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Investigation of the Relationship Between Anaerobic Performance and Agility in Elite Ski Mountaineers

Elit Dağ Kayağı Sporcularında Anaerobik Performans ile Çeviklik Arasındaki İlişkinin İncelenmesi

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INVESTIGATION OF THE RELATIONSHIP BETWEEN ANAEROBIC PERFORMANCE AND AGILITY IN ELITE SKI MOUNTAINEERS

ABSTRACT

This study examined the relationship between anaerobic performance and agility in elite ski mountaineers. Cross-sectional survey model was used in the study. 14 male ski-mountaineering athletes who competed in the final stage of Ski-mountaineering Turkey Cup" individual race category participated voluntarily. The anaerobic performance of the athletes was evaluated using parameters such as peak power, average power, and fatigue index were assessed via the Wingate test, while agility was measured by Hexagon test. After the data were subjected to descriptive statistics, normality, linearity and homoscedasticity preliminary analyses were performed and the data were analyzed by Pearson correlation and simple regression test. As a result of the study, it was found that there were strong negative relationships between peak power and average power values normalized by body weight and agility times. In contrast, statistically insignificant relationships were found between minimum power and time to peak power and agility. In addition, relative peak power explained 33.9% of the agility variance and relative average power explained 31.1%. This study emphasized that maximal anaerobic power and power output normalized to body weight play a critical role for the success of technical movements in elite alpine skiers. However, the fact that approximately 65-70% of agility is affected by neuromuscular coordination, balance and technical skills indicates that training programs should be multifaceted. Accordingly, explosive strength training, lactic tolerance training and discipline-specific simulations are recommended. The results of the study provide an important contribution to the literature by clarifying the role of anaerobic capacity in ski-mountaineering performance optimization.

Keywords: Anaerobic Capacity, Change of Direction Ability, Explosive Strength, Ski Mountaineering.

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ELİT DAĞ KAYAĞI SPORCULARINDA ANAEROBİK PERFORMANS İLE ÇEVİKLİK ARASINDAKİ İLİŞKİNİN İNCELENMESİ

ÖZ

Bu araştırma, elit dağ kayakçılarında anaerobik performans ile çeviklik arasındaki ilişkiyi incelemeyi amaçlamıştır. Kesitsel tarama modeli kullanılan araştırmaya, Dağ Kayağı Türkiye Kupası" bireysel yarış kategorisinde final etabında yarışan 14 erkek dağ kayağı sporcusu gönüllü olarak katılmıştır. Sporcuların anaerobik performansı Wingate testi ile zirve güç, ortalama güç ve güç kaybı gibi parametreler üzerinden değerlendirilirken; çeviklik, Altıgen testi ile ölçülmüştür. Veriler tanımlayıcı istatistiklere tabi tutulduktan sonra normallik, doğrusallık ve homoscedascticity ön analizleri yapılarak veriler Pearson korelasyon ve basit regresyon testi ile analiz edilmiştir. Araştırma sonucunda vücut ağırlığına göre normalize edilen zirve güç ve ortalama güç değerleri ile çeviklik süreleri arasında güçlü negatif ilişkiler olduğu tespit edildi. Buna karşılık, minimum güç ve zirve güce ulaşma süresi ile çeviklik arasında istatistiksel olarak anlamsız ilişki bulunmuştur. Ayrıca rölatif zirve gücün çeviklik varyansının %33.9'unu, rölatif ortalama gücün ise %31.1'ini açıkladığını belirlemiştir. Bu çalışma elit dağ kayakçılarında teknik hareketlerin (hızlı yön değiştirme, yan basamak atma, v açma, kontrollü iniş ve geçiş teknikleri) başarısı için maksimal anaerobik güç ve vücut ağırlığına normalize edilmiş güç çıktılarının kritik rol oynadığı vurgulanmıştır. Ancak, çevikliğin yaklaşık %65-70'inin nöromüsküler koordinasyon, denge ve teknik becerilerden etkilenmesi, antrenman programlarının çok yönlü olması gerektiğine işaret etmektedir. Bu doğrultuda, patlayıcı kuvvet antrenmanları, laktik tolerans çalışmaları ve disipline özgü simülasyonlar önerilmektedir. Çalışma sonuçları, dağ kayağı performans optimizasyonunda anaerobik kapasitenin rolünü netleştirerek literatüre önemli bir katkı sağlamaktadır.

