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Araştırma Makalesi / Research Article

The Effects of Muscle Soreness-Based Modified Training on Physical, Physiological, and Competition Performance in Cross-Country Skiers*

Kas Ağrısına Göre Modifiye Edilmiş Antrenmanların Kayaklı Koşu Sporcularında Fiziksel, Fizyolojik ve Yarışma Performansları Üzerine Etkisinin İncelenmesi

Tunç İlçin[1], Serkan Hazar[2]

[1] Vocational School of Social Sciences, Bitlis Eren University, Bitlis, Türkiye
[2] Department of Coaching Education, Sivas Cumhuriyet University, Sivas, Türkiye

ABSTRACT

This study aimed to investigate the effects of muscle soreness-based modified training on the physical, physiological, and competition performance of cross-country skiers. A total of 30 cross-country skiers, aged 15–20 years, who had participated in competitions organized by the Turkish Ski Federation for at least five years, voluntarily participated in the study. The participants were divided into an experimental group (n = 15) and a control group (n = 15). Anthropometric measurements including height, body weight, body fat percentage (PBF), lean body mass (LBM), and body mass index (BMI) were recorded. Cardiopulmonary parameters were assessed using a maximal exercise test to determine VO_2max, VCO_2, respiratory quotient (RQ), maximum heart rate (HR), and VO_2max/HR ratio. One week later, the Wingate anaerobic test was conducted to evaluate peak, average, and minimum power, power drop, and total energy production. The experimental group followed a 12-week training program modified according to muscle soreness levels assessed using the Wong-Baker Faces Pain Rating Scale, while the control group continued their routine training program. Data were analyzed using paired-samples and independent t-tests ($p < 0.05$). Significant improvements were observed in the experimental group in peak, average, and minimum power, as well as total energy production in Wingate test results. Cardiopulmonary variables, including VO_2max, HR, and VO_2max/HR, also showed significant improvements. Between-group comparisons revealed significant differences in favor of the experimental group for anaerobic and selected cardiopulmonary parameters. Additionally, competition performance outcomes indicated significant improvements in race times, durations, and time differences in favor of the 2024 season. Muscle soreness-based modified training programs positively influence physical, physiological, and competition performance in cross-country skiers and can be considered an effective alternative training approach.

Keywords: Cross-country skiing, muscle soreness, performance, endurance, physiology

ÖZET

Bu araştırmanın amacı, kas ağrısına göre modifiye edilmiş antrenmanların kayaklı koşu sporcularının fiziksel, fizyolojik ve yarışma performansları üzerindeki etkilerini incelemektir. Araştırmaya, Türkiye Kayak Federasyonu tarafından düzenlenen yarışmalara en az beş yıldır katılan, yaşları 15–20 arasında değişen, 15 deney 15 kontrol gurubu olmak üzere toplam 30 kayaklı koşu sporcusu gönüllü olarak katılmıştır. Katılımcıların boy, vücut ağırlığı, vücut yağ yüzdesi (PBF), yağsız vücut kütlesi (LBM) ve beden kütle indeksi (BMI) ölçümleri alınmıştır. Kardiyopulmoner parametreler maksimal egzersiz testi ile VO_2max, VCO_2, solunum katsayısı (RQ), maksimum kalp atım hızı (HR) ve VO_2max/HR oranı olarak belirlenmiştir. Bir hafta sonra Wingate anaerobik testi uygulanarak zirve güç, ortalama güç, minimum güç, güç düşüşü ve toplam enerji üretimi değerlendirilmiştir. Deney grubu, Wong-Baker Yüz Ağrı Değerlendirme Ölçeği kullanılarak belirlenen kas ağrısı düzeylerine göre modifiye edilmiş 12 haftalık bir antrenman programı uygularken, kontrol grubu rutin antrenman programına devam etmiştir. Veriler eşleştirilmiş örneklem t-testi ve bağımsız örneklem t-testi ile analiz edilmiştir ($p<0.05$). Deney grubunda Wingate testi sonuçlarında zirve, ortalama ve minimum güç ile toplam enerji üretiminde anlamlı artışlar belirlenmiştir. Kardiyopulmoner parametrelerde VO_2max, HR ve VO_2max/HR değerlerinde anlamlı gelişmeler görülmüştür. Gruplar arası karşılaştırmalarda anaerobik ve bazı kardiyopulmoner değişkenlerde deney grubu lehine anlamlı farklılıklar tespit edilmiştir. Ayrıca yarışma performansına ilişkin sonuçlarda, süre, derece ve zaman farkı açısından 2024 sezonu lehine anlamlı gelişmeler belirlenmiştir. Kas ağrısına göre modifiye edilmiş antrenman programlarının kayaklı koşu sporcularının fiziksel, fizyolojik ve yarışma performanslarını olumlu yönde etkilediği ve alternatif bir antrenman yöntemi olarak kullanılabileceği görülmektedir.

Anahtar kelimeler: Kayaklı koşu, kas ağrısı, performans, dayanıklılık, fizyoloji

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Corresponding Author: Tunç İLÇİN
Bitlis Eren University, Bitlis, Türkiye
E-mail: tunc.ilcin@gmail.com **ORCID ID:** 0000-0003-2681-7046
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1. Introduction

Training can be defined as the systematic development of performance components to achieve optimal athletic performance. According to established definitions, training induces stress-related changes in the organism, ultimately enhancing performance. One of the key elements of training is strength. Although the concept of strength remains fundamentally consistent, its definitions vary across different fields. Skeletal muscles, through neural stimuli and subsequent biochemical processes, either move or stabilize joints or groups of joints (Günay & Yüce, 2001).

