FACTA UNIVERSITATIS
Series: **Physical Education and Sport** Vol. 13, N° 2, 2015, pp. 167 - 176

Systematic review

LIMITING FACTORS FOR SUCCESS IN ALPINE SKIING

UDC 796.926:531.1

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Abstract. *For success in skiing, it is essential to know the characteristics of the kinematics and motion dynamics, morphological, functional and motor characteristics of skiers. Skiing is characterized by movements down the slope during which a skier overcomes inertia forces of approximately three times the weight of his own body. The movements of moderate speed dominate mainly in terms of isometric and eccentric contractions. The intensity of the forces of the engaged muscle groups, positions of body segments, amplitude and speed of movements in different joints vary depending on the competitive discipline. The knowledge of the mentioned characteristics of skiing is important for quality planning of training, choice of exercises and training methods. The choice of tests to assess this ability should be based on the knowledge gained by analyzing the characteristics of the movement of skiers. This paper analyzes the basic morpho-functional, kinematic and dynamic characteristics of skiing.*

Key words: *alpine skiing, kinematics, dynamics*

INTRODUCTION

Alpine skiing is a sport that is practiced recreationally or for competitions by 200 million people around the world. Only in the United States ski resorts, in the 2011/012 season, there were 7 million skiers who made 58.9 million ski days. Studies in the field of competitive and recreational skiing date back to the 1970s. The results of these studies should be interpreted in accordance with the methods and equipment used in the different periods but also in accordance with the significant changes that followed in the last 10-15 years. The following was improved: snow conditions (solid snow-surface, more compact artificial snow); the technical characteristics of skis (smaller radius of the side cut of the skis, better torsional stiffness); "rapid gate" poles (which allow shortening of the path in a turn); new discoveries in the technology of training etc. The changes have caused faster, more dynamic skiing, greater demands on the morpho-functional capabilities of

Received October 13, 2014/ Accepted February 20, 2015
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competitors and changes in the methodology of training. For the detection of the success factors in skiing, it is necessary to know the characteristics of movement, type and intensity of muscle activity, the characteristics of the energy mechanisms, combination of morpho-functional characteristics, characteristics of sex, age, etc. It should be borne in mind that skiing takes place in the particular circumstances of high altitude, cold, moisture etc. The study aimed to analyze characteristics of modern skiing in terms of morpho-functional capabilities and kinetic and kinematic characteristics of the movements in various disciplines. Examining the structure of the following characteristics allows for a more effective analysis of the movements as well as better planning of the training cycle.

CHARACTERISTICS OF MODERN SKIING

One of the characteristics of modern skiing is an extension of the competitive career. In the 1967-71 seasons, the average age of medalists (OWG, WSC, WC) was 20.7 (♀) and 24.3 (♂) years and in the 2009-13 seasons it was extended to 25.8 (♀) and 28.7 (♂) years, which is a career move by approximately 5 years (FIS, 2014). Alpine skiing, whether it is competitive or recreational, involves increased physical effort, work at a higher altitude, use of specific equipment and movement in non-standard conditions. Competition in Alpine skiing consists of two speed and two technical disciplines, determined by a vertical offset between gates and the length of the course regulated by the International Ski Federation. In this manner the turning radius and speed of movement are indirectly determined. Speed disciplines: Downhill (DH) and the Super Giant (SG) imply an average speed of around 70-100 km/h (some sections up to 130 km/h), large-radius turns, jumps and race duration of 90-150 s. Technical disciplines include: Giant slalom (GS) and Slalom (SL) with a shorter and more frequent turns, at speeds of 20-60 km/h and duration of 60-90 s (GS) and 45-60 s (SL). These data indicate that in assessing the ability of the competitors, the differences and particularities of competitive disciplines: duration, intensity, frequency, movement, the types of muscle strain etc. must be taken into account. Alpine skiing is seen as a complex sport of high intensity from the category of acyclic polystructural sports that requires specific skills. During the turn in skiing, both legs conditionally perform the same task, in such a way that each leg alternately plays the role of the dominant (the guide) and the other follows the activity with reduced intensity and load (Ilić, Ropret, Ilić, 2010, p. 112). Therefore skiing can be categorized as a bilateral, rather than unilateral sport. By moving down the slope, a skier generates high kinetic energy. Changes of direction cause an increase in the centrifugal force and an increase in kinetic energy, thus causing severe compression forces that primarily load the leg extensors. The development of modern equipment and the processes of the snow surface preparation caused the change in kinetic and kinematic parameters of movement and thus the need for the adaptation of skiers' abilities to the new requirements.

