Chapter 7

Physical Performance Test Parameters For Alpine Ski Athletes

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Abstract

Alpine skiing competitions require high levels of isometric, eccentric and concentric muscle activation throughout a wide range of motion in the hip, knee and ankle joints. Track times exceeding approximately 40 seconds in slalom and 2.5 minutes in downhill competitions require athletes to have both high-level anaerobic endurance and advanced aerobic capacity and force production ability. However, the structure of alpine skiing, which requires high technical competence, makes neuromuscular coordination one of the determining elements of performance. In this branch, where high-speed turns and sudden changes of direction are dominant, motor skills such as balance, agility, reactive force production and proprioceptive control come to the fore. Therefore, athletes need to go through a multifaceted preparation process supported by special training aimed at not only the physical but also the neuromuscular system. In this study, performance tests specific to alpine skiing competitions are systematically addressed; the relationship between these tests and physiological parameters specific to the sport is explained on a scientific basis. In addition, the contributions of the tests in terms of individualization of training programs, athlete monitoring and performance prediction are also evaluated.

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Introduction

Performance tests play a highly critical role in the assessment of an athlete's physical capacity and sport-specific skills. For these tests to yield effective and meaningful results, they must be directly related to the physiological and biomechanical characteristics of the sport in question. In other words, the tests used are expected to reflect the energy systems, muscle groups, and movement patterns that determine athletic performance. However, this alone is not sufficient; it is equally important that the test protocols applied are scientifically reliable and valid. Reliability refers to the consistency of test results when repeated under similar conditions, while validity indicates the extent to which a test accurately measures what it is intended to measure. In this context, effective performance test protocols should not only include physiological measurements, but also encompass movement mechanics analysis, biomechanical data, identification of injury risk factors, and parameters tailored to the athlete's position, age, training history, and performance level. Moreover, in the design of such tests, factors such as the specific needs of the athlete population, the place of the test within the training periodization, ease of implementation, and suitability for field conditions should also be taken into consideration. This comprehensive approach enables coaches and sports scientists to better interpret the data obtained, thereby supporting individualized training planning, load monitoring, performance tracking, and injury prevention strategies (1). An effective test battery allows for the identification of athletes' strengths and weaknesses, and this information can serve as a foundation for future training plans. Moreover, when appropriately scheduled, regular testing enables the quantitative assessment of training effects on the targeted physiological attributes of each athlete. In addition, the primary purpose of testing is to provide coaches and athletes with guidance based on scientific evidence. Therefore, it is essential that the tests used demonstrate reliability, validity, and a high degree of repeatability (2). Tanner et al. emphasize the need for a systematic approach in the collection, processing, analysis, and reporting of test data. They state that the value of the data obtained is only as meaningful as the quality of the data collection methods and the accuracy of the statistical analyses applied (2).

Achieving high performance in alpine skiing depends on the development of multiple physiological and technical abilities. While all four primary alpine skiing disciplines—Slalom, Giant Slalom, Super-G, and Downhill—impose similar physiological requirements, they differ in the specific patterns of muscular engagement, biomechanical movements, and the relative contributions of energy systems throughout performance.

Alpine skiers exhibit high levels of isometric, slow eccentric, and concentric muscle activations, which distinguishes alpine skiing from many other sports due to the requirement for simultaneous and sustained muscle contractions (3). Successful alpine skiers demonstrate high aerobic power (VO□max), anaerobic endurance, neuromuscular coordination and force generation capacity (4). There is no clear muscle fiber type predominance in alpine skiers, but type I (slow-twitch) fibers appear to predominate (5). Considering the demands of alpine ski racing, a carefully selected test battery is vital for monitoring athletes' performance. For most World Cup skiers, the competitive season lasts from late November to early April. Therefore, conducting regular testing throughout the season is crucial for determining whether athletes are maintaining their physiological capacities and whether they are approaching an increased risk of injury (6). After a short transition period following the competition season, testing can be conducted in late April or early May to assess fundamental performance characteristics and determine the extent to which training residuals have diminished over the course of the season (1). If possible, another test battery should be administered in mid-summer to evaluate progress in the targeted performance attributes. During this period, a noticeable improvement in aerobic capacity and anaerobic endurance is expected (1). The third and final test battery should be conducted in late October or early November, just before the start of training on snow. These final tests allow athletes to predict their progress during off-season training and their safety or injury risks during the competition season. Tests should also be conducted during the competition season at times that suit athletes' schedules and readiness. In this way, it is possible to monitor whether the training has preserved the athletes' physiological qualities (1).