Foam rolling is widely believed to alleviate muscle fatigue and soreness (such as delayed onset muscle soreness [DOMS]) following intense exercise and to enhance muscle performance. Therefore, foam rolling could serve as an effective therapeutic method for improving muscle recovery while reducing DOMS (Pearsey et al., 2015). Many athletes tend to avoid physical training during the off-season due to a loss of adaptation to the eccentric phase of training at the beginning of a new season (Cheung et al., 2003). Consequently, it is recommended that athletes engage in at least two months of preparatory training prior to the competition season (Clear et al., 2002). Extensive and well-controlled human studies have demonstrated that muscle strength is associated with muscle damage and soreness (Smith & Miles, 2000). Endurance exercise induces various biochemical adaptations in skeletal muscle that may enhance cellular resistance to physiological and pathological stressors. These adaptations, commonly referred to as “exercise preconditioning,” have been associated with protective effects against conditions such as doxorubicin-induced muscle damage and disuse-induced muscle atrophy (Powers et al., 2020). Such adaptations highlight the capacity of skeletal muscle to respond to repeated exercise stimuli and may contribute to improved tolerance to subsequent muscular stress. Studies have suggested that muscle soreness may be caused by intramuscular edema resulting from muscle damage and the pressure associated with this edema (Nosaka & Sakamoto, 2001).

Ensuring appropriate loading and sufficient recovery is critical for an athlete's development. One of the most challenging tasks for coaches is determining the optimal balance between training load and recovery (Haugen, Seiler & Sandbakk, 2019). Given the relationship between muscle damage and soreness, it is essential to investigate the degree of fatigue induced by training, and whether modifying training programs based on pre-exercise muscle soreness assessments might be more effective than traditional progressive overload methods. Furthermore, determining whether pre-training muscle soreness levels can serve as a criterion for adjusting training loads is of significant importance for both coaches and athletes. The purpose of this study is to examine the effects of ski training programs modified according to muscle soreness levels over a 12-week period on the physical, physiological, and competition performance of athletes (Pexa et al., 2023).

Delayed onset muscle soreness (DOMS) commonly occurs following unfamiliar or strenuous exercise, particularly activities involving eccentric muscle contractions. It is generally associated with symptoms such as muscle pain, stiffness, swelling, reduced range of motion, and temporary decreases in muscle strength, which may negatively affect subsequent physical performance. Various strategies, including cold and heat applications, compression, massage, physical therapy, and nutritional interventions, have been investigated to alleviate DOMS symptoms and facilitate recovery. However, the effectiveness of these approaches may vary depending on the intervention and individual responses (Heiss et al., 2019). Therefore, monitoring muscle soreness may provide coaches and sports scientists with useful information for adjusting training loads according to athletes' recovery status. Individualizing training intensity and duration based on pre-exercise muscle soreness may help optimize recovery and training adaptation while minimizing excessive muscular stress. Such an approach may be particularly relevant for athletes during periods of intensive training or return to sport.

Cross-country skiing is a physiologically demanding endurance sport that requires high aerobic

capacity, muscular endurance, and coordinated involvement of both the upper and lower body (Sandbakk & Holmberg, 2017; Hansen et al., 2022). The high training loads associated with this sport highlight the importance of monitoring fatigue and recovery to prevent excessive fatigue and optimize physiological adaptation and performance (Yu et al., 2023). In this context, muscle soreness may provide useful information regarding an athlete's recovery status and readiness for subsequent training. However, limited attention has been given to the use of pre-training muscle soreness as a criterion for modifying training intensity and duration in cross-country skiers. Therefore, the originality of the present study lies in investigating the effects of a 12-week individualized training program, in which training intensity and duration were modified according to pre-training muscle soreness levels, on the physical, physiological, and competition performance of cross-country skiers.

2. Methods

2.1. Research Design

This study employed a quasi-experimental pre-test–post-test control group design to examine the effects of a 12-week cross-country skiing training program modified according to pre-training muscle soreness levels. The study included an experimental group (n = 15), which followed the soreness-modified training program, and a control group (n = 15), which continued the routine training program. Physical, physiological, and competition performance variables were assessed before and after the intervention period (Köklü & Büyüköztürk, 2000). ***Ethical Approval****:* An application for ethical approval was submitted to the Non-Interventional Clinical Research Ethics Committee of Sivas Cumhuriyet University, and approval was granted (Decision No: 2023-02/07, dated 21.02.2023) (Appendix I). Prior to the measurements, participants were provided with a detailed presentation regarding the study and signed informed consent forms (Appendix II). This study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2. Research Group

The study population consisted of cross-country skiers aged 15–20 years residing in Bitlis, Turkey. The sample comprised 30 athletes from the Bitlis Youth and Sports Club who had participated consecutively for at least five years in competitions organized by the Turkish Ski Federation. While the control group continued with their regular team training programs for 12 weeks, the experimental group underwent modified training programs based on muscle soreness levels determined by the Wong-Baker Faces Pain Rating Scale, in addition to their regular team training. Training sessions were conducted five days a week for 90 minutes each over a period of twelve weeks.

Inclusion criteria: Participants were eligible for inclusion in the study if they were between 15 and 20 years of age, were licensed cross-country skiers, had participated in official competitions organized by the Turkish Ski Federation for five consecutive years, and regularly attended the scheduled training sessions each week throughout the study period.

Exclusion criteria: Athletes were excluded from the study if they were outside the 15–20-year age range, were not licensed cross-country skiers, had not participated in official competitions organized by the Turkish Ski Federation for five consecutive years, or did not regularly attend the scheduled weekly training sessions. Participants who failed to maintain regular training attendance during the study period were also excluded from the final evaluation.