ANTHROPOMETRIC CHARACTERISTICS OF COMPETITORS

Today's athletes are heavier than their predecessors 30 years ago (White & Johnson, 1991), probably due to a higher volume of training for the muscles of the arms and shoulders (Neumayr et al., 2003). In search of the predictors of success in skiing, the assessments of impact of body composition on the performance of athletes in skiing were carried out. It was found that the average value of the percentage of body fat in senior competitors was 20-24.5% (♀), and 8-15.5% (♂). In the junior age group, the most common was endomorph/endo-mesomorph (♀) and mesomorph (♂) while in the age of senior women, the mesomorph somatotype was prevalent. This parameter is not associated with success in skiing competitions, except in the case of boys (r=0.70, p=0.003) (Emeterio & Badillo, 2010). Studies on the role of body mass (BM) and body height (BH) were conducted on male and female skiers, participants in OWG, WC and WCH, in the 1997-2000 and 2006-2010 seasons (Hraski & Hraski, 2010). The descriptive indicators showed that shorter and lighter competitors have more success in SL, and taller and heavier in DH. Within each discipline, among the top 30 skiers, there were no statistically significant differences in basic anthropometric characteristics. Significant differences were noted between the categories of top versus lower placed competitors, i.e. between those placed between the 1st and 10th place and those above the 30th place.

Previous studies have found no significant association between anthropometric characteristics and competitive results, which was another contribution to the view that competitive success in Alpine skiing does not depend on one, but a number of motor skills as well as other psychological factors (Emeterio et al., 2010).

Table 1 Anthropometric characteristics of female/male skiers in the 1999/2000 season (Neumayr et al., 2003)

	Mean value (♀/♂)	SD	Range of values (♀/♂)
Age	25,2 / 27,6	3,9/3,5	19-33 / 21-34
BH (m)	1,66 / 1,81	0,05/0,06	1,59-1,76 / 1,72-1,96
BM (kg)	65,1 / 87	6,5/7,1	52,5-77 / 72-103
BMI (Kg/m²)	23,6 / 26,5	1,7/1,7	19,6-26,1 / 22,2-29,1
Percentage of fat (%)	24,5 / 15,8	3,6/3,7	16,3-30,6 / 9,4-21,3
Thigh circumference (cm)	59 / 64,5	2,5/1,5	53-63 / 59-67

Characteristics of Muscle Activities during Skiing

Activity of muscle groups

For the further determination of the elements that influence success in skiing, it is necessary to know the role of muscle groups, the mode and intensity of their activities. In addition to the dominant role of the leg muscles, muscles of the lumbar-abdominal section with the muscles of the pelvis are actively involved in skiing, while the percentage of arms and shoulders, in terms of strength and power, is of minor importance. Previous studies were predominantly focused on the monitoring of EMG activity from 3 to 12 different muscle groups of the legs and body during different variants of the turn (Grimm, Krexa & Asang, 1978; Müller, 1994; Berg, Eiken & Tesch, 1995; Hintermeister et al., 1995; Hintermeister et al., 1997; Kroll Wakeling, Seifert & Muller, 2010). Depending on the type of turns, *m rectus femoris* manifested the greatest activity, *m adductor* was the most active at the end of the snowplow turn (Pl) and in SL, *m tibialis anterior* and *m peroneus longus* were active during all the turns, *m gluteus maximus* and *m quadriceps* especially during movements of extension, while *m tricepsure* had a minimal role. Muscle activity increased from the Pl over the SL and the largest recorded was during GS (Pl<Sl<GS). The exception is the *m gluteus max*, which