Anahtar Kelimeler: Anaerobik Kapasite, Dağ kayağı, Yön Değiştirme Yeteneği, Patlayıcı Güç.

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INTRODUCTION

Ski-mountaineering is an endurance sport with high physiological, technical and cognitive demands, combining ascents, descents and technical transitions on natural snowy terrain (Bortolan et al., 2021). Unlike traditional alpine skiing, athlete's complete complex courses that require the ability to climb steep slopes using mobile bindings and skin systems (Fornasiero et al., 2023). Cross-country skiing is one of the most strenuous, energy-demanding and demanding endurance sports.

This is supported by existing research (Schenk et al., 2011; Praz et al., 2014; Gaston et al., 2019). Performance depends on the optimal balance of both the aerobic and anaerobic systems of the athlete, as well as neuromuscular skills such as agility, balance, and explosive strength. Especially for elite level competitors, rapid adaptation to the technical challenges of the course (steep descents, sharp curves, obstacles) is one of the critical elements that determine success in competitions. Although in recent years, most studies on optimizing performance in ski-mountaineering have focused on aerobic capacity and strength training (Sandbakk et al., 2016; Andersson et al., 2020), the relationship between anaerobic performance and agility has been the subject of relatively limited research. This deficiency has been of particular interest to sports scientists, especially when considering the short bursts of explosive effort required during competition (e.g., acceleration, sudden change of direction) and maneuvers that require dynamic balance.

In recent years, most studies on performance optimization in ski mountaineering have focused on aerobic capacity and strength training (Sandbakk et al., 2016; Andersson et al., 2020). However, considering the explosive effort bursts (e.g., acceleration, sudden direction changes) and dynamic balance maneuvers required during races, the relationship between anaerobic performance and agility has been the subject of relatively limited research. This gap is a particular area of interest for sports scientists.

In ski mountaineering, the sudden power outputs required, especially during acceleration at the start, overcoming unexpected obstacles on the course, or tackling an opponent, are dependent on anaerobic capacity. In such activities, the efficiency of the ATP-PCR system and the lactic acid system directly affect the athlete's performance (Girardi et al., 2021). For example, it is estimated that anaerobic power and capacity measured by 30-second maximal sprint tests (such as the Wingate test) can shorten skiers' race time by 5-8% (Losnegard et al., 2019). However, these findings are mostly limited to similar sports such as alpine skiing and snowboarding; studies specific to ski-mountaineering are still limited.

Agility is defined as the athlete's ability to change speed, direction or body position with minimal loss of time (Sheppard & Young, 2006). In ski mountaineering, this skill is especially critical in uneven terrain, obstacle jumping and low visibility. Agility is directly related to static and dynamic balance, reaction time and proprioception (Pavlova et al., 2023). Recent studies have shown that agility training not only improves technical skills but also reduces injury risk (Román et al., 2022). However, it remains unclear how to measure this parameter in elite ski mountaineers and which physiological factors are associated with it.

When the existing literature is examined, inferences about the relationship between anaerobic performance and agility are mostly based on team sports (soccer, basketball) or short distance running (Chaouachi et al., 2020; Lockie et al., 2021). Studies examining this relationship in sports that require both technical and physiological complexity, such as ski mountaineering, are limited. In particular, the following questions remain to be answered: (1) Is there a significant correlation between anaerobic power and agility scores in elite ski mountaineers? (2) To what extent can anaerobic capacity predict agility performance? Not answering these questions leads coaches to rely on insufficient data when designing performance development programs. For example, it is not known whether training to increase anaerobic threshold also improves agility-related skills. Furthermore, the lack of a standardized protocol for the validity and reliability of agility tests used in ski-mountaineering makes comparative analyses difficult (Fernández-Cortés et al., 2023).