2.3. Data Collection Instrument

All members of the sample group were included in the study, and only those who accepted the informed consent form participated. Laboratory measurements were conducted at Van Yüzüncü Yıl University, School of Physical Education and Sports, Performance Measurement Laboratory,

while field tests were carried out at sports facilities and Nemrut Ski Center in Bitlis. Initially, participants' height, body weight, and body fat percentage were measured as pre-test assessments. Subsequently, a maximal exercise test was performed to determine oxygen consumption (MaxVO2), carbon dioxide production (VCO2), respiratory quotient (RQ), maximum heart rate (HR), and MaxVO2/HR values. One week later, the Wingate Anaerobic Test was administered, and anaerobic power parameters such as Peak Power (W/kg), Average Power (W/kg), Minimum Power (W/kg), Power Drop (W/kg), Power Drop (%) and total energy production were measured. Following the pre-tests, modified ski training programs based on the Wong-Baker Faces Pain Rating Scale were applied to the experimental group, while the control group continued with their regular training routines. At the end of the 12-week period, post-test measurements were conducted under the same conditions and protocols as the pre-tests using a h/p/cosmos treadmill (Quark Cped Cosmed brand) and Monark Ergomedic 894 E model cycle ergometer (peak bike). Statistical analyses were then performed to compare pre- and post-test results.

Pain Scale Assessment: The experimental group's modified training programs were adjusted according to their annual training plans and their muscle soreness ratings. Each participant was interviewed before training, and manual palpation was applied to the muscle groups expected to be activated during exercise to determine pain intensity.

Data Collection

Before starting the training protocols, participants underwent BMI measurements, the Wingate Anaerobic Test, and maximal treadmill exercise tests as pre-tests. Participants' height and weight were also recorded. After completing the pre-tests, the control group continued with their regular training programs, and their progress was monitored over the 12-week period. The experimental group received detailed explanations regarding the modification of training sessions according to muscle soreness and completed a one-week adaptation period. During the 12-week training period, each training session was adjusted based on muscle soreness assessed using the Wong-Baker Faces Pain Rating Scale, a widely used self-reported instrument for evaluating pain intensity (Li et al., 2023).

Pain levels were categorized as follows:

0 =	No pain
1–3 =	Mild pain
4–6 =	Moderate to severe pain
7–9 =	Very severe pain
10 =	Unbearable pain

Adjustments were made accordingly:

At pain levels 1–3, training duration and intensity were increased.
At pain levels 4–6, participants continued with their existing training regimen.
At pain levels 7–9, training intensity and duration were reduced.
At a pain level of 10, active or passive rest was prescribed based on the athlete's condition.

Training modifications were individualized according to each athlete's pre-training muscle soreness level rather than using a predetermined fixed percentage of increase or decrease. At pain levels of 1–3, which represented minimal muscle soreness and adequate readiness for training, training intensity and/or duration were progressively increased according to the athlete's individual tolerance and training status. At pain levels of 4–6, the existing training program was maintained without modification. At pain levels of 7–9, training intensity and/or duration were reduced according to the severity of muscle soreness to facilitate recovery and minimize the potential risk of injury. Athletes reporting a pain level of 10 did not perform the planned training

session and were prescribed passive rest to promote recovery. Therefore, all increases and reductions in training load were individualized based on the athlete's pre-exercise muscle soreness level and tolerance. At the end of the 12-week intervention, post-test measurements were conducted under the same conditions and in the same sequence as the pre-tests.

Height and Body Weight Measurements: Participants' height was measured (cm) barefoot and with standard sports clothing, with heels together, knees straight, and head positioned upright using a sliding stadiometer. Body weight was measured barefoot and in shorts using a Tanita BIA device with 0.1 kg sensitivity. Foot length was measured to the nearest 0.1 cm using a tape measure. Ages were recorded based on national ID documentation.

Body Fat Percentage Measurement: Body fat percentage was assessed using a Tanita body composition analyzer. Participants were instructed to abstain from eating, drinking (including caffeine or alcohol), and engaging in sauna use, bathing, or exercise for at least four hours before the measurement. During measurement, participants stood barefoot on the device's metal surface, held the handles, and maintained arms parallel to the body. Data collected included Percent Body Fat (PBF), Lean Body Mass (LBM), and Body Mass Index (BMI).

Wingate Anaerobic Test: The anaerobic Wingate test (WanT) was performed to evaluate anaerobic performance components (lactate and alactic pathways) (Inbar, 1986). The cycle ergometer resistance was set at 75 g/kg of body weight, and participants were instructed to pedal as fast as possible for 30 seconds. Peak power, minimum power, average power, and fatigue index were recorded.

Maximal Exercise Test: The maximal exercise test started at a running speed of 7 km/h at 0% incline, with speed increments of 1 km/h per minute until volitional exhaustion. VO2max attainment criteria included reaching maximum heart rate (220 - age), a respiratory exchange ratio (RER) greater than 1.10, and achieving a plateau in oxygen uptake despite increased exercise intensity (Staron & Hikita, 2000). The highest oxygen uptake recorded over 15 seconds was considered the VO2max (ml/kg/min). The total duration of the test was recorded as the time to exhaustion. Anaerobic threshold was determined non-invasively using the V-slope method (Murray et al., 1998), where a nonlinear increase in VCO2 relative to VO2 indicates the threshold. Additionally, ventilatory threshold and respiratory thresholds were assessed.