manifested the greatest activity in Pl. The reason is the role of this muscle group as an antagonist and stabilizer during the internal rotation of the thigh, which is typical in the Pl turn position. The muscle activity of competitors was more dynamic, with more pronounced changes in the activation and relaxation, as opposed to recreational skiers with dominant long-term phases of continuous low-intensity activities. The average intensity of muscles in competitors ranged from moderate to high (58%-112% MVC). The highest peak of activities was detected in the *m biceps femoris* (283±52% MVC), *m erector spinae* (268±55% MVC) and *m adductor* (245±51% MVC) which indicated the size of the external load, the role and importance of these muscle groups. The lowest average intensity of activity was detected in the *m obliques external* (16% MVC) but it showed considerable variation depending on the phase of the turn. The difference in the EMG activity of the *m rectus femoris* in the inner and outer leg was not significant and in the *m vastus lateralis* was increased by 54% in the outer (dominant) leg (Kroll et al., 2010). The difference can be explained by the fact that the outer leg is dominant, leading the turn and that the load is on the outer leg, as well as that the work is performed under the conditions of eccentric contractions. At the same time, the inner leg is often lifted from the ground with the participation of the *m rectus femoris* as a flexor in the hip joint. The increase in slope (from 13º to 29º) significantly altered the intensity of muscle activity of the *m vastus lateralis* by 90.8% and the *m rectus femoris* by 115% (Kroll et al., 2010). It is obvious that the slope increases the speed and thus the inertial forces that must be overcome by increased muscle activity. These functional requirements can be of importance in the training methodology and the choice of an appropriate terrain in accordance with the students' abilities.

Based on the abovementioned, it can be concluded that muscle activity depends on the type of turn, phase of turn, slope of the terrain, speed of movement and the level of skiing knowledge.

Muscle fibres composition

The effectiveness of movement is significantly associated with the structure of the fibres of active muscle groups. Previous studies (Thorstensson, Larsson, Tesch & Karlsson, 1977; Karlsson, Eriksson, Forsberg, Kallberg & Tech, 1978; Nygaard et al., 1978; Tesch, Larsson, Ericsson & Karlsson, 1978; 1995) found that top skiers primarily recruited slow twitch muscle fibres, while less skilled skiers used fast twitch fibres with pronounced static positions. The percentage of slow fibres was about 10% higher among top class skiers compared to lower quality skiers. These results should be taken with caution because the study was conducted on a small sample, based on the consumption of glycogen, which requires a relatively long activity (over 10 min), in this case, after a day's skiing. The comparison is not possible with competition activity that is of significantly shorter duration and higher intensity. For real parameters, we need studies on international level competitors in different disciplines, bearing in mind the features of eccentric contraction, whose physiological characteristics have not been not fully explained (Ferguson, 2009).

Regime of muscular work

Downhill displacement under the force of gravity and centrifugal force causes a specific mode of muscle work. In previous studies, experiments with the intensity of maximal voluntary contraction (MVC), a significant portion of eccentric contractions compared to concentric ones was established. During the GS turn, the intensity of the eccentric contraction was considerably higher (about 80% MVC) compared to the concentric ones (less than 50% MVC) (Berg & Eiken, 1999; Hintermaister et al., 1997). Eccentric contractions were characteristic for the second phase of the turn (two thirds of the complete turn) when movements of a relaxing mode of operation dominated for the purpose of opposing the inertial forces and maintaining the position (Berg et al., 1995). Compared with national level athletes, national team skiers exhibited greater strength during eccentric but not during concentric contractions of the knee extensors, indicating the dominance of this mode as well as the specificity of Alpine skiing (Hoshino, Tsunoda & Sasaki, 2007). The significant duration of the co-contraction phase of the *m quadriceps* and hamstrings thigh muscles indicates the existence of phases of isometric contraction during the second phase of the turn (Hintermeister et al., 1995).

Based on the abovementioned, it can be concluded that during the turn a skier generates significant kinetic energy which he must oppose to achieving great power in the eccentric contraction. The largest load is in the second part of the turn phase (2/3 of the total length of the turn) and therefore the muscles need to achieve an adequate force which will be proportional to the mass and speed of skiers, and inversely proportional to the radius of the turn.