The main objective of this study is to quantitatively examine the relationship between anaerobic performance parameters (maximal power, average power, fatigue index) and agility skills in elite ski mountaineers and to discuss the possible implications of this relationship for training strategies. To fill the gap in the current literature (Fernández-Cortés et al., 2023), the development of discipline-specific agility tests and the identification of anaerobic system components were targeted."

METHOD

Research Model

In this study, the cross-sectional survey model, one of the general survey models, was used. Cross-sectional survey studies are designed to describe a specific population or sample, describe the current situation, examine the relationships between variables, or measure opinions, behaviors, or characteristics at a specific point in time. The key distinguishing feature of this model is that data are collected at a single point in time; it provides a 'snapshot' or 'cross-section' (Fraenkel & Wallen, 2006).

Research Group

Fourteen male ski-mountaineering athletes who participated in the final stage of the "International Open Ski-mountaineering Turkey Cup" individual race category voluntarily participated in the study. Power analysis was performed with G.Power 3.1. program to determine the number of participants. The sample size analysis with G*power 3.1.9.6 (Cohen's $f^2 = 0.25$, $\alpha = 0.05$, $1\text{-}\beta = 0.80$) showed that 14 participants were sufficient to determine the medium effect size (Kang, 2021). The inclusion criteria were: (1) active participation in official international competitions, (2) ranking in the top 10 in the Turkish Ski-mountaineering Cup at least twice in the last 3 years, (3) training 15 hours per week, (4) competing in the final stage of the International Open Ski-mountaineering Turkey Cup. Exclusion criteria were: (1) any musculoskeletal injury reported in the six months prior to the study; (2) use of performance-enhancing drugs or any medical condition. Participants were recruited from volunteers who had not been previously diagnosed with any cardiovascular disease or disorder, were not taking any medication known to have an effect on autonomic nervous systems and were participating in the competition. Written official permission was obtained from the Turkish Mountaineering Federation (E-98943679-125.99-8820216). Written informed consent was obtained from all participants. Then, the study was approved by Trabzon University Non-Interventional Clinical Research Ethics Committee (Date: 16.02.2025; Issue no: E-81614018-050.04-2500018986).

Data Collection Tools

In this study, anthropometric measurements, lower extremity anaerobic power and capacity test and agility tests (Hexagon test) were performed.

Anthropometric Measurements: Anthropometric measurements were taken by a single investigator while fasting, following standard protocols. Height was measured using a portable stadiometer (Holtain, London, United Kingdom) with an accuracy of 0.1 cm. Body weights were measured using a scale (Tanita TBF 401/A, Japan) with an accuracy of (±100 g). Body mass and composition were measured with a multi-frequency bioelectrical impedance analyzer (TANITA MC-780, Japan) with an accuracy of 0.1 kg (Harbili et al., 2008).

Lower Extremity Anaerobic Power and Capacity Test: The Wingate Anaerobic Power Test (WAnT), which is widely used to measure short-term maximal effort capacity and anaerobic performance parameters of athletes, was preferred. The test was performed using a Lode BV (Lode BV, Groningen, The Netherlands) lower extremity bicycle ergometer.

Agility test (Hexagon test): The hexagon test (AT) is a test used to measure coordination, agility and balance. The test is performed in 3 rounds around a hexagon with a side length of 66 cm and angles of 120 degrees, jumping over the diagonals one by one and returning back, with the participant's face always facing the starting point. The hexagon test has high test-retest reliability (ICC = 0.89) and validity for measuring agility in athletes (Eroğlu, 2014; Lockie et al., 2022). The effectiveness of the test in measuring multidirectional agility has been supported by additional studies such as Lockie et al. (2022).

