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Elite Cross-Country Skiers Develop Greater Physiological Adaptations Than Biathletes in Summer Macrocycle

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Abstract

Feofilaktov, VV, Heil, D, Myakinchenko, EB, Smith, DM, and Kruchkov, AS. Elite cross-country skiers develop greater physiological adaptations than biathletes in summer macrocycle. *J Strength Cond Res* 39(7): 788–797, 2025—The study aimed to compare changes in aerobic, anaerobic, body composition, and training load parameters during a 6-month macrocycle in elite cross-country skiers (XC) and biathletes (BI). Twenty-six physiological and 8 training load parameters were analyzed retrospectively every month throughout a 6-month summer macrocycle for 32 elite male XC and 41 BI during 7 consecutive years. During the macrocycle, XC demonstrated lower body fat (6.7 ± 1.7 vs. 7.5 ± 1.5 kg, $p < 0.001$) and higher muscle mass (39.7 ± 3.0 vs. 38.5 ± 3.6 kg, $p < 0.001$) compared with BI. In addition, XC exhibited superior aerobic capacities at ventilatory threshold (VT), including oxygen pulse, oxygen uptake, power output, stroke volume, maximum oxygen uptake ($\dot{V}O_2\text{max}$), and cardiac output, and maximum rate and power output for 10-second Wingate double poling (all $p < 0.001$). Both XC and BI showed simultaneous improvements in aerobic and anaerobic capacities, peaking during the competition period. The most consistent improvements observed throughout the macrocycle were in the upper-body power output at VT and $\dot{V}O_2\text{max}$ (correlation with the number of training days $r = 0.3\text{--}0.4$, $p < 0.05$). Cross-country skiers engaged in significantly higher volumes of low-intensity training (LIT), total strength training, and sport-specific training (SST) compared with BI (all $p < 0.001$). Conversely, BI had higher volume of high-intensity interval training (HIIT) in the final 4 months of the macrocycle. In conclusion, differences in training volumes (LIT, SST, and total strength) likely contributed to superior adaptations observed in XC. The study found that physiological adaptations were delayed rather than concurrent throughout the macrocycle.

Key Words: periodization, seasonal adaptations, elite athletes, strength and power, endurance performance, body composition

Introduction

Endurance sports performance is closely correlated with several key physiological parameters: maximal oxygen uptake ($\dot{V}O_2\text{max}$), lactate and ventilatory threshold (VT), economy or gross efficiency (GE), and maximal power output (10,15). These parameters, alongside body composition metrics, are routinely assessed in physiological laboratories to provide diagnostic insights into changes in athletes' functional and motor abilities, crucial for athletes and coaches alike. However, the specific time course for sport-specific physiological adaptations during a macrocycle remains unclear. For instance, it is uncertain which physiological parameters need to reach or approach peak values to maximize endurance performance. Are all physiological parameters equally critical, or do specific parameters need to carry more weight in enhancing performance?

Recent decades have underscored the significant role of strength and power training in enhancing endurance performance and aerobic capacity (1,2,19,20,25). Given the varying durations of adaptations in aerobic endurance, anaerobic capacities, power, and strength, effectively coordinating these adaptations can

profoundly impact sport performance. In a recent systematic review on training intensity distribution, Sperlich et al. (2023) concluded that the optimal distribution of training intensities in elite endurance sports depends on multiple factors such as intensity, volume, type of training, competition schedule, among others. This complex interplay necessitates a comprehensive approach (30). Further advancement in training intensity distribution and the concept of periodization can be achieved through detailed analyses of training loads relative to the time course of physiological changes.

Cross-country skiing (XC) and biathlon (BI) are demanding winter Olympic sports that place high requirements on both aerobic and anaerobic capacities. Although these sports share similarities in training and competition, XC athletes engage in both skating and classic skiing techniques, whereas BI athletes focus exclusively on skating combined with shooting. Recent studies have identified XC and BI training periodization models as “pyramidal” (22) or “polarized” (24,33), characterized by higher volumes of strength and endurance training in XC and a greater emphasis on high-intensity interval training (HIIT) in BI (22). However, there is a scarcity of studies examining continuous short-term (1–2 months) changes throughout a macrocycle. Previous research has shown that XC athletes experienced their highest training volumes (26,29) and significant improvements in

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$\dot{V}O_2\text{max}$ and oxygen cost during the summer preparatory period, with more modest gains in roller-skiing performance and aerobic capacities observed during the competitive winter period (13). Notably, these studies predominantly monitored whole-body exercises at 3- to 4-month intervals, potentially overlooking variations in adaptations across upper body (UB), lower body (LB), and body composition parameters. In another investigation focusing on elite development XC athletes over a 2-year period (9), substantial improvements in whole-body and UB lean mass were noted across genders, with female XC athletes showing significant enhancements in LB lean mass, reduction in body fat, and improvements related to lactate threshold. Further exploration into the time course of adaptations across major physiological parameters during a macrocycle could elucidate fundamental principles of training and adaptations among elite endurance athletes. Therefore, the purpose of this study was to compare changes in aerobic and anaerobic capacities, along with body composition, over a 6-month summer macrocycle in elite XC and BI athletes. Building upon previous findings (21,22), our hypothesis suggested that XC athletes would exhibit greater physiological adaptations potentially influenced by their distinct training regimens.

Methods

Experimental Approach to the Problem

To explore the temporal patterns of anthropometric and physiological adaptations within a macrocycle, international-level XC and BI athletes underwent standardized testing using a comprehensive battery of tests during successive summer training periods from April 30 to November 13 across the seasons from 2014 to 2021. The macrocycle encompassed a preparatory phase (May–August) followed by the competitive phase, during which athletes participated in the National Championships (September). Subsequently, the winter preseason preparatory phase (October and the first half of November) involved mini blocks of increased low-intensity training (LIT) and reduced high-intensity training (HIT) in preparation for the Winter Cup competitions (16). Each month, test results were recorded with an 8- to 10-day delay (e.g., from September 10th to October 10th), under the assumption that it takes approximately 8–10 days of training to induce detectable changes in physiological parameters during laboratory tests (17,18).

Subjects

The subjects for this study were male athletes from the Russian National Teams in cross-country skiing and biathlon from 2014 to 2021. Because of a lack of female athletes tested in the laboratory, only male athletes were included in the analysis. Inclusion criteria were (a) passing a comprehensive medical examination, being free of injuries or illnesses, and being cleared for training; (b) participating 3–5 times per season in the standardized testing program; and (c) regularly competing in international events. The study was approved by the Ethics Committee of the Russian Scientific Research Institute of Physical Education and Sports (Moscow, Russia) and was conducted as part of the Federal Sports Research Program (No 777-00026-22-00, Topic No 001-22/5), in accordance with the Helsinki Declaration's ethical standards. All athletes provided informed consent and agreed to the anonymous use of their data for scientific research. In total, 73 international-level athletes met the inclusion criteria: 32 cross-

country (XC) athletes (international ranks = 2 to 202; age = 25 ± 4 years; $\dot{V}O_2\text{max} = 77.8 \pm 3.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and 41 biathlon (BI) athletes (international ranks = 2 to 206; age = 25 ± 3 years; $\dot{V}O_2\text{max} = 76.1 \pm 5.2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).