2.4. Training Protocol and Soreness-Based Modification

During the 12-week intervention period, both the experimental and control groups followed their regular cross-country skiing training programs. The training program consisted primarily of endurance training, roller-ski training, strength training, and sport-specific exercises. Endurance sessions included low- to moderate-intensity continuous training as well as higher-intensity training sessions. Roller-ski training was performed to develop sport-specific endurance and technical skills, while strength training targeted the upper-body, lower-body, and core muscle groups involved in cross-country skiing. The control group continued their routine training program throughout the 12-week period without any modification based on muscle soreness. The experimental group followed the same general training structure; however, the intensity and/or duration of the training sessions were individually modified according to muscle soreness. Muscle soreness was assessed using the Wong-Baker Faces Pain Rating Scale, taking into account the severity of soreness that developed during the recovery period from the completion of the previous training session until the subsequent training session, as well as soreness experienced during the ongoing training session. Accordingly, training modifications were based on each athlete's individual soreness response both between consecutive training sessions and during exercise. No predetermined fixed percentage was used to increase or decrease training intensity or duration; instead, adjustments were individualized according to the athlete's reported soreness

level and tolerance. At pain levels of 1–3, representing minimal muscle soreness, training intensity and/or duration were progressively increased according to the athlete's individual tolerance and training status. At pain levels of 4–6, the planned training session was performed without modification. At pain levels of 7–9, training intensity and/or duration were reduced according to the severity of muscle soreness to facilitate recovery and minimize excessive muscular stress. Athletes reporting a pain level of 10 did not perform the planned training session and were prescribed passive rest. Therefore, the primary difference between the experimental and control groups was the individualized modification of training intensity and duration according to pre-training muscle soreness levels in the experimental group.

2.5. Data Analysis

Data collected in the study were entered into SPSS version 22.0 for statistical analysis. Descriptive statistics including mean, median, standard deviation, minimum, and maximum values were calculated. The normality of data distribution was assessed using the Shapiro–Wilk test. As the data were normally distributed, paired-samples t-tests were used to compare pre- and post-test results between groups. The level of significance was set at $p<0.05$.

3. Results

Table 1. Pre-Test and Post-Test Comparison of Wingate Test Results for Experimental Group Participants

Variables		N	x̄	SD	t	p
Peak power W/kg	Pre Test	15	12.6	2.90	-3.45	***,004***
	Post Test	15	14.3	3.19		
Avarage power W/kg	Pre Test	15	8.99	1.89	-4.52	***,001***
	Post Test	15	10.8	2.19		
Minimum power W/kg	Pre Test	15	5.65	2.08	-3.91	***,002***
	Post Test	15	7.23	1.99		
Power drop (%)	PreTest	15	56.1	12.01	2.06	,066
	Post Test	15	49.4	10.2		
Total energy production	Pre Test	15	16.1	3.93	-3.55	***,004***
	Post Test	15	17.8	3.60		

p<0.05

As shown in Table 1, the experimental group demonstrated significant improvements in peak power, average power, minimum power, and total energy production from pre-test to post-test ($p<0.05$), whereas no significant difference was observed in power drop ($p>0.05$).

Table 2. Pretest–Posttest Comparison of Cardiorespiratory Exercise Outcomes in the Experimental Group

Variables		N	x̄	SD	t	p
MaxVO2/ml/kg/dk	Pre Test	15	61,9	8,68	-4,82	***,001***
	Post Test	15	64,3	8,36		
RQ	Pre Test	15	1,06	,035	2,00	,066
	Post Test	15	1,04	,049		
Max pulse HR	Pre Test	15	185,4	9,27	4,29	***,001***
	Pro Test	15	182,3	8,81		
MaxVO2/HR (%)	Pre Test	15	19,8	3,43	-6,37	***,001***
	Post Test	15	20,9	3,43		

p<0.05

As shown in Table 2, the experimental group demonstrated significant improvements in $MaxVO_2$, maximum heart rate, and $MaxVO_2$/HR from pre-test to post-test ($p<0.05$), whereas no significant difference was observed in RQ ($p>0.05$).

Table 3. PBF-LBM-BMI Pre-test-Post-test Comparison Table of Experimental Group Participants

Variables		N	x̄	SD	t	p
PBF (%)	Pre Test	15	13.1	6.48	1.69	,114
	Post Test	15	12.6	5.62		
LBM (kg)	Pre Test	15	50.8	4.00	-3.26	**,006**
	Post Test	15	51.5	3.97		
BMI (%)	Pre Test	15	20.5	2.91	-1.19	,254
	Post Test	15	21.3	3.64		

p<0.05

When Table 3 was examined, the experimental group demonstrated a significant increase in LBM from pre-test to post-test ($p<0.05$), whereas no significant changes were observed in PBF or BMI ($p>0.05$).

Table 4. Wingate Anaerobic Post-test Comparison Table of Experimental and Control Group Participants

Variables		N	x̄	SD	t	p
Peak power W/kg	Experimental	15	14.3	3.19	2.78	***,016***
	Control	15	11.1	2.95		
Avarage power W/kg	Experimental	15	10.8	2.19	4.07	***,001***
	Control	15	7.97	1.85		
Minimum power W/kg	Experimental	15	7.23	1.99	2.90	***,012***
	Control	15	5.40	1.78		
Power drop (%)	Experimental	15	49.4	10.2	-,374	,714
	Control	15	50.9	11.5		
Total energy production	Experimental	15	17.8	3.60	3.45	***,004***
	Control	15	12.9	4.01		

p<0.05

As shown in Table 4, the experimental group demonstrated significantly higher post-test peak power, average power, minimum power, and total energy production compared with the control group ($p<0.05$), whereas no significant difference was observed in power drop ($p>0.05$).

