during the task (a measure of the aerobic system only), rather than the overall expenditure rate, which includes the oxygen cost of anaerobic sources (Veicsteinas et al., 1984). The variations seen in these investigations could be explained by this. Researchers Veicsteinas et al. (1984) and Saibene et al. (1985) looked at the relative energy contribution to skiing. Both studies found that the anaerobic system contributes 65% of the time during ski racing and recommended that force generation and neuromuscular synchronisation be the main training objectives (Veicsteinas et al., 1984; Saibene et al., 1985). Both Veicsteinas et al. (1984) and Saibene et al. (1985) research used blood lactate measurements to infer lactate contribution to energy metabolism, depending on the presumption that 1 mmol/L blood lactate translates to 3.15 mL O2/kg (Saibene et al., 1985). Although this is believed to be pretty accurate, it does contain some error and may grow more inaccurate with the addition of variables like higher intensity exercise and altitude (Veicsteinas et al., 1984; Saibene et al., 1985). Alpine skiing has a greater anaerobic input than an aerobic one, according to research by Veicsteinas et al. (1984) and Saibene et al. (1985). Thus, it might be claimed that larger aerobic contributions would lessen stress on the neuromuscular system and minimise reliance on anaerobic and force production/training (Duvillard, 1995; Kyrolainen et al., 1998). The importance placed on each system during physical training will depend on a better understanding of the relative input of the aerobic vs. anaerobic system.

Influences on aerobic metabolism

Before getting into the specifics of the aerobic system, it's crucial to remember that a lot of the early, ground-breaking research on aerobic and strength metrics in skiing ignores variations in lean body mass (Haymes& Dickinson, 1980; George et al., 1999). When comparing performance in any activity where the forces being sustained are related to the athlete's body weight, this knowledge is crucial. For instance, when Haymes and Dickinson (1980) examined absolute VO2max vs. body weight-adjusted VO2max and anaerobic power, females showed more similar (o23% difference) to males than absolute measures would suggest. Investigations should take body size disparities between skiers into account to provide a relevant comparison of physiological measurements, such as aerobic capacity and muscle power, between-skiers (Markovic&Jaric, 1995). Contradictory findings on VO2 while skiing show how difficult it is to utilise the aerobic system during ski racing. Vascular occlusion caused by isometric ski racing contractions impairs aerobic metabolism (Foster et al., 1999; Tesch et al., 1978). Together with the hypoxic environment of altitude, this blockage increases lactate production. For instance, Gladden and Welch (1978 in Saibene et al., 1985, pp. 315) found a 15% increase in the anaerobic lactate system's contribution to exercise when cycling at 120% VO2max at about 2000 m above sea level. The anaerobic system is strained more severely by cold and the hypoxic, hypobaric environment (typical of 1500–2000 m altitude), which results in lower alveolar and arterial oxygen pressure and lower glycogen stores (Kuno et al., 1994; Haman et al., 2002; Roberts, 2005; Seifert et al., 2005; Svensson, 2005). The effects of altitude and cold on muscle metabolism are depicted in a simplified, step-by-step manner. Using both power and endurance athletes, Koistinen et al. (1995) discovered that those with higher aerobic capacities displayed a greater relative decline in their capacity to tolerate lactate and to work aerobically at higher altitudes (Kuno et al., 1994; Koistinen et al., 1995; Haman et al., 2002; Seifert et al., 2005). Furthermore, the percentage drop in VO2max increased with the athlete's level of training (Martin &O'Kroy, 1993). Finally, at a given VO2max, more ST fibres that are more effective may assist the body adapt to environmental conditions including hypoxia, hypobaria, and hypothermia by reducing the anaerobic load (Haman et al., 2002; Seifert et al., 2005). Understanding how the various skiing disciplines affect physiology and energy system contribution will further complicate matters. Simple technical events seem to rely more on anaerobic metabolism, whereas longer-distance races have more of an aerobic metabolism component (Duvillard, 1995). Similar overall energy costs for SL and GS were reported by Veicsteinas et al. in 1984. Given that GS may last 15 or more seconds longer than SL, the rate of energy supply is higher for SL than for GS (200% VO2max vs. 160% VO2max, respectively), implying a higher energy requirement from anaerobic sources (Veicsteinas et al., 1984). In both male and female skiers, Neumayr et al. (2003) observed minimal difference in the fitness levels of technical (SL/GS) or speed (SG/DH) experts compared to combined/all-arounders (GS/SG/DH). Based on the results of the 1997–2003 World Championships, the relationship between aerobic power (or maximal oxygen uptake, VO2max) among male and female experts and racing performance was positive (Neumayr et al., 2003). The authors hypothesised that this may be due to slalom skiers receiving more intensive on-snow training than is actually physiologically necessary for the event (Neumayr et al., 2003). There aren't many examples of direct comparisons with different events in the literature, with Haymes and Dickinson's (1980) study of the traits of Elite SL and DH skiers being one of the few. Finally, it was found that DH skiers had a larger body size and body fat percentage than SL skiers (Haymes& Dickinson, 1980).