Procedures

The data collection and calculation methods have been described in detail elsewhere (21). In brief, all testing used standardized equipment and protocols specific to the National Teams and was administered by experienced staff. Athletes were familiar with the procedures, and all tests were conducted within a single day. Although the total duration of the test battery was approximately 3 hours, the workload was relatively low for athletes of this caliber, with the maximal oxygen consumption test being conducted last. Blood lactate levels were monitored multiple times throughout the testing (Figure 1). The standardized testing program was developed based on procedures used with National Team athletes in 2010–2011. To manage fatigue, standardized rest periods and active bicycle rest were incorporated, and follow-up tests were performed only if lactate levels were below $2 \text{ mmol}\cdot\text{L}^{-1}$ and subjective fatigue was rated at 4 out of 10 or lower before the next test (21). The test order is illustrated in Figure 1. Good-to-excellent test-retest reliability was shown for ski-specific laboratory testing (34).

Before physiological testing, anthropometric parameters were measured using the Matejko modified method (16) with GPM Anthropological Instruments (DKSH Switzerland Ltd., Zurich, Switzerland). Parameters measured included Body Mass, Body Fat, Muscle Mass, upper-body muscle volume relative to body surface area (UB Volume/BSA), and lower-body muscle volume relative to body surface area (LB Volume/BSA). Upper-body volume was calculated as the sum of muscle volumes of the forearm, arm, and thorax, whereas LB Volume was the sum of the leg and pelvic girdle volumes. Body surface area (BSA) was calculated using the formula: $BSA = \sqrt{(\text{Body Height}(\text{cm}) \times \text{Body Mass}(\text{kg}))/3,600}$.

After a standard warm-up, athletes performed an incremental nonmaximal ventilatory threshold (VT) double pole (DP) test on a ski ergometer (Concept2 SkiErg; Concept2 INC, Morrisville, VT). The test began with an initial workload of 80 Watts for 2 minutes, increasing by 15 Watts each minute. Continuous measurements of heart rate (HR), ventilation, and gas exchange parameters were taken, and the second VT was determined from HR and gas exchange graphs. Ventilatory and gas exchange parameters were measured using the MetaLizer3B (Cortex Biophysik GmbH, Leipzig, Germany), and HR was recorded with the Polar RS800CX (Polar Electro Oy, Kempele, Finland). Testing was stopped 1–2 minutes after achieving VT. Parameters measured during this test included UB oxygen uptake at VT (UB VT $\dot{V}O_2$), UB power output at VT (UB VT PO), UB oxygen pulse at VT (UB O_2 pulse), UB work per one DP cycle at VT (UB VT Work per Cycle), and gross efficiency at VT (UB GE). After a short rest and additional warm-up, athletes performed 2 attempts of 3 maximum single-arm pulls for each arm, and one attempt of 3 maximum pulls for both arms on the same ski ergometer. The UB power was averaged from maximal power outputs for right, left, and double arm pulls (UB Power). After this, athletes completed two 10-second DP Wingate tests on the ski ergometer, measuring peak power and maximal pulling cadence (UB Wingate and UB Max Rate). Next, athletes performed a countermovement jump test without arm swing (CJ Power) and a 10-second Wingate test (LB Wingate) on a cycle ergometer (Monark 894E; Monark Exercise AB, Vansbro, Sweden). Using the Biodex System 4 Pro

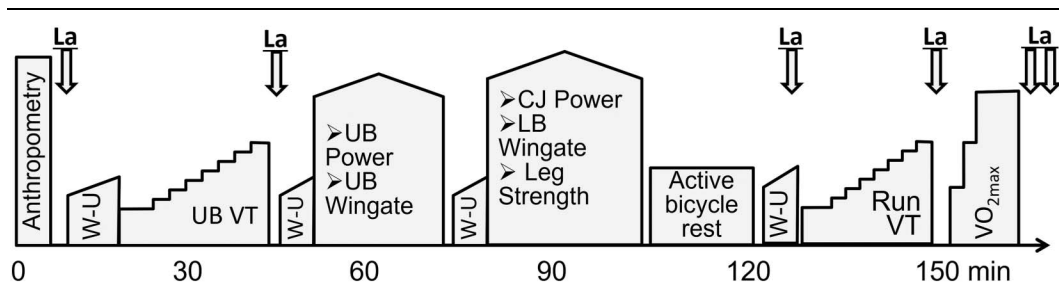


Figure 1. The order and duration of the standardized testing program. CJ = countermovement jump; La = blood lactate; LB = low body; SA = single arm; UB = upper body; VT = ventilatory (anaerobic) threshold; W-U = warm-up.

machine (Biodex Medical Systems, Inc., Shirley, NY), maximal strength of the knee extensor and flexor muscles was measured in a sitting position at an isokinetic velocity of 60°/sec (Leg Strength). After 10–15 minutes of active rest, athletes underwent whole-body VT testing on the Fitnex treadmill (Fitness Master, INC., Dallas, TX) using methods and equipment similar to the UB incremental test. During this test, athletes performed an uphill run (10%) while using ski poles to simulate the classic diagonal stride skiing technique. The initial treadmill speed was 6 km·h⁻¹, increasing by 0.5 km·h⁻¹ every minute. After reaching the VT level, athletes were stopped and allowed to recover for 5 minutes. Parameters from this test included oxygen uptake at VT in running (Run VT $\dot{V}O_2$), power output at VT in running (Run VT PO), Stroke Volume Index, oxygen pulse at VT in running (Run VT O₂ Pulse), and Running GE (Run GE). After a 5-minute recovery, athletes performed $\dot{V}O_{2max}$ testing on the same treadmill. They started walking with ski poles at 6 km·h⁻¹ and 0% grade, with the grade increased to 16% during the first 45 seconds. The speed was then increased to 9 km·h⁻¹, and subsequently to 12 km·h⁻¹ over the next 30 seconds. Athletes continued the running test until volitional exhaustion, with typical run durations between 2:50 and 4:20 minutes. The highest 30-second $\dot{V}O_2$ value was recorded as $\dot{V}O_{2max}$, provided there was evidence of a plateau in oxygen consumption. Capillary blood samples were taken during the third and fifth minutes of recovery to determine peak lactate concentration. The outcomes included $\dot{V}O_{2max}$, Cardiac Output Index, and Peak La. For further details on the testing procedures and calculations, refer to Myakinchenko et al., 2022 (21).

