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Oona Kettunen

Nutrition and Performance in Young Female Cross-Country Skiers

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
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ABSTRACT

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Cross-country (XC) skiing is an endurance sport in which training significantly increases dietary energy and macronutrient requirements. As inadequate dietary intake may compromise health and performance, this dissertation aimed to investigate if energy availability (EA) and macronutrient intake are associated with performance and physiological symptoms of low EA in young female XC skiers. In addition, the study investigated the extent to which young female XC skiers meet the current nutritional recommendations for endurance athletes. In experiment I, 19 female XC skiers (16–18 years) completed 48-hour food and training logs during normal training period at home and during a 5-day training camp. Anthropometric measurements, fasting blood samples, and performance tests (submaximal running, vertical jumps) were performed on the first and the last morning of the training camp. In experiment II, 27 female XC skiers (15–19 years) completed five 3-day food and training logs during different training periods of the annual training cycle. Laboratory measurements including body composition measurements, fasting blood samples, and performance tests (aerobic capacity, lactate threshold, double poling, vertical jumps) were performed at the end of each training period. Competition performance was determined from the results of Finnish Junior National Championships. The Low Energy Availability in Females Questionnaire (LEAF-Q) and nutrition knowledge questionnaire were completed in both experiments. Most participants had suboptimal EA and carbohydrate intake during all of the training periods despite increasing dietary intake during more intense training periods. Athletes with higher EA and macronutrient intake tended to perform better both in competitions and in laboratory performance tests. In addition, lower EA and carbohydrate intake during the training camp was associated with signs of under-recovery at the end of the camp. Higher nutrition knowledge and lower prevalence of physiological symptoms of low EA (lower LEAF-Q score) were associated with higher carbohydrate intake. In conclusion, young female XC skiers have difficulties to meet optimal EA and carbohydrate intake, which may have a negative impact on their performance and health. These results highlight the importance of enhanced high-quality nutrition education for young female XC skiers.

Keywords: body composition, carbohydrate, endurance athlete, energy availability, macronutrient, periodized nutrition, protein, sports nutrition

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Kettunen, Oona
Ravitsemus ja suorituskyky nuorilla naismaastohiihtäjillä
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Maastohiihto on kestävyyslaji, jolle tyypillinen harjoittelu kasvattaa huomattavasti energian ja makroravintoaineiden tarvetta. Koska riittämätön ravinnonsaanti voi vaikuttaa negatiivisesti terveyteen ja suorituskykyyn, tämä väitöskirjatutkimus pyrki selvittämään energiansaatavuuden ja makroravintoaineiden yhteyksiä suorituskykyyn ja matalan energiansaatavuuden fysiologisiin oireisiin nuorilla naismaastohiihtäjillä. Lisäksi selvitettiin, kuinka nuoret naismaastohiihtäjät syövät suhteessa kestävyysurheilijoiden suosituksiin. Ensimmäisessä osatutkimuksessa 19 naismaastohiihtäjää (16–18-v) täytti 48-tunnin ruoka- ja harjoituspäiväkirjat normaalin kotiharjoittelunsa sekä intensiivisen viiden vuorokauden harjoitusleirin aikana. Kehonkoostumusmittaus, verikokeet ja suorituskykytestit (submaksimaalinen juoksutesti, vertikaalihypyt) suoritettiin leirin ensimmäisenä ja viimeisenä aamuna. Toisessa osatutkimuksessa 27 naismaastohiihtäjää (15–19-v) täytti kolmen vuorokauden ruoka- ja harjoituspäiväkirjat viidellä eri harjoitusjaksolla vuoden eri vaiheissa. Kunkin harjoitusjakson lopussa suoritettiin laboratoriomittaukset, jotka sisälsivät kehonkoostumusmittauksen, verikokeet ja suorituskykytestit (aerobinen kapasiteetti, laktaattikynnys, tasatyöntö ja vertikaalihypyt). Kilpailusuorituskyky määritettiin nuorten Suomen mestaruus hiihtojen perusteella. Molemmissa osatutkimuksissa selvitettiin kyselylomakkeilla matalan energiansaatavuuden fysiologisia oireita ja ravitsemusosaamista. Energiansaatavuus ja hiilihydraatinsaanti olivat suurimmalla osalla tutkittavista suositeltua matalammalla tasolla kaikilla harjoitusjaksoilla. Korkeampi energiansaatavuus ja hiilihydraatinsaanti olivat yhteydessä parempaan suorituskykyyn sekä kilpailuissa että laboratoriomittauksissa. Matalampi energiansaatavuus ja hiilihydraatinsaanti harjoitusleirillä olivat yhteydessä alipalautumismarkkereihin harjoitusleirin lopussa. Parempi ravitsemusosaaminen ja vähäisempi matalan energiansaatavuuden fysiologisten oireiden esiintyvyys olivat yhteydessä suurempaan hiilihydraatinsaantiin. Tämän tutkimuksen perusteella nuorilla naismaastohiihtäjillä on haasteita suositellun energiansaatavuuden ja hiilihydraatinsaannin saavuttamisessa, mikä voi vaikuttaa negatiivisesti heidän terveyteensä ja suorituskykyynsä. Tulokset korostavat ravitsemuskoulutuksen merkitystä nuorille naismaastohiihtäjille.

Asiasanat: energiansaatavuus, hiilihydraatti, kehonkoostumus, kestävyysurheilu, makroravintoaine, proteiini, urheiluravitsemus

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ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

This dissertation is based on the following original research articles that are referred to by their Roman numerals in the text. This dissertation also includes previously unpublished data.

I Kettunen, O., Heikkilä, M., Linnamo, V., & Ihalainen, J. K. (2021). Nutrition knowledge is associated with energy availability and macronutrient intake around training in young female cross-county skiers. *Nutrients, 13*(6), 1769. https://doi.org/10.3390/nu13061769

II Kettunen, O., Ihalainen, J. K., Ohtonen, O., Valtonen, M., Mursu, J., & Linnamo, V. (2021). Energy availability during training camp is associated with changes in performance in young female cross-country skiers. *Biomedical Human Kinetics, 13*, 246–254. https://doi.org/10.2478/bhk-2021-0030

III Kettunen, O., Mikkonen, R., Mursu J., Linnamo, V., & Ihalainen, J. K. (2023). Carbohydrate intake in young female cross-country skiers is lower than recommended and affects competition performance. *Frontiers in Sports and Active Living, 5*, 1–7. https://doi.org/10.3389/fspor.2023.1196659

IV Kettunen, O., Mikkonen, R., Linnamo, V., Mursu J., Kyröläinen, H., & Ihalainen, J. K. (2023). Nutritional intake and anthropometric characteristics are associated with endurance performance and markers of low energy availability in young female cross-country skiers. *Journal of the International Society of Sports Nutrition, 20*(1), 2226639. https://doi.org/10.1080/15502783.2023.2226639

The design and experimental approaches for publications were planned by the author in collaboration with her supervisors. The author has prepared the experiments and collected the data for dissertation. Collecting and analyzing the blood samples was completed with assistance from the nurses of Medika Lääkäripalvelu in Vuokatti, Finland and Dr. Johanna Ihalainen. The author was primarily responsible for data and statistical analyses whereas writing the original articles was completed in cooperation with coauthors.

FIGURES

TABLES

ABBREVIATIONS

BM	Body mass
BMD	Bone mineral density
BMI	Body mass index
CAMP	A 5-day training camp
CHO	Carbohydrate
CMJ	Counter movement jump
DP	Double poling
DXA	Dual-energy X-ray absorptiometry
EA	Energy availability
EASY	<150 min low intensity training
EE	Energy expenditure
EEE	Exercise energy expenditure
EI	Energy intake
F%	Body fat percentage
FFM	Fat free body mass
FIS	International Ski Federation
FM	Body fat mass
HOME	"Normal" training at home
HR	Heart rate
IGF-1	Insulin-like growth factor 1
KEY	Speed, strength, moderate-high intensity, or > 150 min training
LEA	Low energy availability
LEAF-Q	The Low Energy Availability in Females Questionnaire
Log_1–Log_5	Food and training logs in experiment II
M_1–M_4	Measurement points in experiment II
OBLA	Onset of Blood Lactate Accumulation
POST	At the end of the 5-day training camp
PRE	At the beginning of the 5-day training camp
RED-S	Relative Energy Deficiency in Sport
REE	Resting energy expenditure
RER	Respiratory exchange ratio
RJ	Reactive jump
RPE	Rate of perceived exertion
T3	Triiodothyronine
T4	Thyroxine
TSH	Thyroid-stimulating hormone
TTE	Time to exhaustion
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen uptake
VO_{2OBLA}	Oxygen uptake at 4 mmol/L lactate level
VO_{2peak}	Peak oxygen uptake
XC	Cross-country

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ORIGINAL PUBLICATIONS

1 INTRODUCTION

Cross-country (XC) skiing is a traditional endurance sport where high aerobic and speed capacities, technical and tactical expertise, as well as competitive equipments are needed for successful performance (Sandbakk & Holmberg, 2017). To meet the versatile demands of the sport, elite level XC skiers typically train 750–950 hours annually (Sandbakk & Holmberg, 2017; Solli et al., 2017; Tønnessen et al., 2014), which can more than double dietary energy requirements compared to sedentary people. Consequently, XC skiers are at a significant risk for under-fueling, which, in turn, may compromise both performance and overall health (Melin et al., 2023; Mountjoy et al., 2018). The risk for inappropriate fueling may be especially high among young athletes, as many of them have moved out of their parental home and started to take more responsibility over their eating practises.

The competition distances in today's XC skiing championships vary from two to three minute sprint races to 50 kilometer races where the duration of a given race may exceed two hours. Although the physiological capacities required may significantly differ between these competition distances, they all are performed at intensities that are highly dependent on carbohydrate (CHO) based fuels for muscle metabolism (Gløersen et al., 2020; Hawley & Leckey, 2015; Losnegard, 2019). This highlights the importance of adequate CHO availability in competitions and high-intensity training sessions to optimize performance and post-exercise recovery. In addition, XC skiers should ensure proper protein and fat intake to support recovery, training adaptations, and health (Thomas et al., 2016). Unfortunately, most studies that have focused on the macronutrient requirements in athletes have been conducted with male participants resulting in a significant gap in knowledge about macronutrient requirements in female athletes.

Total intake of CHO, protein, and fat determines total energy intake (EI). Adequate EI is an important factor supporting XC skiers' performance and health. The adequacy of EI can be assessed using the concept of energy availability (EA), which describes the energy left after training for other energy-consuming physiological processes in the body (Loucks et al., 2011). During long periods of low EA (LEA), the body starts to conserve energy from its natural physiological processes. This may ultimately lead to severe, and even irreversible, health consequences, such as menstrual dysfuntion and decreased bone mineral density (BMD). Females under 20 years of age, who compete in endurance sport where low body mass (BM) may benefit performance (e.g., running, XC skiing), are especially prone to LEA associated health and performance problems (Mountjoy et al., 2018; Nose-Ogura et al., 2019). While a risk for LEA has previously been demonstrated to be high in young female runners (Ihalainen et al., 2021), less is known about the prevalence of LEA among young female XC skiers.

The aim of this dissertation was to investigate if EA and macronutrient intake are associated with different aspects of performance in young female XC skiers. In addition, the study aimed to investigate the extent to which young female XC skiers meet the current nutritional recommendations for endurance athletes, and to evaluate the prevalence of LEA associated conditions. Finally, the associations between nutrition knowledge and dietary intake were investigated to determine the importance of knowledge for dietary intake in practise.

2 LITERATURE REVIEW

2.1 Nutrition in endurance athletes

Nutrition plays a key role in maintaining optimal health and sport performance by providing nutrients needed as fuel and substrate to support body functions. In endurance athletes (e.g., XC skiers, long-distance runners, and cyclists), a high training load significantly increases daily energy and nutrient requirements, with CHO playing a special role in maintaining high intensity during key training sessions and competitions (Burke et al., 2011). Although the importance of micronutrients (i.e., vitamins and minerals) for health and performance are recognized (Thomas et al., 2016), this dissertation will concentrate on energy and macronutrient (i.e., CHO, protein, and fat) requirements and intake.

2.1.1 Energy availability

Adequate EI is an essential component of an athlete's diet as it supports optimal body function, determines macro- and micronutrient intake, and influences body composition (Thomas et al., 2016). Due to high training loads, exercise energy expenditure (EEE) can be remarkably high in endurance athletes, which in turn, increases energy requirements (Heikura et al., 2021a). The adequacy of EI relative to EEE can be assessed using the concept of EA, which describes the energy left after EEE for other energy-consuming physiological processes in the body (Loucks et al., 2011). EA reflects the difference between dietary EI and EEE relative to fat-free mass (FFM) and can be calculated as follows (Loucks et al., 2011):

$$EA = \frac{EI - EEE}{FFM}$$

Although there are no absolute cutoff values for athletes, an optimal EA has often been defined as > 45 kcal/kg FFM/d and LEA as < 30 kcal/kg FFM/d (Heikura et al., 2018; Heikura et al. 2021b; Loucks et al., 2011) based on laboratory studies in sedentary females (Loucks & Thuma, 2003). An EA of 45 kcal/kg FFM/d has been suggested to describe a state of energy balance in healthy young adults (Loucks et al., 2011), and thus an optimal EA is suggested to best support physiological functions of the body (Mountjoy et al., 2018). LEA, in turn, has been recognized to underpin the development of the female athlete triad and/or relative energy deficiency in sport (RED-S), which have several negative consequents for health and performance (see chapter 2.3) (Melin et al., 2023; Mountjoy et al., 2014; Nattiv et al., 2007). Although the definition of EA is relatively simple, there are several methodological challenges related to the EA assessment in field (Heikura et al., 2021b) (see chapter 2.1.4).

2.1.2 Macronutrient requirements

Macronutrients (CHO, protein, and fat) are food components that contain energy. Energy from macronutrients is either consumed to fuel the body's physiological functions or stored in several tissues (i.e., muscle, adipose tissue, and liver) (Thomas et al., 2016). While alcohol also includes energy, the available data does not support frequent alcohol consumption for athletes due to the several negative effects performance and recovery (Thomas et al., 2016). Therefore, the next chapters concentrate on reviewing the role of CHO, protein, and fat in support of performance, recovery, and training adaptations.

2.1.2.1 Carbohydrate

The main function of dietary CHO is to provide a major source of energy for metabolic functions (McArdle et al., 2010). One gram of CHO contains ~4 kcal of energy (McArdle et al., 2010). Adequate CHO intake is especially important for endurance athletes as most key training sessions and competitions are performed at intensities that are highly dependent on CHO based fuels for muscle metabolism (Gløersen et al., 2020; Hawley & Leckey, 2015; Losnegard, 2019). The size of the body's CHO stores is relatively limited, whereas depletion of these stores may impair performance in several ways (Thomas et al., 2016). First, CHO is an important fuel for the central nervous system, and therefore impaired skills and concentration, increased perception of effort, and difficulties to maintain intensity are typical consequences of low CHO availability (i.e., amount of CHO available for metabolic functions) (Thomas et al., 2016). Second, a lack of CHO based fuels is associated with impaired Ca^{2+} release in muscles, which may contribute to muscle fatigue (Ørtenblad et al., 2011). Third, oxidation of CHO for metabolic energy consumes less oxygen than fat oxidation (Krogh & Lindhard, 1920). Consequently, CHO as an energy source improves metabolic efficiency by reducing the oxygen cost at a particular intensity and/or permitting a higher intensity for the same absolute oxygen uptake (VO_2) (Burke et al., 2019). Finally, inadequate CHO intake may delay recovery (Burke et al., 2017; Meeusen et al., 2013), and increase the risk of lost training days due infection (Costa et al., 2005) or injury (Fensham et al., 2022), and thus hamper long-term performance development.

As CHO requirements are highly dependent on training intensity and volume, they can significantly vary between days and longer training periods. CHO requirements for different situations are summarized in Table 1. CHO requirements may vary even within a single day indicating that extra caution should be taken to ensure that pre-exercise meals contain adequate CHO for training sessions where training quality and/or intensity needs to be high (Burke et al., 2011; Thomas et al., 2016). Nevertheless, during prolonged (> 90 min) high intensity exercise, even fully-loaded CHO stores are depleted, and thus CHO intake during long training sessions and competitions enhances performance (Burke et al., 2011, 2019). Restoration of muscle CHO stores, in turn, may take up to 24 hours. This highlights the importance of post-exercise CHO intake in situations where recovery time between intensive training sessions is limited (Burke et al., 2017). This situation is typical for endurance athletes during hard training weeks and between competitions that take place on consecutive days. Although CHO is known to be important for performance and recovery, adequate CHO intake seems to be a challenge for endurance athletes even at the elite level (Carr et al., 2019).

TABLE 1 Summary of athlete recommendations for carbohydrate intake. Modified from (Burke et al., 2011).

Situation	Carbohydrate recommendations
Daily requirements for fuel and recovery	
Light: low-intensity/skill-based training	3–5 g/kg/d
Moderate: ~1 h moderate intensity	5–7 g/kg/d
High: 1–3 h moderate to high intensity	6–10 g/kg/d
Very high: 4–5 h moderate to high intensity or fueling up to competition	8–12 g/kg/d
Acute carbohydrate requirements	
Pre-event fueling before key training sessions or competitions	1–4 g/kg 1–4 h before training session or competition
During short (< 45 min) training session or competition	Not needed
During 45–75 min high intensity training session or competition	Small amounts or mouth rinse
During 1–2.5 h high intensity training session or competition	30–60 g/h
Speedy refueling: limited time between key training sessions or competitions	1–1.2 g/kg/h for first 4 h after training session or competition

2.1.2.2 Protein

Proteins are composed of 20 different amino acids that are joined together to form long amino acid chains with variety of lengths and amino acid sequences

(McArdle et al., 2010). Dietary proteins are digested into amino acids that are further resynthesized into body proteins that have high variety of vital functions for normal body functions (McArdle et al., 2010). Amino acids can be also utilized as a fuel, especially in situations when CHO availability is limited, or protein intake is excessive compared to protein requirements (Moore et al., 2015). One gram of protein contains ~4 kcal of energy (McArdle et al., 2010).

Endurance athletes have an increased protein requirements compared to their non-exercising counterparts (Kato et al., 2016). Protein is needed to replace oxidative losses of amino acids during training and competitions (Tarnopolsky, 2004) and to provide trigger and substrates for post-exercise recovery and training adaptations (Phillips & van Loon, 2011). Athletes are recommended to consume 1.2–2.0 g/kg/d of protein (Thomas et al., 2016). In addition to daily intake, timing of protein intake may also influence recovery and training adaptations. To optimize post-exercise adaptations, protein intake should be divided in 4–6 equal 20 g (or 0.25–0.30 g/kg) portions throughout the day while higher portions may not provide extra benefits. It should be noted that post-exercise requirements may increase up to 30 g after a 90-minute endurance training session in a fasted state (Churchward-Venne et al., 2020), possibly due to reduced EA and/or CHO availability (Areta et al., 2014; Gillen et al., 2019).

2.1.2.3 Fat

Fat is an essential component of a healthy diet providing energy, essential fatty acids, elements of cell membranes, and aid for the absorption of fat-soluble vitamins (Thomas et al., 2016). Most (~98%) of the dietary fat exist as triglycerides that are formed from three fatty acid chains that are linked to single glycerol molecule (McArdle et al., 2010). One gram of fat contains ~9 kcal of energy (McArdle et al., 2010), and consequently, fat oxidation from intramuscular triglycerides and adipose tissue provides a plentiful source of energy at rest and during low-intensity exercise (Thomas et al., 2016). Unfortunately, fat oxidation is not efficient enough to meet muscle energy requirements during high-intensity exercises. Therefore, fat plays only a minor role in fuel oxidation during endurance events up to 200 minutes and exercises performed near competition intensity (Hawley & Leckey, 2015; O'Brien et al., 1993).

Although excessive dietary fats should not be consumed at the expense of CHO and protein, they are an energy-dense option to increase EI during intense training and competition periods, thus assisting in maintaining adequate EA and normal body functions (Heikura et al., 2021a; Thomas et al., 2016). Therefore, athletes are recommended to consume fat 20%–35% of total EI (Thomas et al., 2016).

2.1.3 Nutritional periodization

As most athletes' training is varied (periodized) between individual training sessions, days, weeks, and months, nutritional intake should be periodized to support the goals and needs of training and competition (Stellingwerff et al., 2019). Periodized nutrition has been defined as planned and purposeful use of nutritional interventions to promote the targeted adaptations of training sessions or periods, or otherwise obtain the effects that will lead to longer term performance development (Jeukendrup, 2017). Nutritional periodization may be implemented by modifying EI, macronutrient composition of the diet, and/or the timing of the energy and macronutrient intake (Stellingwerff et al., 2019).

Given that EEE may vary markedly between training days and periods, EI should also vary according to energy needs to maintain optimal EA (Stellingwerff et al., 2019). In some cases, EI may periodically be manipulated to modify body mass (BM) or composition in adult athletes to achieve an optimal power-to-weight ratio in preparation for peak performance in competitions (Stellingwerff, 2018). However, these manipulations increase the risk for both health and performance consequences associated with LEA (see chapter 2.3). Therefore, the implementation and timing of manipulated EI should be carefully planned in cooperation between the athlete and coach, as well as medical and nutritional professionals (Ackerman et al., 2020; Mountjoy et al., 2018). Notably, EI manipulations to alter BM should not be performed in young developing athletes (Ackerman et al., 2020). Instead, the aim of EI periodization in young athletes should be to maintain an optimal EA between periods of different EEE.