Aerobic exercise

There is controversy over how crucial this ability is and why, despite the fact that several authors have reported on the impact of aerobic power for ski racing (Bacharach &Duvillard, 1995). For instance, Tesch (1995) declares audaciously that "maximal aerobic power, or aerobic capacity, are improbable factors for success in competitive Alpine skiing." Additionally, White and Johnson (1993) state that "aerobic power, although significant, does not discriminate competitors of varying ability categories." (p. 170). In contrast to these prior studies, a new analysis of the dominant Austrian National Team revealed a high correlation between aerobic power and international skiing success (Neumayr et al., 2003). However, it is unclear whether aerobic energy supply is crucial for ski racing or if it is a result of the intense training regimen some countries require (Tesch, 1995; Neumayr et al., 2003). It is understandable that changes in the aerobic power of ski racers are not documented in the literature given the misunderstanding surrounding the significance of the aerobic system. In fact, there has been some reported variation in aerobic power among trials that have been made public so far. For instance, national-level male skiers were found to have VO2max of 58.9 2.2 and 63.1 1.3 mL/kg/min, respectively, according to Saibene et al. (1985) and Brown and Wilkinson (1983). Veicsteinas et al. (1984) report lower values (52 mL/kg/min), however Andersen and Montgomery (1988) indicate significantly higher values (67 mL/kg/min). Recent statistics on the World Champion Austrian team found values of 59.5 4.7 and 58.7 3.2 mL/kg/min for the 1999 and 2000 seasons, respectively (Neumayr et al., 2003), which are comparable to those published 20 years earlier. Early research employed treadmill tests to determine baseline aerobic power, while more recent studies use cycle-based tests as previously stated (Veicsteinas et al., 1984; Saibene et al., 1985; Neumayr et al., 2003), which may account for some of this variation. Most of the research on aerobic training acknowledges the importance of aerobic power in terms of its function in recovery rather than in energy provision. In order to recuperate between runs, endure the gruelling competition and on-snow training seasons, and maintain performance, an effective aerobic system is required (Neumayr et al., 2003). For instance, after skiing for 5-7 days, individuals were shown to maintain average HRs equivalent to 75% of expected HRmax despite rarely surpassing peak values when exercising at high labour loads compared to their individual fitness (Grover et al., 1990; Kahn et al., 1993, 1996). Karvonen et al. (1985) came to the conclusion that the demands of SL were insufficient to further enhance aerobic power when they discovered that the only significant change after 3 months of relatively hard SL training was the increase in anaerobic capacity and lactate tolerance.

Aerobic conditioning

Tests of anaerobic power have a stronger correlation with success on the slopes than tests of aerobic power, according to Duvillard (1995), especially when body mass is taken into account. While Haymes and Dickinson (1980) discovered that vertical leap had a strong correlation with FIS points, White and Johnson (1993) claimed that vertical jump was the best measure of skier performance. Because the feet must be moved away from the centre of mass when doing the Box Jump and Hex test, Andersen et al. (1990) came to this conclusion.

Flexibility and strength of the muscles

Skiers are renowned for having strong legs (Berg et al., 1995). According to early studies (Tesch et al., 1978; Haymes& Dickinson, 1980), strength, as determined by isometric and isokinetic techniques, was the best predictor of skiing ability for members of the US ski team. Recent studies have found no association between strength and World Cup ranking, despite a move toward power training and bigger skiers (Andersen & Montgomery, 1988; Neumayr et al., 2003). Anecdotal evidence indicates that DH skiers are more powerful than skiers in other disciplines. The Technical, Speed, or Combined skiers do not differ in strength, according to research (Berg &Eiken, 1999; Neumayr et al., 2003). When measured at slow movement velocities (i.e., 301/s), skiers exhibit extremely strong leg strength. Skiers, however, display strength comparable to other athletic populations when tested at higher velocities, such as those present in running (1801/s) or Freestyle moguls (FM). According to Berg and Eiken (1999), the fastest angular knee velocity for slalom was 691/s, with other disciplines being considerably slower. Researchers have questioned the applicability of the speed training techniques used frequently in ski competition (Berg et al., 1995; Berg &Eiken, 1999; Neumayr et al., 2003) in light of evidence like this. When compared to GS, the shorter, faster turns of SL produce a bigger cyclical motion, which lowers centrifugal forces and snow speed. As a result, the isometric duty cycle is reduced, and a correspondingly higher posture/knee angle results (Szmedra et al., 2001). As a result, less blood occlusion may occur in SL than GS during the specified duration at the proportional percentage of MVC force. According to Neumayr et al. (2003), higher strength is not a factor in skiing skill past a certain point, depending on body weight and how it interacts with speed and slope angle. However, the exact amount of this threshold is not stated and needs more investigation. Athletes with stronger maximal strength may be able to perform at a lower percentage of MVC, which would lessen the metabolic effects of prolonged high-intensity activity (Rundell, 1996; Foster et al., 1999; Szmedra et al., 2001).