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Data Collection/Processing

Anaerobic Power Test: Saddle and pedal length settings were made for each athlete before the test. In the lower extremity wingate test, the load corresponding to 7.5% of body weight was automatically calculated on the computer and placed on the bicycle pan (Figure 1). Before starting the WanT, the athletes pedaled between 60-80 pedaling speed (Rpm) for 3 min on the bicycle for warm-up. In the last 5 seconds of each 1 minute, a high-speed load of 120-160 Rpm was applied. After the warm-up was completed, 2 minutes of stretching was performed, and the athlete was allowed to recover. After the start command was given as soon as the athlete was ready, the test started and the athlete was asked to turn against the weight of the pan for 30 seconds. After the end of the test, the athlete continued pedaling at low speed for 3 minutes for cooling purposes and the test was terminated. At the end of the test, parameters such as peak power (W), average power (W), minimum power (W), percentage of power decrease (%) and time to reach peak power (s) were recorded.

Agility test (Hexagon test): The test was performed in a standard indoor environment (22-24°C, laminate floor) at the TDF Mümtaz Çankaya Mountaineering Training Center and Mountain House (Figure 1). The effect of environmental variables was minimized by keeping the floor slippery index and temperature constant. Before the test, each athlete was informed about the protocol of the test. When the athletes started, the stopwatch was started, when they reached the starting point again, they were considered to have completed the first lap and the stopwatch was stopped after three laps. The athlete's score was the time it took to complete three full rotations. The best score from two attempts is recorded. They continued this pattern for three full laps and kept looking forward throughout the test. They performed the test clockwise.

Figure 1: Wingate test and hexagonal test application of ski-mountaineering athletes.

Data Analysis

The data obtained from the participants were analyzed using IBM SPSS Statistics 26 software (SPSS Inc, Chicago, Illinois). The normality distribution of the data was determined by examining the Shapiro-Wilk test results, skewness kurtosis values, Q-Q plot and histogram graphs. For normally distributed data, first descriptive statistics and frequency analysis were performed. The relationship between anaerobic performance parameters and agility skills in ski mountaineers was investigated using Pearson correlation coefficient. Data were checked for normality, linearity and homoscedascticity preliminary analyses to ensure that the regression assumptions were met. Linear regression analysis was used for each dependent variable and independent predictor variables. The association was calculated as coefficient of determination (R^2).

FINDINGS

Table 1. Physical and demographic characteristics of ski-mountaineering athletes

Variables	**n**	$\bar{X}$	**SD**	**Min-Max**
Age (years)	14	19,21	2,32	16-23
Body Weight (kg)	14	68,35	6,23	51-73
Height Length (cm)	14	159.82	46.19	154-182
BMI (kg/m^2)	14	22.49	2.38	19,49-29,52
BFP%	14	11,72	4.74	6,43-19,50
Experience (years)	14	4.14	1.23	3-7

BMI: Body mass index; BFP: Body fat percentage

The mean age of the ski-mountaineering athletes participating in the study was 19.21 ± 2.32 years, body weight 68.35 ± 6.23 kg, height 159.82 ± 46.19 cm, body mass index 22.3 ± 1.27 kgm^2, skiing experience 4.14 ± 1.23 years and body fat percentage 11.72%± 4.74

Table 2. Anaerobic power and agility performances of ski-mountaineering athletes

Variables	n	$\overline{X}$	SD	95% CI
Peak Power (W)	14	759,23	177,10	667,59-845,45
Relative Peak Power (W/kg)	14	11,50	2,01	10,50-12,45
Average Power (W)	14	520,67	111,22	464,35-576,29
Relative Average Power (W/kg)	14	7,90	1,16	7,32-8,45
Minimum Power (W)	14	319,23	91,42	270,61-364,43
Relative Minimum Power (W/kg)	14	4,85	1,21	4,21-5,44
Time to Peak Power (ms)	14	1918,86	904,25	1501,65-2374,73
Power Loss per Second (W/s/kg)	14	0,22	0,05	0,20-0,25
Percentage Power Loss (%)	14	57,24	8,92	53,14-61,88
Agility (sec)	14	13,25	1,65	12,49-14,18