Nutritional periodization of macronutrient intake should mainly be performed by manipulating the proportion of CHO and fat of total EI while appropriate and properly timed protein (see chapter 2.2.2.2) and micronutrient intake should be maintained across training periods (Stellingwerff et al., 2019). Some evidence suggests that restricted CHO intake (and sometimes simultaneously increased fat intake to maintain EA) may promote endurance training adaptations (Burke et al., 2018a). However, inadequate CHO availability may decrease the maintainable training intensity and load thereby impairing training quality and increasing risk of under-recovery and even overtraining syndrome (Burke et al., 2011; Meeusen et al., 2013; Stellingwerff et a., 2021; Thomas et al., 2016). Therefore, CHO availability should be periodized according to the principle of "fuel for the work required" by ensuring adequate CHO availability in key sessions and competitions while restricting CHO intake around some easier sessions (Impey et al., 2018). Notably, despite the theoretical benefits of low CHO availability for certain endurance training adaptations, a recent systematic review revealed that periodized CHO restriction does not improve performance in endurance-trained athletes (Gejl & Nybo, 2021). In addition, even short periods of low CHO availability may lead to increased risk of infection (Costa et al., 2005) and unfavorable bone turnover responses to exercise in endurance athletes (Fensham et al., 2022; Heikura et al., 2020). Taken together, the risks related to periodized CHO restriction may be higher than benefits and should be considered with caution.

2.1.4 Assessing dietary intake

There are several tools to assess dietary intake in field conditions of which 3–7-day food logs are the most common tools used with athletes (Capling et al., 2017).

Dietary assessment using food logs involves collecting data on timing and amount of food and beverage intake (i.e., using paper-based or electronic logs) and then analyzing energy and nutrient intake using software (Deakin et al., 2015). A recording time of 3–4 days seems to be an optimal choice while longer periods may reduce compliance, impair accuracy, and increase drop-out rate (Deakin et al., 2015).

Although food logs are the best available tool to assess food intake in field conditions, they are prone to several biases such as under-/over-/misreporting and failure to gain a true or typical picture of longer-term food intake (Heikura et al., 2021b). For example, a recent meta-analysis reported that, on average, athletes underreported their EI by ~19% representing daily intake of ~600 kcal (Burke et al., 2018b). In addition, food logs place a substantial burden on participants to document information accurately and truthfully, as well as a reliance on researchers to code the data correctly using appropriate databases/software (Capling et al., 2017). While no better tool for field conditions exists, weighted food logs (amount of food ingested is measured using kitchen scales) and motivated participants may increase the validity of the data (Burke et al., 2018b). To gain reliable information of the overall practices, food logs should be completed across different types of training days (Heikura et al., 2021b). Ultimately, caution must be always paid when interpreting results from food logs (Burke et al., 2018b).

2.1.5 Nutrition knowledge

Since nutrition has an essential role in athletic performance and overall health, an athlete should have adequate nutrition knowledge to understand the importance of daily food choices on performance, recovery, and health (Heikkilä et al., 2018b; Janiczak et al., 2022). Nutrition knowledge can be estimated using validated questionnaires developed for the specific target population, such as endurance athletes (Heikkilä et al., 2018a). The use and development of such questionnaires is important to obtain realistic information regarding nutrition knowledge, which may further be utilized to develop nutritional education for the athletes (Janiczak et al., 2022).

Adequate nutrition knowledge is particularly important in today´s society, where media and social media enable quick spreading of misinformation and inappropriate comments. For example, advertisements for "super diets" may lead to unnecessary dietary manipulation while comments about appearance may lead to severe consequences such as eating disorders and/or RED-S (Martinsen & Sundgot-Borgen, 2013; Mountjoy et al., 2014). Young athletes without adequate nutrition knowledge may be particularly vulnerable to such misunderstanding and inappropriate dietary intake. The role of nutrition knowledge is emphasized when young athletes move out of their parental home and start to take more responsibility over purchasing and preparing food. Notably, Heikkilä et al. (2018) found that nutrition knowledge is relatively low among Finnish endurance athletes between age of 16 and 20 years. This highlights the importance of nutritional education and regular monitoring in young athletes.

2.2 Consequences of low energy availability

It is well known that long-term LEA supports the development of negative adaptations of body systems to reduce energy expenditure (EE), resulting in the disruption of many metabolic, hormonal, and functional processes (Loucks, 2004). Consequently, long-term LEA may have detrimental, and possibly irreversible, effects on both health and performance, highlighting the importance of effective prevention, screening, and treatment (Mountjoy et al., 2018).

2.2.1 Health consequences of low energy availability

The relationships between energy deficiency, menstrual dysfunction, and impaired bone health in female athletes have been recognized for decades (Drinkwater et al., 1984). These associations are referred to as the female athlete triad: a continuous spectrum ranging from a healthy athlete with optimal EA, regular menstrual cycle (eumenorrhea), and healthy bones to the opposite end of the spectrum characterized by LEA, absence of menstrual bleeding (amenorrhea), and osteoporosis (Figure 1) (Nattiv et al., 2007). As scientific knowledge regarding this phenomenon has developed, it has become evident that in addition to menstrual function and bone health, LEA affects many aspects of physiological function including metabolic rate, immunity, protein synthesis, and cardiovascular and psychological health. Consequently, in 2014 the International Olympic Committee Consensus Group introduced the syndrome of relative energy deficiency in sport (RED-S) to describe overall syndrome more comprehensively (Mountjoy et al., 2014).

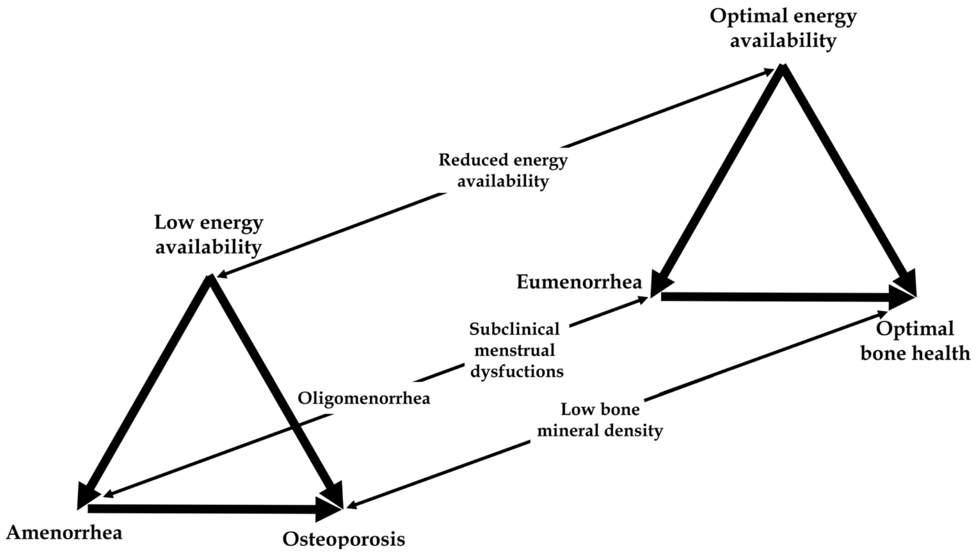


FIGURE 1 Female athlete triad. An athlete's condition moves along the thin arrows of the spectrum according to her diet and exercise habits. Thick arrows show the effects of energy availability on menstrual function and bone health as well as the effects of menstrual function (estrogen) on bone health (Nattiv et al., 2007).

Several health consequences identified in RED-S are described in Figure 2. LEA induces several unfavorable endocrine effects that may further influence menstrual function, bone health, and metabolism (Elliott-Sale et al., 2018). LEA may lead to menstrual dysfunction by inhibiting gonadotropic releasing hormone pulsatility at the hypothalamus, which leads to abnormal pituitary secretion of follicle-stimulating and luteinizing hormones, resulting in decreased estradiol and progesterone concentrations, inadequate folliculogenesis, and anovulation (Gordon et al., 2017). As can be seen in Figure 1, the severity of menstrual dysfunction typically increases from subclinical menstrual dysfunction (e.g., luteal phase defects, anovulation) to oligomenorrhea (cycle length from 5 weeks to 3 months (De Souza et al., 1998)), and further to amenorrhea when the duration and degree of LEA increases. In addition to sex hormones, decreased concentrations of leptin, insulin, insulin-like growth factor 1 (IGF-1), and triiodothyronine (T3) as well as increased cortisol concentrations are typically detected in female athletes who suffer long-term LEA (Elliott-Sale et al., 2018).

Several hormones mentioned above influence bone metabolism, which explains why athletes with LEA and menstrual dysfunction often present with decreased bone mineral density or even osteoporosis (Figure 1) (Elliott-Sale et al., 2018). In addition, LEA may directly reduce the levels of bone formation markers (Fensham et al., 2022; Lambrinoudaki & Papadimitriou, 2010). As peak bone mass in females is reached around 18–20 years (Baxter-Jones et al., 2011; Cvijetic et al., 2008), avoiding long-term LEA is especially important in adolescence to ensure optimal bone development. Notably, bone loss may be irreversible and consequently increase fracture risk for the rest of an athlete's life, which highlights the importance of early detection and treatment of RED-S (Mountjoy et al., 2014).

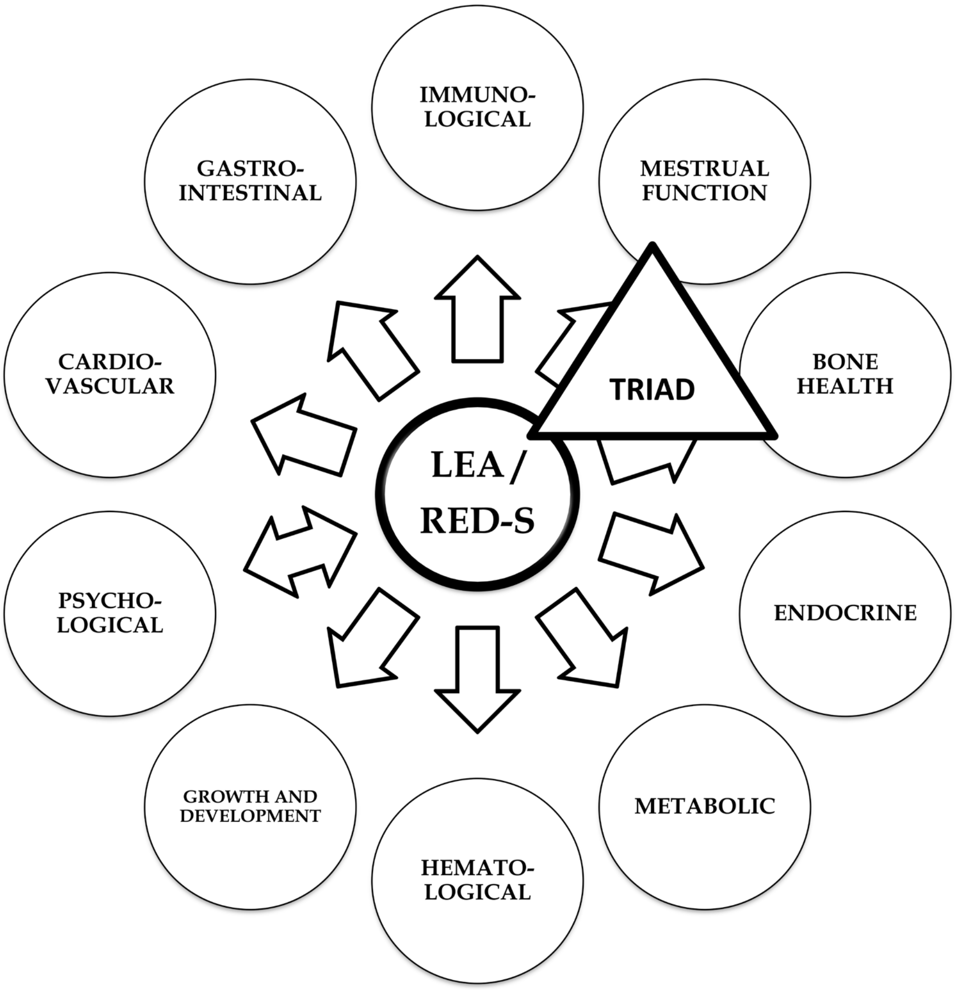


FIGURE 2 Health consequences of long-term low energy availability (LEA) according to the model of Relative Energy Deficiency in Sport (RED-S). The triangle represents the three component of female athlete triad (Mountjoy et al., 2014).

In addition to impaired endocrine function and bone health, several other physiological functions are suggested to be impaired in the RED-S model. Due to LEA, the body conserves energy for basic physiological functions leading to a decrease in resting metabolic rate (Koehler et al., 2016; Areta et al., 2021) which, in turn, can prevent weight loss despite energy deficit (Koehler et al., 2017). In addition, LEA can impair normal growth in adolescents, contribute to iron deficiency and anemia, promote endothelial dysfunction and unfavorable lipid profiles, increase gastrointestinal symptoms, and impair immunological functions (Mountjoy et al., 2018). Finally, various psychological problems, such as eating disorders and depression, can either precede or be caused by LEA (Mountjoy et al., 2014).

Although RED-S symptoms are mainly associated with LEA, the role of individual macronutrients and diurnal variation of EA should also be considered. For example, low CHO availability may reduce concentrations of T3 (Spaulding et al., 1976) and leptin (Jenkins et al., 1997) that, in turn, may suppress resting metabolic rate and affect the menstrual cycle via altered sex hormone concentrations (Elliott-Sale et al., 2018). In addition, some evidence suggests that inadequate CHO intake, even in cases where adequate EA (~40 kcal/kg FFM/d) is maintained, may be a trigger for decreased bone health (Fensham et al., 2022; Heikura et al., 2020) as well as for altered iron metabolism and immune response (McKay et al., 2022a). Finally, some cross-sectional studies show that within-day periods of LEA are associated with RED-S symptoms despite adequate daily total EA (Deutz et al., 2000; Fahrenholtz et al., 2018).

2.2.2 Performance consequences of low energy availability

Figure 3 shows the potential performance consequences of LEA within the RED-S model. Despite the various potential ways in which LEA may impair performance, knowledge on this topic is still limited (Melin et al., 2023; Mountjoy et al., 2018). Nevertheless, it is apparent that many of the health consequences of long-term LEA have direct or indirect effects on performance (Mountjoy et al., 2014). Since intervention studies assessing long-term LEA and sport performance are lacking (Mountjoy et al., 2018) and valid EA assessment in field-conditions is difficult (Heikura et al., 2021b), most studies have investigated the associations between sport performance and physiological RED-S markers instead of direct assessment of EA.

One of the most concerning health and performance consequences of long-term LEA is decreased bone mineral density, which significantly increases the risk for bone injuries and substantial loss of training and competition days (Mountjoy et al., 2014). For example, Heikura et al. (2018) found that amenorrheic track and field endurance athletes had lower BMD and a 4.5-fold higher injury rate, compared with eumenorrheic (normally menstruating) females. In addition, Ihalainen et al. (2021) found that amenorrheic female runners had a higher injury rate and lower running volume compared with eumenorrheic runners. Only eumenorrheic runners increased their competition performance during the follow-up year, which may be due to injuries and reduced running volumes caused by LEA in the amenorrheic runners (Ihalainen et al., 2021). Interestingly, both studies assessed EA with food logs, but neither found LEA in amenorrheic females nor differences in EA between amenorrheic and eumenorrheic athletes, which may be explained by the previously mentioned challenges in assessing EA in field conditions (Heikura et al., 2021b). Conversely, Vanheest et al. (2014) reported that female swimmers with menstrual dysfunction suffered from LEA and impairment in 400 m swimming performance compared with eumenorrheic swimmers. Another study by Tornberg et al. (2017) found no relationship between menstrual function and endurance performance but did find that LEA associated symptoms, such as amenorrhea, elevated cortisol and decreased T3 concentrations negatively correlated with neuromuscular performance.

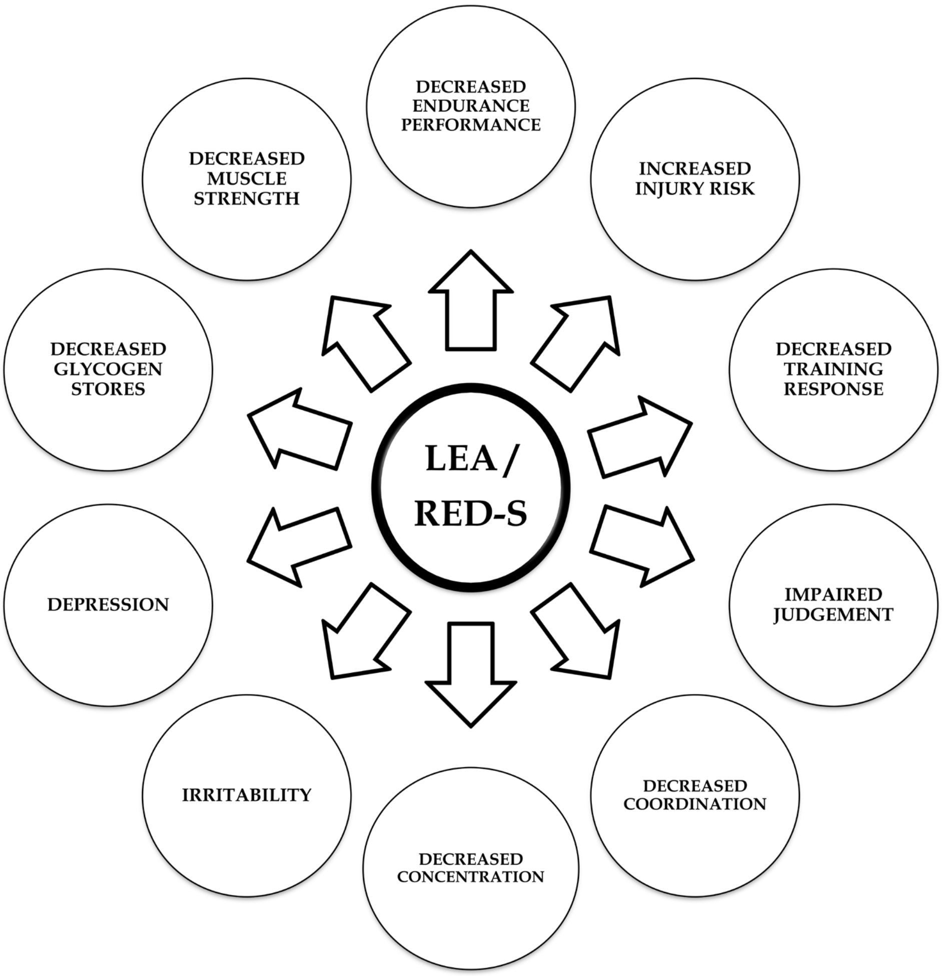


FIGURE 3 Potential performance consequences of long-term low energy availability (LEA) according to the model of Relative Energy Deficiency in Sport (RED-S) (Mountjoy et al., 2014).

Recently, researchers have drawn attention to the common pathways and symptoms of RED-S and overtraining syndrome (Kuikman et al., 2022; Stellingwerff et al., 2021). Indeed, under-fueling (LEA and/or insufficient CHO intake) may be a factor for under-performance and fatigue (Stellingwerff et al., 2021). The systematic review by Kuikman et al. (2022) found that under-performance after a training period with maintained or increased training loads may be present with or without LEA and LEA, in turn, did not automatically lead to under-performance after the training block. It is noteworthy that only relatively short (6 weeks, on average) training periods were analyzed, and it is possible that performance impairments occur when more prolonged periods of LEA lead to more severe symptoms within the RED-S model (Kuikman et al., 2022).

2.2.3 Prevention, screening, and treatments for RED-S

Due to the serious and only partially reversible health and performance consequences of RED-S, effective prevention, screening, and treatment are necessary. The prevention of RED-S requires greater awareness among athletes and the people working and living with them (Mountjoy et al., 2018). In addition, a training environment should not emphasize the performance and appearance benefits of a lean body composition, which may be especially harmful for young females, whose body and identity are still developing (Ackerman et al., 2020). Instead, food should be emphasized as positive source of fuel, which is needed for performance (Ackerman et al., 2020).

Early detection of athletes at risk for RED-S is critical to prevent long-term health consequences. Numerous questionnaires have been developed for identifying RED-S symptoms. For example, the Low Energy Availability in Females Questionnaire (LEAF-Q) was first developed and validated to detect females with physiological symptoms related to long-term LEA (Melin et al. 2014). Menstrual function and injury rate highly influence the LEAF-Q score, but these markers are often detected after months or years of chronic LEA, where the negative effects on bone health can be irreversible (Heikura et al., 2021b). Unfortunately, there is currently no validated tool to integrate objective physiological markers for early detection of LEA and more understanding is needed to determine if hormones, such as leptin, thyroid hormones, and IGF-1, and measurements of resting metabolic rate may be effectively used for screening purposes (Heikura et al., 2021b).