In this context, a systematic performance monitoring approach should be developed, and tests conducted at specific times throughout the year should be used to track changes in the athlete's physiological capacity. Transition period tests conducted after the competition season are important for identifying performance characteristics that have improved or declined over the season. Summer testing allows for the evaluation of developmental goals, while pre-season testing provides an objective assessment of training effectiveness and the athlete's readiness for competition. Finally, regular and periodic testing during the competitive season helps determine whether performance levels are being maintained and whether injury risks are increasing. Therefore, this book chapter aims to comprehensively address the design of test batteries tailored to the physiological and biomechanical demands of alpine skiing, the selection of tests based on validity and reliability, and their integration into the training process.

Movement Analysis in Alpine Skiing Performance

Alpine skiing requires a high level of neuromuscular coordination, particularly during turns between gate combinations, which are considered critical elements of race performance. These turns involve maintaining edge control and balance while effectively managing the applied forces, a process that necessitates sufficient lower-body agility (7, 8). This movement is generally divided into four main phases: initiating the turn, turning, completing the turn, and transitioning. Hydren et al. (7), summarize the start phase as the moment when the shoulder passes the gate closely and the athlete's body weight is supported by the rolled ski edge on both uphill and outside legs. The turn phase occurs when the shoulder becomes parallel to the snow surface and the outside leg is extended and the inside leg is bent, bringing the hips closer to the snow surface, achieving a higher edge angle (7). Then, the completion phase is observed with the bending of the outer leg and the elevation of the hips, which reduces the edge angle of the skis (7). In the phase of transition, the athlete's feet move inward beneath the hips and descend, enabling a shift in body weight from the outer ski to the inner one (7). This process is repeated sequentially throughout the course and varies depending on the speed and forces encountered by the athlete, the slope gradient, and the discipline being raced. The forces generated during turns typically range between 1 and 2.5 g (and can reach up to 3 g in some cases, where "g" refers to gravitational acceleration), with these forces primarily exerted through the outside ski, which is responsible for steering (7, 9). Throughout the turning motion, knee flexion (eccentric force), static contractions (isometric force), and knee extension (concentric force) occur. During turns, the average angular velocity of the knee is approximately 69±118°/s in Slalom (SL), 34±62°/s in Giant Slalom (GS), and around 178°/s in Super-G (SG) (7, 9). These velocities are considerably slower compared to approximately 300°/s observed in running gait and about 650°/s in sprinting gait, indicating that muscle contractions in alpine skiing occur at a slower rate (5). The duration to complete a turn is approximately 1.6 seconds for Slalom (SL), 3.5 seconds for Giant Slalom (GS), and around 4.1 seconds for Super-G (SG) (5). Turnbull et al. note that near-maximal voluntary muscle contractions are observed in SL races, which reduces muscle blood flow and insufficient strength limits a skier's ability to maintain stance and resist high forces (5).

Various biomechanical elements also play a significant role in skiing performance, such as how energy is managed throughout each turn, the influence of aerodynamic resistance and surface friction, the magnitude and direction of ground reaction forces, the curvature of the turn, and the path followed by the skier's center of mass (10). SL and GS are generally affected by early initiation of turns, longer path lengths and trajectories, and earlier, more uniform ground reaction force cut-off (11, 12). Achieving high velocities in downhill (DH) skiing largely depends on minimizing air resistance and consistently maintaining an aerodynamic posture. In support of this, Federolf et al. explored how variations in skier body motion impact glide duration and performance outcomes in competitive settings. Analysis of 68 recorded passes shows that glide times are affected by the use of the skis' edges, while forward and backward leaning does not have the opposite effect (12). This suggests that this is due to increased ski-snow friction and that skiers should minimise their use of edges during the sliding portions of the race whenever possible to improve performance (12). In conclusion, alpine skiing requires a series of movements characterized by relatively slow knee angular velocities, combining slow eccentric and concentric muscle contractions with periodic isometric muscle actions. The biomechanical factors influencing performance are not only related to force production capacity or muscle contractions but also involve the reduction of friction, aerodynamic drag, and overall ground reaction forces. Careful evaluation is necessary when analyzing alpine skiing movements, as significant variations exist between each discipline.

Physiological Assessment

The contribution of energy systems in alpine skiing has long been a subject of ongoing debate among sports scientists and coaches. This is primarily due to the diverse metabolic demands of different race disciplines and the physiological differences between elite-level athletes and recreationally trained individuals. Research has shown that speed skiing is composed of approximately 46% aerobic, 26% glycolytic, and 28% phosphagenic energy system contributions, whereas technical skiing consists of about 30–35% aerobic, 40% glycolytic, and 25–30% phosphagenic contributions (4, 5, 7, 13-17). Elite skiers tend to have higher lactate levels compared to non-elite or novice skiers and possess a greater capacity for repeated force production (5, 18). Moreover, elite-level skiers often reach 80–90% of their VO_2max, whereas less experienced or less skilled skiers rarely exceed 60–70% of their VO_2max (4). Moreover, elite downhill (DH) and super-G (SG) skiers can reach speeds of nearly 160 km/h during competition (16). One could argue that aerobic capacity is critical for recovery during training, which can last for several hours and require multiple (anywhere from 4 to 14) runs, thus allowing for increased training capacity that ultimately contributes to the highly technical skill aspect of the sport (19-21). In conclusion, the contribution of energy systems in alpine skiing varies depending on the characteristics of the race discipline and the athlete's skill level. This variability necessitates the individualization of training programs and performance assessment methods. The fact that elite athletes possess higher metabolic demands and advanced physiological adaptations indicates that training should focus not only on general endurance but also on tolerance to metabolic by-products and the maintenance of neuromuscular function. In this context, discipline-specific and skill-level–specific approaches are crucial for maximizing the athlete's performance potential and ensuring optimal performance during competition. The primary goal of training is to increase the athlete's resistance to the accumulation of metabolic by-products at high levels, thereby minimizing the impact on force production capacity and neuromuscular coordination (3).