Training-load monitoring was conducted in collaboration with National Team coaches who were specially trained for this purpose. A typical 4-week mesocycle included 2–3 weeks of training camps and 7–10 days of regional “home” training. Using a time-in-zone approach, endurance training parameters were classified as follows: Low Intensity Training (LIT) with HR below the aerobic threshold (ventilatory threshold 1—VT1), Moderate Intensity Training (MIT) with HR between the aerobic and anaerobic thresholds (VT1 to VT), and High Intensity Training (HIT) with HR above the anaerobic threshold (above VT) and La concentration greater than 5 mmol·L⁻¹. HIT included intervals with durations of 21–59 seconds, 60–240 seconds, and >240 seconds. The number of intervals and total time were recorded. See more details in Myakinchenko et al., 2020 (22). Strength training was focused on either strength and hypertrophy in May–August, or strength and power in September–November (Table 1). Strength training loads were classified as heavy (above 85% of RM), moderate (60–85% of 1 RM), and low (30–60% of 1 RM). The total strength training time and number of sets were recorded for Total Strength (overall volume of strength training), UB Strength (the upper body and core-muscle exercises), LB

Strength, and LB Power (sprints, plyometrics, and explosive exercises for the lower body). Sport-specific training (SST) involved aerobic-resistance exercises (Verhoshanskiy, 36), emphasizing powerful propulsions in sport-specific movements against additional resistance (35), such as running, bounding, roller skiing uphill with a dragging device or with a weight vest. Sport-specific training was typically performed as 6–10 intervals of 4–10 minutes each with 2–3 minutes of recovery, and the total interval time was recorded (Table 2). On average, athletes trained 20–25 hours per week, starting with 2–3 strength training and 2–3 SST sessions per week at the beginning of the macrocycle, reducing to 1–2 sessions by the competition period.

Statistical Analyses

Before performing inferential statistics, data were examined for normality and other basic assumptions. Normality was assessed using skewness and kurtosis ratios, with values in the range of -2.0 to +2.0 considered acceptable (37). All parameters were found to be mostly normally distributed with no significant outliers, which were defined as values greater than ± 3.29 standard deviations (37). To evaluate differences in physiological parameters between sports each month, we employed a 2 × 6 factorial MANOVA (Sport × Month) with ANOVA for post-hoc comparisons. Effect sizes were determined using partial eta squared (η_p^2): values less than 0.06 indicated a small effect, 0.06 to 0.14 a medium effect, and greater than 0.14 a large effect (37). Trends in macrocycle changes were analyzed using linear regression with Pearson’s correlation coefficient for data points from May to September 10th. All statistical analyses were conducted using SPSS 26.0 (SPSS, Inc., Chicago, IL) with a significance level set at 0.05. A Bonferroni adjustment was applied to account for multiple comparisons, resulting in a corrected alpha level of 0.002.

Results

A total of 209 lab testing sessions were conducted for XC athletes, and 289 for BI athletes. According to prior power analysis for MANOVA (power = 0.80, effect size $f = 0.25$), a minimum of 211 testing sessions was required. Although equal sample sizes among the 12 groups were not achieved, the total sample size ($N = 498$) met the necessary assumptions. The assumption of univariate homogeneity of variance was met for most parameters except Body Mass, Body Fat, CJ Power, Peak La, Cardiac Output Index, $\dot{V}O_{2max}$, UB VT PO, Run VT $\dot{V}O_2$, and Run VT PO. However, the Box’s M test indicated significant variance/covariance homogeneity violations ($p < 0.001$), likely because of varying sample sizes across months. Consequently, Pillai’s Trace was used in MANOVA to address these issues. Descriptive

Table 1
Typical strength training sessions of elite cross-country skiers and biathletes in the summer macrocycle.*†

Activity	May–August Goal/sets × reps/rest/velocity	September–November Goal/sets × reps/rest/velocity
Upper body		
Pullups	Hypertrophy: 3–4 × 10–12/2–3 min/slow Strength: 3–4 × 5/3 min/slow	Strength: 3–4 × 5/3 min/slow Power: 3 × 5–6/3–4 min/high
Standing pull down	Hypertrophy: 3–5 × 10–15/2–3 min/medium	Strength: 3–4 × 5/3 min/slow Power: 3 × 5–6/3–4 min/high
Suspended dips	Hypertrophy: 3–5 × 10–12/2–3 min/slow Strength: 3–4 × 5/3 min/slow	Strength: 3–4 × 5/3–4 min/slow
Bench press	Hypertrophy: 3–5 × 10–12/2–3 min/slow Strength: 3–4 × 5/3 min/slow	Strength: 3–4 × 5/3–4 min/slow
Bench pull	Hypertrophy: 3–5 × 10–12/2–3 min/slow Strength: 3–4 × 5/3 min/slow	Strength: 3–4 × 5/3 min/slow
Lower body		
Back squat or front squat	Hypertrophy 1: 4–5 × 12–15/3 min/slow Hypertrophy 2: 3–5 × 10–12/3 min/slow	Strength: 3–4 × 5/3 min/slow Power: 3 × 15/3–4 min/high
Bulgarian split squat	Hypertrophy: 3–5 × 10–12/3 min/medium Strength: 3–4 × 5–6/3 min/slow	Strength: 3–4 × 5/3 min/slow Power: 3–4 × 12–15/3 min/high
Barbell lunge	Hypertrophy: 3–5 × 12–15/3 min/medium Power: 3–4 × 12–15/3 min/high	Power: 3–4 × 5–6/3 min/high Power: 3–4 × 12–15/3 min/high
Hip thrust	Hypertrophy 1: 4–5 × 12–15/3 min/slow hypertrophy 2: 3–5 × 10–12/3 min/slow Strength (July–August): See on the right	Strength: 3–4 × 5–6/3 min/slow Plyometrics (BW): 3–4 × 4–5/3 min/high
Plyometrics	Squat jump variations with a weight vest (30% of BW): 4–5 × 20–30/3–4 min/high Box jump (box height: 0.70–0.75 m): 4–5 × 12–15/3–4 min/high	No Box jump (box height: 0.75–0.80 m): 3–4 × 4–5/3 min/ high
Core/stabilization exercises		
Performed as a circuit, rest 10–20 s, and 3–4 min between circuits		
Crunch	3–4 × 1 min/medium	2–3 × 1 min/medium
Alternating leg raise crunch	3–4 × 1 min/medium	2–3 × 1 min/medium
Side plank	3–4 × 2 min/isometric	2–3 × 2 min/isometric
Plank	3–4 × 2 min/isometric	2–3 × 2 min/isometric
Back extension	3–4 × 15–20/slow	2–3 × 15–20 slow
Side-lying hip raise	3–4 × 15–20/slow/each side	2–3 × 15–20/slow/each side

*BW = body weight.