The key to treatment of RED-S is to optimize EA, which can be achieved by increasing EI, reducing exercise, or a combination of both (Mountjoy et al., 2018). Studies have shown that approaches that address LEA and increase BM have often been successful in restoring normal menstrual function (Arends et al., 2012; Mallinson et al., 2013). Oral contraceptives do not correct RED-S and do not improve bone health despite monthly bleeding and are not recommended for treatment (Mountjoy et al., 2018). Supplemental calcium and vitamin D intake (Kitchin, 2013) as well as training programs including high impact loading and resistance training (Nattiv et al., 2007) are recommended to support bone mineral density. Since RED-S is both physiological and psychological syndrome, optimal treatment requires the support of a multidisciplinary team including coach, sports physician, nutritionist, psychologist, physiotherapist, and physiologist (Mountjoy et al., 2014).

2.3 Cross-country skiing

Cross-country (XC) skiing is a demanding endurance sport that requires a variety of physiological, biomechanical, and psychological capabilities (Sandbakk & Holmberg, 2017). High aerobic and anaerobic capacities, adequate strength and ski-specific power, well-developed skiing technique, and the ability to attain and maintain high speeds are required for successful performance (Sandbakk & Holmberg, 2017). Although maximal aerobic capacity (or maximal oxygen uptake (VO_{2max})) is still considered to be the most important factor determining performance in XC skiing (Sandbakk et al., 2016; Talsnes et al., 2021), the importance of anaerobic and neuromuscular capacities has increased during the last decades due significantly increased race speeds (Sandbakk & Holmberg, 2017). In addition, high technical capability is needed in XC skiing where athletes must adapt to continuously varying terrain by changing between the sub-techniques of classical (diagonal stride, double poling with a kick, double poling, and herringbone) and skating skiing (V1 (Gear 2), V2 (Gear 3), V2 alternate (Gear 4), and skating without poles (Gear 5)) (Nilsson et al., 2004).

The race program of XC skiers in the Nordic Junior World Ski Championships, organized by the International Ski Federation (FIS), consists of race distances ranging from sprint (~1–1.8 km and 2–3 minutes) to 20 km (~1 hour) (FIS, 2022). A similar competition program, including a sprint race, 10 km interval starts, and a 20 km mass start is used at the Finnish Junior National Championships in under 18 and 20 years old XC skiers (www.hiihtokalenteri.fi). In senior XC skiers, the longest race distance for females has traditionally been 30 km, but from the 2022–23 season onwards FIS has decided to harmonize the competition program in female and male XC skiers (FIS, 2023). Consequently, the longest race distance for the 2023-24 season will be 50 km for both males and females (FIS, 2023).

2.3.1 Physiological demands of cross-country skiing

Aerobic metabolism accounts for 85%–95% of total energy expenditure during XC distance competitions while the percentage of aerobic (i.e., oxygen-dependent) metabolism in sprint competitions varies between 75% and 85% (Sandbakk & Holmberg, 2017). Consequently, 5%–25% of total energy expenditure must be provided by anaerobic (i.e., oxygen-independent) metabolism (Losnegard, 2019). Noteworthy, the winners in mass start competitions (3 of 4 individual starts in FIS World Championships) are often decided in final sprints (Sandbakk & Holmberg, 2017), which highlights the importance of anaerobic and speed capacities for winning a race.

2.3.1.1 Aerobic capacity

World-class XC skiers have some of the highest VO_{2max} values ever reported with values 70–80 mL/kg/min and 4.0–4.5 L/min being common for female elite XC skiers (Sandbakk et al., 2016; Tønnessen et al., 2015). In addition to high VO_{2max}, XC skiers also need the ability to utilize a high fraction of their VO_{2max} in a variety of sub-techniques. In the other words, XC skiers should aim to reach peak oxygen uptake (VO_{2peak}, highest movement-specific oxygen uptake), in each subtechnique as close to their VO_{2max} as possible. The VO_{2max} values for XC skiers are typically reported in diagonal skiing (Sandbakk et al., 2016; Sandbakk & Holmberg, 2017), but the ability to achieve high oxygen uptake even when employing sub-techniques that involve relatively little muscle mass (e.g., double poling (DP)) have improved significantly during past decades (Holmberg, 2015). VO_{2peak} seems to be a major factor explaining sex difference in XC skiing performance (Losnegard, 2019; Sollie & Losnegard, 2022). For example, a recent study found that sex difference in VO_{2peak} in roller ski skating was 21% in 18-year-old juniors, which was similar to the 19% sex difference observed in world-class senior skiers (Sollie & Losnegard, 2022).

In addition to VO_{2max}, fractional utilization of VO_{2max} during competition is an important performance determining factor. In most endurance sports, anaerobic threshold is considered as one of the most important factors influencing the intensity that can be maintained during an endurance competition (Bassett & Howley, 2000; Joyner & Coyle, 2008). Nevertheless, the significance of anaerobic threshold is more questionable in XC skiing, where the constantly varying terrain and intensity lead to variations in oxygen demands (Sandbakk & Holmberg, 2017). Consequently, the ability to rapidly increase VO_2 during non-steady work-rate and the ability to recover from oxygen deficit during downhills are important factors determining the percentage of VO_{2max} that can be maintained during competition (Losnegard, 2019; Sandbakk & Holmberg, 2017).

2.3.1.2 Anaerobic and speed capacity

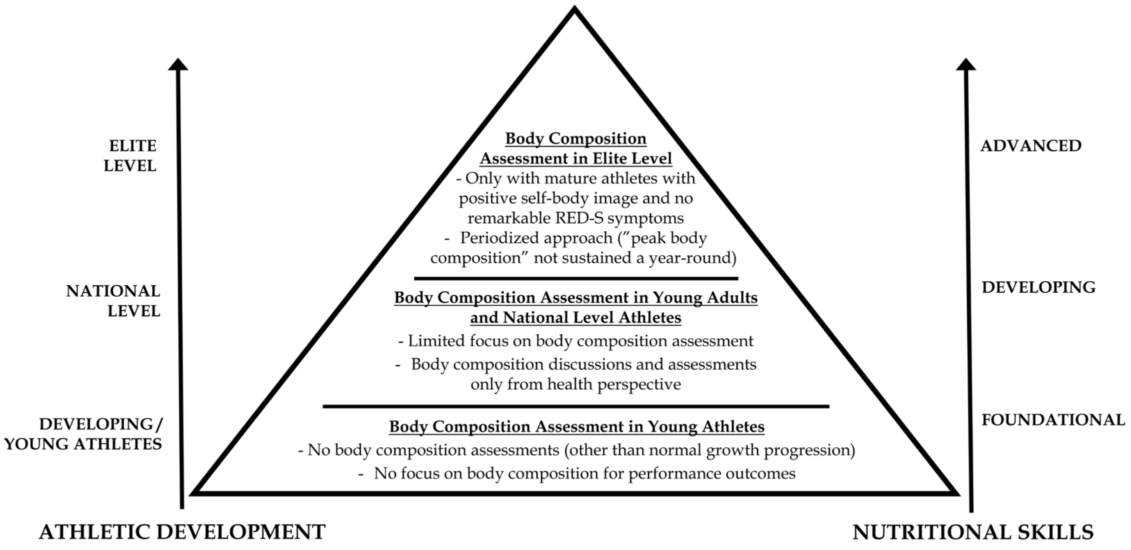
The significance of anaerobic and speed capacities for performance depends on competition type. The relative contribution of anaerobic metabolism is most important for the shortest distances (Sandbakk & Holmberg, 2017). Indeed, anaerobic power, measured as oxygen deficit, as well as ski-specific maximal speed and strength are correlated with sprint performance (Andersson et al., 2010; Losnegard et al., 2012; Stöggl et al., 2011). Furthermore, the ability to attain and maintain high maximal speed is important in distance mass starts, where most races are decided in speed changes over the race distance or in final sprints (Sandbakk & Holmberg, 2017). This highlights the importance of anaerobic and speed capacities in all XC ski distances where ski-specific strength, power, and technique are important attributes enabling high XC skiing speed (Sandbakk & Holmberg, 2017).

2.3.1.3 Skiing efficiency

"Efficiency" is an important factor contributing to endurance performance by determining the power or speed that can be generated at certain VO_2 (Joyner & Coyle, 2008). Both physiological factors, such as a higher percentage of type I muscle fibres, and biomechnanical factors, such as skiing technique, influence skiing efficiency (Joyner & Coyle, 2008; Sandbakk & Holmberg, 2017). Consequently, efficient skiing technique, characterized by e.g. optimal cycle rate and length, smooth changing between the subtechniques, and good arm-leg cooperation, enables the effective transformation of metabolic energy into skiing speed and ultimately performance. Not surprisingly, efficient skiing technique has been found to correlate with performance both in distance and sprint XC skiing (Sandbakk et al., 2010). Therefore, in addition to physiological attributes, well-developed technique is needed for successful XC skiing performance (Sandbakk & Holmberg, 2017). Furthermore, increased muscle strength may improve skiing efficiency (Hoff et al., 2002).

2.3.1.4 Body composition

A low BM may be beneficial in sports where the body is moved against gravity due to a lower energy and oxygen needs (Ackland et al., 2012). Therefore, a decrease in BM may lead to improved uphill skiing performance. On the other hand, lean mass may be an important factor for XC skiing performance, especially in sprint distances (Carlsson et al., 2016) and DP technique (Vahtra et al., 2022). Indeed, a high level of strength and power is required to produce forces efficiently in the various skiing techniques and especially in the sprint races and final sprints in distance competitions (Sandbakk, 2018). Consequently, reductions in BM with simultaneous increase in upper body lean mass may predict performance improvements in distance races that alternate flat and uphill sections (Jones et al., 2021).



Body Composition Assessment in Elite Level
- Only with mature athletes with positive self-body image and no remarkable RED-S symptoms
- Periodized approach ("peak body composition" not sustained a year-round)

Body Composition Assessment in Young Adults and National Level Athletes
- Limited focus on body composition assessment
- Body composition discussions and assessments only from health perspective

Body Composition Assessment in Young Athletes
- No body composition assessments (other than normal growth progression)
- No focus on body composition for performance outcomes

FIGURE 4 Implementation of body composition assessments within the context of athlete stage of development and their nutritional skills. Modified from (Ackerman et al., 2020)

As changes towards leaner body composition may enhance performance in XC skiing, carefully implemented manipulation of EA, in conjunction with strength training, has the potential to improve performance by reducing BM while maintaining lean mass. However, dietary restrictions increase the risk of negative health and performance consequences of LEA and may result in inadequate macro- and micronutrient intake (see chapter 2) and should thus be considered with caution. This is especially important with young, under 20 years of age, athletes, who are particularly prone to LEA associated health consequences (Mountjoy et al., 2018; Nose-Ogura et al., 2019) and may have inadequate nutrition knowledge to implement weight reduction practices safely and successfully (Heikkilä et al., 2018b). Furthermore, overemphasis of weight regulation is recognized as a risk for disordered eating (Sundgot-Borgen, 1994). Therefore, young athletes´ body composition should be assessed only from a health perspective (Figure 4) and even in elite level strategies aimed to modify body composition should be overseen by qualified medical and nutritional professionals (Ackerman et al., 2020; Mountjoy et al., 2018).

2.3.2 Training of cross-country skiers

Most elite XC skiers train 750–950 hours annually including 700–850 hours of endurance training (Sandbakk & Holmberg, 2017; Solli et al., 2017). Approximately 80% of XC skiers' training is performed at a low intensity, 10% at moderate to hard intensity, and 10% by doing speed and strength training (Sandbakk & Holmberg, 2017). Training volume typically increases gradually from the junior to senior level. For example, Karlsson et al. (2021) reported that young XC skiers aged 16-22 years gradually increased their annual endurance training volume by ~56 h/year from ~470 h/year to ~730 h/year, while the proportions of low and high intensity training remained stable at a ratio of approximately 90:10 (Karlsson et al., 2021). In addition, a case study found that the world's most successful female XC skier increased her training volume from 500 h/year at age of 20 to over 900 h/year between the ages of 30 and 34 (Solli et al., 2017). The total training volume appears to be highest during the general preparation period (June–August) and slightly lower during specific preparation (September–November) and competition (December–March) periods leaving more time for recovery after high intensity training and competitions (Losnegard et al., 2013; Tønnessen et al., 2014).

To tolerate high training volume, XC skiers alternate between sport-specific (skiing and roller skiing) and cross-training (e.g., running and biking) while the proportion of sport-specific training increases gradually as training year progress toward main competitions (Sandbakk & Holmberg, 2017). The relative proportion of sport-specific training has been found to increase from ~65% to ~75% of the total annual endurance training volume from the age of 16 to 22 years (Karlsson et al., 2021).

2.3.2.1 Nutritional requirements and intake in cross-country skiers

XC skiers have relatively high energy and macronutrient requirements due to their high training load. Unfortunately, there are only a few studies that have attempted to quantify EE in XC skiers. A study by Sjödin et al. (1994) measured daily total EE via gold standard method doubly labelled water during a week-long training camp in Swedish elite XC skiers. Estimates of total daily EE averaged 4374 kcal/d in females and 7218 kcal/d in males. Interestingly, EI estimates from food logs (4350 kcal/d in females and 7218 kcal/d in males) matched well with EE despite the high energy requirements. Other studies have also reported relatively high EI in elite XC skiers during training camps (3181–3963 kcal/d in females 4593–5450 kcal/d in males) (Carr et al., 2019; Ellsworth et al., 1985) while lower EI have been reported outside the training camp conditions (2414–2820 kcal/d in females, 3492–3800 kcal/d in males) (Ellsworth et al., 1985; Fogelholm et al., 1992).

All XC skiing competition distances in Senior and Junior National and World Championships are performed at intensities that are highly dependent on CHO based fuels for muscle metabolism (Gløersen et al., 2020; Hawley & Leckey, 2015; Losnegard, 2019). Consequently, XC skiers should ensure adequate CHO availability in competitions and high-intensity training sessions to support performance. This can be ensured by a high-CHO (6–12 g/kg/d depending on training load) diet with specific attention paid to the timing and adequacy of CHO intake before and after training sessions or competitions (Burke et al., 2011; Heikura et al., 2021a; Thomas et al., 2016). Despite the importance of CHO for performance and recovery (Burke et al., 2019; Hawley & Leckey et al., 2015), previous studies have shown that XC skiers, even at the elite level, struggle to consume recommended amounts of CHO (Carr et al., 2019; Ellsworth et al., 1985). Similarly, a study by Heikkilä et al., (2019) showed that adequate CHO intake was a major nutritional challenge for young endurance athletes of whom 48% were XC skiers and biathletes.

In line with the general recommendations for endurance athletes, protein intake of 1.2–2.0 g/kg/d is recommended for XC skiers (Heikura et al., 2021a; Thomas et al., 2016). The upper range of the recommendations may be required for XC skiers due to high training load (Carr et al., 2019). Indeed, endurance training (Churchward-Venne et al., 2020), whole body exercise (Macnaughton et al., 2016), energy deficiency (Areta et al., 2014), and low CHO availability (Gillen et al., 2019) may all increase protein requirements compared to the general recommendations for athletes. Because no study has examined specific protein requirements for XC skiers, it is not known if recommended protein intake is optimal for athletes using whole-body musculature during high load endurance training. Notably, both male and female elite XC skiers seem to consume significantly higher amounts of protein (2.8–3.6 g/kg/d) compared to general athlete recommendations (Carr et al., 2019). On the other hand, older studies reported that protein intake in elite XC skiers (~1.4–2.2 g/kg/d) varied within the recommended range (Ellsworth et al., 1985; Fogelholm et al., 1992). Similarly, percentages of protein of total EI were lower in older studies (13%–14%) (Ellsworth et al., 1985; Fogelholm et al., 1992; Sjödin et al., 1994) than in a more recent study (~21%) (Carr et al., 2019), which may be influenced by the prevailing "protein hype" and increased protein intake in general population (Valsta et al., 2017).

Endurance athletes, including XC skiers, are recommended to consume fat 20%–35% of total EI (Thomas et al., 2016; chapter 2.1.2.3) to maintain adequate EA and support normal body functions. Previous studies have shown that fat intake of 28%–32% of total EI seems to be typical for elite XC skiers (Carr et al., 2019; Fogelholm et al, 1992; Sjödin et al., 1994) and young endurance athletes (Heikkilä et al., 2019). In contrast, Ellsworth et al., (1985) reported that 38%–39% of total EI came from fat in US elite XC skiers. Therefore, it must be acknowledged that cultural and generational differences may have affect dietary practices among XC skiers especially in the older studies, where general understanding of the dietary requirements of the XC skiers may have been more limited.

2.3.3 Determining performance in cross-country skiers

2.3.3.1 Competition performance (FIS points)

The level of an XC skier's performance can be indicated by FIS points (Pellegrini et al., 2021). An athlete's FIS points are calculated as the average top 5 results over the last 365 days (an adjustment factor of > 1.0 is applied if fewer than 5 results are available). A lower FIS score suggests better performance (FIS, 2021). Separate FIS point lists for distance and sprint competitions are publicly available on the FIS website (https://www.fis-ski.com/DB/cross-country/fis-points-lists.html).

The number of FIS points gained in a single FIS level competition is determined by adding the individual race points (P) to the race penalty score, where P is calculated as follows:

$$P = \frac{F \times T_x}{T_o} - F$$

Where F is the race factor (800 for all individual time trials; 1200 for sprints and pursuit; 1400 for mass start and skiathlon), T_x is the finish time (in seconds) and T_o is the winning time (in seconds) (FIS, 2021).

The race penalty is calculated by adding together the three highest FIS points scores (from the current FIS points list) from the top five finishers in the competition and then dividing by 3.75 (FIS, 2021).

2.3.3.2 Performance tests

Many aspects of an XC skier's performance capacity can be measured with various laboratory- and field-based tests (Talsnes et al., 2021). The key determinants of performance commonly monitored in the laboratory are VO_{2max}, anaerobic energy contribution, anaerobic threshold, and work efficiency (Pellegrini et al., 2021). Sport-specific testing is generally recommended, but a recent study by Talsnes et al. (2021) revealed that VO_{2max} and maximal aerobic speed predicted FIS points and roller-ski skating competition performance regardless of how laboratory testing was performed (e.g., by running or roller-ski skating). In addition, lower VO_2 and heart rate (HR) in relation to maximum values and lower blood lactate during suboptimal running or roller-skiing predicted FIS points and roller-ski skating competition performance (Talsnes et al., 2021).

The major challenge in sport-specific field-based testing is that the interaction between the skis and the snow (or the roller-skis and the ground) changes depending on the weather conditions, which can exert a considerable impact on measurable parameters (Pellegrini et al., 2021). Therefore, the equipment and conditions used in field-based tests should always be standardized, accounted for, and reported as well as possible (Pellegrini et al., 2021). Despite the challenges related to field-testing, both DP and uphill running time trials are reported to correlate with FIS points and roller-ski skating competition performance (Talsnes et al., 2021).

In addition to endurance testing, speed and strength testing may provide important information about the attributes needed for successful XC skiing performance. Indeed, some evidence suggests that better results in strength and power production tests are related to better maximum speed and sprint performance (Stöggl et al., 2007, 2011).

3 PURPOSE OF THE STUDY

XC skiing is an endurance sport where high training volume is needed for successful performance (Sandbakk & Holmberg, 2017). A typical XC skier's training can more than double daily dietary energy requirements compared to sedentary people. Consequently, XC skiers are at significant risk for under-fueling, which, in turn, may compromise both performance and overall health. Unfortunately, knowledge about dietary practices among female XC skiers is limited and based mostly on older studies (Ellsworth et al., 1985; Fogelholm et al., 1992; Sjödin et al., 1994). Moreover, previous studies have investigated dietary intake generally among senior national team athletes (Ellsworth et al., 1985; Carr et al., 2019; Fogelholm et al., 1992; Sjödin et al., 1994) and among heterogenous group of young endurance athletes from mixed sports and genders (Heikkilä et al., 2019). Therefore, little is known about dietary intake among young female XC skiers. In addition, it is currently unknown if dietary intake is associated with performance in XC skiers. Therefore, the aim of this study was to investigate the associations between dietary intake and various aspects of performance in young female XC skiers.

The specific aims and hypotheses of the study were:

1. To investigate how well young female XC skiers meet current nutritional recommendations at home compared to a training camp with intensified training load.

   Hypothesis 1: Young female XC skiers will have challenges to meet CHO recommendations especially during hard training periods but will meet other macronutrient recommendations (Carr et al., 2019).

2. To investigate if young female XC skiers periodize their dietary intake between different micro- and macrocycles.

Hypothesis 2: EI and macronutrient intake will be higher during periods of higher EEE (Fogelholm et al., 1992). Nevertheless, CHO intake will be suboptimal especially during hard training periods and around key training sessions (Carr et al., 2019; Ellsworth et al., 1985).

3. To investigate if dietary intake is associated with signs of overreaching/under-recovery after short-term training-overload.

   Hypothesis 3: LEA and low CHO availability will be associated with signs of overreaching/under-recovery, such as decreased muscular performance (Jurov et al., 2022; Stellingwerff et al., 2021). LEA and low CHO availability will be associated hormonal changes that are typical in under-recovered athletes (Loucks & Thuma, 2003, Meeusen et al., 2013)

4. To monitor XC skiers′ nutritional intake, performance, hormonal function, and body composition and to investigate whether EA and macronutrient intake is associated with the monitored variables.