Providing postural control and balance during skiing is extremely important for the athlete to be able to stabilize the body during gliding and adapt to fast movements. This process requires the active and coordinated involvement of large muscle groups, especially the quadriceps. The quadriceps muscles play a critical role in the stabilization and control of the knee joint, helping to maintain balance and support the body during sudden position changes. In addition, effective use of these muscle groups makes it possible to resist external forces generated during gliding and thus reduce the risk of injury. Hintermeister et al., analyzed the EMG activity of skiers from the U.S. and British national teams and found that the quadriceps muscles exhibit their highest activation during the final phase of the turn and the early part of the carving motion. This phase corresponds to when the skier experiences the greatest forces. Additionally, the tibialis anterior muscle showed significant activation, as it is responsible for producing the dorsiflexion that helps position the skier leaning forward towards the tips of the skis. (22). In addition to the quadriceps, several other muscle groups play a vital role in maintaining stability and performance during skiing. The primary muscles involved consist of the rectus and transverse abdominis, external obliques, inner thigh muscles (adductors), the spinal erectors, and the gastrocnemius. These muscles work together to provide core stability, support proper posture, and facilitate dynamic movements required on the slopes. Furthermore, the hamstrings and gluteal muscles exhibit significant eccentric muscle actions, which are essential for absorbing and controlling the impact forces encountered on uneven and variable terrain. This eccentric loading helps to protect the joints from excessive stress, enhance shock absorption, and maintain balance during rapid changes in direction or unexpected perturbations. Collectively, the coordinated function of these muscle groups is critical for effective movement, injury prevention, and optimal skiing performance (7, 10, 23). High levels of muscle co-contraction occur at various stages throughout a run, playing a crucial role in supporting both balance and postural stability. This coordinated activation of opposing muscle groups helps to stabilize the joints, maintain body alignment, and enable precise control during dynamic movements on the course (22, 24).

Evaluation of Athletic Performance

For performance tests to be successfully administered and the results to be accurately interpreted, it is of great importance that the tests used are highly reliable, valid, and relevant to the specific sport discipline. Therefore, during the evaluation process, it is critically essential to select a test battery that is scientifically grounded, tailored to the characteristics of the athlete, and possesses sport-specific qualities (2). To comprehensively monitor athlete performance, five key assessments are recommended, ideally conducted over two separate training sessions. The suggested testing sequence includes: (a) dynamic balance evaluation via the Star Excursion Balance Test (SEBT), (b) assessment of explosive lower-body power through the countermovement jump, (c) measurement of maximal strength using the isometric squat, (d) evaluation of power endurance with a weighted repeated jump protocol lasting 2.5 minutes, and (e) estimation of aerobic capacity through the 20-meter maximal shuttle run test. The recommended sequence for completing the tests is as follows, ideally divided across two separate training days to minimize fatigue and ensure accurate results: (a) the Star Excursion Balance Test (SEBT), which assesses dynamic balance and postural control; (b) the countermovement jump, used to evaluate lower-body explosive power; (c) the isometric squat, which measures maximal strength in a static position; (d) the 2.5-minute Loaded Repeated Jump Test (LRJT), designed to assess anaerobic capacity and fatigue resistance under load; and finally, (e) the maximum 20-meter shuttle test, which evaluates aerobic endurance and change of direction ability. It is important that these tests are completed in the specified order, as fatigue resulting from one test may negatively influence performance in the subsequent tests. Conducting the assessments in this particular sequence helps to minimize such interference and ensures more accurate and reliable results. This test battery is strategically designed to evaluate, in order, neuromuscular coordination (via the balance test), muscular power (through the countermovement jump), maximal strength (with the isometric squat), anaerobic endurance and fatigue resistance (during the loaded repeated jump test), and finally, aerobic capacity (assessed by the 20-meter shuttle run) (53).