KINEMATIC AND DYNAMIC CHARACTERISTICS OF SKIERS' MOVEMENT

Joint angles and amplitudes of movement

During skiing, the average joint angle values are in the range of 81º-129º in the hip, 114±26º in the knee of the outer and 101±16º of the inner leg (full extension=180°). Angle values depend on the phase of the turn and the competition discipline. Average values of the angle in the knee joint in SL are greater than in GS and DH (lower position for lower air resistance). The amplitude of the knee joint angles during the movement of extension and flexion ranges from 20° to 50º (Berg et al., in 1995, Berg et al., 1999; Spitzenpfeil, Huber & Waibel, 2009). The inner leg in turn always has lower angle values (is more flexed) than the outer one in all disciplines, by about 20° in the knee and 11° in the hip joint (Berg et al., 1995).

Knowledge of the position, amplitude and speed of movement is important for defining the methodology for testing and training planning. A common measurement of knee extensor strength in isometric and isokinetic conditions at an angle of 90° does not correspond to real situations in skiing. Measurements should be made at angles of 100° to 120° (Raschner, Pühringer, Patterson & Platze, 2004).

Table 2 Basic parameters of turn in various disciplines (Berg et al., 1999)

	Angles of the knee at maximum and minimum load (º)	Angular velocity (º/s)	Turn duration L + D (s)
SL	98-111	69±11	1,6±0,2
GS	86-114	34±2	3,5±0,6
SG	83-96	~17	~4,1
FM*	62-133	~300	~0,8

*FM- free moguls (skiing on a mogul slope)

Movement speed

Contrary to the impression that Alpine skiing is a dynamic activity with a lot of explosive movements, the values of movement speed and angular velocity of the knee and hip joints showed the opposite, i.e. that skiing was not a sport that was characterized by high movement speed (Berg et al., 1995; Patterson, Raschner & Platzer, 2009). Even the highest movement speed of 69º•s^{-1} in SL was far from the knee angular velocities of a sprinter (1000º•s^{-1}) or a cyclist (200-400º•s^{-1}) (Abe, Kawakami, Ikegawa, Kanehisa &, Fukunaga, 1992; Jacobs, Bobbert & Van Ingen Schenau, 1993; Tech, 1995; Berg et al., 1999). The shortest movements (unloading during the initial phase of the turn) had an average duration of 150 ms in SL and 250 ms in GS (Kroll et al., 2010). Angular velocities of the knee joint amounted, depending on the discipline, from 20-69°• s^{-1}. The highest ones were found in SL and in other disciplines they were significantly lower (Berg et al., 1995; 1999). There were no significant differences in hip joint angular velocity during the movements of extending (21°•s^{-1}) and flexing (22°•s^{-1}). While measuring ground reaction forces, it was observed that skiers attained maximum results later and the measurement of this parameter was suggested in the first 200 ms instead of the usual 100 ms (Patterson et al., 2009). These data are important in terms of the selection of tests for strength and power. The tests that are used to estimate ground reaction forces should be aligned with the characteristics of skiing movements.

Aerobic and anaerobic capacities

Bearing in mind the short duration of a competitive activity (45-90 s), high intensity and work at a high altitude, the question is the role and importance of aerobic capacities of skiers for their competitive success. Previous studies established different values of VO_2max: 52 ml/kg/min (Veicsteinas, Ferreretti, Margonato, Rosa & Tagliabule, 1984), 59-67 ml/kg/min (Andersen & Montgomery, 1988); 65 ml/kg/min (Tesch, 1995); 55±3.5 ml/kg/min (♀) and 60±4.7 ml/kg/min (♂) (Neumayr et al., 2003). After the GS race, values were recorded from 75%-95% and after the SL the values went up to 200% of VO_2max (Veicsteinas et al., 1984, Andersen et al., 1988). In the total energy requirements of GS and SL races, aerobic sources accounted for 40%, alactate 20% and lactate 40% (Andersen et al., 1988). Significant differences in aerobic capacities were registered only in the comparison of top skiers with those of lower rank, but not within the category of top skiers. In comparing a group of specialists and a group of all-round competitors, extensive differences in aerobic power were not found.