†Exercises for hypertrophy were performed with 60–75% of 1RM, for strength with 80–85%, for power with 60–70% of 1RM.

statistics and macrocycle dynamics for 26 physiological parameters across both sports are shown in Figures 2–4, and Table 3.

The MANOVA revealed a significant interaction effect: Pillai's Trace (Sport × Month) = 0.441, $F(130,2320) = 1.73, p < 0.001, \eta_p^2 = 0.088$. Significant main effects were observed for Sport (Pillai's Trace = 0.448, $F(26,460) = 14.36, p < 0.001, \eta_p^2 = 0.448$) and Month (Pillai's Trace = 0.655, $F(130,2320) = 2.63, p < 0.001, \eta_p^2 = 0.131$). Post-hoc factorial ANOVAs identified significant interactions for Body Fat ($F = 3.863, p < 0.01, \eta_p^2 = 0.038$), Leg Strength ($F = 2.897, p < 0.05, \eta_p^2 = 0.029$), UB O₂ Pulse ($F = 2.873, p < 0.05, \eta_p^2 = 0.029$), and UB GE ($F = 3.540, p < 0.01, \eta_p^2 = 0.035$) as detailed in Figures 2 and 3.

Cross-country skiers had significantly lower Body Fat compared with BI athletes in the third, fourth, and sixth months ($p < 0.001$). In month-to-month comparisons, XC athletes showed a significant reduction in Body Fat in the second month and an increase in the fifth month ($p < 0.05$). In contrast, BI athletes exhibited significant reductions in Body Fat in the second month but increases in the third ($p < 0.05$) and sixth months ($p < 0.01$). Leg Strength was significantly higher in BI athletes than in XC athletes in the first ($p < 0.001$), third ($p < 0.01$), and sixth months ($p < 0.001$). Cross-country skiers athletes showed a significant reduction in Leg Strength in the second month ($p < 0.05$), whereas BI athletes experienced reductions in the third and fifth

Table 2
Sport-specific training sessions of elite cross-country skiers and biathletes in the summer macrocycle.

Activity	May–August (intervals/duration/resistance/lactate)	September–November (intervals/duration/resistance/lactate)
1. Roller-skiing or bounding	1a: 5–6 × 5–15 min/uphill and dragging device or a weight vest 8–12% of body weight/3–4 min/La 4–6 mmol·L ⁻¹ 1b: 8–10 × 5–6 min/uphill/3 min/La 4.5–6.5 mmol·L ⁻¹	1a: 5–6 × 5–15 min/dragging device or a weight vest 8–12% of body weight/3–4 min/La 4–6 mmol·L ⁻¹ 1b: 8–10 × 5–6 min/uphill/3 min/La 4.5–6.5 mmol·L ⁻¹
2. Swim pulling bench	4–5 × 60–90 sec/2–3 min/La 4.5–6.5 mmol·L ⁻¹	No
3. Ski ergometer	3a: 10–12 × 2 min/2–3 min/moderate resistance/La 4 mmol·L ⁻¹ 3b: 3 sets × 5 × 0.5 min/0.5 min/3 min/moderate resistance/La 5–7 mmol·L ⁻¹	3a: 10–12 × 2 min/2–3 min/moderate resistance/La 4 mmol·L ⁻¹ 3b: 3 sets × 5 × 0.5 min/0.5 min/3 min/moderate resistance/La 8–10 mmol·L ⁻¹

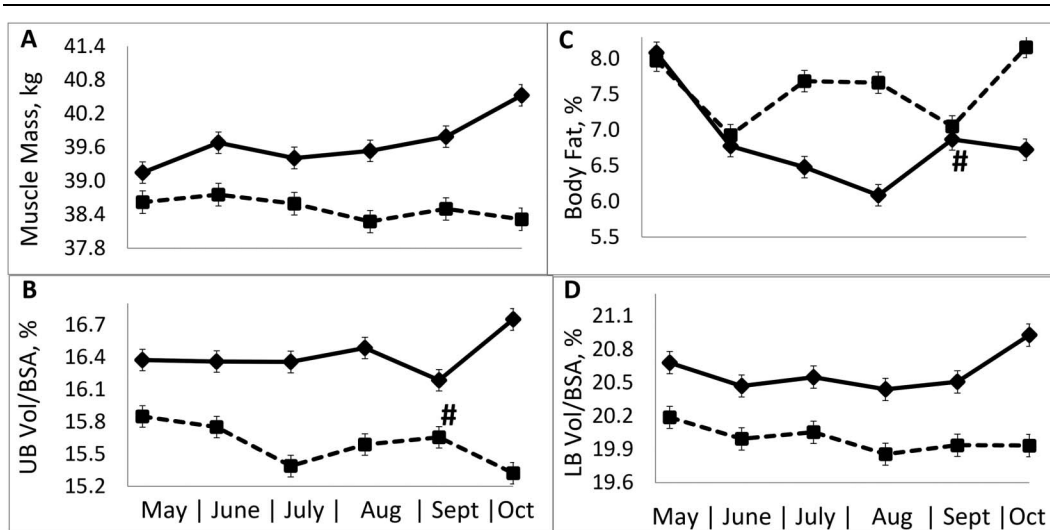


Figure 2. Changes in the parameters of body composition in elite cross-country skiers (◆—◆) and biathletes (■---■) from May to October. #The trend from May to September was significant ($p < 0.05$); BSA = body surface area; LB Vol = lower-body volume; UB Vol = upper-body volume.

months ($p < 0.05$). Cross-country skiers had higher UB O₂ Pulse than BI athletes throughout the macrocycle, with significant differences in all months ($p < 0.05$ to $p < 0.001$). There was a notable increase in UB O₂ Pulse in the second month for both sports ($p < 0.05$). Cross-country skiers also had higher UB GE in the second month ($p < 0.05$), but BI athletes surpassed XC skiers in the third and fifth months ($p < 0.05$). XC athletes experienced a significant decrease in UB GE in the third month ($p < 0.05$).

For other physiological parameters, XC athletes showed significant superiority ($p < 0.05$ – 0.001) in most months for UB Volume, Max Rate in DP, UB VT Work per Cycle, Indexes of Stroke Volume and Cardiac Output Indexes, Running O₂ Pulse, UB VT \dot{V}_{O_2} , UB VT PO, Running VT \dot{V}_{O_2} , and Running VT PO (Figures 1–3). By September, the competition period, athletes achieved

peak values in \dot{V}_{O_2max} , UB Power, UB VT \dot{V}_{O_2} , UB VT PO, UB and Running O₂ Pulse, UB and LB Wingate, and UB GE in BI athletes. Conversely, Running GE was at its lowest for both sports during this period. Peak La values were highest in July and September, whereas Stroke Volume and Cardiac Output Indexes peaked in August and slightly decreased in September.