1. Star Excursion Balance Test

The Star Excursion Balance Test (SEBT) is one of the most commonly used assessments for evaluating dynamic balance and postural control of the lower extremities, with its reliability and validity well-supported by scientific research. This test is specifically designed to measure an individual's balance ability and postural control during movement. The SEBT is performed on lines drawn on the ground in eight different directions, each spaced 45 degrees apart. While standing on one leg, the individual reaches as far as possible in each direction with the opposite leg, performing a controlled squat-like motion. The maximum distance reached in each direction without losing balance is measured for evaluation. This method provides valuable information about lower limb stability, functional symmetry, and motor control capabilities (25). Thanks to this test, dynamic balance can be assessed through a simple, reliable, and cost-effective method without the need for complex and expensive equipment. The results of the test not only provide insights into an individual's balance capacity but also offer indirect information about lower limb muscle strength, joint flexibility, and proprioception—that is, the ability to perceive body position in space. In this regard, the SEBT stands out as a valuable tool for evaluating athletic performance and conducting injury risk assessments in athletes (26). Reach distances are considered indicators of dynamic postural control, with greater reach distances reflecting better dynamic postural control (27). Filipia et al. (28), propose the Star Excursion Balance Test (SEBT) as an effective functional screening method designed to evaluate athletes' dynamic postural stability, neuromuscular control, and potential for lower limb injury. During the test, individuals maintain single-leg balance as they extend their free leg as far as possible in the anterior, posteromedial, and posterolateral directions, ensuring the supporting leg remains stable and upright throughout the movement (28). This test can serve as an effective tool to evaluate whether the current strength and conditioning program being implemented is successfully targeting and improving key physical attributes such as neuromuscular coordination, lower-extremity strength, and core stability. By analyzing changes in athlete performance over time through this test, coaches and trainers can determine the effectiveness of their training protocols and make necessary adjustments to better address these critical components of athletic performance. In scientific studies conducted on 27 physically active males, the SEBT demonstrated moderate to high reliability, with an intraclass correlation coefficient of 0.87 for the dominant leg and 0.74 for the non-dominant leg (29). These results support that the SEBT is a reliable and highly reproducible method for assessing changes in postural control and neuromuscular coordination within athletic populations. Its consistency and validity make it a valuable tool for monitoring athletes' functional performance over time and for detecting subtle improvements or declines in their balance and motor control abilities, which are critical for both injury prevention and performance enhancement (29). As in many other sports disciplines, balance plays a crucial role in controlling motor activities in alpine skiing competitions. It is a fundamental component for achieving high performance and maintaining a healthy athletic career. Effective balance control allows athletes to execute precise movements, adapt quickly to changing terrain conditions, and minimize the risk of injuries, all of which are essential for sustained success in the demanding and dynamic environment of alpine skiing (30, 31). In conclusion, the Star Excursion Balance Test (SEBT) stands out as a reliable, valid, and reproducible measurement tool for assessing dynamic balance and postural control of the lower extremities. This test provides comprehensive information about neuromuscular coordination, muscle strength, flexibility, and proprioceptive abilities, which is crucial for monitoring athlete performance and early identification of injury risk. Especially in sports disciplines like alpine skiing, which require a high level of balance and motor control, the SEBT is considered to play a critical role in performance evaluation and in tracking the effectiveness of conditioning programs. In this context, regular balance assessments of alpine skiing athletes and the use of functional tests such as the SEBT are thought to offer valuable guidance for coaches and sports scientists in optimizing performance and minimizing the risk of injury (30, 54).

2. Countermovement Jump Test

The countermovement jump (CMJ) is a widely used test to assess athletes' lower body strength and explosive power. The CMJ involves a rapid upward jump following a downward movement (countermovement). This movement takes advantage of the stretch-shortening cycle of the muscles to achieve a higher jump. Additionally, the test provides valuable data for measuring athletes' ability to produce explosive power and for monitoring the effectiveness of training programs (32, 33). CMJ performance is also used to monitor athletes' training progress, assess fatigue levels, and identify lower extremity asymmetries. The simplicity and practicality of the test have made it an indispensable tool in sports science and training monitoring processes (34, 35). According to Jordan et al. (16), the countermovement jump (CMJ), when assessed via force platform data, provides a valuable means for evaluating not only explosive strength and force generation rate, but also functional asymmetries that occur during different jump phases. A key aspect of this evaluation involves examining asymmetry between the limbs through the force-time curve. This asymmetry can be quantified using the following formula: **(Impulse from left leg − impulse from right leg) / (Greater of the two impulses)x100.** In their research, Jordan et al. (16) reported that ski racers who had undergone ACL reconstruction exhibited significantly higher asymmetry indices during the concentric phase of the countermovement jump as well as during the second phase of the static jump when compared to uninjured athletes ($p<0.05$) (36). The countermovement jump (CMJ) allows for precise measurement of the concentric and eccentric forces that an athlete generates during the upward and downward phases of the jump, as well as the forces experienced upon landing. This detailed information makes the CMJ an invaluable tool for enhancing the specific strength and power qualities that are essential for optimal skiing performance. Furthermore, if an athlete demonstrates any abnormal or asymmetrical movement patterns during the test, these issues can be identified quickly and addressed through targeted interventions. By correcting such imbalances or faulty mechanics, the likelihood of injury occurring during training or competition can be significantly reduced, ultimately contributing to improved athlete safety and performance longevity (36) . When combined with slow-motion video analysis, this test captures a wide range of kinetic characteristics, including power and force production, as well as functional asymmetries. These measurements can be easily monitored and tracked over time, providing valuable insights into an athlete's development and allowing for timely adjustments to training and rehabilitation programs (37, 38). In conclusion, the CMJ test possesses high validity and reliability for assessing both lower extremity explosive power and functional asymmetries. It stands out as an indispensable evaluation tool for monitoring the performance of alpine skiing athletes, assessing the effectiveness of training programs, and predicting injury risks.