Table 5. Cardiopulmonary Exercise Post-test Comparison Table of Experimental and Control Group Participants

Variables		N	x̄	SD	t	p
MaxVO2/ml/kg/dk	Experimental	15	64.3	8.36	2.69	***,018***
	Control	15	55.6	6.71		
RQ	Experimental	15	1.04	,049	-1.87	,084
	Control	15	1.08	,035		
Max pulse HR	Experimental	15	182.3	8.81	-1.43	,174
	Control	15	186.1	7.88		
MaxVO2/HR (%)	Experimental	15	20.9	3.43	2.86	***,013***
	Control	15	17.5	2.89		

p<0.05

As shown in Table 5, the experimental group demonstrated significantly higher post-test $MaxVO_2$ and $MaxVO_2$/HR values compared with the control group ($p<0.05$), whereas no

significant differences were observed in the other variables (p>0.05).

Table 6. Comparison Table of the Results of the 2023-2024 Season 1st Stage Classic and Freestyle Competitions of the Experimental Group Participants

Variables	N	x̄	SD	t	p
2023 classical degree	15	12.6	5.85	3.53	***,003***
2024 classical degree	15	9.06	6.60		
2023 classic duration	15	25.9	9.47	5.50	***,000***
2024 classic duration	15	23.09	8.53		
2023 classic second difference	15	5.42	3.66	3.58	***,003***
2024 classic second difference	15	2.63	1.75		
2023 free degree	15	9.46	5.15	3.50	***,004***
2024 free degree	15	5.73	4.19		
2023 free time	15	25.5	7.71	1.03	,320
2024 free time	15	24.6	8.23		

p<0.05

As shown in Table 6, the experimental group demonstrated significant improvements in the 2024 season compared with 2023 in the 1st Stage classic-style race rankings, race times, and time gaps from the first-place finisher (p<0.05). In freestyle, significant improvements were observed in race rankings and time gaps from the first-place finisher (p<0.05), whereas race times did not differ significantly between seasons (p>0.05).

Table 7. Comparison Table of the Results of the 2023-2024 Season 2nd Stage Classic and Freestyle Competitions of the Experimental Group Participants

Variables	N	x̄	SD	t	p
2023 classical degree	15	10.6	4.74	2.20	***,045***
2024 classical degree	15	8.80	5.40		
2023 classic duration	15	20.2	7.69	1.56	,141
2024 classic duration	15	18.8	5.55		
2023 classic second difference	15	2.75	2.67	3.11	***,008***
2024 classic second difference	15	1.94	1.98		
2023 free degree	15	10.2	4.69	2.72	***,017***
2024 free degree	15	8.80	5.40		
2023 free time	15	19.1	5.35	1.35	,197
2024 free time	15	18.8	5.53		
2023 free second difference	15	2.04	1.87	1.16	***,015***
2024 free second difference	15	,94	1.43		

p<0.05

As shown in Table 7, the experimental group demonstrated significant improvements in the 2024 season compared with 2023 in the 2nd Stage classic-style race rankings and time gaps from the first-place finisher (p<0.05). Similarly, significant improvements were observed in freestyle race rankings and time gaps from the first-place finisher (p<0.05), whereas race times did not differ significantly between seasons in either style (p>0.05).

Table 8. Comparison Table of Results of Experimental Group Participants in 2023-2024 Season Turkish Championship Classical and Freestyle Competitions

Variables	N	x̄	SD	t	p
2023 classical degree	15	9.76	4.32	5.33	***,000***
2024 classical degree	15	7.30	4.38		
2023 classic second difference	15	2.61	2.17	1.09	***,007***
2024 classic second difference	15	1.35	2.04		
2023 free degree	15	8.92	4.00	2.21	***,047***
2024 free degree	15	6.76	4.43		
2023 free second difference	15	3.24	4.16	1.42	,066
2024 free second difference	15	2.43	3.87		

p<0.05

As shown in Table 8, the experimental group demonstrated significant improvements in the 2024 Turkey Championship compared with 2023 in classic-style race rankings and time gaps from the first-place finisher ($p<0.05$). In freestyle, race rankings also improved significantly ($p<0.05$), whereas the time gap from the first-place finisher did not differ significantly between seasons ($p>0.05$).

Table 9. Comparison Table of the 2023-2024 Season 1st Stage Freestyle Competition Results of the Experimental and Control Group Participants

Variables	N	x̄	SD	t	p
2023 experiment degree	15	9.46	5.15	-1.23	,231
2023 degree of control	15	11.3	5.82		
2023 experiment duration	15	26.5	7.71	-,234	,818
2023 control time	15	26.2	7.02		
2023 experiment seconds difference	15	4.09	2.83	,268	,793
2023 control second difference	15	3.83	3.18		
2024 experiment degree	15	5.92	4.28	-2.20	,046
2024 degree of control	15	11.1	7.27		
2024 experiment duration	15	24.2	8.12	-,201	,784
2024 control time	15	25.4	7.12		
2024 experiment second difference	15	2.35	2.41	-1.27	,223
2024 control seconds difference	15	3.59	3.46		

p<0.05

As shown in Table 9, no significant differences were observed between the experimental and control groups in the 2023 1st Stage freestyle race outcomes ($p>0.05$). In 2024, the experimental group achieved significantly better race rankings than the control group ($p<0.05$), whereas no significant between-group differences were found in race times or time gaps from the first-place finisher ($p>0.05$).