A moderate positive relationship was observed between the number of training days in the macrocycle and UB VT PO and \dot{V}_{O_2max} ($r = 0.3$ – 0.4 , $p < 0.001$, Table 3). Parameters with high variability ($\geq 10\%$) included Body Fat (24% in XC athletes), Leg Strength, UB Power, UB GE, Peak La, UB O₂ Pulse, UB VT \dot{V}_{O_2} , and UB VT PO. Parameters with moderate variability (5–10%) included UB Wingate, CJ Power, UB Max Rate, Indexes of Stroke Volume and Cardiac Output, \dot{V}_{O_2max} , Running O₂ Pulse, Running VT \dot{V}_{O_2} ,

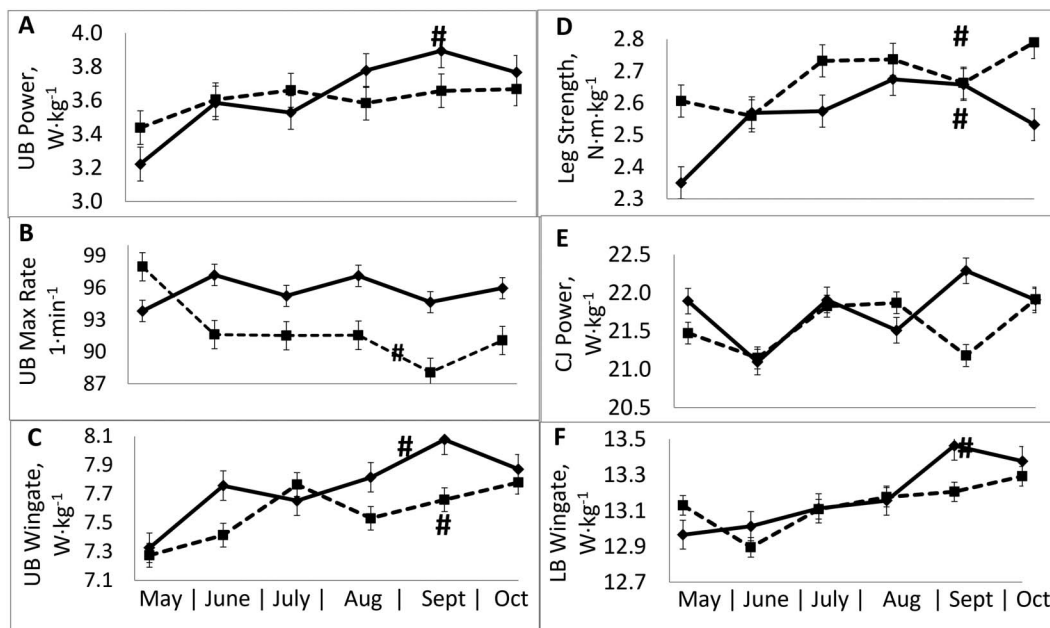


Figure 3. Changes in physiological parameters of strength and power in elite cross-country skiers (◆—◆) and biathletes (■---■) from May to October. #The trend from May to September was significant ($p < 0.05$); CJ = countermovement jump; LB = low body; SA = single arm; UB = upper body.

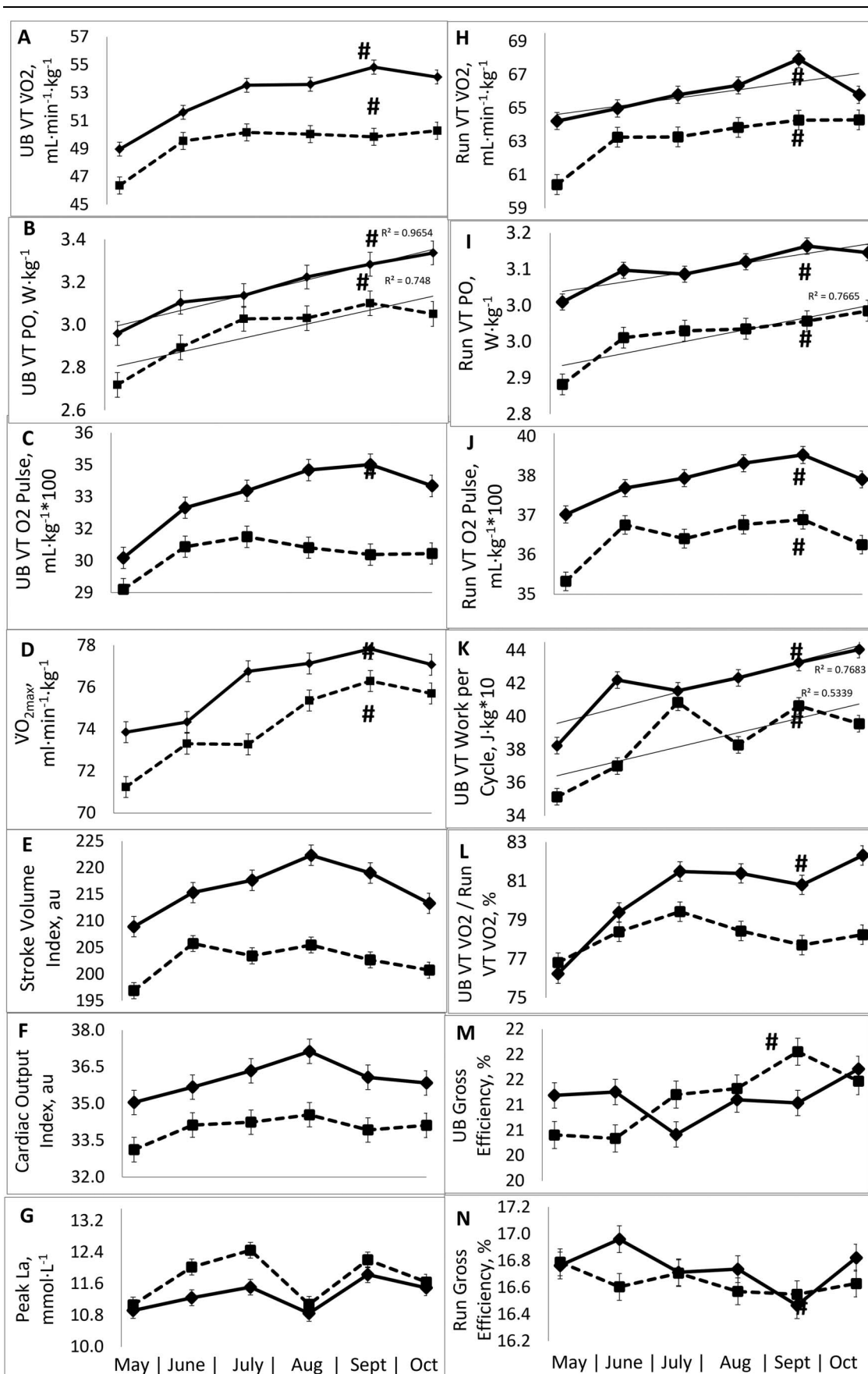


Figure 4. Changes in physiological parameters of endurance in elite cross-country skiers (◆—◆) and biathletes (■ - - - ■) from May to October. #The trend from May to September was significant ($p < 0.05$); La = lactate; LB = lower body; PO = power output; UB = upper body; VT = ventilatory threshold.