X: mean; SD.: standard deviation; CI: confidence interval

The maximum absolute power values reached by the ski mountaineers during the test were 759.23 ± 177.10 W and the peak power values normalized for body weight were 11.50 ± 2.01 W/kg. The mean absolute power values maintained throughout the test were 520.67 ± 111.22 W and the mean power values normalized for body weight were 7.90 ± 1.16 W/kg. The lowest absolute power values recorded during the test were 319.23 ± 91.42 W with a range of 270.61-364.43 W. The minimum power according to body weight was measured as 4.85 ± 1.21 W/kg. The time to reach maximum power was 1918.86 ± 904.25 ms and the normalized power loss per second was 0.22 ± 0.05 W/s/kg. The power decline observed during the test was recorded as 57.24 ± 8.92%. According to the results of the hexagon test, the mean agility time was determined as 13.25 ± 1.65 s.

Table 3. The relationship between anaerobic power parameters and agility in ski-mountaineering athletes

	Agility		
Variables	**n**	**r**	**p**
Peak Power (W)	14	-0.583*	**0.029***
Relative Peak Power (W/kg)	14	-0.624*	**0.017***
Average Power (W)	14	-0.572*	**0.033***
Relative Average Power (W/kg)	14	-0.603*	**0.022***
Minimum Power (W)	14	-0.247	0.394
Relative Minimum Power (W/kg)	14	-0.114	0.699
Time to Peak Power (ms)	14	0.175	0.549
Power Loss per Second (W/s/kg)	14	-0.485	0.079
Percentage Power Loss (%)	14	-0.289	0.317

*=p<0,05

Table 3 shows the results of the analysis of the relationship between anaerobic power parameters and agility times of ski mountaineers. According to these results, peak power (W) (r = -0.583, p = 0.029), relative peak power (W/kg) (r = -0.624, p = 0.017), average power (W) (r = -0.572, p = 0.033) and relative average power (W/kg) (r = -0.603, p = 0.022) parameters and agility times ($p<0.05$). These findings suggest that higher explosive and sustained power capacity is associated with shorter agility times (i.e. better performance). On the other hand, minimum power (r = -0.247, p = 0.394), relative minimum power (r = -0.114, p = 0.699), time to peak power (r = 0.175, p = 0.549), power loss per second (r = -0.485, p = 0.079) and power loss per percentage (r = -0.289, p = 0.317) parameters did not have a significant relationship with agility ($p>$ 0.05).

Table 4. Regression analysis results for predicting agility performance of relative strength parameters of ski-mountaineering athletes

Predictors	***B***	***SE***	***β***	***t***	***p***
(Constant)	19.131	2.155		8,876	0.00**
Relative Peak Power (W/kg)	-0.512	0.185	-0.624	-2.767	0.01**
F= 7.657; p= 0.017; R^2=0.390; AR^2= 0.339; Durbin-Watson=1.975; VIF=1.026					
(Constant)	19.984	2.596		7.689	0.00**
Relative Average Power (W/kg)	-0.853	0.325	-0.6033	-2.620	0.02*
F= 6.865; p= 0.022; R^2=0.364; AR^2=0.311; Durbin-Watson=1.717; VIF=1.014					

*=p<0.05 **=p<0.01 AR^2: Adjusted R^2

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Table 3 shows the results of two separate simple linear regression models to evaluate the effect of relative peak power and relative average power (W/kg) parameters on agility time of elite ski mountaineers. According to these results; it was seen that relative peak power of mountain ski racers predicted agility time significantly (β = -0.624, p = 0.017). In addition, it was determined that the relative peak power value of mountain ski racers explained 33.9% of the agility variance (AR^2 = 0.339). When the t-test results of the regression coefficient were analyzed, it was seen that all variables had a significant effect on competition performance ($p<0.05$). In the second model, it was seen that the relative average power of mountain ski racers predicted agility time at a statistically significant level (β = -0.603, p = 0.022). Relative mean power value of mountain ski racers explained 31.1% of the agility variance.