   <u>Hypothesis 4:</u> Inadequate EA and/or macronutrient intake may compromise performance (Melin et al., 2023) and lead to hormonal dysfunctions (Elliot-Sale et al., 2018), while excess EI may lead to BM gains, which can negatively affect performance (Ackland et al., 2012). Long-term performance development is best supported by optimal EA and macronutrient intake (Melin et al., 2023).

5. To investigate, the prevalence of LEA and surrogate markers of LEA in Finnish female XC skiers.

   <u>Hypothesis 5:</u> The risk for LEA and surrogate markers of LEA/RED-S is significant in young female XC skiers (Carr et al., 2019). About one third of the participants will have at least one marker of RED-S (Carr et al., 2019).

6. To assess, if nutrition knowledge is associated with EA and macronutrient intake in young female XC skiers.

   <u>Hypothesis 6:</u> Young female XC skiers have significant gaps in nutrition knowledge (Heikkilä et al., 2018b), which may be associated with suboptimal dietary intake (Janiczak et al., 2022).

4 MATERIAL AND METHODS

This dissertation is based on the results of two experiments. Experiment I (original research articles I and II) investigated dietary intake, nutrition knowledge, and performance at home and during a training camp. Experiment II (original research articles III and IV) investigated dietary intake, body composition, hormonal concentrations, nutrition knowledge, and performance throughout the training year.

4.1 Participants

Experiment I. A total of 31 highly trained (McKay et al., 2022b) female XC skiers from the Finnish Ski Association's under 18-year-old National Team were invited to participate. Of those, a total of 19 athletes (age 16–18 years) participated. Anthropometric characteristics of the participants are shown in Table 3 in the results section.

Experiment II. A total of 27 highly trained (McKay et al., 2022b) female XC skier and biathletes from a local high school sport academy (age 15–19 years) participated. The proportion of the participants, who belonged to the youth XC or biathlon national team was 64%. Due to the dropouts, the final number of the participants was 25 in original article III and 23 in original article IV. Anthropometric and performance characteristics of the participants are shown in Tables 4 and 9 in the results section.

4.1.1 Ethics statement

The participants provided written informed consent prior to their involvement in experiment I or II and were allowed to drop out of the experiment at any time. The ethical board of the University of Jyväskylä approved both experiments and included procedures (30.8.2019 & 20.3.2020), and the experiments were conducted in accordance with the Declaration of Helsinki.

4.2 Experimental designs

4.2.1 Experiment I: nutrition at home and during a training camp

Experiment I was carried out before and during a 5-day training camp in October during a specific preparation season (Figure 5). Participants filled in 48-hour food and training logs before the training camp (HOME) and during the second and third day of the training camp (CAMP). Anthropometric measurements, fasting blood samples, and performance tests (submaximal running test and vertical jump tests) were performed on the first (PRE) and the last morning (POST) of the CAMP. The time between PRE and POST was approximately 96 hours. LEAF-Q (Melin et al., 2014) and nutrition knowledge questionnaire (Heikkilä et al., 2018a) were completed at PRE.

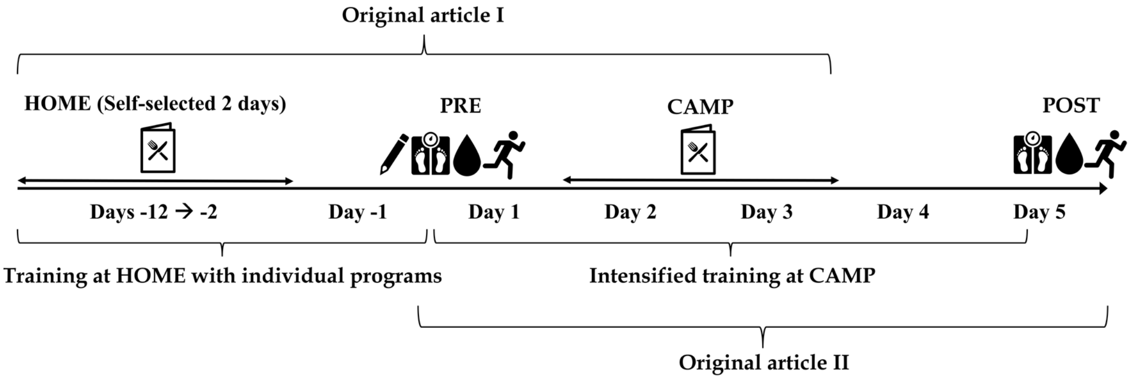


FIGURE 5 The design of experiment I. "Menus", 48-hour food and training logs; "pen", questionnaires; "scales", anthropometric measurements; "droplets", fasting blood samples; and "runners", performance tests. PRE, at the beginning of the CAMP; POST, at the end of the CAMP.

4.2.2 Experiment II: nutrition throughout a training year

Data in eperiment II were collected for 16 months from the beginning of May 2020 to the end of August 2021 (Figure 6). The participants completed five 3-day food and training logs, one for each training period (macrocycle) of the training year as follows: preparation (2020) (Log_1), specific preparation (Log_2), competition (Log_3), transition (Log_4), and preparation (2021) periods (Log_5). Laboratory measurements including body composition measurements, fasting blood samples, and performance tests (aerobic capacity, lactate threshold, DP, force plate jumps) were performed at the end of the preparation (M_1), specific preparation (M_2), competition (M_3), and preparation periods (M_4). Total training volume (total hours) was recorded daily using an electronic training log (eLogger, eSportwise Oy, Finland). Competition performance was determined by FIS points earned from the Finnish Junior National Championships.

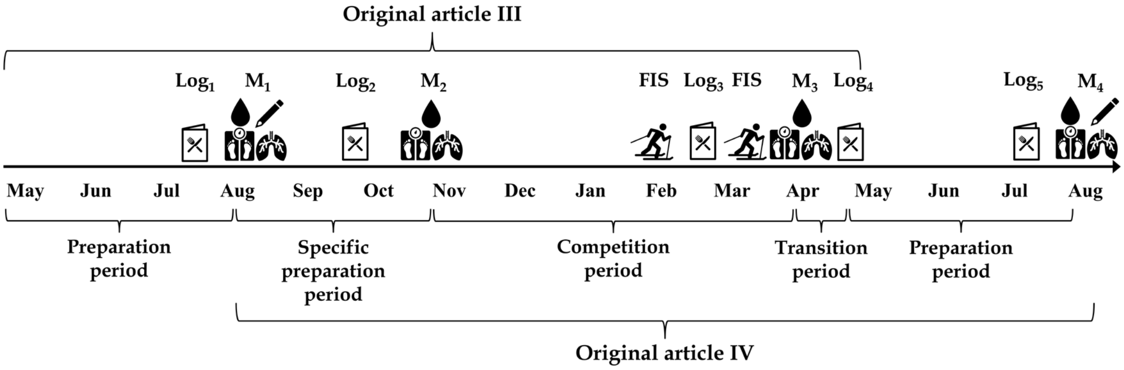


FIGURE 6 The design of experiment II. "Menus", 3-day food and training logs (Log_1-Log_5); "skiers", Finnish Junior National Championships; M_1-M_4, measurement points including: "scales", body composition measurements; "droplets", fasting blood samples; "lungs" performance tests; "pens", questionnaires.

4.3 Data collection and analysis

4.3.1 Anthropometric measurements

Anthropometric measurements were completed in the morning following an overnight fast. Height of the participants was measured with a wall-mounted stadiometer. BM, FFM, body fat mass (FM), and body fat percentage (F%) were measured using bioimpedance (Inbody 720, Biospace Co., Seoul, Korea). Body mass index (BMI) was calculated as:

$$BMI = \frac{BM}{Height^2}$$

4.3.2 Blood samples and analysis

Fasting blood samples were collected from an antecubital vein for analysis of serum hormone concentrations. Samples from each participant at different measurement points were collected at the same time of day between 7 and 9am. Blood was drawn into Vacuette gel serum tubes (Greiner-Bio-One GmbH, Kremsmünster, Austria). The tubes were centrifuged at 3600 rpm for 10 minutes to collect serum, which were frozen at -20°C. Hormone concentrations were analyzed by an immunometric chemiluminescence method (Immulite 2000 XPi, Siemens Healthcare, United Kingdom).

Experiment I. Concentrations of cortisol, leptin, free T3, insulin, and IGF-1 were analyzed. The assay sensitivities were 5.5 nmol/L for cortisol, 8.2 ug/L for leptin, 1.5 pmol/L for free T3, 2 U/L for insulin, and 1.7 nmol/L for IGF-1. Reliability expressed as a coefficient of variation were 7.7% for cortisol, 4.9% for leptin, 8.1% for free T3, 5.2% for insulin, and 4.4% for IGF-1.

Experiment II. Concentrations of insulin, cortisol, IGF-1, free T3, free thyroxine (T4), thyroid-stimulating hormone (TSH), leptin, and testosterone were analyzed. The assay sensitivities were 2.0 U/L for insulin, 5.5 nmol/L for cortisol, 2.6 nmol/L for IGF-1, 1.5 pmol/L for free T3, 1.4 pmol/L for free T4, 0.004 mU/L for TSH, 0.2 ug/L for leptin, and 0.5 nmol/L for testosterone. Reliability expressed as a coefficient of variation was 8.8% for insulin, 7.7% for cortisol, 4.4% for IGF-1, 10.3% for free T3, 6.6% for free T4, 9.2% for TSH, 4.9% for leptin, and 10.9% for testosterone.

4.3.3 Performance tests

4.3.3.1 Vertical jumps

Vertical jump tests on a force plate (HUR FP8, Kokkola, Finland) were performed after a self-selected warm-up. For the countermovement jump (CMJ), participants were instructed to stand with their feet shoulder-width apart and their hands on hips while flexing the knees and trying to jump as high as possible. The best jump height of three attempts was calculated from impulse (Linthorne, 2001) using Coachtech system (Ohtonen et al., 2016).

Reactive jumps (RJ) were performed ~3 minutes after the CMJ. Participants were instructed to jump ten times in a row with knees extended and as high as possible, and with a contact time as short as possible. Only a small downward knee flexion after landing was allowed. Participants performed 2 × 10 jumps and the average power of the two best jumps from a single trial was calculated using equations by Bosco et al. (1983a). It has been shown that both vertical jumps (e.g., CMJ) and continuous jumps (e.g., RJ) are valid tests for determining explosive power (Bosco et al., 1983b).

4.3.3.2 Submaximal running test

A submaximal treadmill running test (4 × 4 minutes) was performed after the jump tests. Participants ran at a constant 10.0 km/h speed and the inclination was increased after each 4-minute stage as follows: minutes 0–4 were run at 2%, minutes 4–8 at 4%, minutes 8–12 at 7%, and minutes 12–16 at 9%. Blood lactate samples after each stage were obtained from the fingertip and collected into capillary tubes (20 µL), which were placed in a 1-mL hemolyzing solution and analyzed after the completion of testing according to the manufacturer's instructions (EKF diagnostic, C-line system, Biosen, Germany). During the treadmill test, HR (Polar V800, Kempele, Finland) and rate of perceived exertion (RPE) (Borg 6–20 scale (Borg, 1970)) were recorded from the final 15 seconds of each stage and values from the last stage were used in final analysis. HR/RPE and lactate/RPE ratios were calculated. The test protocols described above were selected as they are generally used to monitor training status among Finnish XC skiers.

4.3.3.3 Aerobic capacity and lactate threshold

The incremental aerobic capacity test was performed by walking or running with poles on a treadmill (Telineyhtymä, Kotka, Finland) ~15 minutes after the force plate jumps. The test started at 3.5° inclination with a speed of 5.0 km/h. The inclination and/or the speed of the treadmill was increased every third minute so that oxygen demand calculated using the equation by Balke & Ware (1959) increased 6 mL/kg/min in every stage. The test was continued until voluntary exhaustion and time to exhaustion (TTE) was used as a measure of endurance performance.

Breathing gases were continuously measured using a mixing chamber system (Medikro 919 Ergospirometer, Medikro Oy, Kuopio, Finland). Volume and gas calibration of the ergospirometer was done prior to every measurement. VO_2 and respiratory exchange ratio (RER) from the last 60 seconds of each stage were recorded. Maximal oxygen uptake (VO_{2max}) was defined as the highest 60-second average VO_2. HR was monitored continuously throughout the test using a Polar H10 HR belt (Polar Electro Oy, Kempele, Finland), and the average HR from the last 60 seconds of each stage was recorded. Blood lactate samples at the end of each stage were obtained from a fingertip and collected into capillary tubes (20 µL), which were placed in a 1-mL hemolyzing solution and analyzed using Biosen C-line analyzer (EKF diagnostics, Barleben, Germany). In addition to VO_{2max}, the VO_2 at 4 mmol/L lactate (Onset of Blood Lactate Accumulation (OBLA)) was determined by plotting VO_2 against lactate concentration and using linear interpolation (VO_{2OBLA}). The test protocol was selected as it is the same that is used for VO_{2max} testing at local sports institute and therefore familiar for the participants.

4.3.3.4 Double poling performance

A maximal double poling test was performed by roller skiing on a treadmill (Rodby Innovation AB, Vänge, Sweden). All skiers used the same pair of Marwe 800 XC roller skis (Marwe Oy, Hyvinkää, Finland) equipped with prolink bindings (Salomon Group, Annecy, France) and standard 6C6 wheels (Marwe Oy, Hyvinkää, Finland). Poles (Swix Triac 3.0, BRAV, Lillehammer, Norway) were selected based on the length of the participants' classic poles and were equipped with a tip customized for treadmill roller skiing. After a self-selected warm-up outside the laboratory, participants performed a 10-minute warm-up at the same workload as the first stage of the subsequent submaximal test including two ~15-second sprints at the workload equal to the fourth to sixth stage of the test. Following the warm-up, athletes performed an incremental DP treadmill test at an incline of 2°, starting at 10 km/h and followed by an increase of 1 km/h every minute until volitional exhaustion. Time to exhaustion was recorded.

4.3.4 Competition performance

Competition performance was evaluated by FIS points (chapter 2.3.3.1). Lower FIS points indicate a better performance. As many FIS level competitions were canceled due to the COVID-19 pandemic, competition performance was determined by FIS points earned from th Finnish Junior National Championships to which both XC skiers and biathletes took part. The best points from three distance competitions and one sprint competition were recorded separately. A total of 20 participants competed in at least one distance race and 14 participants competed in the sprint race.

4.3.5 Questionnaires

Questionnaires were completed on paper at PRE (experiment I) as well as at M_1 and M_4 (experiment II).

4.3.5.1 Nutrition knowledge

A validated nutrition knowledge questionnaire for young endurance athletes (Heikkilä et al., 2018a) included 79 statements in true/false format, divided into five sections: (1) nutrition recommendations for endurance athletes, (2) dietary supplements, (3) fluid balance and hydration, (4) energy intake and recovery, and (5) the association between food choices and body image. Each correct answer yielded one point and each wrong answer zero points. Nutrition knowledge score refers to the proportion (percentage) of correct answers.

4.3.5.2 The Low Energy Availability in Females Questionnaire (LEAF-Q)

LEAF-Q was used to assess the risk of LEA (Melin et al., 2014) and prevalence of self-reported amenorrhea (absence of menstrual cycles for more than 90 days (Nattiv et al., 2007)). A LEAF-Q-score of ≥ 8 indicates the risk of long-term LEA (Melin et al., 2014).

4.3.6 Food and training logs

Experiment I. 48-hour food and training logs were filled in twice during the study. The first logs were filled in between 12 and 2 days before the training camp (HOME) on self-selected days. The second logs were filled in during the second and third day of the 5-day training camp (CAMP). At CAMP, participants had prescheduled breakast, lunch, and dinner times in the restaurant of the local sport institute. Participants selected the contents of their meals from a buffet, which included salad and bread tables, several main course options, and dessert. The energy and macronutrient contents of the dishes were obtained from the JAMIX MENU software (JAMIX Oy, Jyväskylä, Finland) where the ingredients of each dish was entered by the restaurant. Participants were allowed to have their own snacks between meals.

Experiment II. 72-hour food and training logs were collected at five time points (Log_1–Log_5). Participants selected three subsequent days for each log from a 4-week period and were asked to select days that reflect their normal life and training as well as possible. In both experiments, participants recorded the timing, type, and weight of foods and fluid consumed, quantifying their intake using kitchen scales (Idéale+, Tokmanni Oy, Mäntsälä, Finland). The timing, type, and average HR of all training sessions performed were recorded in training logs. Written and verbal instructions were given for accurate record keeping.

4.3.6.1 Assessment of energy and macronutrient intake

Food logs were analyzed for EI and macronutrient intake using Aivodiet-software (version 2.0.2.3, Mashie, Malmö, Sweden). Macronutrient intake was expressed in relation to BM (g/kg/d) and EI in relation to FFM (kcal/kg FFM/d). In addition, fat intake is expressed as precentages of total EI to allow for comparisons to athlete recommendations (Thomas et al., 2016).

In addition to average intake of the logs, original article I assessed CHO and protein intake aroud KEY (speed or strength exercises, moderate to high intensity (target blood lactate > 2.5) exercises, and long (> 150 min) exercises) and EASY (other exercises) training sessions. CHO intake was recorded in the 4-hour pre-exercise period as well as in 1- and 4-hour post-exercise periods, while protein intake was recorded in the 2-hour post-exercise period. Mean CHO and protein intake around KEY and EASY training sessions were calculated for each athlete separately at HOME and at CAMP. Thus, every athlete had single values describing her intake around different training situations (KEY at HOME; EASY at HOME; KEY at CAMP; EASY at CAMP).

4.3.7 Assessment of exercise energy expenditure and energy availability

Experiment I. Training logs were analyzed for EEE based on the duration of the training sessions and EE equation by Charlot et al. (2014):

$$EE = 113.2 + 6.88 \times HR_{avg} + 7.45 \times BM - 3.15 \times HR_{rest} - 6.88 \times HR_{max} + 10.14 \times VO_{2max}$$

Where EE is energy expenditure in kcal/h, HR_{avg} is the average HR of the training session, BM the body mass of the participant, HR_{rest} the self-reported resting HR, HR_{max} the self-reported maximum HR, and VO_{2max} the self-reported maximal oxygen uptake in mL/kg/min.

Experiment II. Assessment of EEE was based on the individual relationship of EE, VO_2, and HR during the aerobic capacity test (chapter 4.3.3.3). EE during the first five stages of the test was calculated using Weir (1949) equation:

$$EE= VO_2 \times (1.1 \times RER + 3.9)$$

Where EE is energy expenditure in kcal/min, VO_2 is the measured oxygen uptake in L/min, and RER is measured respiratory exchange ratio (exhaled carbon dioxide divided by VO_2)

Calculated EE and HR from the first five stages of the test were used to form an individual regression line for each subject as described by Tomten &

Hostmark (2006). Figure 7 shows an example of an individual regression line. EEE of each training session was calculated from the mean HR and duration of the training session using this regression line. As the relationship between EE and HR may change within a year, the regression line was updated based on the results of the nearest measurement point (M_1–M_4).

Stage	HR (bpm)	RER	VO_2 (L/min)	EE (kcal/min)
1	123	0.77	1.5	7.3
2	135	0.85	1.9	9.2
3	148	0.87	2.3	11.3
4	163	0.91	2.8	13.7
5	181	0.99	3.2	15.9

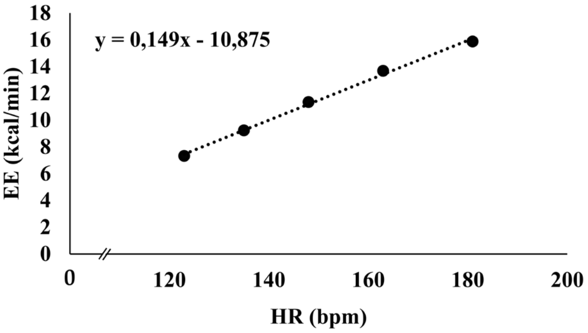


FIGURE 7 An example of the individual regression line used in the assessment of exercise energy expenditure in experiment II. The table shows the individual results from the first five stages of the aerobic capacity test. HR, heart rate; RER, respiratory exchange ratio; VO_2, oxygen uptake; EE energy expenditure calculated using the Weir equation (Weir, 1949).

In both experiments, resting EE (REE) was subtracted from EEE in line with the latest definition of EA (Areta et al., 2021). Thus, only the additional energy cost of exercise is included in the final EEE. Daily REE was estimated by the Cunningham (1991) equation:

$$REE = 370 + 21.6 \times FFM$$

Daily EA was calculated as presented by Loucks et al. (2011):

$$EA = \frac{EI - EEE}{FFM}$$

FFM in REE and EA equations was obtained from the bioimpedance measurements and updated during the experiment based on the results of the nearest measurement point (M_1–M_4).

The following cutoff values were used for EA interpretation: LEA < 30 kcal/kg FFM/d, moderate EA 30–45 kcal/kg FFM/d, and optimal EA > 45 kcal/kg FFM/d (Heikura et al., 2018; Loucks et al., 2011). EA < 45 kcal/kg FFM/d is considered suboptimal in this study.