It can be concluded that skiing itself is not an activity that significantly stimulates aerobic capacity, despite high labour intensity at high altitude. High values in some cases (individuals and teams) refer to their individuality and the results of aerobic training in the pre-competitive season. The values of the aerobic capacities of skiers may be associated with their indirect role of providing basic skills important for the development of anaerobic abilities and recovery after specific training and everything related to work at a high altitude. Lower values in aerobic capacity should not be a limiting factor in the ability of individuals to become top competitors.

The assessment of the anaerobic power of skiers and correlation with the success rate has been the subject of several studies (Simoneau, Lortie, Bouray & Bouchard, 1983; Stark, Reed & Wenger, 1987, White et al., 1991; Bacharach & Duvillard, 1995). The conclusion of the researchers was that the standard Wingate test lasting 30 s did not significantly correlate with the success rate as opposed to the test lasting 90 s, where the level of correlation with success in SL and GS was within the limits of significance. The conclusion and recommendation of these studies is to make an assessment of the anaerobic capacities of skiers using the 90 s test.

Muscle strength

A simple observation of the skiers' movements indicates that leg strength and power have an important role in controlling movement on skis. Initial studies showed a high correlation between strength and power and success in skiing (Tesch et al., 1978; Haymes & Dickinson, 1980). Along with the development of the technology of strength training, studies showed that it was not in direct proportion with success (Andersen et al., 1988; Neumayr et al., 2003). Bearing in mind the different methods of evaluating strength, it is difficult to compare the results of previous studies. Only the conclusions based on data can be compared. Top skiers, in the conditions of isometric contractions manifest force, on average, of 3.7-4.2 N/kg^{-1} and female skiers of approximately 10-15% less (Tesch et al., 1978; Haymes et al., 1980; Berg et al., 1995). The importance of leg muscle strength is reflected in the fact that, during the turn, the increase from 0.5 to more than three times the body weight of skiers was registered (Klous, Muller & Schwameder, 2007). The highest values were recorded during the second phase of the turn. The measured values represented the load of the outer leg while the inner leg showed significantly lower values in the approximate ratio 70%:30% (Spitzenpfeil et al., 2009). The intensity of the demonstrated force depends on the type of turn and movement speed. It is largest during the GS turn, slightly lower during the SL and significantly lower during the Pl turn (GS>SL>Pl) (Spitzenpfein et al., 2006). The centrifugal force exerted on a skier during the turn is directly proportional to the mass and the square of the speed of skiers and inversely proportional to the radius of the turn. As speed increases and/or reduces the radius of the turn, the centrifugal force increases. Lower speed with a smaller radius in the SL (35-45 km/h) as opposed to a higher speed and a larger radius in the GS (45-55 km/h) may be explained by the relatively small difference in the activity of the muscle groups during the SL and GS turns in relation to the Pl turn (8-20 km/h) (Supej, 2009).

Given that skiers overcome the considerable inertia force of their own body, it is important to relativize the values to their own BM. In future studies, it is necessary to apply the appropriate methodology and the selection of tests which take into account the specific nature of skiing.

Muscle power

Quick changes of direction require dynamic movements of flexion and extension, i.e. the expression of a significant level of power. Experiments from 30 years ago, when weight training was not used in the training of skiers, indicated that elite skiers possessed great power, primarily of the leg extensors. Today, this is confirmed by isokinetic tests in which the values of power are realized during relatively slow movements, when the angular velocity of movement in the knee joint does not exceed 30°/s (Tech, 1995; Thorstensson et al., 1977; Berg et al., 1999). Researchers believe that there is no other sport that is characterized by the dominance of the high volume of slow eccentric movements and generally movements that require power at such low speeds (20-40°•sec^{-1}). Compared with other athletes, in the conditions of slow movements, skiers show significantly better results. However, when power is tested by movements at high angular velocities, the level of demonstrated power is similar to that of other athletes. Elite skiers compared with less successful skiers showed significantly greater muscle strength of the knee in eccentric but not in concentric contractions (Abe et al., 1992). At low speeds (30°/sec) there was no difference in the manifested power between men and women (relativized according to BM), while at high speeds (180°/sec) men have higher power (Haymes et al., 1980). These results are yet another confirmation of the dominance of small angular velocities and eccentric movements in skiing. Taking into account previous studies on the speed of movement and manifested power, the assessment of the force development rate should be measured in the first 200 ms because the usual standard protocols of 100 ms are not suitable for skiing (Patterson et al., 2009).