DISCUSSION

This study fills an important gap in the literature by examining the relationship between anaerobic performance parameters and agility in elite ski mountaineers. The findings revealed that anaerobic capacity indicators, especially peak power (PP) and average power (AP), showed significant negative correlations with agility performance. These results point to the critical role of the anaerobic system in sports with high technical and physiological demands such as ski mountaineering.

Looking at the anaerobic power and agility performances of ski-mountaineering athletes in the study, the absolute peak power values (759.23 ± 177.10 W) and peak power values normalized to body weight (11.50 ± 2.01 W/kg) of the athletes exhibit a profile compatible with the short bursts of explosive outputs required in ski-mountaineering but lower compared to other winter sports. For example, relative peak power values in alpine skiers athletes have been reported in the range of 12-14 W/kg (Gross et al., 2020). This difference may be attributed to the additional burden of equipment weight (e.g., bindings, boots) in ski-mountaineering and the limitation of force transfer efficiency on unstable ground (Müller et al., 2022). Furthermore, the fact that relative peak power reaches 15-18 W/kg in sports requiring high anaerobic capacity, such as cycling or sprinting (Tomazin et al., 2021), suggests that more focus should be placed on explosive force production in the training programs of ski-mountaineering athletes. Furthermore, compared to the higher values of 15-20 W/kg observed in cycling or sprint athletes, which require high anaerobic capacity (Tomazin et al., 2021), ski-mountaineering athletes exhibit relatively low performance in explosive force production. This may be attributed to discipline-specific technical requirements (e.g. unstable ground and equipment weight) and differences in muscle activation patterns (Supej et al., 2013). Accordingly, we can say that there should be more focus on explosive force production in the training programs of ski-mountaineering athletes.

In the present study, the long time to reach maximum power (1918.86 ± 904.25 ms) indicates a slow development of neuromuscular activation. This may be related to the skiers' deficiencies in eccentric contraction and acceleration skills on resistant surfaces. In addition, this difference may be explained by the duration of loading in the test protocol or deficiencies in the athletes' training history. Similarly, in a study conducted in ski-mountaineering athletes, it was reported that the time to reach maximum power was in the range of 1600-1800 ms and it was emphasized that this time was negatively correlated with technical skill (Fornasiero et al., 2021). This finding supports that technical training, and neuromuscular coordination can optimize power parameters in ski-mountaineering athletes.

The agility performance of the athletes in the study (13.25 ± 1.65 s) was measured using the hexagonal test, and these results reflect an intermediate level of performance compared to winter athletes. For example, hexagonal test times in freestyle skiers have been reported in the range of 11.5-12.5 s (Reid et al., 2019), whereas in ice hockey players these values drop to 10-11 s (Rogers et al., 2016; Behm et al., 2023). The slower agility times in backcountry skiing can be explained by the sport's inherent requirements for dynamic balance and low-speed changes of direction. However, it is predicted that improving this performance with training can reduce the rate of technical errors in competitions (Praz et al., 2022).

The high-power loss observed during the test (57.24 ± 8.92%) should be considered as an important limitation in terms of anaerobic endurance. This value is higher than the losses reported in the range of 45-50% in ski-mountaineering athletes (Pellegrini et al., 2023). This difference is related to the fact that the activity in ski-mountaineering involves more continuous and repetitive high-intensity ascents. Furthermore, this value is significantly higher than the 30-40% losses reported in sports that require repetitive sprint performance (e.g. soccer) (Glaister, 2005). This suggests that ski-mountaineering athletes have areas for improvement with training in lactic tolerance or replenishment of glycogen stores. It is also emphasized in the literature that training to increase lactic acid tolerance can be effective in reducing performance loss (Stöggl et al., 2020).