Skiing injuries, particularly those involving the knee, are prevalent (Kalbermatten& Ballmer, 2000; Muller et al., 2005; Koyangi et al., 2006). While strength from a performance standpoint may have a threshold past which no performance advantages would be gained. Skiers' capacity to tolerate the tremendous forces and eccentric loads of ski racing may be restricted by a lack of strength. The super side-cut ski and rigid boot and binding system have decreased the radius of the carving ski turn, which has caused noticeably greater increases in valgus subluxation forces within the knee joint (Koyangi et al., 2006). The burden on the skier's muscular system depends on the accelerative force, which is related to the skier's body weight and speed but inversely proportional to the turn radius (Hintermeister et al., 1995, 1997; Berg &Eiken, 1999).According to recent research, the skier's physiological capabilities may soon be surpassed by the radius of a carving ski turn (Kalbermatten& Ballmer, 2000; Neumayr et al., 2003; Muller et al., 2005; Koyangi et al., 2006). While there are still many risk factors for ski injuries, there is a higher chance of knee damage if the quadriceps and/or hamstrings are overtrained or undertrained. To determine a person's propensity for suffering such an injury, the hamstring to quadriceps strength ratio is used. In a group of world-class skiers, Neumayr et al. (2003) discovered hamstring/quadriceps ratios of 0.57 to 0.60, showing good regulating hamstring strength in relation to power-producing quadriceps activity. These values are comparable to those noted by Brown and Wilkinson (1983) over 20 years ago ,when a lack of strength was documented in the lower level athletes, but they are not exceptionally high when compared to some sprint athletes. Although it is unclear whether relatively weak hamstrings or strong quadriceps are to blame for the poor ratio in lower level athletes, the authors have noticed that most developing ski racers are very aware of the importance of quadriceps strength but very little of the importance of hamstring strength.

While Brown and Wilkinson (1983) and Andersen and Montgomery (1988) showed minimal difference between National, Divisional, and Club level skiers, flexibility is frequently regarded crucial for injury prevention and strength/stability through a joint range of motion. This suggests that, similar to the strength characteristics described by Neumayr et al. (2003), a lack of flexibility may not significantly impede performance at a certain minimal threshold.

Physiology and mechanics of muscles

Skiing is frequently described as "explosive" sport. This can be shown in how much time trainers devote to teaching quick concentric movements (Steadman et al., 1987; Tesch, 1995). High-speed resistance training, however, may not be the best method of such training, as was stated above and taken into account when comparing FM and running to ski racing's slower angular knee velocities (Tesch, 1995; Berg &Eiken, 1999). Berg et al. (1995) looked at the impact of the accelerative pressures brought on by swift downhill skiing and a series of quick, strong slalom turns. They discovered that during ski racing, eccentric motions accounted for the majority of the muscle contraction force. (Tesch, 1995; Szmedra et al., 2001) FM has demonstrated more frequently eccentric/concentric patterns akin to those of running. These results imply that eccentric exercise should predominate in strength training for skiing (Berg et al., 1995; Berg &Eiken, 1999). It should be emphasised that while the angular velocity might be slow, the contraction velocity might not be. In fact, the necessity to quickly shift directions necessitates high rates of force development, albeit erratic force. Therefore, when using explosive dynamic motions, the downward eccentric part of the action should be the focus rather than the explosive concentric phase. Such a predominance of eccentric load has not been observed in other sports, and is assumed to occur from continual downward displacement, removing the necessity for the forceful concentric actions typical of running and jumping or pushing off from a bicycle pedal (Berg &Eiken, 1999; Foster et al., 1999). Szmedra et al. (2001) observed a considerable intramuscular pressure increase during ski racing, which results in a higher anaerobic load during the turning phase by recognising the eccentric components of ski racing. Muscle hypoxia and ischemia, as well as changed ion concentration and substrate availability, are some of the metabolic processes that follow (Seifert et al., 2005). Due to exhaustion of creatine phosphate (CP), the body uses more glycogen than it did before exercise by up to 50% (Tesch, 1995; Seifert et al., 2005). Aerobic metabolism is also inhibited. Reduced VO2max, larger blood volume reductions, increased lactate accumulations at given speeds, and disproportionately high heart rates are all effects of the large knee flexion and large slow sustained contractions typical of ski racing. These effects ultimately lead to decreased blood perfusion of the active muscle (Petrofsky&Hendershot, 1984). As a result, muscular ischemia and an increased reliance on anaerobic metabolism also happen (Rundell, 1996; Foster et al., 1999; Szmedra et al., 2001). The variations in mechanics and physiology between the various professions are also intriguing and important for training. For instance, Szmedra et al. (2001) studied SL and GS utilising near-infrared spectraphotometry to assess blood volume oxygen desaturation of the VastusLateralis, compared with maximal values identified during thigh cuff ischemia. During GS, the change in blood volume was 30% larger than during SL. In GS compared to SL, HRmax was greater and muscle oxygen desaturation was 33% higher. Berg and Eiken (1999) examined the joint range of movements and velocities of the several disciplines. While the speed of movement was more than twice as rapid in SL as GS, the angles at the ankle, knee, and hip were all smaller for GS (Berg &Eiken, 1999; Szmedra et al., 2001).