3. Isometric Back Squat

The Isometric Back Squat Test is an isometric (static muscle contraction) strength test used to measure the maximal force production capacity of the lower body muscles. During this test, the individual holds a squat position and attempts to push against a fixed bar with maximum force, although the bar does not move. The force generated is measured using a force platform or load cell (39, 40). Alpine skiing requires a high level of isometric and eccentric muscle actions to change direction and maintain posture throughout the course; therefore, it is important to assess each athlete's lower body strength capacity (7). Due to its high consistency across repeated tests and ease of administration, the isometric squat is considered a more favorable method for evaluating strength compared to the traditional one-repetition maximum (1RM) back squat (41). Moreover, this test offers a more sport-specific evaluation of the isometric muscle contractions frequently encountered in alpine skiing, compared to the primarily dynamic concentric contractions measured by the one-repetition maximum (1RM) back squat. In a study by Blazevich et al., the reliability and validity of the isometric squat test were examined, revealing a very high reliability with an intraclass correlation coefficient of 0.97. Additionally, a strong correlation was observed between participants' performances in the isometric test and the 1RM back squat ($r = 0.77$; $p < 0.01$). Although the validity relative to the 1RM back squat was moderate ($r < 0.8$), possibly due to the limited sample size ($n = 14$), the isometric squat test remains a valuable tool for assessing overall force production (41). Given the high reliability and moderate validity demonstrated by the isometric squat test, this assessment tool can be effectively used to evaluate changes in lower-body strength before and after training interventions. Monitoring these strength adaptations is essential, as lower-body strength is a critical component of alpine skiing performance, directly influencing an athlete's ability to maintain posture, generate power, and execute precise movements on the course (3, 5, 15, 16, 19, 23, 42, 43). In conclusion, the isometric back squat test provides a reliable and practical method for assessing lower body strength capacity in alpine skiing athletes, making it an important tool for performance monitoring and evaluating the effectiveness of training programs.

4. Loaded Repeated Jump Test

This test is a performance assessment primarily used to evaluate lower extremity muscle endurance, strength endurance, and the maintenance of explosive power over time. It is applied to analyze athletes' performance in sports that demand intense and prolonged efforts, such as alpine skiing, basketball, and volleyball (44-46). The ability to sustain adequate anaerobic capacity and muscle strength is among the key factors that significantly contribute to the success of alpine skiing athletes (18). Traditionally, 60- and

90-second box jumptests have been used to assess the performance (7, 14, 18, 21, 47). Although traditional testing methods have generated valuable data over the years, their ability to reflect the specific muscle actions involved in alpine skiing remains uncertain. While continuous box jump tests primarily evaluate the efficiency of stretch-shortening cycle and explosive power, alpine skiing predominantly involves slower eccentric and concentric muscle contractions performed in a controlled and sustained manner (9, 18). The 2.5-minute Loaded Repeated Jump Test (LRJT) offers a highly applicable and sport-specific method for assessing anaerobic capacity and the ability to maintain muscular power through the specific muscle actions observed during ski racing. In this test, athletes perform 60 loaded countermovement jumps (CMJs) while carrying a load equivalent to 40% of their body weight on a barbell positioned across their back, similar to the positioning used in a back squat. Unlike continuous jump tests, the LRJT incorporates brief pauses between jumps, which more accurately mimic the intermittent effort and rhythm characteristic of skiing turns during races. Specifically, the timing of these pauses aligns closely with the turn rhythms observed in different alpine disciplines—approximately 1 to 1.5 seconds for slalom (SL), 1.5 to 2 seconds for giant slalom (GS), and 2.4 to 3 seconds for super-G (SG). Additionally, the total of 60 jumps corresponds roughly to the number of gates encountered in SL and GS courses, while the 2.5-minute duration represents the upper time limit typical of downhill skiing courses. These features make the LRJT a versatile and relevant test that can be effectively applied across all alpine skiing disciplines (18). Con versely, the 60- and 90-second box jump tests provide no data on mean power, nor do they last long enough to parallel the length of a DH race. An original research study conducted by Patterson et al. (24) showed a high degree of reli ability in a test-retest trial of the LRJT with a 95%confidence interval and inter class correlation of 0.987 supporting its efficacy (18). With these characteristics, the 2.5-minute LRJT test stands out as a highly reliable and sport-specific performance assessment tool that more accurately reflects the physiological and technical demands of alpine skiing. Its design closely mimics the intermittent nature and muscular requirements of ski racing, making it particularly well-suited for evaluating athletes' anaerobic capacity and muscular power endurance in a manner that is directly relevant to their sport. Consequently, the LRJT provides coaches and sports scientists with valuable, realistic insights into an athlete's readiness and performance potential within the context of alpine skiing competition.