The study revealed that peak power (W), relative peak power (W/kg), average power (W) and relative average power (W/kg) parameters showed statistically significant negative correlation with agility times. These results support that high explosive strength and sustainable power capacity positively affect the agility performance of athletes. Similarly, the negative relationship between anaerobic power and agility has been consistently reported in the literature (Sporis et al., 2008; Haff & Triplett, 2015; Chaouachi et al. (2020), especially in sports that require high intensity and multidirectional movements (e.g. basketball, soccer). For example, Sporis et al. (2008) emphasized that anaerobic power is directly related to athletes' ability to change direction quickly. In ski mountaineering, sudden turns and maintaining balance on steep slopes are related to both maximal power output and the ratio of this power to body weight (relative power). This may explain the stronger correlation between relative peak and average power parameters (Hoffman, 2006). On the other hand, it is noteworthy that minimum power, time to peak power and power loss parameters did not show a significant relationship with agility. This finding suggests that agility performance depends primarily on maximal and sustained power capacity, but the timing of submaximal efforts or power production is not critical in this context. It also suggests that sudden power outputs are prioritized over repetitive efforts in ski mountaineering. This may be explained by the fact that trails involve high-intensity activities of short duration (Sandbakk et al., 2016). Similarly, Tomlin and Wenger (2001) stated that in short-term agility tests, energy supply is largely provided by the phosphogen system, therefore, minimum power or late power loss plays a limited role in determining performance. Furthermore, the insignificant time to peak power may be explained by the "reactive" nature of technical movements in ski mountaineering, suggesting that athletes' maximal power levels, rather than the rate of power production, are more decisive in adapting to sudden changes in resistance (Haff & Triplett, 2015).

In the study, the predictive effect of both relative peak power (PP (W/kg)) and relative average power (AP (W/kg)) parameters on agility performance of elite ski mountaineering athletes was analyzed by simple linear regression model. The findings show that both power parameters have a significant negative relationship with agility time. These results are consistent with the literature on the role of anaerobic capacity as a performance determinant, especially in sports branches that require high intensity and repetitive explosive movements (Faiss et al., 2013). The fact that relative peak power significantly predicted agility time negatively ($\beta = -0.624$, $p = 0.017$) and explained 33.9% of the variance ($AR^2 = 0.339$) emphasizes the importance of power development normalized for body weight in training programs. It also suggests that peak power output is critical in agility tasks that require sudden and maximal muscle activation. Relative average power significantly negatively predicted agility time ($\beta = -0.603$ ($p = 0.022$) and explained 31.1% of the variance ($AR^2 = 0.311$), indicating the importance of the capacity of these athletes to produce not only maximal but also repetitive power. The effect of relative mean power suggests that sustained power is critical for maintaining performance in repetitive maneuvers. These findings are in line with the arguments of Bishop et al. (2004) that "high power output is decisive in short-term performance tasks". The negative beta coefficients emphasize that increasing power values are associated with lower agility times (i.e. better performance). However, the adjusted R^2 values of both models (0.339 and 0.311, respectively) remained moderate, suggesting that approximately 65-70% of agility performance may be influenced by different physiological (e.g. reaction time, balance) or biomechanical (e.g. technical efficiency) factors. Sporis et al. (2010) stated that agility is a multidisciplinary component and that neuromuscular coordination as well as strength parameters shape performance.

This study has shed light on discipline-specific physiological dynamics by revealing the relationship between anaerobic power parameters and agility performance in elite ski mountaineers. It was found that relative peak power (W/kg) and relative average power (W/kg) parameters, normalized to body weight, significantly predict agility. However, neuromuscular coordination and technical skills, which account for 65-70% of agility, emphasize the need for training programs to be multifaceted. Personalized training models that integrate explosive strength development, lactate tolerance training, and discipline-specific simulations are critical for performance optimization. Future research should examine the role of biomechanical and cognitive factors in this relationship using interdisciplinary approaches.