Fatigued muscles

The mechanical mechanisms causing fatigue and the ensuing decreases in force generation and performance further complicate the metabolic milieu of eccentric load described above.

Eccentric load has been discovered as a significant mechanical destroyer due to its impact on the actin-myosin crossbridge rupturing (Seifert et al., 2005). Increases in the indicators of muscle injury were a sign of metabolic stress, according to Seifert et al. (2005) who discovered this by regulating the work (mechanical) load among all individuals. Muscle ischemia, hypoxia, changed ion concentrations, and substrate availability are some of these stresses. Ski conditioning includes the development of the metabolic system to handle these shocks. It has been discovered that endurance training lowers phosphocreatine depletion (and lowers ADP buildup), improves ATP synthesis, increases lactic acid's oxidative capacity (by preventing the accumulation of lactic acid and inorganic phosphate, which results in an altered ion concentration), and raises antioxidant levels (Kuno et al., 1994; Subidhi et al., 2001). In contrast to more conventional high-intensity interval-based training, the effects of low-intensity, high-volume aerobic exercise on muscle metabolism and force output in skiers are still unknown. However, it's possible that the capillarization produced by low-intensity, high-volume activity helps the body adapt to the mechanical and metabolic milieu of persistent eccentric contractions, which causes weariness (Duvillard, 1995; Kyrolainen et al., 1998).

Muscle fibre type has an impact

The concept of the impact of type I and type II fibres and how they affect skiing performance was first proposed by Tesch et al. in 1978. Examining patterns of glycogen depletion, elite DH skiers showed increased. For 30 junior racers, mean joint angles and heamoglobin/myoglobin oxygen desaturation were measured during simulations of giant slalom (GS) and slalom (SL) skiing. (2002) Szmedra et al.

O2 desaturation in the arterial maximum (%) Heart rate (beats per minute) 79.2 65.7 177.3 10.6 171 14.7 *1801 5 complete joint extension Turnbull et al. 152 during race training (Tesch et al., 1978; Steadman et al., 1987) than unskilled (ski school) individuals, with less fast twitch (FT) fibre depletion. Additionally, compared to novice skiers, elite skiers have 10% more ST fibres (Steadman et al., 1987). The research of Thorstensson et al. (1977, in Koutedakis et al., 1992) and Nygaard et al. (1978), which discovered less ST recruitment in leisure skiers than in more experienced skiers, are comparable to the findings of the present study. An STendowed skier may be better able to withstand the ischemia and hypoxia of low angular velocity contractions, enabling them to use their aerobic capacity more effectively than a skier who is mostly FT. Since ST fibres are surrounded by more capillaries than FT fibres, anaerobic byproducts that cause fatigue will enter the circulation more readily (Duvillard, 1995; Kyrolainen et al., 1998). Early research revealed patterns of ST dominance, however the impact of new ski technology and the creation of quicker courses may indicate that a higher proportion of FT fibres may be beneficial (Steadman et al., 1987; Hartmann et al., 2005). To better understand how different fibre types respond to ischemia circumstances and the high forces needed for racing turns, more research is needed.