Table 3

Descriptive statistics, comparison, and correlations of body-composition and physiological parameters with number of training days in summer macrocycle for elite cross-country skiers and biathletes.*†

	XC‡ N = 209	BI‡ N = 288	XC vs. BI		Correlation, r	
			p	η ² _p	XC	BI
Body mass, kg	75.0 ± 4.6	74.1 ± 5.9	0.064	0.01	-0.07	-0.02
Muscle mass, kg	39.7 ± 3.0	38.5 ± 3.6	0.001	0.03	0.02	-0.03
Body fat, kg	6.7 ± 1.7	7.5 ± 1.6	0.001	0.05	-0.16	-0.10
UB volume/BSA, %	16.4 ± 1.2	15.6 ± 1.1	0.001	0.10	-0.02	-0.07
LB volume/BSA, %	20.6 ± 1.3	19.9 ± 1.4	0.001	0.04	-0.03	-0.06
UB SA power, W·kg ⁻¹	3.7 ± 0.6	3.6 ± 0.6	0.29	0.00	0.26	0.07
UB wingate, W·kg ⁻¹	7.8 ± 0.7	7.6 ± 0.8	0.01	0.01	0.23	0.14
UB max rate, 1·min ⁻¹	95.8 ± 12.1	91.1 ± 12.6	0.001	0.02	-0.01	-0.20
CJ power, W·kg ⁻¹	21.7 ± 1.9	21.6 ± 1.8	0.26	0.00	0.13	0.02
LB wingate, W·kg ⁻¹	13.2 ± 0.8	13.1 ± 0.8	0.55	0.00	0.20	0.10
Leg strength, N·m·kg ⁻¹	2.5 ± 0.3	2.6 ± 0.3	0.001	0.04	0.27	0.15
UB VT $\dot{V}O_2$, ml·min ⁻¹ ·kg ⁻¹	53.0 ± 4.6	49.4 ± 4.3	0.001	0.14	0.31	0.22
UB VT PO, W·kg ⁻¹	3.2 ± 0.3	3.0 ± 0.3	0.001	0.13	0.34	0.40
UB VT O ₂ , pulse, ml·kg ⁻¹ × 100	33.2 ± 2.9	30.3 ± 3.0	0.001	0.19	0.40	0.09
UB VT work per cycle, J·kg ⁻¹ × 10	41.6 ± 5.9	38.1 ± 6.2	0.001	0.07	0.20	0.26
Run VT $\dot{V}O_2$, ml·min ⁻¹ × kg ⁻¹	65.9 ± 3.7	63.3 ± 4.1	0.001	0.10	0.32	0.27
Run VT PO, W·kg ⁻¹	3.1 ± 0.2	3.0 ± 0.2	0.001	0.18	0.16	0.23
Run VT O ₂ pulse, ml·kg ⁻¹ × 100	38.3 ± 2.3	36.4 ± 2.4	0.001	0.15	0.27	0.18
$\dot{V}O_{2max}$, ml·min ⁻¹ ·kg ⁻¹	76.2 ± 3.9	74.3 ± 5.1	0.001	0.05	0.38	0.36
Stroke volume index/BSA	216.7 ± 17.3	202.7 ± 17.9	0.001	0.13	0.18	0.04
Cardiac output index/BSA	36.1 ± 2.7	34.0 ± 2.5	0.001	0.13	0.14	0.09
Peak LA, mmol·L ⁻¹	11.3 ± 1.7	11.8 ± 2.2	0.01	0.01	0.12	0.10
UB gross efficiency, %	21.2 ± 1.5	21.3 ± 1.6	0.89	0.00	0.01	0.28
Run gross efficiency, %	16.7 ± 0.7	16.6 ± 0.9	0.15	0.00	-0.24	-0.08
$\dot{V}O_2$ at VT/ $\dot{V}O_{2max}$	86.5 ± 4.4	85.4 ± 4.4	0.01	0.01	-0.04	-0.10
UB $\dot{V}O_2$ VT/Run $\dot{V}O_2$ VT	80.6 ± 6.5	78.2 ± 6.0	0.001	0.03	0.14	0.20

*BI = biathletes; BSA = body surface area; CJ = countermovement jump; La = lactate; LB = low body; η²_p = partial eta squared; p = significance level; PO = power output; XC = cross-country skiers; UB = upper body; $\dot{V}O_2$ = oxygen consumption; VT = ventilatory threshold.

†Significant p-values with applied Bonferroni adjustment (<0.002) marked in bold.

‡Values presented as means ± SD.

and Running VT PO. Parameters with the least variability (<5%) were Body Mass, Muscle Mass, UB and LB Muscle Volumes, LB Wingate, and the ratio of Running VT $\dot{V}O_2$ to $\dot{V}O_{2max}$.

Comparing training programs, XC athletes engaged in significantly (p < 0.01) greater volumes of LIT and Total Strength training in a weight room and SST (Figure 5, panels A, D, and E). The volumes of MIT, HIT, and LB Power did not differ (Figure 5, panels B, C, and H). During the transitional period in April (data not shown) and at the beginning of the preparatory period in May, there were low volumes of LB Power, SST, MIT, and HIT. These volumes peaked in June and July before declining until September. Low-intensity training and Total Strength volumes increased again in October, whereas HIT volumes increased until August and then decreased until October for both sports (Figure 5, panels A, E, and C). For more details, see Myakinchenko et al., 2022 (22).

Discussion

Cross-country skiing and biathlon are closely related winter Olympic sports that place extremely high demands on human endurance. Periodization of training programs in these 2 sports are very similar with greater emphasis on endurance and strength training in XC, and on HIT and shooting in BI (21). In joint XC skiing competitions (i.e., those in which both XC and BI athletes ski race together), XC skiers usually demonstrate higher racing velocities (7). To better understand the superior skiing performance of XC skiers, this study aimed to compare changes in aerobic and anaerobic capacities, body composition, and training load parameters over a 6-month summer

macrocycle in elite XC and BI athletes. To our knowledge, this is the first study to measure anthropometric and physiological variables monthly throughout the entire summer macrocycle in these athletes. The main finding was that XC athletes showed greater improvements in physiological and anthropometric adaptations compared with BI athletes during the macrocycle (Figures 2–4). These observations may be attributed to differences in training programs between XC and BI athletes. Consistent with our previous findings (21), XC athletes had a much higher volume of LIT, SST, and all modes of strength training except for LB Power training in June. In turn, BI athletes had higher volumes of HIT in the last 4 months of the macrocycle and MIT in July (Figure 5). Consequently, XC athletes experienced greater reductions of body fat in July, August, and October. Although there were no differences in body mass, XC athletes achieved larger muscle mass and LB muscle volume to the end of the macrocycle (October), and the UB muscle volume starting from June till the end of the macrocycle (Figure 2). Previous research has shown that superior XC skiing performance was associated with reduced body fat and increases in UB, LB, and whole-body lean mass (3,9).