As shown in Table 10, the experimental group demonstrated significantly better 2nd Stage freestyle race times than the control group in the 2024 season ($p<0.05$). No significant between-group differences were observed in race rankings or time gaps from the first-place finisher in either the 2023 or 2024 season ($p>0.05$).

Table 10. Comparison Table of the Results of the 2023-2024 Season 2nd Stage Freestyle Competition of the Experimental and Control Group Participants

Variables	N	x̄	SD	t	p
2023 experiment degree	15	10.2	4.69	-,254	,803
2023 degree of control	15	10.4	6.31		
2023 experiment duration	15	19.1	5,.35	-,540	,598
2023 control time	15	20.3	5.50		
2023 experiment seconds difference	15	2.54	1.87	-1.25	,230
2023 control seconds difference	15	2.86	2.50		
2024 experiment degree	15	8.60	5.10	-1.17	,261
2024 degree of control	15	10.8	6.91		
2024 experiment duration	15	16.8	5.15	-,675	***,011***
2024 control time	15	20.3	5.47		
2024 experiment seconds difference	15	1.74	1.88	-1.24	,229
2024 control seconds difference	15	2.77	2.54		

p<0.05

As shown in Table 11, no significant differences were observed between the experimental and control groups in the 2023 Turkey Championship classic-style race outcomes (p>0.05). In 2024, the experimental group achieved significantly better race rankings than the control group (p<0.05), whereas no significant between-group difference was observed in the time gap from the first-place finisher (p>0.05).

Table 11. Comparison Table of the Results of the 2023-2024 Season Turkish Championship Classical Style Competition of the Experimental and Control Group Participants

Variables	N	x̄	SD	t	p
2023 experiment degree	15	8.54	3.41		
2023 degree of control	15	7.18	4.89	1.36	,204
2023 experiment second difference	15	2.22	2.13		
2023 control second difference	15	2.19	2.02	-,097	,825
2024 experiment degree	15	6.09	3.50		
2024 degree of control	15	8.72	3.74	-2.22	***,048***
2024 experiment second difference	15	1.93	1.92		
2024 control second difference	15	2.65	2.16	-,847	,417

p<0.05

As shown in Table 12, no significant differences were observed between the experimental and control groups in the 2023 Turkey Championship freestyle race outcomes (p>0.05). In 2024, the experimental group achieved significantly better race rankings than the control group (p<0.05), whereas no significant between-group difference was observed in the time gap from the first-place finisher (p>0.05).

Table 12. Comparison Table of 2023-2024 Season Turkish Championship Freestyle Competition Results of Experimental and Control Group Participants

Variables	N	x̄	S.S	t	p
2023 experiment degree	15	2.72	3.48		
2023 degree of control	15	2.59	4.81	-3.37	,711
2023 experiment second difference	15	3.45	3.27		
2023 control second difference	15	2.56	2.03	2.42	,121
2024 experiment degree	15	1.41	3.32	1.74	
2024 degree of control	15	3.09	4.32		***,045***
2024 experiment second difference	15	2.11	3.25		
2024 control second difference	15	2.49	2.13	-,500	,628

p<0.05

4. Discussion

In practice, the inability to consistently detect muscle damage after each training session presents an important challenge for training-load management. Based on previous studies demonstrating a strong relationship between muscle damage and muscle soreness (Hazar et al., 2006), the present study compared a progressive training program modified according to the severity of muscle soreness with classical progressive loading and evaluated its effects on physical, physiological, and competitive performance. From this perspective, muscle soreness may provide a practical indicator that can contribute to decisions concerning training load and recovery when direct assessment of muscle damage is not feasible.

Exercise-induced muscle damage (EIMD) is strongly influenced by the mechanical characteristics of exercise, particularly eccentric contractions. Reductions in maximal isometric strength have been associated with histological muscle damage, while fiber strain, contraction force, and contraction velocity appear to contribute to the magnitude of damage (Faulkner, Brooks, & Opiteck, 1993; Lieber & Friden, 1993). These mechanisms are relevant to progressive training because inadequate recovery between successive high-load sessions may impair force production and subsequent training quality. Accordingly, modifying training intensity according to the severity of muscle soreness may provide a practical strategy for maintaining progressive overload while allowing sufficient recovery.

The importance of controlling EIMD may extend beyond transient muscle soreness and performance impairment. EIMD has been associated with systemic inflammatory and thermoregulatory responses that may contribute to more serious physiological consequences under extreme and prolonged exercise conditions, including exertional heat stroke and acute kidney injury (Goto et al., 2023; Roberts et al., 2023; Li, 2021). Although these conditions were not primary outcomes of the present study, these findings emphasize the broader importance of monitoring responses to strenuous exercise. In this context, adjusting training load according to muscle soreness and recovery status may contribute to limiting excessive physiological stress while maintaining training continuity.

In the present study, significant improvements were observed in several anaerobic performance variables in the experimental group following the intervention. These improvements may be associated with the modification of training loads according to the severity of muscle soreness, which may have contributed to a more favorable balance between training stimulus and recovery. Exercise-induced muscle damage and delayed-onset muscle soreness (DOMS) can impair force production and athletic performance, particularly following exercise involving substantial eccentric loading (Douglas et al., 2017; Owens et al., 2019). Muscle cramps and soreness may also negatively affect physical performance and force-production capacity (Marcora & Bosio, 2007; Twist & Eston, 2009), while the severity of soreness has been associated with the magnitude of performance impairment (Douglas et al., 2017). Therefore, adjusting subsequent training loads according to soreness may allow athletes to maintain training quality while limiting the accumulation of excessive fatigue.