4.4 Statistical analyses

Statistical analyses were conducted using SPSS Statistics 28 (IBM, Armonk, NY, USA). Results are reported as means ± SD. Normality was assessed via Shapiro–Wilk, and nonparametric tests were used with non-normally distributed data. Statistical significance was defined as $p < 0.05$.

Experiment I. The changes between HOME and CAMP as well as between different training situations (KEY at HOME; EASY at HOME; KEY at CAMP; EASY at CAMP) were assessed using a repeated-measures analysis of variance, followed by a Student's paired t-test as a *post hoc* test to determine the p-values in the pairwise comparisons. Wilcoxon signed rank test was used in the case of non-normally distributed variables. Pearson's (normally distributed data) or Spearman's (non-normally distributed data) correlation coefficient was used to analyze correlations between variables. To test knowledge about nutrition recommendations more specifically, section 1 (44 questions) of the 79-question nutrition knowledge questionnaire (Heikkilä et al., 2018a) was used in the correlation analysis.

Experiment II. The changes in variables between different parts of the training year (M_1–M_4 and Log_1–Log_5) were analyzed using a one-way analysis of variance for repeated measurements followed by the Bonferroni *post hoc* test. The Wilcoxon signed rank test was used for nonparametric variables. Pearson's (normally distributed data) or Spearman's (nonparametric data) correlation coefficient were used to analyze correlations between variables. A 9-day mean was calculated from Log_1–Log_3 to analyze associations between dietary intake and FIS points (i.e., logs before Junior National Championships). A 12-day mean was calculated from Log_2–Log_5 to analyze associations between dietary intake and year-to-year changes in performance, body composition, and hormone concentrations (i.e., logs between M_1 and M_4). A 15-day mean was calculated from Log_1–Log_5 to analyze associations between dietary intake and performance, body composition, hormone concentrations, and questionnaire scores at M_4 (i.e., logs before M_4).

Stepwise linear regression analysis was used to determine which of the nutritional (EI, EEE, EA, and macronutrient (CHO, protein, fat) intake), anthropometric (BM, FFM, FM, F%), and training volume variables best explained performance variables. When FIS sprint and distance points were used as dependent variables, a 9-day mean dietary intake from Log_1–Log_3, body composition variables at M_3, and ~11-month mean training volume prior M_3 were used as independent variables. When laboratory measured performance variables were used as dependent variables, a 15-day mean dietary intake from Log_1–Log_5, body composition variables at M_4, and ~16-month mean training volume prior M_4 were used as independent variables. When M_1 to M_4 changes in performance were used as dependent variables, a 12-day mean dietary intake from Log_2–Log_5, body composition changes from M_1 to M_4, and ~12-month mean training volume between M_1 and M_4 were used as independent variables. Homoscedasticity was tested by estimating Pearson and Spearman's correlations between the standardized predicted values and the absolute standardized residuals and was not violated in any of the analyses. The relative importance of predictors was calculated based on R Square (R^2).

5 RESULTS

5.1 Anthropometric characteristics

Experiment I. Table 2 shows that BM ($p < 0.01$), BMI ($p < 0.01$), and FFM ($p < 0.001$) increased during the CAMP. In contrast, FM ($p < 0.01$) and F% ($p < 0.01$) decreased during the CAMP.

TABLE 2 Anthropometric characteristics before (PRE) and after (POST) 96-hour intensified training period (CAMP) in young female cross-country skiers (n = 19).

	PRE	POST
Body mass (kg)	59.9 ± 6.1	60.3 ± 6.1**
Height (cm)	166.8 ± 3.5	166.8 ± 3.5
BMI (kg/m^2)	21.5 ± 2.3	21.7 ± 2.3**
Fat free mass (kg)	50.1 ± 4.3	50.9 ± 4.1***
Fat mass (kg)	9.8 ± 3.2	9.3 ± 4.1**
Fat percentage (%)	15.9 ± 4.0	15.2 ± 4.4**

** significantly different from PRE $p < 0.01$; *** $p < 0.001$

Experiment II. Table 3 shows anthropometric characteristics at the end of four training periods. BM, BMI, FM, and F% were higher at M_3 than at other measurement points ($p < 0.001$–0.05). In addition, BM ($p < 0.001$), BMI ($p < 0.01$), FFM ($p < 0.001$), and FM ($p < 0.05$) increased from M_1 to M_4.

TABLE 3 Anthropometric characteristics at the end of four macrocycles in young female cross-country skiers (n = 22)

	M_1 (August)	M_2 (November)	M_3 (April)	M_4 (August)
Body mass (kg)	61.8 ± 7.1	63.2 ± 7.1 ^{aaa}	64.7 ± 7.3 $^{aaa, bb}$	64.5 ± 7.7 $^{aaa, b}$
Height (cm)	168.4 ± 5.2	168.7 ± 5.2	168.9 ± 5.1	169.1 ± 5.1
BMI (kg/m^2)	21.8 ± 2.2	22.2 ± 2.2 ^{aaa}	22.7 ± 2.4 $^{aaa, bb}$	22.5 ± 2.3 $^{aa, c}$
Fat free mass (kg)	51.1 ± 5.3	52.1 ± 5.0 ^{aa}	51.6 ± 5.0	52.5 ± 5.0 $^{aaa, ccc}$
Fat mass (kg)	10.4 ± 3.4	10.7 ± 3.6	12.9 ± 4.4 $^{aaa, bbb}$	11.8 ± 4.4 $^{a, ccc}$
Fat percentage (%)	16.8 ± 4.4	16.8 ± 4.5	19.8 ± 4.9 $^{aaa, bbb}$	18.0 ± 5.0 ^{ccc}

^{a} significantly different from M_1 $p < 0.05$, ^{aa} $p < 0.01$, ^{aaa} $p < 0.001$; ^{b} significantly different from M_2 $p < 0.05$, ^{bb} $p < 0.01$, ^{bbb} $p < 0.001$; ^{c} significantly different from M_3 $p < 0.05$, ^{ccc} $p < 0.001$

5.2 Dietary intake and requirements

Experiment I. Table 4 shows daily EI, EEE, EA, macronutrient intake, and training volume at HOME and at CAMP. Daily intake of energy ($p < 0.001$), protein ($p < 0.01$), and CHO ($p < 0.001$), as well as EEE ($p < 0.001$) and training volume ($p < 0.001$) were lower at HOME compared to CAMP, while an increased trend from HOME to CAMP was observed in EA ($p = 0.065$). At HOME, 11% of athletes had optimal EA, 63% moderate EA, and 26% LEA. At CAMP, 42% of athletes had optimal EA, 21% moderate EA, and 37% LEA.

EEE and macronutrient intake around KEY and EASY training sessions are presented in Table 5. EEE was significantly higher during KEY training sessions compared to EASY training sessions at HOME ($p < 0.01$) and at CAMP ($p < 0.001$). Furthermore, EEE in KEY training sessions was lower at HOME than at CAMP ($p < 0.001$). CHO intake during the 4-hour period before KEY sessions was lower at HOME than at CAMP ($p < 0.01$), while CHO intake remained similar between HOME and CAMP before EASY training sessions. CHO intake was significantly lower at both 1 and 4 hours after KEY and EASY training session at HOME compared to CAMP ($p < 0.001$). Protein intake was higher after KEY training sessions at CAMP than after EASY training sessions at CAMP ($p < 0.05$) and KEY training sessions at HOME ($p < 0.05$). Many athletes did not meet the lower end of the recommended CHO intake on a daily basis or around KEY training sessions while the percentages of athletes who did not meet these recommendations were higher at HOME (42%–100%) compared to CAMP (11%–95%). All athletes met the minimum recommendations for post-exercise protein intake.

TABLE 4 Mean (± SD) daily training volume, energy and macronutrient intake, exercise energy expenditure, and energy availability in young female cross-country skiers (n = 19).

	HOME	%	CAMP	%	Recommendation
Training (min/d)	120 ± 26	-	214 ± 20***	-	-
EI (kcal/kg FFM/d)	51.4 ± 10.4	-	72.3 ± 16.6***	-	-
EEE (kcal/kg FFM/d)	17.7 ± 4.8	-	32.9 ± 4.7***	-	-
EA (kcal/kg FFM/d)	33.7 ± 9.6	11	40.3 ± 17.3	42	> 45
CHO intake (g/kg/d)	5.0 ± 1.2	26	7.1 ± 1.6***	37	6–10/8–12
Protein intake (g/kg/d)	2.1 ± 0.3	100	2.5 ± 0.5**	100	1.2–2.0
Fat intake (g/kg/d)	1.5 ± 0.6	-	2.2 ± 0.8***	-	-
Fat intake (% of EI)	30 ± 6	95	32 ± 7	100	20–35

EI, energy intake; EEE, exercise energy expenditure; EA, energy availability; CHO, carbohydrate; HOME, during home training; CAMP, during training camp; %, the percentage of athletes who met the lower threshold for recommended intake for optimal performance and recovery (Loucks et al., 2011; Thomas et al., 2016); * significant difference between HOME and CAMP $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

TABLE 5 Mean (± SD) exercise energy expenditure and macronutrient intake around training sessions in young female cross-country skiers (n = 19).

	HOME			CAMP			Recom-
	EASY	KEY	%	EASY	KEY	%	mendation
EEE (kcal/kg FFM)	8.2 ± 4.4	12.8 ± 4.3**	-	9.9 ± 3.8	17.4 ± 2.1***†††	-	-
Protein POST2 (g/kg)	0.6 ± 0.3	0.6 ± 0.2	100	0.7 ± 0.3	0.8 ± 0.1*†	100	0.25–0.30
CHO PRE4 (g/kg)	1.2 ± 0.8	1.0 ± 0.3	58	1.7.±.1.2	1.3 ± 0.3**	89	1–4
CHO POST1 (g/kg)	0.5 ± 0.5	0.8 ± 0.5	26	1.7±1.0***	1.7±0.7***	89	1.0–1.2
CHO POST4 (g/kg)	1.5 ± 0.7	1.6 ± 0.7	0	2.7 ± 1.2***	2.7 ± 0.8***	5	4.0–4.8

EEE, exercise energy expenditure; CHO, carbohydrate; PRE4, within four hours before a training session; POST1, within an hour after a training session; POST2, within two hours after a training session; POST4, within four hours after a training session; HOME, during home training; CAMP, during training camp; KEY, key training sessions; EASY, non-KEY training sessions; %, the percentage of athletes who met the lower threshold for recommended intake for optimal performance and recovery (Thomas et al., 2016) around key training sessions; * significant difference between HOME and CAMP $p < 0.05$, ** $p < 0.01$; *** $p < 0.001$; † significant difference between EASY and KEY $p < 0.05$; ††† $p < 0.001$.

Experiment II. Food and training log data from Log_1 to Log_5 are shown in Table 6. Figure 8 shows the individual variation of EA and CHO intake at different measurement points. Dietary intake and requirements remained similar between Log_1–Log_3. EI, EEE and training volume were lower in Log_4 than in the other logs (p < 0.001–0.05) while EA remained similar compared to previous logs. EA was lower in Log_5 than in the other logs (p < 0.001–0.05). In total, 482 training days were recorded in the electronic training logs with the mean daily training volume of 1.7 ± 0.3 h/d. Electronic training logs showed that training volume was lower in Log_3 than in Log_1, Log_2, and Log_5 ($p < 0.01$). Training volume in Log_4 was lower than in the other logs ($p < 0.001$).

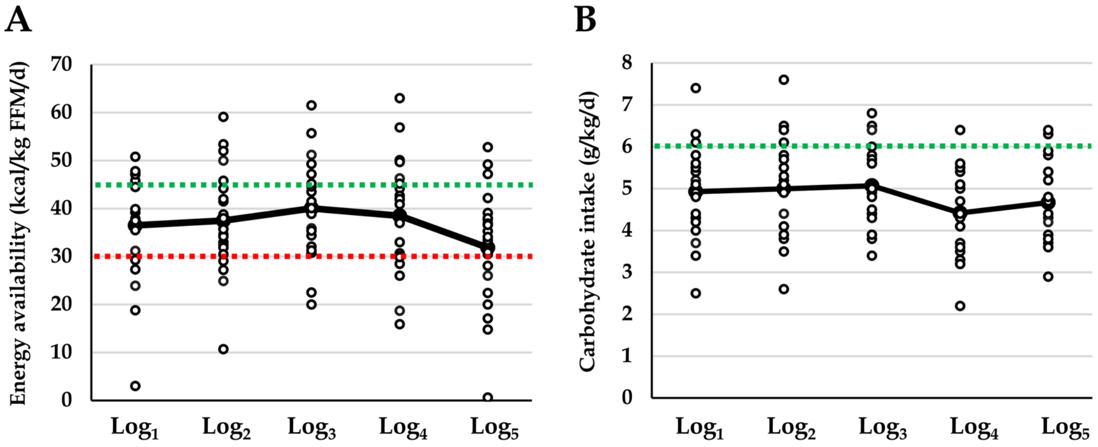


FIGURE 8 Energy availability (A) and carbohydrate intake (B) between five training periods in young female cross-country skiers (n = 22). The circles represent individual values, the black lines represent group means, the red dotted line represent the threshold for low energy availability (Loucks et al., 2011), and the green dotted lines represent the lower limit for optimal energy availability (Loucks et al., 2011) and carbohydrate intake (Thomas et al., 2016). Log_1, preparation period; Log_2, specific preparation period; Log_3, competition period; Log_4, transition period; Log_5, preparation period a year after Log_1.

TABLE 6 Food and training log data between five training periods in young female cross-country skiers (n = 22).

	Log$_1$	Log$_2$	Log$_3$	Log$_4$	Log$_5$	15-day mean
EI (kcal/kg FFM/d)	50.9 ± 10.8	52.2 ± 9.5	53.4 ± 9.1	46.3 ± 11.0 $^{bbb, ccc}$	48.2 ± 9.9 ^{c}	50.2 ± 7.7
EEE (kcal/kg FFM/d)	14.5 ± 5.2	14.2 ± 5.5	13.3 ± 5.9	7.8 ± 7.0 $^{aa, bbb, ccc}$	16.3 ± 6.0 $^{c, ddd}$	13.3 ± 4.3
EA (kcal/kg FFM/d)	36.5 ± 11.1	37.5 ± 10.8	40.0 ± 9.8	38.5 ± 11.5	31.9 ± 12.1 $^{aaa, b, ccc, dd}$	36.9 ± 8.9
Optimal EA (% of participants)	32	23	27	27	14	23
Moderate EA (% of participants)	45	59	64	50	50	59
LEA (% of participants)	23	18	9	23	36	18
CHO intake (g/kg/d)	4.9 ± 1.1	5.0 ± 1.2	5.1 ± 1.0	4.4 ± 1.1	4.7 ± 1.0	4.8 ± 0.8
Protein intake (g/kg/d)	2.0 ± 0.5	2.1 ± 0.4	2.0 ± 0.4	1.6 ± 0.4 $^{aaa, bbb, ccc}$	1.8 ± 0.4 $^{aa, bb, c, d}$	1.9 ± 0.3
Fat intake (g/kg/d)	1.5 ± 0.5	1.5 ± 0.4	1.5 ± 0.4	1.3 ± 0.5	1.4 ± 0.4	1.4 ± 0.4
Fat intake (% of EI)	31 ± 6	32 ± 5	31 ± 5	32 ± 5	31 ± 5	31 ± 4
Training (logs) (h/d)	2.1 ± 0.7	2.0 ± 0.6	1.9 ± 0.7	1.1 ± 0.7 $^{aaa, bb, cc}$	2.0 ± 0.6 ^{ddd}	1.8 ± 0.4
Training (eLogger) (h/d)	1.9 ± 0.3	1.8 ± 0.3	1.5 ± 0.5 $^{aa, bb}$	0.5 ± 0.4 $^{aaa, bbb, ccc}$	1.8 ± 0.4 $^{cc, ddd}$	1.7 ± 0.3

Log$_1$, preparation period; Log$_2$, specific preparation period; Log$_3$, competition period; Log$_4$, transition period; Log$_5$, preparation period a year after Log$_1$; EI, energy intake; EEE, exercise energy expenditure; EA, energy availability; LEA, low energy availability; CHO, carbohydrate; ^{a} significantly different from Log$_1$ $p < 0.01$ ^{aaa} $p < 0.001$; ^{b} significantly different from Log$_2$ $p < 0.05$, ^{bb} $p < 0.01$, ^{bbb} $p < 0.001$; ^{c} significantly different from Log$_3$ $p < 0.05$, ^{cc} $p < 0.01$, ^{ccc} $p < 0.001$; ^{d} significantly different from Log$_4$ $p < 0.05$, ^{dd} $p < 0.01$, ^{ddd} $p < 0.001$

5.3 Performance

Experiment I. Table 7 shows the performance measures at PRE and POST. HR ($p < 0.001$), HR/RPE ($p < 0.01$), lactate/RPE ($p < 0.05$), and CMJ ($p < 0.05$) decreased while RPE increased ($p < 0.05$) from PRE to POST. In addition, a statistically insignificant decrease in RJ was detected ($p = 0.065$).

TABLE 7 Mean (± SD) values from the last stage of the submaximal treadmill running test and force plate jumps before (PRE) and after (POST) a 96-hour intensified training period (CAMP) in young female cross-country skiers (n = 19).

	PRE	POST
HR (bpm)	189 ± 10	183 ± 10***
Lactate (mmol/L)	5.0 ± 1.6	4.6 ± 1.9
RPE (6-20)	15.8 ± 1.4	16.4 ± 1.3*
HR/RPE	12.0 ± 1.0	11.2 ± 1.0**
Lactate/RPE	0.31 ± 0.08	0.28 ± 0.08*
Counter movement jump (cm)	32.0 ± 3.7	31.2 ± 3.2*
Reactive jump (W/kg)	44.6 ± 8.1	43.1 ± 8.0

RPE, rate of perceived exertion; HR, heart rate; * significantly different from PRE $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Experiment II. Table 8 shows performance measures at the end of four macrocycles. Figure 9 shows the individual variation of VO_{2max} at different measurement points TTE, VO_{2max}, and VO_{2OBLA} were lower at M_3 than at other measurement points ($p < 0.001–0.05$). In addition, VO_{2max} in relation to BM decreased from M_1 to M_4 ($p < 0.05$). DP test time, CMJ, and RJ remained statistically similar between the measurement points.

TABLE 8 Performance measures at the end of four macrocycles in young female XC skiers.

	N	M_1 (August)	M_2 (November)	M_3 (April)	M_4 (August)
TTE (min)	17	21.3 ± 1.6	20.6 ± 1.8	19.3 ± 2.0 $^{aaa, bb}$	20.3 ± 2.3
VO_{2max} (L/min)	17	3.3 ± 0.3	3.3 ± 0.3	3.2 ± 0.3 $^{a, b}$	3.3 ± 0.3 ^{c}
VO_{2max} (mL/kg/min)	17	53.8 ± 4.0	52.7 ± 4.0	49.9 ± 4.5 $^{aaa, bb}$	52.0 ± 4.6 $^{a, cc}$
VO_{2OBLA} (L/min)	17	2.9 ± 0.3	3.0 ± 0.3	2.8 ± 0.3 ^{bb}	3.0 ± 0.3 ^{cc}
VO_{2OBLA} (mL/kg/min)	17	47.3 ± 3.4	47.6 ± 2.8	44.0 ± 5.1 $^{aa, bb}$	46.8 ± 4.5 ^{ccc}
DP (s)	16	495 ± 71	499 ± 79	474 ± 89	499 ± 71
CMJ (cm)	16	31.1 ± 4.0	29.9 ± 4.2	30.6 ± 4.3	30.9 ± 4.5
React jump (W/kg)	16	44.7 ± 5.7	43.9 ± 6.5	44.1 ± 6.7	43.6 ± 6.4

TTE, time to exhaustion; VO_{2max}, maximal oxygen uptake; VO_{2OBLA}, oxygen uptake at 4 mmol/L lactate level; DP, double poling test time; CMJ, counter movement jump; ^{a} significantly different from M_1 $p < 0.05$, ^{aa} p < 0.01, ^{aaa} $p < 0.001$; ^{b} significantly different from M_2 $p < 0.05$, ^{bb} $p < 0.01$, ^{bbb} $p < 0.001$.