5. Max 20-m Shuttle Run Test

The Maximum 20-Meter Shuttle Run Test (Max 20-m Shuttle Run Test) is a field-based, easy-to-administer, and standardized exercise test commonly used to assess aerobic endurance. This test is especially utilized to estimate an athlete's maximal oxygen consumption capacity (VO_2max) (48-50). The aerobic system accounts for approximately 30 to 46 percent of the total energy contribution during alpine ski racing. Therefore, assessing this particular aspect of an athlete's fitness is crucial for understanding their overall performance capacity in the sport (7). In their study, Veicsteinas et al. reported that elite skiers demonstrated approximately 20–30% higher VO_2max values compared to their non-athlete counterparts, emphasizing the importance of aerobic fitness in skiing performance. Enhancing aerobic capacity can contribute to faster recovery between training efforts and support increased overall training loads. One effective and widely used method for estimating VO_2max in field settings is the maximal multistage 20-meter shuttle run test (MST) (4, 51). The administration of the Maximum Shuttle Test (MST) allows multiple athletes to be tested simultaneously while still providing accurate and reliable results. This feature makes the MST particularly advantageous in club and collegiate-level settings, where time constraints often limit the feasibility of conducting traditional treadmill tests that require running to exhaustion. Consequently, the MST serves as an efficient and practical alternative for assessing aerobic capacity in environments with limited testing time (52). In another conducted research study, 8 female national-level U18 soccer players participated in both the Maximum Shuttle Test (MST) and a traditional treadmill run test. The study found a statistically significant correlation in performance between the two tests ($p < 0.05$), indicating that the MST is a valid and reliable field-based assessment tool for measuring maximal aerobic capacity in athletic populations. This finding supports the use of the MST as an effective alternative to laboratory-based tests, especially in settings where accessibility and practicality are important considerations (52). With these characteristics, the MST serves as an effective field test that allows for practical, economical, and reliable assessment of aerobic capacity in athletes participating in endurance-demanding sports such as alpine skiing. In this regard, it is considered an important tool for training planning and performance monitoring processes.

Conclusion

Considering the unique nature of alpine skiing competitions, the implementation of a specially designed test battery is essential for effectively monitoring physiological adaptations related to performance. The combination of relatively slow eccentric and concentric muscle contractions with a high level of neuromuscular coordination creates complex demands that require careful analysis of the athletes. Additionally, assessing physiological parameters that directly impact performance such as lower extremity agility, core strength, anaerobic endurance, aerobic capacity, and force production capacity is of great importance. Measuring and regularly monitoring these characteristics through appropriate test protocols enables a scientific evaluation of whether strength and conditioning programs elicit the desired adaptations. Although advanced research is needed to fully elucidate the overall demands alpine skiing places on the human body, the test battery summarized here provides effective tools for analyzing changes in alpine skiing performance.