This issue is particularly relevant to cross-country skiing because competitive performance requires the integration of endurance, strength, power, and sport-specific technical efficiency. Strength and power training have become increasingly important components of modern cross-country skiing, and improvements in strength-related characteristics can contribute to skiing-specific performance (Stöggl & Holmberg, 2022). Therefore, the improvement in anaerobic performance observed in the present study may not simply reflect progressive loading itself but may also be associated with a more appropriate organization of the load–recovery relationship in the experimental group.

In terms of body composition, no significant differences were observed in body fat percentage

or body mass index, whereas lean body mass improved significantly in the experimental group. Previous studies examining the effects of strength and endurance training on body composition have reported reductions in body weight, body fat percentage, BMI, and skinfold thickness together with increases in body density and lean body mass (Gökdemir et al., 2007; Patlar et al., 2003). Strength training is generally more closely associated with increases or maintenance of muscle mass, whereas endurance training produces adaptations that depend on training volume, intensity, and the characteristics of the athletes. In the present study, maintaining training continuity through load modification according to muscle soreness may have contributed to the favorable change in lean body mass by allowing athletes to complete the planned training process with fewer interruptions related to excessive soreness.

The importance of organizing training to reduce the negative consequences of muscle damage is also supported by studies examining recovery strategies. Preconditioning exercise has been reported to reduce creatine kinase release, DOMS, loss of maximum voluntary contraction strength, and reductions in range of motion following subsequent muscle-damaging exercise (Boyd et al., 2023). Similarly, localized vibration therapy has been reported to improve muscle oxygen saturation and strength following EIMD (Percival et al., 2022). Although these interventions differ from the training modification used in the present study, they collectively demonstrate that the physiological and performance consequences of EIMD can be influenced by the way exercise and recoveries are managed. Thus, muscle soreness should not necessarily be considered merely an unavoidable consequence of training but may provide useful information for planning subsequent training loads.

The experimental group also demonstrated favorable improvements in aerobic performance variables, including Max VO2 and Max VO2/HR, compared with the control group. Although muscle soreness and EIMD are commonly associated with neuromuscular performance impairment, inadequate recovery may also compromise endurance-training quality by limiting the athlete's ability to sustain the prescribed intensity and volume. Accordingly, modifying training loads based on soreness may have enabled the athletes in the experimental group to perform subsequent endurance sessions under more favorable recovery conditions.

This interpretation is especially relevant in cross-country skiing, where endurance performance is combined with considerable upper- and lower-body muscular demands. Recent literature demonstrates that strength and power training are important complementary components of cross-country skiing performance. Stöggl and Holmberg (2022), in a systematic review of competitive cross-country skiers, showed that strength- and power-oriented interventions can improve relevant strength characteristics and may contribute to skiing performance. Similarly, evidence from strength-training interventions in cross-country skiers indicates that maximal strength and concurrent endurance–strength training can improve variables relevant to performance, including double-poling economy and skiing performance. Thus, the adaptations observed in the present study should be interpreted within the multidimensional physiological demands of cross-country skiing rather than solely as isolated changes in aerobic or anaerobic capacity.

The organization of day-to-day training load is another important consideration when interpreting the present findings. Walther et al. (2025) investigated daily endurance-training periodization in world-class cross-country skiers and demonstrated that training was organized by alternating days with different demands, including high-volume days, elevated-intensity sessions, reduced-load days, and complete rest. Intensive sessions were generally separated by approximately three to four days, while reduced-load or rest days were systematically incorporated into the training process. These findings demonstrate that even at the world-class level, progressive training does not imply continuously increasing or maintaining high loads on successive days; rather, high training stimuli are integrated with periods of reduced loading and recovery. This principle is consistent with the rationale of the present study, in which the

subsequent training load was modified according to the athlete's muscle soreness.

Recent evidence also emphasizes the importance of monitoring the internal response to training in cross-country skiers. Du et al. (2026) examined internal load and fatigue characteristics during a three-week summer training period in male cross-country skiers and reported differences in internal load and fatigue responses according to the training methods employed and their combinations. These findings are relevant because athletes exposed to similar external training prescriptions may experience different internal physiological and fatigue responses. Therefore, individualized indicators such as perceived muscle soreness may provide complementary information for determining whether the planned subsequent training load is appropriate for the athlete's current recovery status.

The importance of recovery becomes even more apparent when muscle damage persists after demanding training or competition. EIMD and DOMS may occur after training sessions and competitions and are particularly associated with highly eccentric or unfamiliar movements (Douglas et al., 2017). Deceleration following sprint running may impose substantial mechanical stress on the lower-extremity muscles (Phomsoupha et al., 2018), while functional impairments associated with EIMD may persist for several days following demanding exercise (Byrne et al., 2001). In addition, recovery following prolonged competition may depend on the duration and physiological demands of the event, with inflammatory responses potentially persisting beyond the recovery of some muscle-damage indicators (Martinez-Navarro et al., 2021). Collectively, these findings reinforce the importance of considering recovery status when determining subsequent training loads.

The competition results in the present study generally demonstrated favorable changes following the intervention, with several performance indicators improving across the 2024 season compared with the previous season and/or favoring the experimental group. Rather than reproducing individual rankings, race times, and time gaps in the Discussion, these findings may be interpreted as evidence that individualized modification of training load according to soreness contributed to maintaining training continuity and improving readiness for competition. Since muscle damage and DOMS can impair force production and physical performance (Marcora & Bosio, 2007; Twist & Eston, 2009; Douglas et al., 2017; Owens et al., 2019), reducing excessive residual soreness before subsequent high-quality training sessions may have contributed to the observed competitive improvements.