The greatest differences in physiological adaptations between elite athletes in XC and BI were observed in UB capacities in XC athletes, such as UB oxygen pulse, oxygen uptake and power output (all at VT), UB VT Work per Cycle, Max Rate in DP, UB Power, and the UB Wingate test. These differences were likely because of higher volumes of training with classic DP technique, SST, Strength Total, and UB Strength in XC athletes (Table 3, Figure 5D–F). As has been shown in numerous studies (5,24,31), DP performance is closely related to success in both classic and skating events. The most

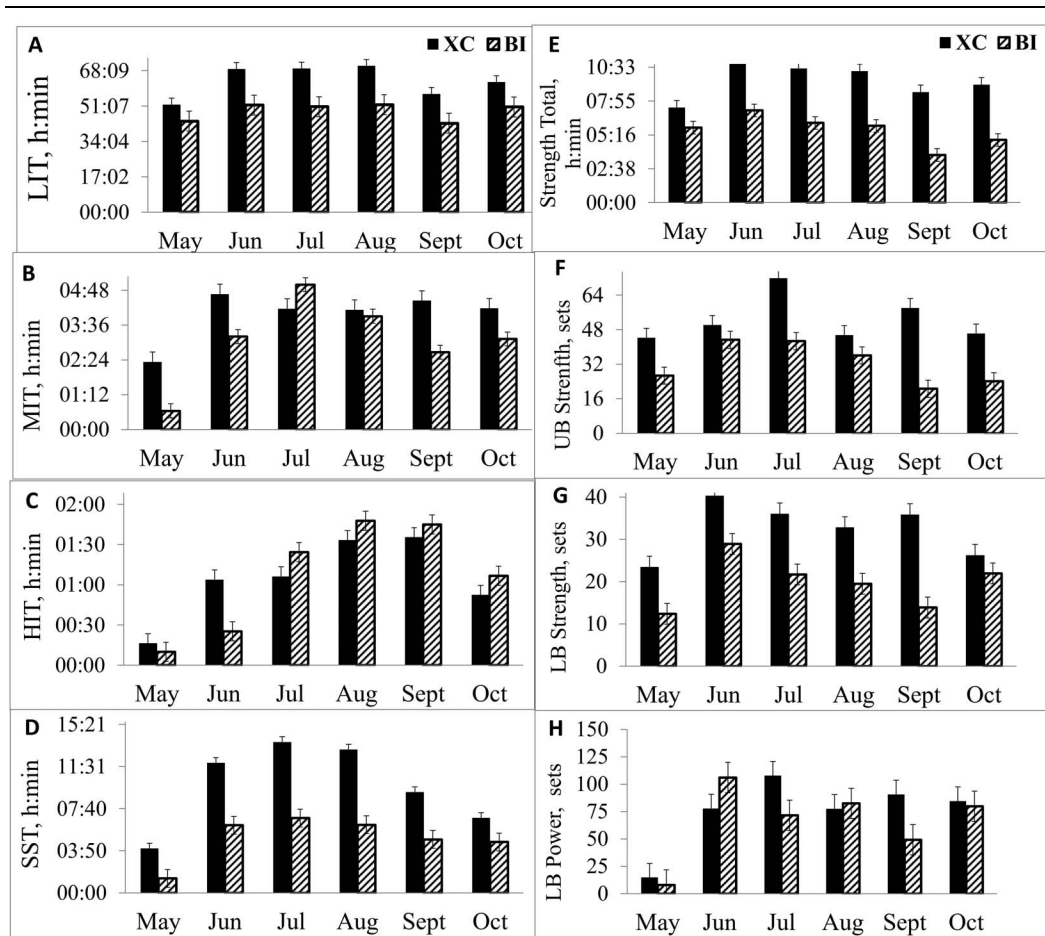


Figure 5. Distribution of training loads in elite cross-country skiers and biathletes. LIT = low-intensity training; MIT = moderate-intensity training; HIT = high-intensity training; SST = sport-specific training; UB = upper body; LB = lower body. For more details, see Myakinchenko et al., 2020 (21).

significant differences were noted for heavy-load strength training (>85% of 1RM) and SST (see detailed strength training analyses in Myakinchenko et al., 22). Losnegard et al. previously reported that heavy resistance training improved performance in elite XC athletes without significant change in the cross-sectional area of working muscles (12). Thus, strength gains were likely mediated through both neurological adaptations (stimulated by heavy-load strength training) and muscle hypertrophy (stimulated by SST and moderate-load strength training) supported by observed increases in strength/power parameters and muscle mass in XC athletes. Despite a lower total volume of strength training, BI athletes demonstrated greater Leg Strength (Figure 3D). This may be attributed to BI athletes' larger volume of LB Power training in June and August, and the need to develop high stability for successful standing shooting performance (27), making leg strength a foundational aspect.

During the preparatory period, walking, running, and bounding with ski poles are common training methods and are frequently used in laboratory testing for XC and BI, involving all major muscle groups (21,34). The primary aim of the treadmill test involving running with ski poles was to evaluate the impact of these exercises on maximal oxygen uptake, which is typically higher in running than in roller skiing among elite XC athletes (11). In our study, XC and BI athletes showed improvements in their aerobic capacities during running (Figure 4D, H, I, J). However, the lack of positive changes in Running Gross Efficiency (GE) (Figure 4N) may be partly attributed to reduced

training volume in running with ski poles and increased specificity in other training methods, such as roller skiing or cross-country skiing. During the competition period in September, BI athletes exhibited higher UB GE, potentially because of compensation for lower UB capacities or a tapering effect (i.e., significantly reduced UB strength training). This reduction may have promoted recovery and improved coordination within the working muscles. In addition, BI athletes' poling technique during skiing with a rifle might closely align with ski-ergometer testing in the lab. Similarly, other researchers studying XC did not observe positive adaptations in GE during diagonal stride roller skiing (9) or in oxygen cost (13), nor in running performance (32,34).

In a study with female XC skiers, maximum oxygen uptake was the most notable physiological parameter distinguishing between world-class and national-level athletes, with no significant difference in GE (23). Other studies with cyclists have shown an inverse relationship between GE and $\dot{V}O_{2max}$, where increased $\dot{V}O_{2max}$ correlated with reduced GE (6,14). In research involving long-distance runners (28), a trivial relationship between GE and $\dot{V}O_{2max}$ was found, suggesting these parameters were largely independent. Thus, our findings support the hypothesis that the GE of elite athletes is likely more dependent on sport-specific movement patterns—such as roller skiing on roads or cross-country skiing on snow—rather than on the economical functioning of physiological systems like cardiovascular and neuromuscular systems, which were improved throughout the macrocycle (the principle of specificity).