References

1. Plisk S. Skiing: Physiological training for competitive alpine skiing. Strength & Conditioning Journal. 1988;10(1):30-3.
2. Tanner R, Gore C. Physiological tests for elite athletes: Human kinetics; 2012.
3. Ferguson RA. Limitations to performance during alpine skiing. Experimental physiology. 2010;95(3):404-10.
4. Veicsteinas A, Ferretti G, Margonato V, Rosa G, Tagliabue D. Energy cost of and energy sources for alpine skiing in top athletes. Journal of Applied Physiology. 1984;56(5):1187-90.
5. Turnbull J, Kilding A, Keogh J. Physiology of alpine skiing. Scandinavian journal of medicine & science in sports. 2009;19(2):146-55.
6. Spörri J, Kröll J, Gilgien M, Müller E. How to prevent injuries in alpine ski racing: what do we know and where do we go from here? Sports medicine. 2017;47:599-614.
7. Hydren JR, Volek JS, Maresh CM, Comstock BA, Kraemer WJ. Review of strength and conditioning for alpine ski racing. Strength & Conditioning Journal. 2013;35(1):10-28.
8. Supej M, Kipp R, Holmberg HC. Mechanical parameters as predictors of performance in alpine World Cup slalom racing. Scandinavian journal of medicine & science in sports. 2011;21(6):e72-e81.
9. Berg HE, Eiken O. Muscle control in elite alpine skiing. Medicine and science in sports and exercise. 1999;31(7):1065-7.
10. Hébert-Losier K, Supej M, Holmberg H-C. Biomechanical factors influencing the performance of elite alpine ski racers. Sports medicine. 2014;44:519-33.
11. Andersen R, Montgomery D, Turcotte R. An on-site test battery to evaluate giant slalom skiing performance. The Journal of sports medicine and physical fitness. 1990;30(3):276-82.
12. Federolf P, Scheiber P, Rauscher E, Schwameder H, Lüthi A, Rhyner HU, et al. Impact of skier actions on the gliding times in alpine skiing. Scandinavian journal of medicine & science in sports. 2008;18(6):790-7.
13. Bacharach DW, von Duvillard SP. Intermediate and long-term anaerobic performance of elite Alpine skiers. Medicine and science in sports and exercise. 1995;27(3):305-9.
14. Gross M, Hemund K, Vogt M. High intensity training and energy production during 90-second box jump in junior alpine skiers. The Journal of Strength & Conditioning Research. 2014;28(6):1581-7.
15. Schmitt K-U, Hörterer N, Vogt M, Frey WO, Lorenzetti S. Investigating physical fitness and race performance as determinants for the ACL

injury risk in Alpine ski racing. BMC sports science, medicine and rehabilitation. 2016;8:1-9.

16. Tesch PA. Aspects on muscle properties and use in competitive Alpine skiing. Medicine and science in sports and exercise. 1995;27(3):310-4.
17. Aktaş BS. Slalom ve Büyük Slalom Sporcularına Uygulanan İnterval Antrenman Programının Aerobik ve Anaerobik Performans Üzerine Etkisinin İncelenmesi. Gümüşhane Üniversitesi Sağlık Bilimleri Dergisi. 2024;13(1):506-13.
18. Patterson C, Raschner C, Platzer H-P. The 2.5-minute loaded repeated jump test: evaluating anaerobic capacity in alpine ski racers with loaded countermovement jumps. The Journal of Strength & Conditioning Research. 2014;28(9):2611-20.
19. Neumayr G, Hoertnagl H, Pfister R, Koller A, Eibl G, Raas E. Physical and physiological factors associated with success in professional alpine skiing. International journal of sports medicine. 2003;24(08):571-5.
20. Raschner C, Müller L, Patterson C, Platzer H, Ebenbichler C, Luchner R, et al. Current performance testing trends in junior and elite Austrian alpine ski, snowboard and ski cross racers. Sport-Orthopädie-Sport-Traumatologie-Sports Orthopaedics and Traumatology. 2013;29(3):193-202.
21. Tomazin K, Dolenec A, Strojnik V. High-frequency fatigue after alpine slalom skiing. European Journal of Applied Physiology. 2008;103:189-94.
22. Hintermeister RA, O'Connor DD, Dillman CJ, Suplizio CL, Lange GW, Steadman JR. Muscle activity in slalom and giant slalom skiing. Medicine and science in sports and exercise. 1995;27(3):315-22.
23. Stricker G, Scheiber P, Lindenhofer E, Müller E. Determination of forces in alpine skiing and snowboarding: Validation of a mobile data acquisition system. European Journal of Sport Science. 2010;10(1):31-41.
24. Maxwell SM, Hull ML. Measurement of strength and loading variables on the knee during alpine skiing. Journal of Biomechanics. 1989;22(6-7):609-24.
25. Gribble P. The Star Excursion Balance Test as a Measurement Tool. Athletic Therapy Today. 2003;8(2).
26. Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of the star excursion balance test. North American journal of sports physical therapy: NAJSPT. 2009;4(2):92.
27. Hertel J, Braham RA, Hale SA, Olmsted-Kramer LC. Simplifying the star excursion balance test: analyses of subjects with and without chronic ankle instability. Journal of Orthopaedic & Sports Physical Therapy. 2006;36(3):131-7.