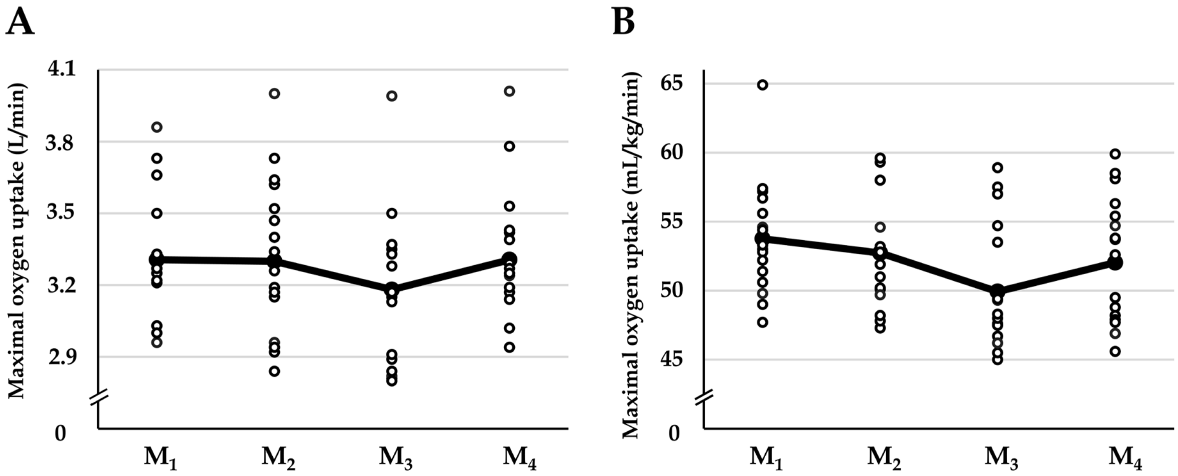


FIGURE 9 Absolute (A) and relative (B) maximal oxygen uptake at the end of four macrocycles in young female cross-country skiers (n = 17). The circles represent individual values, and the black lines represent group means. M_1, at the end of the preparation period (August); M_2, at the end of the specific preparation period (November); M_3, at the end of the competition period (April); M_4, at the end of the preparation period a year after M_1 (August).

5.4 Hormone concentrations

Experiment I. Table 9 shows hormone concentrations at PRE and POST. Leptin ($p < 0.01$), free T3 ($p < 0.05$), and insulin ($p < 0.05$) concentrations decreased during CAMP while the concentrations of cortisol and IGF-1 remained similar.

TABLE 9 Hormone concentrations before (PRE) and after (POST) a 96-hour intensified training period (CAMP) in young female cross-country skiers (n = 19).

	PRE	POST
Cortisol (nmol/L)	506 ± 70	499 ± 49
Leptin (ug/L)	31.6 ± 22.5	22.9 ± 13.6**
Free T3 (pmol/L)	5.5 ± 1.1	5.2 ± 0.7*
Insulin (U/L)	7.7 ± 4.5	5.9 ± 2.9*
IGF-1 (nmol/L)	40.7 ± 6.3	37.9 ± 7.1

T3, triiodothyronine; IGF-1, insulin-like growth factor 1; * significantly different from PRE $p < 0.05$; ** $p < 0.01$

Experiment II. Table 10 shows hormone concentrations at the end of four macrocycles. Leptin concentrations at M_1 were lower than at the other measurement points ($p < 0.001$–0.05) while concentrations at M_3 were higher than at the other measurement points ($p < 0.001$). Other analyzed hormone concentrations remained similar between the measurement points.

TABLE 10 Hormone concentrations at the end of four training periods (macrocycles) in young female cross-country skiers (n = 23).

	M_1 (August)	M_2 (November)	M_3 (April)	M_4 (August)
Insulin (mU/L)	9.0 ± 6.6	12.3 ± 9.1	10.2 ± 6.6	7.9 ± 4.3
Cortisol (nmol/L)	554 ± 150	585 ± 160	613 ± 173	591 ± 161
IGF-1 (nmol/L)	34.6 ± 10.0	39.3 ± 12.1	35.4 ± 9.8	36.0 ± 12.1
Free T3 (pmol/L)	4.7 ± 1.1	4.8 ± 1.1	4.5 ± 1.1	4.6 ± 1.0
Free T4 (pmol/L)	13.5 ± 2.4	12.7 ± 1.4	13.4 ± 1.7	13.2 ± 1.8
TSH (mU/L)	2.5 ± 1.4	2.7 ± 1.4	3.2 ± 2.4	2.4 ± 0.9
Leptin (ng/L)	22.9 ± 12.3	29.1 ± 14.9 ^{a}	44.1 ± 26.3 $^{aaa, bbb}$	30.1 ± 15.9 $^{a, ccc}$
Testosterone (nmol/L)	0.8 ± 0.4	0.8 ± 0.5	0.8 ± 0.5	0.7 ± 0.3

IGF-1, insulin-like growth factor 1; T3, triiodothyronine; T4, thyroxine; TSH, thyroid-stimulating hormone ^{a} significantly different from M_1 $p < 0.05$, ^{aa} $p < 0.01$, ^{aaa} $p < 0.001$; ^{b} significantly different from M_2 $p < 0.05$, ^{bb} $p < 0.01$, ^{bbb} $p < 0.001$; ^{ccc} significantly different from M_3 $p < 0.001$.

5.5 Questionnaires

Experiment I. LEAF-Q score was 6 ± 4. Five of the 19 athletes (26%) had a total score of ≥ 8 and were therefore categorized as being at risk for LEA in line with Melin et al. (2014) and 3 athletes (16%) had self-reported amenorrhea. Total nutrition knowledge score was 76.0 ± 7.3% while the scores from the different sections of the questionnaire were: 73.4 ± 8.4% (section 1), 67.4 ± 19.1% (section 2), 92.5 ± 10.0% (section 3), 71.8 ± 14.6% (section 4), and 87.1 ± 11.3% (section 5).

Experiment II. LEAF-Q score remained statistically similar, but a trend towards an increased score from M_1 (6 ± 4) to M_4 (7 ± 4) was detected ($p = 0.067$). Five of the athletes had a score of ≥ 8 at both M_1 and M_4, four athletes only at M_1, and four athletes only at M_4. Consequently, the total number of athletes with LEAF-Q score of ≥ 8 was nine (36%) at both measurement points. One participant had self-reported amenorrhea at both M_1 and M_4.

Total nutrition knowledge remained statistically significant, but a trend towards an increased score from M_1 (78.7 ± 7.9%) to M_4 (81.8 ± 8.6%) was detected ($p = 0.058$). Scores from the different sections of the questionnaire were: 75.0 ± 10.1% (section 1), 73.3 ± 15.2% (section 2), 95.9 ± 8.9% (section 3), 78.6 ± 10.8% (section 4), and 87.5 ± 10.5% (section 5) at M_1 and 78.9 ± 8.5% (section 1), 78.3 ± 20.4% (section 2), 95.2 ± 6.9% (section 3), 79.2 ± 15.2% (section 4), and 89.4 ± 12.5% (section 5) at M_4. There was no statistically significant change in any of the sections.

5.6 Associations between the variables

5.6.1 Dietary intake, training volume, and performance

Experiment I. EA correlated with PRE to POST changes in blood lactate ($r_s = 0.54$, $p < 0.05$) and lactate/RPE ratio ($r = 0.65$, $p < 0.01$, Figure 10A) from the last stage of the submaximal running test, and RJ ($r = 0.47$, $p < 0.05$, Figure 10B). There was also a positive trend between EA and changes in CMJ ($r = 0.42$, $p = 0.071$). CHO intake correlated with PRE to POST changes in RJ ($r = 0.48$, $p < 0.05$). No statistically significant correlations between blood variable changes and nutrition were detected.

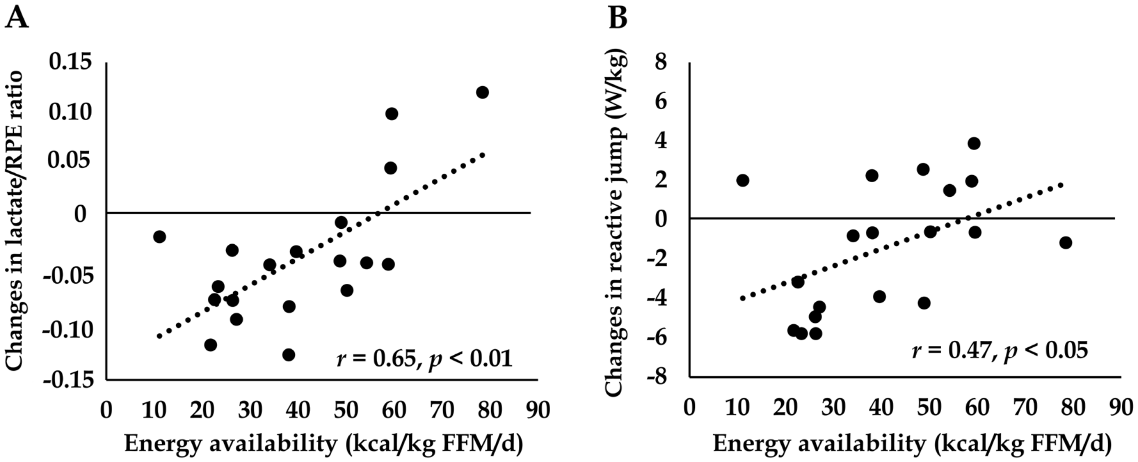


FIGURE 10 Associations between energy availability and changes in lactate/rate of perceived exertion (RPE) ratio (A) and between energy availability and changes in reactive jump performance (B) during a 96-hour intensified training period (CAMP).

Experiment II. Better success in XC distance races, indicated by lower FIS distance points, was associated with higher 9-day mean EA ($r = -0.47$, $p < 0.05$) and macronutrient intake from Log_1 to Log_3 ($r = -0.51–0.65$, $p < 0.01–0.05$) (Figure 11). In addition, athletes with better DP test time and TTE as well as higher relative VO_{2max} and VO_{2OBLA} at M_4 tended to eat more macronutrients in relation to their BM ($r/r_s = 0.47–0.68$, $p < 0.01–0.05$) (Table 11). Changes in performance were not associated with dietary variables.

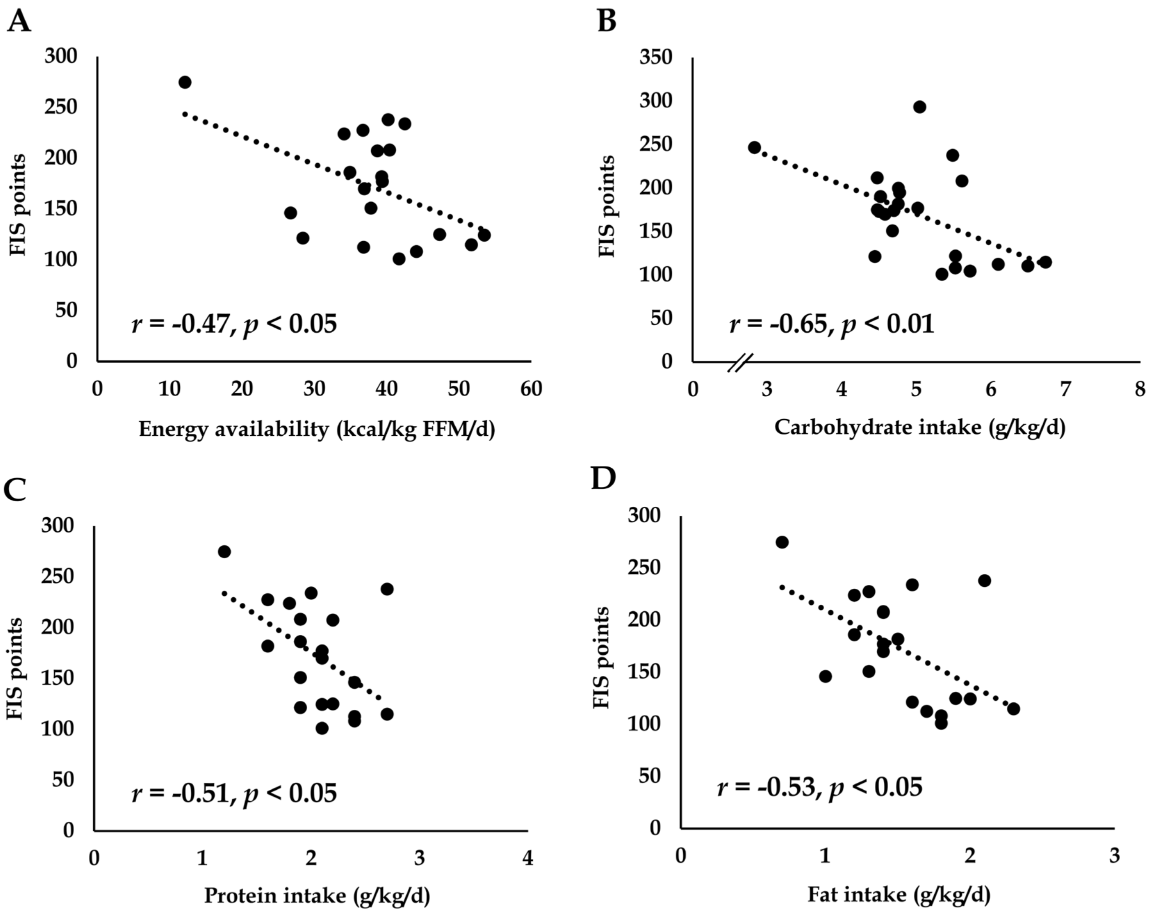


FIGURE 11 Associations between FIS distance points and energy availability (A), between FIS distance points and carbohydrate intake (B), between FIS distance points and protein intake (C), and between FIS distance points and fat intake (D). All the dietary variables are presented as 9-day mean from Log$_1$–Log$_3$ (i.e., the logs recorded before Junior National Championships).

5.6.2 Body composition and performance

Experiment II. Athletes with better performance in distance events (lower FIS distance points) tended to have lower FM and F% (Figure 12). In laboratory tests at M$_4$, BM, BMI, and FFM were positively associated with absolute VO$_{2\text{max}}$ VO$_{2\text{OBLA}}$ (r/r_s = 0.56–0.76, p < 0.001–0.05) while BM, FM, and F% were negatively associated with relative VO$_{2\text{max}}$ and VO$_{2\text{OBLA}}$ (r/r_s = -0.58–0.72, p < 0.001–0.01) (Table 12).

TABLE 11 Pearson's (*r*) or Spearman's (r_s) correlation coefficients between dietary intake (15-day mean from Log_1–Log_5) and performance at the end of the study (M_4).

	TTE (min)	VO_{2max} (L/min)	VO_{2max} (mL/kg/min)	VO_{2OBLA} (L/min)	VO_{2OBLA} (mL/kg/min)	DP (s)	CMJ (cm)	RJ (W/kg)
Energy availability (kcal/kg FFM/d) (r_s)	0.30	-0.18	0.23	-0.10	0.30	0.10	0.04	-0.13
Carbohydrate intake (g/kg/d) (*r*)	**0.52***	-0.19	**0.56***	0.06	**0.62****	**0.47***	0.29	0.28
Protein intake (g/kg/d) (*r*)	**0.59****	0.00	**0.59****	0.15	**0.68****	0.43	0.33	0.13
Fat intake (g/kg/d) (*r*)	0.43	-0.22	**0.47***	-0.02	**0.61****	0.32	0.28	-0.07

TTE, time to exhaustion; VO_{2max}, maximal oxygen uptake; VO_{2OBLA}, oxygen uptake at 4 mmol/L lactate level; DP, double poling test time; CMJ, counter movement jump; RJ, react jump; * statistically significant correlation $p < 0.05$, ** $p < 0.01$. Statistically significant correlations are bolded.

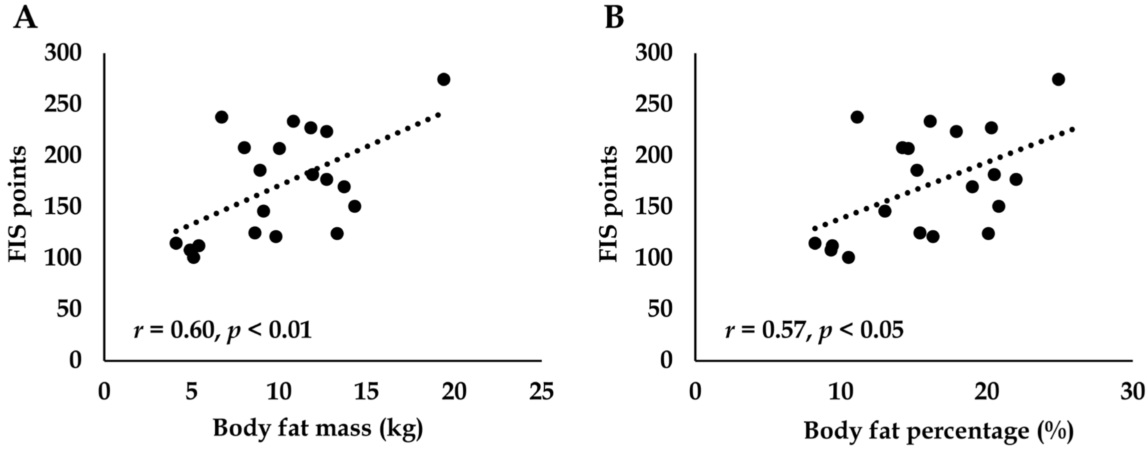


FIGURE 12 Associations between FIS points and body fat mass at the end of the competition period (M_3) (A) and FIS points and body fat percentage at M_3 (B).

TABLE 12 Pearson's (*r*) or Spearman's (r_s) correlation coefficients between body composition and performance variables at the end of the study (M_4).

	TTE (min)	VO_{2max} (L/min)	VO_{2max} (mL/kg/min)	VO_{2OBLA} (L/min)	VO_{2OBLA} (mL/kg/min)	DP (s)	CMJ (cm)	RJ (W/kg)
Body mass (kg) (r_s)	**-0.47***	**0.56***	**-0.67****	**0.61****	**-0.58****	-0.12	-0.35	-0.14
Body mass index (kg/m^2) (*r*)	-0.17	**0.74*****	-0.40	**0.64****	-0.40	0.13	**-0.50***	-0.22
Fat free body mass (kg) (*r*)	-0.19	**0.76*****	-0.37	**0.72*****	-0.31	0.09	-0.27	0.04
Body fat mass (kg) (r_s)	**-0.63****	0.18	**-0.72*****	0.20	**-0.61****	-0.30	-0.40	-0.26
Fat percentage (%) (*r*)	**-0.60****	0.24	**-0.67****	0.21	**-0.61****	-0.38	-0.37	-0.38

VO_{2max}, maximal oxygen uptake; VO_{2OBLA}, oxygen uptake at 4 mmol/L lactate level; DP, double poling test time; CMJ, counter movement jump; * statistically significant correlation $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Statistically significant correlations are bolded.

Changes in DP test time from M_1 to M_4 were positively associated with the changes in FFM ($r = 0.47$, $p < 0.05$) and negatively associated with the changes in FM ($r = -0.51$, $p < 0.05$) and F% ($r = -0.54$, $p < 0.01$, Figure 13A). Changes in absolute VO_{2max} ($r = 0.46$, $p < 0.05$) and VO_{2OBLA} ($r = 0.63$, $p < 0.01$) were positively associated with the changes in BM while a statistically insignificant negative trends were found between the changes in RJ and FM ($r_s = -0.42$, $p = 0.059$), and F% ($r_s = 0.42$, $p = 0.061$, Figure 13B). Changes in TTE, relative VO_{2max} or VO_{2OBLA}, or CMJ were not associated with changes in body composition.

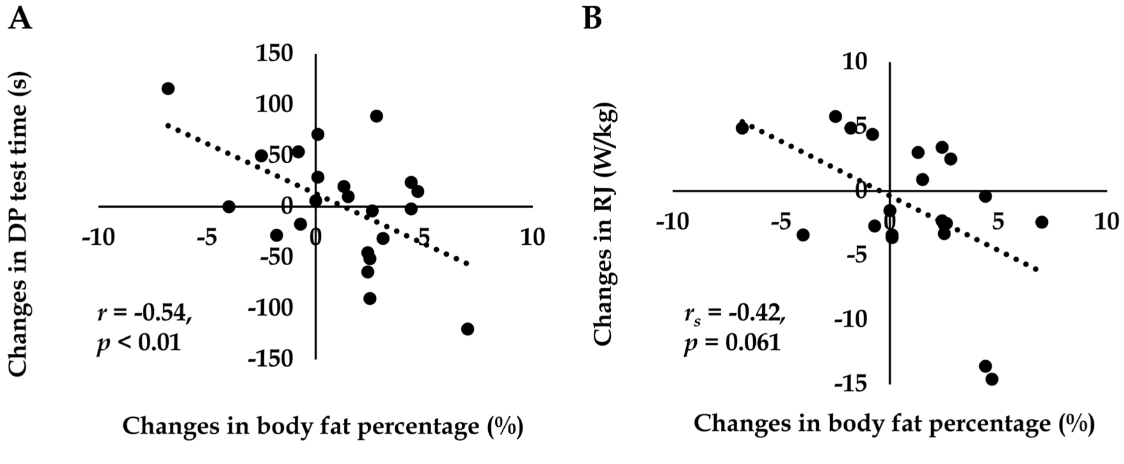


FIGURE 13 Associations between the year-to-year (from M_1 to M_4) changes in double poling (DP) test time and fat percentage (A) and between year-to-year (from M_1 to M_4) changes in reactive jump (RJ) and fat percentage (B).

5.6.3 Dietary intake, training volume, and body composition

Experiment I. There were no associations between body composition and dietary intake at HOME. In contrast, athletes with higher BM, BMI, FFM, and FM tended to have higher EA ($r = 0.66, p < 0.01$; $r = 0.71, p < 0.001$; $r = 0.49, p < 0.05$; $r = 0.63, p < 0.01$, respectively) and fat intake ($r = 0.65, p < 0.01$; $r = 0.64, p < 0.01$; $r = 0.43, p = 0.069$; $r = 0.66, p < 0.01$, respectively) at CAMP.