CONCLUSION

In conclusion, this study sheds light on discipline-specific physiological and performance dynamics by revealing the relationships between anaerobic power parameters and agility performance in ski mountaineering athletes. The findings showed that parameters normalized to body weight such as relative peak power (W/kg) and relative mean power (W/kg) significantly predicted agility performance. These results support that maneuvers requiring sudden turns and dynamic balance in ski mountaineering are directly related to both maximal explosive force and sustained power capacity. However, approximately 65-70% of agility is influenced by other factors such as neuromuscular coordination, technical efficiency and reaction time, emphasizing that performance is a multidisciplinary component. In the study, parameters such as minimum power and time to peak power did not show a significant relationship with agility, suggesting that performance in alpine skiing is primarily shaped by "sudden power outputs" and "power sustainability in repeated efforts". In this context, explosive power development (e.g. plyometric exercises, short sprints) and interval protocols that increase lactic tolerance should be prioritized in training programs. In addition, discipline-specific simulation exercises that integrate technical skill and neuromuscular coordination (e.g., change of direction drills on unstable surfaces) can play a critical role in optimizing agility performance. Equipment optimization (e.g., lighter materials) and body composition management can also contribute to performance by increasing relative strength values. In future research, it is recommended to examine the effect of different training interventions (e.g. resistance ski simulators, reactive strength training) on these parameters through longitudinal studies. Furthermore, the analysis of biomechanical (e.g. joint angles, force transfer efficiency) and cognitive (e.g. decision-making times) factors affecting agility using multidisciplinary models will contribute to a holistic understanding of alpine skiing performance.

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Consequently, these findings may guide coaches to design personalized programs that synchronize athletes' physiological capacities with the technical requirements of the discipline.

Recommendations

To optimize the performance of elite ski-mountaineering athletes, explosive strength development should be prioritized in training programs. High-intensity training such as plyometric exercises (e.g., box jump, depth jump) and short-distance sprints can increase athletes' capacity for sudden power output. In addition, interval training that improves lactic tolerance (e.g., 30 seconds maximal effort + 2 minutes recovery) should be used to build endurance for repetitive high intensity exits. Agility performance should be supported by integrating technical skills and neuromuscular coordination with discipline-specific simulation exercises (change of direction drills on unstable surfaces). The weight of the equipment used in ski-mountaineering may limit the relative power output of athletes. Therefore, the use of equipment such as bindings and boots made of lightweight materials can contribute to performance by increasing energy efficiency. Furthermore, regular monitoring of athletes' body composition and maintenance of lean mass will improve the power-to-weight ratio

This study is limited to male athletes. The inclusion of female athletes and different age groups in future studies will increase the generalizability of the findings. In addition, biomechanical factors (force transfer angles, joint mobility) and cognitive components (decision-making speed, visual perception) affecting agility should be examined with multidisciplinary approaches.

Limitations and Strengths

The study was conducted on elite athletes actively participating in international competitions. This contributed to the understanding of the physiological and technical requirements specific to a high-performance sport such as ski mountaineering. Concrete recommendations were provided for coaches to design personalized training programs that integrate athletes' physiological capacities with technical skills. Especially the importance of explosive strength and lactic tolerance training was emphasized. Being one of the pioneering studies examining the relationship between anaerobic performance and agility in ski-mountaineering has filled the knowledge gap in this field.

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The authors declare that they have no financial, personal or professional conflicts of interest related to this study.

Conflict of interest

There is no personal or financial conflict of interest between the authors of the article within the scope of the study.

Ethical Statement

This study was approved by Trabzon University Clinical Research Ethics Committee (Date: 16.02.2025; Issue no: E-81614018-050.04-2500018986). Written informed consent was obtained from all participants, including parental/guardian consent for minors. All procedures were performed in accordance with the principles of the Declaration of Helsinki.

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