Seasonal variations in physiological parameters

There isn't much time for improving physical fitness due to the duration of the competition season and the requirement for as much technical, on-snow training as possible throughout the off-season. If there are little opportunities to develop physical attributes, genetic skill may become more and more crucial to success. However, a large portion of the work has focused on preserving physiological capacity and measuring changes in these parameters within and across seasons (Koutedakis et al., 1992; Bosco et al., 1994). Before, during, and after a period of on-snow training, as well as during a 5-month competition period with no regular off-snow physical training, Bosco et al. (1994) studied the effect of strength and jumping exercises in comparison to typical aerobic conditioning. Over the course of the training period, a considerable improvement was made in the neurological capacity for strength and explosiveness. Skiing provided a sufficient training effect to preserve the ability to use explosive strength, since this effect was not considerably reduced and was even somewhat boosted when training was substituted with ski racing (Bosco et al., 1994). In agreement, Neumayr et al. (2003) asserted that training on snow provides adequate anaerobic power training. Instead of emphasising anaerobic power techniques, they suggested that high-intensity training should concentrate on anaerobic capacity and "lactate tolerance." While using a 30-s Wingate to measure power, Koutedakis et al. (1992) and Karvonen et al. (1985) discovered post-season decreases in average and peak power. As the season went on, Koutedakis et al. (1992) also discovered that the force capacity at low angular velocity (601/s) significantly decreased. Last but not least, the same study noted rising weight and body fat measurements over a competitive season and linked this to a deficiency in regular, systematic "on-snow" training. These studies highlight the importance of developing a thorough grasp of on- and off-snow work rates as well as a reliable integrated nutrition, recovery, and aerobic power programme.

Directions for future research

The energy requirements of a single ski run or the general skiing capacity are extensively discussed in the current skiing literature. Little attention has been given to the physiological requirements of single or multiple day race training, with the exception of Kahn et al(1993, .'s 1996) work with sedentary volunteers evaluating the cardiovascular responses to many days of skiing. It is necessary to quantify the amount of energy used, muscle damage, and nutritional requirements over one or more days of intense race preparation. The race itself, as well as activities like free skiing, lift riding, waiting in lines, and discussions with coaches, all have an impact on the training, recovery, and dietary needs. Quantifying the more qualitative elements of skiing, such as agility, balance, flexibility, motor ability, skill, and psychological variables, such as imagery and concentration, among top racers is of interest given the conflicting reports of aerobic vs. anaerobic requirements in ski racing and the fact that

technical skill remains crucial (White & Johnson, 1993). Additionally, technology like EMG, high-speed video, GPS, insole force plates, and fusion motion capture technology might be used more for general research as well as to give specific athlete feedback regarding course type (difficult or fast) and terrain (steepness and snow/ice condition) (Brodie et al., 2007).
It is also required to perform a more detailed physiological analysis of World Class skiers, paying particular attention to tissue oxidation, fibre type, mitochondrial density, and enzymatic variations. Further research is required, in particular, to understand how fibre types are distributed and how they are metabolised in relation to an athlete's ability to handle cold, altitude, high force, and ischemia circumstances. The effects of low-intensity/high-volume versus high-intensity/low-volume labour on muscle metabolism and force output during ischemia ski conditions need to be better understood. Short-term and descriptive research are frequent in the ski industry. Longitudinal research must be conducted in order to fully comprehend ski racing and how physical conditioning may affect performance. The type of athlete who can succeed as a skier can be revealed by tracking athletes from their entry into top-level competition through their physiological development as they mature. The periodization of training and the identification of talent may benefit from this information (Bacharach &Duvillard, 1995). Additionally, a number of authors mention a possible cutoff point at which further enhancements in physical ability (like increased flexibility or strength) stop enhancing skiing performance (Brown & Wilkinson, 1983; Neumayr et al., 2003). If this is the case, identifying these points will assist national teams in establishing criteria for team selection and provide guidance for training regimens.

2. CONCLUSIONS

Ski racing is a complex sport that draws heavily on a range of energy systems. Skiers practise and compete in extremely cold, high-altitude, and physically demanding conditions that require unpredictable, prolonged, high-force muscle contractions. The circumstances and intricacy of ski racing make research challenging and it challenging to precisely assess the physiological demands of ski racing. This situation poses an ongoing challenge for sport scientists and conditioning specialists to develop properly structured training and periodization programmes, explain who is most suitable for ski racing, or identify whose physical capabilities may lend them to alternative sports until more research is conducted. Accurate athlete profiles that are free from prejudice resulting from nation-specific training methods must still be created for today's top athletes on the international stage. Given advancements in ski technique and technology as well as physiological monitoring technologies, it is also necessary to determine the precise physiological costs of ski racing and the efficacy of aerobic vs. anaerobic training techniques.

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