Experiment II. Athletes with higher 15-day mean CHO ($r = -0.49, p < 0.05$ and protein ($r = -0.70, p < 0.001$) intake from Log_1 to Log_5 tended to have lower F% at M_4 (Figure 14). Training volume during the study was not associated with dietary intake or body composition at M_4. Dietary intake and training volume were not associated with changes in body composition.

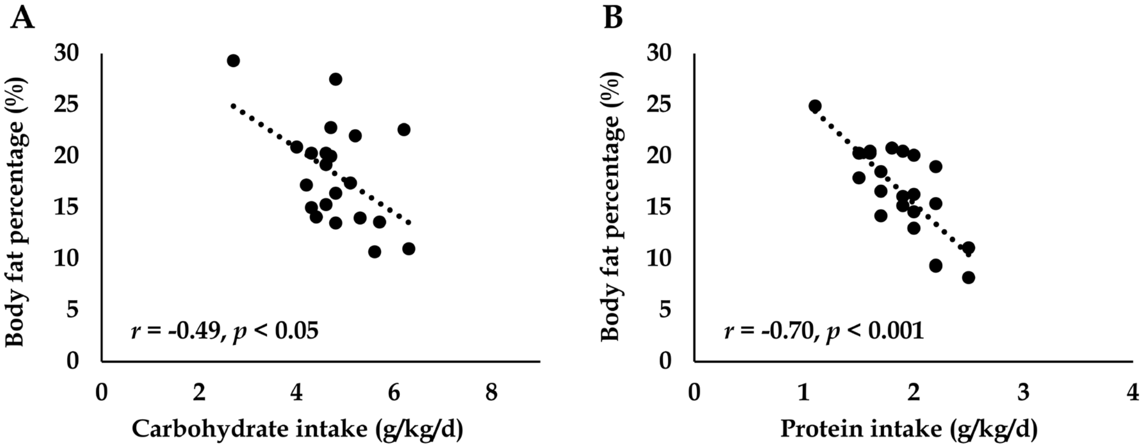


FIGURE 14 Associations between carbohydrate intake (15-day mean from Log_1–Log_5) and fat percentage at the end of the study (M_4) (A) and between protein intake (Log_1–Log_5) and fat percentage at M_4.

5.6.4 Dietary intake and hormonal concentrations

Experiment I. EA and macronutrient intake at CAMP were not associated with the changes in cortisol, leptin, T3, insulin, and IGF-1 concentrations.

Experiment II. TSH concentrations at M_4 were associated with 15-day mean intake (Log_1–Log_5) of CHO ($r = 0.58, p < 0.01$) and fat ($r = 0.44, p < 0.05$). In addition, changes in insulin concentrations from M_1 to M_4 were negatively associated with the 12-day mean (Log_2–Log_5) EI ($r_s = -0.45, p < 0.05$) and fat intake ($r_s = -0.52, p < 0.05$). There were no other associations between dietary intake and hormone (insulin, cortisol, IGF-1, free T3, free T4, TSH, leptin, testosterone) concentrations.

5.6.5 Nutrition knowledge and dietary intake

Experiment I. A higher nutrition knowledge score was associated with higher EI and EA at HOME ($r = 0.59, p < 0.01$; $r = 0.52, p < 0.05$, respectively) while the same associations at CAMP were not statistically significant ($r = 0.44, p = 0.062$; $r = 0.32$, $p = 0.19$). Nutrition knowledge was positively associated with daily CHO intake as well as CHO intake around KEY training sessions at HOME ($r/r_s = 0.58–0.72$, $p < 0.001–0.01$, Figure 15) while no associations were found between nutrition knowledge and daily or post-exercise protein intake at HOME. In contrast, there was a positive association between nutrition knowledge and daily intake of CHO and protein at CAMP ($r = 0.52$; $p < 0.05$; $r = 0.48$; $p < 0.05$, respectively), but no associations between nutrition knowledge and CHO and protein intake around KEY training sessions. Nutrition knowledge was not associated with fat intake or EEE at HOME or at CAMP.

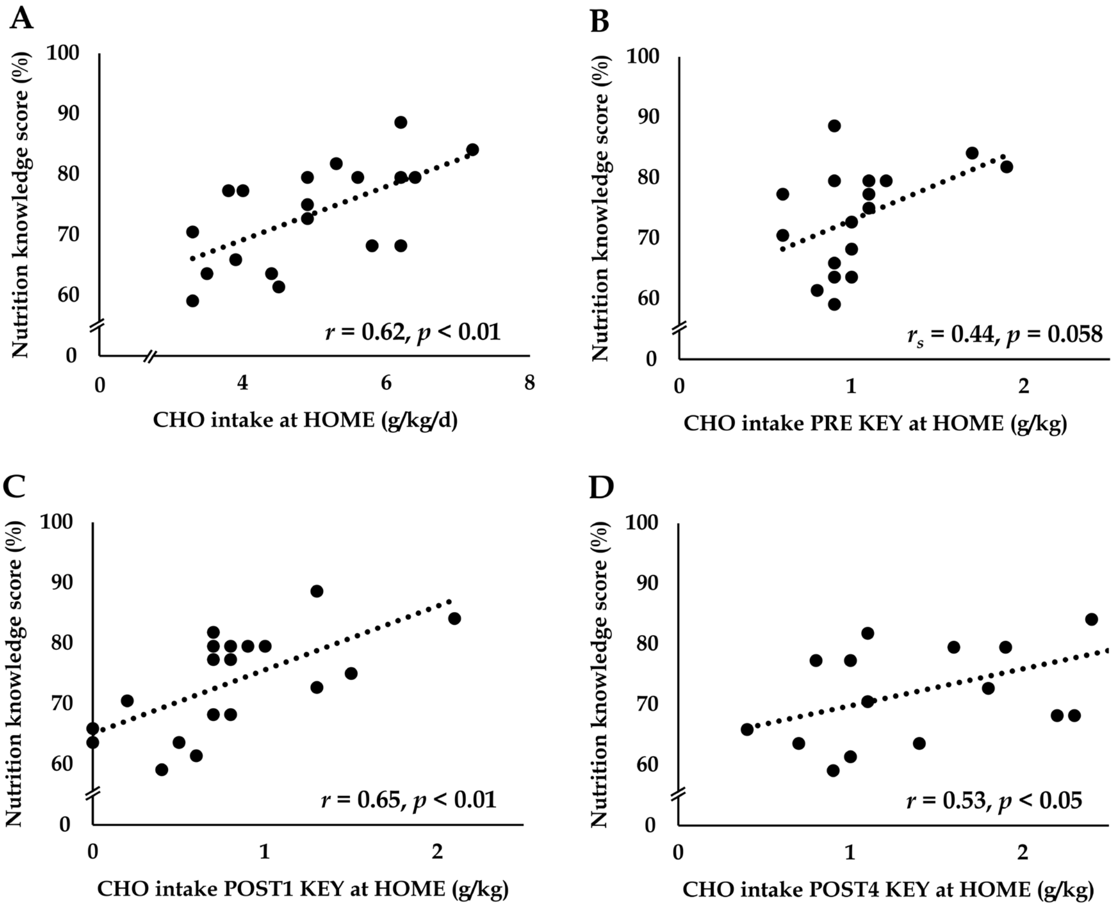


FIGURE 15 Associations between nutrition knowledge and carbohydrate (CHO) intake at HOME (A), between nutrition knowledge and CHO intake 1–4 hours before KEY training sessions (PRE KEY) at HOME (B), between nutrition knowledge and CHO intake within an hour after KEY training sessions (POST1 KEY) at HOME (C), and between nutrition knowledge and CHO intake within four hours after KEY training sessions (POST4 KEY) at HOME (D).

Experiment II. Nutrition knowledge at M_4 was associated with 15-day mean EA ($r_s = 0.45$, $p < 0.05$), CHO intake ($r = 0.43$, $p < 0.05$), and protein intake ($r = 0.50$, $p < 0.05$).

5.6.6 LEAF-Q and dietary intake

Experiment I. LEAF-Q score was not associated with dietary intake at HOME or at CAMP.

Experiment II. LEAF-Q score at M_4 was associated with 15-day mean CHO intake from Log_1–Log_5 (r = -0.47, $p < 0.05$). Similarly, the direction of the associations between LEAF-Q score at M_4 and 15-day mean EA (r_s = -0.33, p = 0.13), protein intake (r = -0.35, p = 0.11), and fat intake (r = -0.38, p = 0.082) were negative but the associations were not statistically significant.

5.6.7 Factors explaining performance

Experiment II. In the stepwise linear regression analysis, CHO intake explained 46% of the variance in FIS distance points (R^2 = 0.46, $p < 0.01$) while training volume explained 34% of the variance in FIS sprint points (R^2 = 0.34, $p < 0.05$).

TTE, relative VO_{2max}, and relative VO_{2OBLA} were best explained by F% (R^2 = 0.37, $p < 0.01$; R^2 = 0.44, $p < 0.01$; R^2 = 0.47, $p < 0.01$, respectively). Absolute VO_{2max} and CMJ were explained by BMI (R^2 = 0.60, $p < 0.001$; R^2 = 0.27, $p < 0.05$, respectively), absolute VO_{2OBLA} by FFM (R^2 = 0.64, $p < 0.001$), and DP test time by the mean training volume during the study (R^2 = 0.31, $p < 0.05$). RJ was not explained by training volume, nutrition, or body composition. Changes from M_1 to M_4 in the DP test time were explained by changes in F% (R^2 = 0.25, $p < 0.05$). Changes in TTE, VO_{2max}, VO_{2OBLA}, CMJ, or RJ were not explained by training volume, nutrition, or changes in body composition.

6 DISCUSSION

The main purpose of this dissertation was to investigate the associations between nutrition and different aspects of performance in young female XC skiers. In addition, the dissertation aimed to investigate the extent to which young female XC skiers meet the current nutritional recommendations for endurance athletes, and to evaluate the prevalence of LEA/RED-S associated conditions. Finally, the associations between dietary intake, nutrition knowledge, body composition, hormone concentrations, training volume, and performance were investigated.

The main finding of this dissertation was that higher performing female XC skiers tend to consume more macronutrients, especially CHO. In addition, higher EA and CHO intake during more intensive periods of training may prevent under-recovery. Noteworthy, EA and CHO intake were at suboptimal levels in most athletes, while the intake of protein and fat was at or above the recommended range (Thomas et al., 2016). Although leaner body composition was associated with better performance, restriction in dietary intake may not be the optimal way to modify body composition in young female athletes. Finally, better nutrition knowledge appeared to support adequate EA and CHO intake on a daily basis as well as around training sessions.

6.1 Dietary intake and recommendations

The present dissertation assessed 19 days of dietary intake from seven 2–3-day food and training logs where the mean EI was 46–72 kcal/kg FFM/d (2390–3653 kcal/d), the mean EEE 8–33 kcal/kg FFM/d (409–1591 kcal/d), and the mean EA 32–40 kcal/kg FFM/d. Thus, on average, young female XC skiers seem to have suboptimal EA quite consistently across the different training periods (macrocycles) of the training year. Fortunately, only a relatively small proportion (9%–36%) of athletes had EA below LEA threshold of 30 kcal/kg FFM/d (Loucks et al., 2011), which may have prevented most athletes from the deleterious health and performance consequences of long-term LEA. Notably, the exact LEA threshold may have limitations in field-conditions as it is based on short-term laboratory studies that showed impaired endocrine (Loucks & Thuma, 2003) and bone turnover markers (Ihle & Loucks, 2004) in eumenorrheic sedentary females after interventions that modified EA. The minimum EA level that can be maintained over longer periods (weeks, months, or years) without negative consequences for health and performance is currently unknown and likely individual (Heikura et al., 2021b; Mountjoy et al., 2018). Therefore, we do not know whether the mean EA observed in the present study could ultimately affect long-term health and/or performance. It is worth noting, however, that athletes tend to underreport their EI by ~19% (Burke et al., 2018b). If the same kind of underreporting existed in the present study, the typical dietary practices of our participants provided optimal EA. Nevertheless, a study by Sjödin et al. (1994) suggested that underreporting may be less likely in a motivated group of high level XC skiers using weighted food logs, which is why we believe that the EI and macronutrient intake in the present study reflected the actual intake of our participants.

XC skiers have increased CHO requirements due to the high training load and need for CHO based fuel during competition and key training sessions. As both experiments showed that ~2 h/d is a typical training volume for young female XC skiers, a CHO intake of 6–10 g/kg/d may be suggested as optimal to support the performance and recovery in these athletes (Thomas et al., 2016). Noteworthy, CHO requirements may increase to upper limits or even above the recommendation during intensified training periods when daily training volume increases to over 3 h/d. In contrast, the recommendation of 3–5 g/d (Thomas et al., 2016) may have been more appropriate during the transition period as training consisted of ~1 h/d low-intensity endurance training, strength training, and skill-based training. Unfortunately, almost all of the athletes had lower than recommended CHO intake throughout the study. While adequate CHO intake seems to be a challenge even for elite female XC skiers (Carr et al., 2019; Ellsworth et al., 1985; Fogelholm et al., 1992), recommended intake may help optimize training quality and intensity (Hawley & Leckey, 2015), performance (Hawley & Leckey, 2015), recovery (Burke et al., 2017), and overall health (Fensham et al., 2022; Heikura et al., 2020; McKay et al., 2022a).

In contrast to CHO intake, recommendations for protein and fat intake appeared to be met or even exceeded in most young female XC skiers. Indeed, the mean protein intake during the study varied between 1.6 and 2.5 g/kg/d, which is in the upper range or slightly above the recommendation of 1.2–2.0 g/kg/d (Thomas et al., 2016) and similar to that previously reported among young Finnish endurance athletes (1.9–2.1 g/kg/d) (Heikkilä et al., 2019). Protein plays an essential role as a substrate for recovery and trigger for adaptation after exercise (Phillips & van Loon, 2011). Given that high load endurance training (Churchward-Venne et al., 2020), whole body training (Macnaughton et al., 2016), adolescence (Desbrow et al., 2019), energy deficiency (Areta et al., 2014), and low CHO availability (Gillen et al., 2019) may increase protein requirements, protein intake in the upper range or slightly above current recommendations (Thomas et al., 2016) may have been beneficial for the participants in the present study. This is also supported by the finding that elite female XC skiers seem to consume up to 3 g/kg/d of protein (Carr et al., 2019). On the other hand, older studies reported that protein intake in elite female skiers (~1.4–2.2 g/kg/d) varied within the recommended range (Ellsworth et al., 1985; Fogelholm et al., 1992). Relatively high protein intake in recent (Carr et al., 2019; Heikkilä et al., 2019) and the present studies may be influenced by the prevailing "protein hype" and increased protein intake in general population (Valsta et al., 2017). Although excessive protein intake has no benefits for performance and recovery and may "take space" from other macronutrients (Thomas et al., 2016), the knowledge of an optimal level for protein intake in highly trained XC skiers is still limited.

The mean fat intake varied between 30% and 32% of total EI, which is in line with the recommended 20%–35% of total EI (Thomas et al., 2016) and the 28%–32% of total EI in elite female XC skiers (Carr et al., 2019; Fogelholm et al., 1992; Sjödin et al., 1994) and young endurance athletes (Heikkilä et al., 2019). Therefore, total fat intake was appropriate to provide essential fat acids, elements of cell membranes, and aid for the absorption of fat-soluble vitamins if fat quality met the recommendations (Thomas et al., 2016). In addition, adequate fat intake may have been an important factor in increasing energy density of the diet and consequently avoiding LEA. On the other hand, fat intake less than 35% of total EI may enable athletes to consume more CHO for fuel in competitions and key training sessions (Hawley & Leckey, 2015; Heikura et al., 2021a).

6.1.1 Nutritional periodization practices

The results of experiment I showed that young female XC skiers increased their energy and macronutrient intake from HOME to CAMP to meet the increased energy requirements of intensified training load. Athletes had almost twice as high EEE at CAMP in comparison to HOME, which highlights the higher energy and macronutrient requirements to support performance and recovery during training periods with high loads. Interestingly, athletes showed nutritional periodization practices by increasing their energy and macronutrient intake to meet the increased requirements and, indeed, the percentage of athletes who met the optimal levels of EA (Loucks et al., 2011) and CHO intake (Thomas et al., 2016) was higher at CAMP than at HOME. It is possible that young athletes, who have recently moved away from their parental home and started to take more responsibility over purchasing and preparing food, have an increased risk for under-fueling when at home. In contrast, the planned and prepared buffet meals during the CAMP may have promoted adequate dietary intake.

Nutritional periodization practices between EASY and KEY sessions were minor and, unfortunately, not in line with the principle of "fuel for the work required" (Impey et al., 2018). Indeed, athletes consumed less CHO before KEY than EASY sessions suggesting that less fuel may have been available when it would have been more needed. As almost half of the athletes failed to meet pre-exercise CHO recommendations before KEY training sessions at HOME, training quality may have been continuously compromised due to fuel deficiencies (Burke et al., 2011; Thomas et al., 2016) when training at home. Moreover, 74% of athletes had suboptimal CHO intake during the first hour after KEY training sessions at HOME, and almost all of the athletes failed to meet recommended CHO intake during the first four hours after training sessions both at HOME and at CAMP. As restoration of muscle CHO stores can take up to 24 hours (Burke et al., 2017), inadequate CHO intake after KEY training sessions may have been especially harmful at CAMP where the time between subsequent KEY sessions was limited. Inadequate post-exercise CHO intake is quite typical even at the elite level, as only 40% of elite endurance runners consumed the recommended amount of CHO during the first hour after training sessions (Heikura et al., 2017) and only 31%–54% of elite female XC skiers met the recommendations within four hours of training sessions (Carr et al., 2019). In turn, pre-exercise CHO recommendations have been met by 74%–100% of elite female endurance athletes (Carr et al., 2019; Heikura et al., 2017), which is similar to that observed in the present study at CAMP (89%) but higher than at HOME (58%).

Experiment II investigated nutritional periodization practices between different training periods over the annual training cycle. The results showed that, EEE and training volume remained similar between preparation (Log_1, Log_5), specific preparation (Log_2), and competition periods (Log_3) but decreased significantly during the transition period (Log_4). Interestingly, EI and macronutrient intake were similar from Log_1 to Log_3 and decreased to Log_4. Therefore, athletes seemed to periodize their EI between the transition period and other training periods. Consequently, athletes were able to maintain a stable EA despite the variation in energy requirements. Similarly, Fogelholm et al. (1992) reported that EI and macronutrient intake in elite XC skiers varied in parallel with EEE. Although EI manipulation to maintain adequate EA despite variations in energy requirements are advisable (Stellingwerff et al., 2019), the data of the present study do not reveal whether the lower EI during the transition period (Log_4) was intentional or spontaneous. Notably, EA was significantly lower in Log_5 than in any of the logs during the previous training year. While we are not able to explain this finding based on our study design, it is possible that some athletes restricted their eating after noticing that BM increased during the competition period (M_3). Unfortunately, eight (36%) of the athletes had EA below LEA threshold of 30 kcal/kg FFM/d (Loucks et al., 2011) during the latter preparation season, which may not have optimally supported their performance development and health during the training period (Melin et al., 2023; Mountjoy et al., 2018).

Taken together, young female XC skiers appeared to spontaneously periodize EI and macronutrient intake between training periods with different energy requirements so that EA remains quite similar between these periods. This periodization may have prevented athletes from experiencing the negative health and performance consequences of LEA by providing adequate fuel and substrate for normal body functions, performance, recovery, and training adaptation (Melin et al., 2023; Mountjoy et al., 2018). Unfortunately, despite some variation, CHO intake was at a suboptimal level during all training periods, except the transition (i.e., recovery) period. In addition, CHO intake was inadequate around KEY training sessions. Consequently, the suboptimal amount and timing of CHO intake may have reduced the available fuel for high-intensity training (Hawley & Leckey, 2015) and delayed recovery prior to subsequent training sessions (Burke et al., 2017). In contrast, post-exercise protein intake was adequate to support recovery and training adaptation (Thomas et al., 2016).

6.2 Dietary intake, body composition, and performance

6.2.1 Dietary intake and signs of under-recovery during short-term training-overload

Experiment I investigated dietary intake and signs on under-recovery during a 96-hour intensified training period (CAMP), which was expected to cause short-term training-overload. Training-overload is a natural part of athletic training and may even be a desirable trigger for performance adaptations (Meeusen et al., 2013). When overloading training is continued, acute fatigue can progress into short-term performance decrements (i.e., overreaching or under-recovery) and ultimately overtraining syndrome, in which recovery from under-performance may take several months (Meeusen et al., 2013; Stellingwerff et al., 2021). In the present study, explosive muscular performance, assessed by force plate jumps, decreased during CAMP. Interestingly, jump performance tended to decrease more in athletes with lower EA and CHO intake suggesting that adequate EA and CHO intake may help to maintain explosive muscular performance during an intensified training period. This is not surprising as CHO is a key fuel for the brain and central nervous system (Karelis et al., 2011) and symptoms of long-term LEA have previously been associated with decreased neuromuscular performance in female athletes (Tornberg et al., 2017). In addition, a recent study by Jurov et al. (2022) found, that CMJ performance in male athletes decreased after 14 days of LEA (< 30 kcal/kg FFM/d) and the decrease was more significant when EA was decreased to 20 kcal/kg FFM/d and further to 10 kcal/kg FFM/d. Maintenance of muscular performance during high-load training may have practical significance in XC skiing where high speed and strength capacities are important for successful performance (Sandbakk & Holmberg, 2017) and therefore, it is important that XC skiers have adequate fuel to support training quality and intensity especially during hard training periods.