This interpretation is supported by the specific training characteristics of high-level cross-country skiers. Walther et al. (2025) demonstrated that world-class skiers systematically alternate training loads rather than continuously combining high volume and high intensity. Only a small proportion of training days simultaneously involved elevated volume and intensity, while reduced-load and rest days were deliberately incorporated into the training sequence. Such observations provide a sport-specific physiological rationale for the present approach: adaptation may depend not only on the magnitude of the training stimulus but also on when the next stimulus is applied relative to the athlete's recovery state.

Strength development is also an important component of competitive cross-country skiing, but its effectiveness depends on appropriate manipulation of training load, intensity, frequency, and recovery. Deviations from optimal loading may lead to performance impairment rather than improvement, making adequate recovery between demanding sessions essential (De Freitas et al., 2011; Kraemer & Ratamess, 2004). A systematic review specifically examining cross-country skiers similarly demonstrated the relevance of strength and power development for skiing performance (Stöggl & Holmberg, 2022). Therefore, the favorable changes observed in the present study may partly reflect the ability of the modified training model to maintain sufficient training stimulus while preventing excessive accumulation of fatigue and soreness.

Previous findings also indicate that muscle-damaging exercise can negatively affect soreness,

CK responses, and subsequent speed performance for approximately 48–72 h (Uçan et al., 2018). From a practical perspective, this is particularly important during periods in which high-intensity training and competitions are performed in close succession. The present training model should therefore not be interpreted as reducing training load whenever muscle soreness occurs. Rather, it represents an individualized approach in which the principle of progressive overload is maintained while the magnitude of subsequent training is adjusted according to the athlete's response to the preceding session.

Overall, the present findings suggest that modifying progressive training loads according to the severity of muscle soreness may contribute to favorable physical, physiological, and competitive outcomes in cross-country skiers. This interpretation is consistent with contemporary evidence showing that world-class cross-country skiing training involves systematic variation in daily training load and deliberate integration of recovery periods (Walther et al., 2025), while internal load and fatigue responses may vary according to the characteristics and sequencing of training sessions (Du et al., 2026). Considering the high aerobic, strength, and power demands of cross-country skiing (Stöggl & Holmberg, 2022), integrating an accessible recovery indicator such as muscle soreness into daily training decisions may provide a practical method for individualizing the balance between overload and recovery. Future studies should combine subjective soreness assessment with direct biomarkers of muscle damage and fatigue to determine more precisely how individualized load modification influences long-term adaptation and competitive performance.

5. Conclusion

This study demonstrated that a 12-week cross-country skiing training program modified according to pre-training muscle soreness levels improved athletes' physical, physiological, and competition performance, with more favorable outcomes observed in the experimental group. These findings suggest that monitoring muscle soreness may provide a practical approach for individualizing training intensity and duration according to athletes' recovery status. However, the relatively small sample size, subjective assessment of muscle soreness, and potential influence of environmental factors should be considered when interpreting the findings. Future studies involving larger and more diverse athlete populations and objective measures of muscle damage and recovery are recommended.

5.1. Study Limitations and Future Research Directions

The study is limited to cross-country skiers aged between 15 and 20 years, residing in the province of Bitlis, Turkey. The sample includes 30 athletes who have consecutively participated in competitions organized by the Turkish Ski Federation for at least five years, and who are affiliated with the Bitlis Youth and Sports Club. This study also highlights that coaches should carefully monitor muscle soreness levels:

When soreness is absent, training intensity and duration should be increased to enhance strength and endurance. When soreness remains within acceptable levels, the current training load should be maintained. When soreness is excessive, training intensity and duration should be reduced to prevent potential injuries.

By following this approach, multidimensional improvements can be achieved in both strength and endurance performance. This perspective offers coaches and sports scientists a new approach for designing general training programs. As this type of study is extremely rare in the literature, it is expected to guide future research in different sports disciplines within the field of sports sciences. Future research should investigate the effects of muscle soreness-based modified training approaches across different age groups, performance levels, and sports disciplines. In particular, studies involving elite athletes, female athletes, and individuals with varying training backgrounds may enhance the generalizability of the current findings. Furthermore, research

conducted with larger sample sizes and longer intervention periods would contribute to a more comprehensive understanding of the long-term effects of this training model. Future studies may also evaluate muscle soreness alongside biochemical markers of muscle damage (e.g., creatine kinase, lactate dehydrogenase), hormonal responses, recovery processes, and psychological variables to better understand the multidimensional effects of training load. In addition, the impact of soreness-based training adjustments on injury risk, athlete health, performance sustainability, and competitive success throughout a season should be examined. Comparing muscle soreness-based modified training programs with different training methods, such as high-intensity interval training, endurance training, strength training, and sport-specific training, may further clarify the effectiveness of this approach. Such investigations are expected to provide important scientific evidence for the development of individualized training strategies within the field of sports science.

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Ethics Statement: An application for ethical approval was submitted to the Non-Interventional Clinical Research Ethics Committee of Sivas Cumhuriyet University, and approval was granted (Decision No: 2023-02/07, dated 21.02.2023) (Appendix I). Prior to the measurements, participants were provided with a detailed presentation regarding the study and signed informed consent forms (Appendix II). This study was conducted in accordance with the principles of the Declaration of Helsinki.

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Data Availability: The datasets used and/or analyzed in the present study are available from the corresponding author upon reasonable request, subject to obtaining the necessary permissions from the relevant institutions.

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