28. Filipa A, Byrnes R, Paterno MV, Myer GD, Hewett TE. Neuromuscular training improves performance on the star excursion balance test in young female athletes. Journal of orthopaedic & sports physical therapy. 2010;40(9):551-8.
29. López-Plaza D, Juan-Recio C, Barbado D, Ruiz-Pérez I, Vera-Garcia FJ. Reliability of the star excursion balance test and two new similar protocols to measure trunk postural control. PM&R. 2018;10(12):1344-52.
30. Noé F, Paillard T. Is postural control affected by expertise in alpine skiing? British journal of sports medicine. 2005;39(11):835-7.
31. Aktaş BS, Kıyıcı F, Atasever G, Seren K, Aktaş S. Kar Sporlarında Denge Performansı ile Reaksiyon Zamanlarının Karşılaştırılması: Deneysel Araştırma. Turkiye Klinikleri Journal of Sports Sciences. 2023;15(3):371-9.
32. McMahon JJ, Suchomel TJ, Lake JP, Comfort P. Understanding the key phases of the countermovement jump force-time curve. Strength & Conditioning Journal. 2018;40(4):96-106.
33. Aktaş BS. Kayak branşı sporcularında bacak sertliği ve reaktif kuvvet indeksi farklılıklarının incelenmesi. Spor ve Performans Araştırmaları Dergisi. 2023;14(3):391-400.
34. Anicic Z, Janicijevic D, Knezevic OM, Garcia-Ramos A, Petrovic MR, Cabarkapa D, et al. Assessment of countermovement jump: what should we report? Life. 2023;13(1):190.
35. Atasever G, Sevindik Aktaş B, Kıyıcı F, Seren K, Aktaş S. Kar Sporlarında Dikey Sıçrama Performansı ile Anaerobik Güç Parametrelerinin Karşılaştırılması: Tanımlayıcı Araştırma. Turkiye Klinikleri Journal of Sports Sciences. 2023;15(3).
36. Jordan MJ, Aagaard P, Herzog W. Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. Scandinavian journal of medicine & science in sports. 2015;25(3):e301-e9.
37. Jordan MJ, Aagaard P, Herzog W. A comparison of lower limb stiffness and mechanical muscle function in ACL-reconstructed, elite, and adolescent alpine ski racers/ski cross athletes. Journal of sport and health science. 2018;7(4):416-24.
38. Alvarez-San Emeterio C, Gonzalez-Badillo JJ. The physical and anthropometric profiles of adolescent alpine skiers and their relationship with sporting rank. The Journal of Strength & Conditioning Research. 2010;24(4):1007-12.
39. McGuigan M, Newton M, Winchester J. Use of isometric testing in soccer players. J Aust Strength Cond. 2008;16:11-4.
40. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. Sports medicine. 2016;46:1419-49.

41. Blazevich AJ, Gill N, Newton RU. Reliability and validity of two isometric squat tests. The Journal of Strength & Conditioning Research. 2002;16(2):298-304.
42. Ferland P-M, Comtois AS. Athletic profile of alpine Ski racers: a systematic review. The Journal of Strength & Conditioning Research. 2018;32(12):3574-83.
43. Kokmeyer D, Wahoff M, Mymern M. Suggestions from the field for return-to-sport rehabilitation following anterior cruciate ligament reconstruction: alpine skiing. journal of orthopaedic & sports physical therapy. 2012;42(4):313-25.
44. Komi PV. Strength and power in sport: Blackwell scientific publications Oxford; 1992.
45. Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. Sports medicine. 2010;40:859-95.
46. Glaister M. Multiple sprint work: physiological responses, mechanisms of fatigue and the influence of aerobic fitness. Sports medicine. 2005;35:757-77.
47. Álvarez-San Emeterio C, Antuñano NP-G, López-Sobaler AM, González-Badillo JJ. Effect of strength training and the practice of Alpine skiing on bone mass density, growth, body composition, and the strength and power of the legs of adolescent skiers. The Journal of Strength & Conditioning Research. 2011;25(10):2879-90.
48. Leger LA, Mercier D, Gadoury C, Lambert J. The multistage 20 metre shuttle run test for aerobic fitness. Journal of sports sciences. 1988;6(2):93-101.
49. Tomkinson GR, Léger LA, Olds TS, Cazorla G. Secular trends in the performance of children and adolescents (1980–2000) an analysis of 55 studies of the 20m shuttle run test in 11 countries. Sports medicine. 2003;33:285-300.
50. Castagna C, Impellizzeri FM, Chamari K, Carlomagno D, Rampinini E. Aerobic fitness and yo-yo continuous and intermittent tests performances in soccer players: acorrelation study. The Journal of Strength & Conditioning Research. 2006;20(2):320-5.
51. Leger LA, Lambert J. A maximal multistage 20-m shuttle run test to predict O2 max. European journal of applied physiology and occupational physiology. 1982;49(1):1-12.
52. Aziz AR, Tan FH, Teh KC. A pilot study comparing two field tests with the treadmill run test in soccer players. Journal of sports science & medicine. 2005;4(2):105.

53. Kıyıcı, F., & Alaeddinoğlu, V. An Evaluation of Talent Selection for the Infrastructure of Alpine Skiing. International Development Academy Journal, 2022; 1(1), 14-32

54. Tatlısu, B., Karakurt, S., Ağırbaş, O., & Uçan, I., The Relationshıp Between Strength, Speed, Flexibility, Agility, and Anaerobic Power in Elite Athletes 2019; 8(3), 1-6.