Throughout the macrocycle, the most stable progression was observed in UB VT PO and $\dot{V}O_{2\max}$, with correlation coefficients for both sports $r = 0.3\text{--}0.4$ and $p < 0.001$ (Table 3). Adaptations in UB VT PO, UB VT Work per Cycle, Run VT $\dot{V}O_2$, and Run VT PO parameters were approximated using linear regression (Figure 4B, H, I, K). Consistent with other studies (4,9,24), UB VT PO, VT velocity, $\dot{V}O_2$ at VT, and $\dot{V}O_{2\max}$ are key criteria for evaluating the efficiency of training programs in laboratory settings throughout the macrocycle. When comparing patterns of physiological adaptations and periodization of training loads (Figures 2–5), a “delayed transformation effect” (17,18) or “long-term delayed effect of training loads” (36) is evident. This effect occurs when physiological parameters peak after 1–2 months of reduced training volume specific to a given capacity. This phenomenon might be a fundamental principle of physiological adaptations in traditional periodization for highly trained athletes. For example, the highest values for UB and Running VT PO were observed in September–October, whereas the highest training volumes for strength and endurance (excluding HIT) were recorded in July–August. When comparing training loads (Figure 5), XC athletes had greater volume of LIT (10–20%), MIT (3–15%), SST (30–50%), Total Strength training (20–40%), including UB Strength (5–50%, with the greatest difference in September likely related to BI athletes’ focusing and tapering for shooting performance), and LB Power (3–25% in May, July, September, and October). In contrast, BI athletes had a greater volume of HIT (10–15% from July to October), MIT (15% in July), and LB Power (3–25% in June and August).

It has been observed in both XC and BI athletes that the volume of strength and aerobic training reaches its peak at the beginning of the macrocycle (June–July). Subsequently, the total training volume decreases, whereas the volume of HIT and the specificity of training loads increase (21). Notably, in XC athletes, the volumes of LIT, SST, and strength training increased almost synchronously (Figure 5A, D, E), which was associated with concurrent improvements in strength and endurance physiological parameters. Therefore, it appears that there is no significant concurrent training effect between strength and endurance (LIT) training in elite endurance athletes. Given the observed improvements in both endurance and strength parameters, this periodization approach can be considered successful (Figures 3 and 4). This approach led to peak values in $\dot{V}O_{2\max}$, UB and LB oxygen uptake and power output at VT, maximum strength, and anaerobic power by the time of the competitions in September.

Comparing the progression of physiological parameters throughout the macrocycle for both sports, XC athletes demonstrated greater values in most parameters and achieved better peaking during the competition period. In contrast, for BI athletes, several parameters reached a plateau or even decreased after July–August, partly because of the additional focus on shooting training. The higher volume of HIT, MIT, sprint, and plyometrics (Figure 5B, D, H) took a relatively smaller proportion of overall training, allowing BI athletes to allocate more time to shooting practice. In addition, the high volume of HIT at the start of the season was necessary for practicing shooting at racing velocities. Interestingly, an increase in $\dot{V}O_{2\max}$ and oxygen uptake and power output at VT, continued to increase in September despite a slight reduction in cardiac output and stroke volume. This could be attributed to tapering and peaking strategies implemented during that month. In previous studies with elite development XC athletes (8,9), researchers did not observe an increase in oxygen uptake over a macrocycle. Johansen et al. found that although roller-skiing performance and maximum power were improved, physiological variables like $\dot{V}O_{2\max}$ and UB $\dot{V}O_{2\text{peak}}$ did not change significantly after 6 months of summer training (6). Similarly, Jones et al. reported no

significant improvements in LB lean mass, body fat, power output, and oxygen uptake at lactate threshold, time-trial results, or $\dot{V}O_{2\text{peak}}$ among male XC athletes from the Swedish development team over a 25-month period (9). This study was done in the March–June window, a transitional period when physiological and anthropometric changes may not be as pronounced. In our study, athletes achieved peak values for both aerobic and anaerobic parameters by the competition period (September). The greater physiological adaptations observed could be attributed to the athletes’ age, status (elite senior athletes), and higher training volumes, particularly in strength and ski-specific-resistance training (Figure 5D, E, F), and effective peaking strategies in August and September.

In this study, both aerobic and anaerobic capacities in elite athletes were simultaneously improved and reached their peak by the competition period. The UB power output at VT and $\dot{V}O_{2\max}$ demonstrated the most stable linear progression. The parameters that exhibited the most variation during the macrocycle were Body Fat, UB Power, Leg Strength, Peak La, UB O₂ VT Pulse, UB VT $\dot{V}O_2$, and UB VT PO. In both sports, GE, measured in DP on the skiing ergometer and running with ski poles on the treadmill, did not show consistent improvements. Prominent differences in physiological and anthropometric adaptations between XC and BI athletes throughout the macrocycle included the following: (a) Body fat was reduced significantly by the end of the macrocycle only in XC athletes; (b) BI athletes excelled only in one parameter: Leg Strength; and (c) XC athletes demonstrated much higher UB muscular endurance, specifically in UB O₂ VT Pulse, UB VT $\dot{V}O_2$, and UB VT PO.

We speculate that the differences in training volumes of LIT, SST, and total strength training are key factors influencing the discrepancies in adaptations between elite athletes in XC and BI. A strength of this study was the relatively large sample size of elite XC and BI athletes ($N = 73$) who were meticulously tested multiple times during the macrocycle over a 7-year observation period. The testing equipment was rigorously validated, and all procedures were conducted by the same staff. In addition, the study’s detailed analysis of strength training loads addressed gaps identified in previous longitudinal studies (9). However, a limitation of the study was the use of independent group factorial MANOVA for analyzing physiological changes because of variations in athlete samples each month, rather than using repeated measures factorial MANOVA. Future studies could benefit from including field measurements, such as gross efficiency (GE) and kinematics in roller skiing or cross-country skiing, and performance metrics like FIS points or time-trial results, to provide a more comprehensive understanding of training effects.

Practical Applications

To enhance race velocity in BI, increasing the volume of LIT, SST, total strength, and focusing more on UB training could be beneficial. A high variability in UB strength and endurance training throughout the macrocycle may lead to a critical decrease in UB capacities. Therefore, a more balanced distribution of UB training loads over the year could potentially improve physiological adaptations and performance during key competitions. The lack of improvement in GE during laboratory tests over the summer macrocycle suggests that GE for competitive movements is a distinct skill and should be targeted through specific training. In laboratory settings, UB power output at VT and $\dot{V}O_{2\max}$ may be the most informative parameters for predicting XC performance.

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