The specificity of skiing as a sport dominated by eccentric contractions makes it difficult to compare with other sports in which this dominance is not expressed as much. Taking into account the specificity, it is clear that in the training of skiers, the method with overload in the eccentric mode should be applied. Traditional resistance training and plyometric exercises are methods and tools that contribute to the development of abilities, but according to these findings, they will not contribute to the development of specific abilities of the muscular system characteristic for efficient skiing. Obviously, the methods and tools should, in addition to concentric, include isometric and eccentric modes at low speeds, with an emphasis on overloads in the eccentric mode.

CONCLUSION

In the last 30 years, there have been significant changes in ski equipment and the competition technique, which led to changes in the methodology and technology of training. The career of competitors has been extended by 5 years. Contemporary skiers have higher body weight than their predecessors. Body weight and height are significant in fast disciplines due to inertia factors. As for the top competitors in individual disciplines, anthropometric characteristics are not associated with the success rate. Given the duration and intensity of the activities, aerobic abilities participate in providing 40% of the total energy needs. Therefore, skiers possess average values of aerobic capacities, and they do not represent a limiting factor for success. They are significant only as a factor of general physical preparedness. Anaerobic sources participate to the extent of 60% of the total energy needs. They are related to the intensity and duration of the activities and the specific mechanical efficiency of eccentric contractions. The development and assessment of anaerobic abilities should be carried out in accordance with the specific nature of skiing. The most loaded muscle groups in skiing are the extensors of the knee joint, rotators and adductors in the hip joint. Slightly less burdened are the pelvic muscles and the muscles of the lumbar region. Because of the specificity of fast downhill displacement and large inertial forces, these muscle groups are exposed to high work in the conditions of isometric and eccentric regime during 2/3 of turn. Loads can range from 0.5 to three times the body weight, and the intensity of muscle activity can be 50-280% of MVC. Speed of movement and angular velocity are relatively small. The work mode conditions, to the greatest extent, the engagement of slow muscle fibres. Positions and relations of body segments, observed through the angles in the knee and hip joints depend on the competition discipline. External loads influenced by the accelerative forces lead to the conclusion that in the methodology of training, it is necessary to apply overload exercises. Maximum forces and the ability of increase in force per unit of time should be trained and assessed in positions and periods close to the specifics of the movement of skiers. Based on the abovementioned, it can be concluded that Alpine skiing is a complex integration of different physiological systems, none of which may be more important than another in overall ability, and that in the development and evaluation of success factors, the specifics of the kinematics and dynamics of skiing must be taken into account.

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LIMITIRAJUĆI FAKTORI USPEHA U ALPSKOM SKIJANJU

Za uspešnost u skijanju bitno je poznavanje svih karakteristika kinematike i dinamike kretanja, morfoloških, funkcionalnih i motoričkih karakteristika skijaša. Skijanje karaktrišu kretanja niz padinu tokom kojeg se savladavaju sile inercije približne trostrukoj težine sopstenog tela. Dominiraju pokreti umerene brzine pretežno u uslovima izometrijskim i ekscentričnih kontrakcija. Intenzitet sila angažovanih mišićnih grupa, položaji segmenata tela, amplitude i brzine pokreta u različitim zglobovima se razlikuju u zavisnosti od takmičarske discipline. Poznavanje pomenutih karakteristika skijanja značajno je za kvalitetno planiranje treninga, izbor vežbi i metoda treninga. Izbor testova za procenu sposobnosti treba zasnivati na saznanjima stečenim analizom karakteristika kretanja skijaša. Predmet rada je analiza osnovnih morfo-funkcionalnih, kinematičkih i dinamičkihi karakteristika skijanja.

Ključne reči: *Alpsko skijanje, kinematika, dinamika.*