In addition to maximal jump performance, a submaximal treadmill running test and hormonal measurements were used to detect signs of under-recovery. The results of the running test showed that submaximal HR, HR/RPE ratio, and lactate/RPE ratio decreased during CAMP. Although reduced submaximal HR and lactate levels may be a result of effective endurance training (Bassett & Howley, 2000; Ekblom et al., 1973), short-term changes during intensified training periods may also be indicators of under-recovery (Meeusen et al., 2013) or glycogen depletion (Snyder, 1998). For example, a decreased lactate/RPE ratio has been associated with under-recovery (Duke et al., 2011; Snyder et al., 1995). As the lactate/RPE ratio seemed to decrease more in athletes with lower EA, the findings of the present study suggest that adequate EA during intensified training periods may prevent signs of under-recovery. In contrast, dietary intake was not associated with hormonal changes suggesting that the detected decreased concentrations of leptin, free T3, insulin, and IGF-1 were mainly caused by training-overload. Although intensified training may have affected hormonal concentrations (Meeusen et al., 2013), it is important to notice that the detected changes were quite small, and their clinical significance is likely to be minimal.

The symptoms of training-overload and under-fueling have many commonalities while both may lead to under-recovery and decreased performance (Kuikman et al., 2022; Stellingwerff et al., 2021). In the present study, however, EA and CHO intake increased from HOME to CAMP and therefore, it is unlikely that the detected signs of under-recovery would be explained by under-fueling at a group level. In addition, increased BM and FFM from PRE to POST may suggest that glycogen stores were at higher level at POST compared to PRE (Burke et al., 2018a). Nevertheless, other mechanism, such as muscle damage, may cause fluid retention after overloading training (Hausswirth & Le Meur, 2011) thus increasing BM. Although intensified training seems to be a major trigger for the detected hormonal and performance changes, our results suggest that the state of under-recovery may be avoided, or at least limited, by higher EA and CHO intake during an intensified training period. Indeed, adequate fueling may support training quality during intense training periods and enable higher overall training load without extensive fatigue and under-performance.

6.2.2 Dietary intake and performance

Adequate dietary intake across the training year leading up to main competitions may be an important factor determining success in those competitions. Indeed, experiment II showed that better XC skiing distance competition performance (FIS points) in the Junior National Championships was associated with higher EA and intake of all macronutrients. Interestingly, CHO intake was the most important single factor explaining better FIS points. Similarly, athletes with higher macronutrient, especially CHO and protein, intake tended to have better TTE, VO_{2max}, VO_{2OBLA}, and DP performance at the end of the study. In contrast, jump performance and year-to-year changes in performance were not associated with dietary intake. Together these finding suggest that higher EA, due to higher CHO and protein intake, may support the long-term development of endurance performance, but the associations found in the present study have likely developed over a longer period of time than what was investigated.

The effects of EA on performance remain largely unexplored in a systematic fashion, but there are several potential ways by which EA may affect competition performance (Melin et al., 2023; Mountjoy et al., 2018). The present study is one of the few that has found an association between higher EA and better endurance performance. Previously, Vanheest et al. (2014) found that eumenorrheic female swimmers with moderate EA (21-day average ~32 kcal/kg FFM/d) improved 400 m swimming time by ~8% while swimmers with LEA (21-day average ~11 kcal/kg FFM/d) and subclinical menstrual dysfunction (suppressed ovarian function) decreased their performance by ~9%. In contrast, Heikura et al. (2018) found that elite female distance runners with LEA and moderate EA had similar distance running performance. Noteworthy was that both studies compared females with LEA and moderate EA but the significance of an optimal EA for performance has actually received very little attention in the literature. A case study by Stellingwerff et al. (2018) suggested that optimal EA should be maintained for the majority of the training year while ~6–8 weeks periods with moderate EA can be used in mature elite athletes to optimize body composition and performance for main competitions. Our results support this suggestion by showing that dietary habits that allow higher EA may have an important role in optimizing long-term performance development.

Investigating the performance effects of EA or LEA in a controlled setting is difficult and as such, most of the studies rely on physiological or functional outcomes of LEA as surrogate measures of likely prolonged exposure to LEA (Heikura et al., 2021b; Melin et al., 2023). For example, menstrual dysfunction has been associated with decreased endurance (Vanheest et al., 2014) and neuromuscular (Tornberg et al., 2017) performance. Furthermore, some evidence suggests that different physiological symptoms of LEA may lead to under-recovery (Stellingwerff et al., 2021), increased risk of injury (Heikura et al., 2018; Ihalainen et al., 2021) and illness (Drew et al., 2018), sleep disturbances (Gillbanks et al., 2022), and negative mood (Bomba et al., 2014), all of which may have negative consequences for performance. Nevertheless, the present study did not find associations between the prevalence of physiological symptoms of LEA (LEAF-Q score) and performance. This suggest that other reasons than LEA outcomes included in the LEAF-Q may explain the positive association between adequate EA and competition performance.

One of the most significant indirect effects of EA on sports performance may be via macronutrient, and especially CHO, availability (Melin et al., 2023). Indeed, the present study suggests that CHO intake might have an important role for enhancing both competition and laboratory measured performance. This is not surprising, as inadequate CHO intake may impair training intensity and competition performance, delay recovery, and increase the risk of lost training days due infection or injury (Hawley & Leckey, 2015; Heikura et al., 2021a; Thomas et al., 2016). Although little evidence exists regarding the relationship between long-term CHO intake and competition performance in endurance events, a recent case-study of an elite male XC skier suggested that increased CHO intake to the recommended range (8–12 g/kg/d) was likely crucial in the process of returning from under-performance to a world-class level (Talsnes et al., 2023). As most of the athletes in the present study had lower than recommended CHO intake, the athletes who had higher intake compared to others have likely had better energy levels during training and competitions, which may have further enhanced their performance.

The associations between performance and intake of protein and fat are difficult to explain based on previous literature. While an adequate amount of protein is needed for recovery and training adaptations (Phillips & van Loon, 2011), higher than recommended 1.2–2.0 g/kg/d protein intake may not have extra benefits (Thomas et al., 2016). In the present study, none of the athletes had lower than recommended protein intake while many of them exceeded the recommendation (Thomas et al., 2016). Nevertheless, high load endurance training (Churchward-Venne et al., 2020), whole body training (Macnaughton et al., 2016), adolescence (Desbrow et al., 2019), and low CHO availability (Gillen et al., 2019) may have increased the protein requirements of our participant compared current recommendations (Thomas et al., 2016). Due to a lack of research on the topic, it remains to be clarified if the recommended 1.2–2.0 g/kg/d protein intake (Thomas et al., 2016) is adequate to optimize long-term performance development in young female XC skiers. Similarly with protein intake, fat intake was within the recommended range (Thomas et al., 2016) in most of our participants and it is therefore unlikely that higher fat intake alone would have had a performance-enhancing role. Nevertheless, a higher protein and fat intake have most likely increased EI and EA. Consequently, athletes with higher protein and fat intake may have been less likely to suffer from the negative performance consequences of suboptimal EA.

6.2.3 Body composition and performance

Lean body composition (i.e., low FM and high FFM) may be beneficial in XC skiing where low BM may reduce oxygen demand while skiing uphill (Ackland et al., 2012) and a high level of strength may increase maximal speed and skiing efficiency (Carlsson et al., 2016; Sandbakk & Holmberg, 2017). Indeed, the present study found that FM and F% during the competition season (M_3) were negatively associated with performance in distance events at the Junior National Championships. In the laboratory tests at M_4, BM, BMI, and FFM were positively associated with absolute VO_{2max} and VO_{2OBLA} while BM, FM, and F% were negatively associated with relative VO_{2max} and VO_{2OBLA}. Noteworthy, F% was the most important factor explaining TTE, relative VO_{2max}, and relative VO_{2OBLA}. Although, BM, FFM, and FM increased during the follow-up year, changes in TTE, relative VO_{2max}, and relative VO_{2OBLA} were not associated with those changes. In contrast, changes in DP performance were explained by the changes in F%.

The present study assessed endurance performance (TTE) and VO_{2max} in the uphill test where the body is moved against gravity, which most likely explains why lower BM, FM, and F% were associated with better TTE and VO_{2max}. As VO_{2max} is one of the most important factors explaining XC skiing performance (Sandbakk & Holmberg, 2017; Talsnes et al., 2021), the positive association between FM, F%, and FIS points is easy to understand. However, BM was not associated with FIS points that may refer that fat free part of the BM may have been beneficial for competition performance. Indeed, the increase in FFM was positively associated with improved DP test time while increased FM and F% were negatively associated with DP performance. These observations are in line with Jones et al. (2021), who also showed that an increase in FFM and decrease in FM improved XC skiing competition performance in young female XC skiers. Especially increased upper body strength and muscle mass may be important performance enhancing factors in female XC skiers (Hegge et al., 2016). Consequently, dietary and training practices that support decreased FM and F% with simultaneous increase in FFM may be conducive to improved XC skiing performance.

Although lower FM and F% were associated with distance competition performance, the results of this study suggest that dietary restriction may not be an effective way to modify body composition in young female athletes. Indeed, athletes with higher F% tended to have lower intake of CHO and protein. Although our data do not reveal causality, athletes with higher F% may have restricted their macronutrient intake to lose body fat without desired results. This may be explained by the finding that low CHO availability can suppress resting metabolic rate by reducing T3 concentrations (Spaulding et al., 1976). Higher protein intake, in turn, may help to maintain muscle mass in athletes with low CHO availability (Gillen et al., 2019). It is also possible that athletes with higher CHO and protein intake have succeeded in maximizing the amount of healthy training days whereby their body composition has adapted to the demands of their sport due to successful training and/or genetics. It is worth noting, however, that the macronutrient intake in the present study and current nutritional recommendations (Thomas et al., 2016) are expressed in relation to BM. Athletes with higher F% have a greater amount of metabolically inactive tissue and therefore, it is possible that they do not need as much fuel in relation to their BM as their leaner counterparts. Finally, some evidence suggests that individuals with higher F% are more likely to underreport their dietary intake (González-Gil et al., 2021), which could explain why athletes with higher F% had lower CHO and protein intake in the present study. However, the associations between F% and underreporting seem not to be evident in athletes (Hill & Davies 2002; Silva et al., 2013), which decreases the likelihood that underreporting would explain the present findings. Importantly, experiment I did not find associations between F% and CHO and protein intake, which limits generalizability of the associations found in experiment II.

FIS sprint points were explained by yearly training volume but were not associated with other variables. In contrast, Carlsson et al. (2016) found that lean body mass predicted XC sprint performance in elite female skiers while Jones et al. (2021) did not find any predictors for FIS sprint points. It is difficult to conclude why training volume predicted sprint performance but not distance competition performance in present study. Noteworthy, only 14 participants took part in the sprint race at Junior Nationals, which limits the generalizability of the findings related to sprint competition performance.

6.3 The associations between nutrition knowledge and dietary intake

Higher nutrition knowledge was associated with higher EA and CHO intake in both experiments. When considering that most of the athletes had suboptimal EA and CHO intake, the findings of this study highlight the importance of adequate nutrition knowledge to prevent the negative health and performance consequences associated with inadequate EA and CHO intake (Melin et al., 2023; Mountjoy et al., 2018; Thomas et al., 2016). Interestingly, experiment I showed that the associations between better nutrition knowledge and higher EA and EI were statistically significant only at HOME. This suggest that adequate nutrition knowledge may be especially important when young athletes are responsible for purchasing and preparing their own food, whereas planned and prepared buffet meals at the sports institute may have reduced the importance of nutrition knowledge at CAMP.

In addition to daily CHO intake, nutrition knowledge may significantly support recommended CHO intake before and after KEY training sessions. Athletes with higher nutrition knowledge were more likely to have higher CHO intake before KEY training sessions at HOME, which may have improved their training intensity and quality and further performance development. Similarly, athletes with better nutrition knowledge tended to have higher CHO intake after KEY training sessions at HOME, which may have supported their recovery between the training sessions. Together these findings highlight the importance of adequate nutrition knowledge and high-quality nutrition education to promote sufficient fueling around training sessions and adequate EA to support training adaptations and overall health. This may be particularly important for high school athletes who have recently moved away from their parental home and started to take more responsibility over the timing and content of their meals.

6.4 Signs and symptoms of low energy availability

6.4.1 The Low Energy Availability in Females Questionnaire (LEAF-Q)

The self-reported symptoms of LEA were investigated by using the LEAF-Q (Melin et al., 2014). In experiment I, the mean the LEAF-Q score was 6 while 26% of athletes had a total score of ≥ 8 and were therefore categorized as being at risk for LEA (Melin et al., 2014). In experiment II, LEAF-Q slightly, but statistically insignificantly, increased from 6 to 7 while the proportion of participants with LEAF-Q score ≥ 8 remained at 36% at both measurement points. The results of both experiments are similar to those previously reported in elite female XC skiers with mean score of 6% and 31% of the participants having total score ≥ 8 (Carr et al., 2019). Furthermore, the total scores in the present study were quite similar to those detected in eumenorrheic female distance runners (8 points) but significantly lower than in amenorrheic runners (12 points) (Ihalainen et al., 2021). Interestingly, the number of participants with self-reported amenorrhea varied between one and three (4%–16%) in the present study while up to eight out of 13 (62%) young runners reported having amenorrhea (Ihalainen et al., 2021). These findings suggest that the incidence of severe LEA associated health outcomes is significantly lower in young female skiers compared to the runners.

The trend towards an increased LEAF-Q score from M_1 to M_4 may be explained by suboptimal EA and CHO intake between the measurement points or lower EA at M_5 than at M_1. Indeed, a higher LEAF-Q score at M_4 was associated with lower dietary, especially CHO, intake during the study suggesting that, in addition to LEA, the questionnaire may be an effective tool to detect inadequate CHO intake. This finding is in line with the present hypothesis that suggest that LEA/RED-S associated health and performance consequences may not be triggered by LEA alone, but due to inadequate CHO intake to support metabolic functions (Heikura et al., 2021b; Melin et al., 2023). Nevertheless, this conclusion is limited by the lack of associations between dietary intake and changes in LEAF-Q score as well as by the results of experiment I showing no association between LEAF-Q score and dietary intake.

6.4.2 Hormone concentrations

Experiment I showed that concentrations of leptin, free T3, and insulin decreased during CAMP. As correlations between EA, macronutrient intake, and hormonal changes were absent, the decreased concentrations could be explained, at least in part, by the intensified training load. Indeed, the symptoms of LEA and low CHO availability have several similarities with the symptoms of under-recovery of which altered hormone concentrations are one example (Stellingwerff et al., 2021).

In experiment II, hormonal concentrations remained similar between the measurement points except leptin, which was lowest at M_1 and highest at M_4. This finding is logical as leptin is known to have a strong correlation with FM (Christo et al., 2008) and FM was lowest at M_1 and highest at M_4. The only association between dietary intake and hormonal changes was the negative correlation between the yearly mean EI, fat intake, and year-to-year change in insulin concentrations. This finding is slightly surprising as all of the athletes achieved the recommended fat intake (20%–35% of total EI (Thomas et al., 2016)) and downregulation of insulin production is generally associated with inadequate EI (Elliott-Sale et al., 2018). Nevertheless, the significance of these associations was likely practically minor as individual year-to-year changes were small and all participants had insulin concentrations well within reference range (2–20 mU/L (Leviskä & Anttonen, 2021)). The reason for why most hormone concentrations remained similar and were not associated with dietary intake may be the due to the fact that hormonal dysfunction is typically reported as a result of LEA (Elliott-Sale et al., 2018; Loucks & Thuma, 2003), which was avoided by most participants in the present study. In addition, only five days of LEA is enough to induce significant hormonal changes (Loucks & Thuma, 2003) and consequently, the analyzed concentrations may reflect the energy state in the days before the measurement rather than mean intake over the training year.

6.5 Methodological strengths and limitations

The present study consisted of two separate experiments that had their own and common strengths and limitations. The main limitation of both experiments was that the methods used to assess dietary intake and EA in field conditions are prone to errors (Burke et al., 2018b; Heikura et al., 2021b). On the other hand, the methods used to minimize methodological errors were the strength of the study. As real-world EA assessment has been criticized due to short recording periods that only give a snapshot of an athlete's dietary and training practices (Burke et al., 2018b; Heikura et al., 2021b), the present study aimed to provide an overall picture of nutritional and training practices by analyzing a total of 19 days of nutrition and training data from different parts of the training year. Although misreporting (see chapter 2.1.4) may limit the validity of the food and training logs, highly motivated participants, comprehensive verbal and written instructions, and weighted food logs may have increased the validity of the present data. Athletes self-selected the days for each log from a pre-determined period and were asked to select days that reflect their normal life and training as well as possible. We believe that possibility to self-select the days gave reliable information of the overall practices as the untypical days (e.g., travelling and sickness days) were excluded and athletes were more likely to have enough time to fill in the logs carefully. Due to involvement in high school sport academy, athletes were able to train twice a day both on weekdays and weekends, which most likely decreased the differences in dietary and training practices between weekdays and weekends. To increase the validity of EEE assessment, laboratory-based associations of HR, VO_2, and EE were utilized (Heikura et al., 2021b) in experiment II. Unfortunately, for practical reasons, we were unable to measure body composition using the golden standard method dual-energy X-ray absorptiometry (DXA), and the use of the less precise bioimpedance method is a minor limitation of the study. To minimize potential confounding factors, each bioimpedance measurement was performed after an overnight fast and after the participants had visited the toilet.

The concept of EA also has some limitations. First, EA does not consider EE from daily activity that is not formal exercise, which limits the validity of EA compared to concept of energy balance (i.e., EI minus total EE) (Areta et a., 2021). While an optimal EA (45 kcal/kg FFM/d) has been suggested to describe a state of energy balance in healthy individuals (Loucks et al., 2011), achieving the state of energy balance does not mean that a healthy metabolic balance has been reached. Indeed, due to the "metabolic adaptation" (or "adaptive thermogenesis") EE decreases in the state of negative energy balance and/or LEA so that body may return to an energy balance although it simultaneously conserves energy from basic physiological functions (Areta et al., 2021). The strength of the concept of EA is that it describes the energy left after EEE for other energy-consuming physiological processes in the body (Loucks et al., 2011). In a state of LEA, there is not enough energy left for basic physiological functions, resulting in the disruption of many metabolic, hormonal, and functional processes (Loucks et al., 2004). Unfortunately, the current body of experimental research is limited to short-term (3–5 days) effects of LEA and more understanding is needed regarding the long-term effects of LEA.

The phase of the menstrual cycle and the potential use of hormonal contraception were not standardized in the present study, which may have influenced some of the variables investigated. Hormonal fluctuations and possible BM changes between menstrual phases (Carmichael et al., 2021) may have confounded the comparisons of hormonal and body composition variables between the measurement points. In addition, the phase of menstrual cycle might affect EE (Benton et al., 2020), substrate metabolism (Hackney et al., 2000), and appetite (Dye & Blundell, 1997), that may have altered dietary requirements and intake between recording periods of the food and training logs. Finally, many females report that their performance varies between menstrual phases (Paludo et al., 2022) while objective performance measurements have shown that the variation is minor at the group-level but may be significant in some individuals (McNulty et al., 2020). Similarly, also hormonal contraception may affect performance, although group level effects appear to be trivial (Elliot-Sale et al., 2020). Therefore, menstrual phase and the potential use of hormonal contraception may have affected the performance measures in some of the participants, of which we were unable to standardize, for practical reasons.

The present study assessed various aspects of XC skiers' performance. Competition performance was assessed by FIS points as recommended by Pellegrini et al (2021). Noteworthy was that FIS points were recorded only from the Junior National Championships instead of utilizing the yearly score. Nevertheless, we believe that this is the best possible description of the competition performance as many races were cancelled due to the COVID-19 pandemic and because the Junior National Championships were among the most important competitions for our participants. As non-physiological factors such as ski selection, waxing, and environmental factors may also affect competition performance, the present study also assessed performance by laboratory measurements. Both ski-specific (DP test) and non-specific (incremental treadmill walking/running) were used as they have previously been shown to be strongly associated with XC skiing competition performance (Talsnes et al., 2021) and are commonly used to monitor XC skier performance development in Finland. In addition, power production capacity, which is important for success in today´s XC skiing, was assessed by jump tests. Consequently, the present study reports comprehensive information about female XC skier performance, in which the association of EA and macronutrient intake was investigated.

7 MAIN FINDINGS AND CONCLUSIONS

This dissertation investigated the associations between nutrition and various aspects of performance in young female XC skiers. In addition, the study aimed to investigate the extent to which young female XC skiers met the current nutritional recommendations for endurance athletes, and to evaluate the prevalence of LEA/RED-S associated conditions. Finally, the associations between dietary intake, nutrition knowledge, body composition, hormone concentrations, training volume, and performance were investigated. The main findings and conclusions of this dissertation can be summarized as follows:

1. Most participants had suboptimal EA and CHO intake that may have compromised performance and recovery. Fortunately, only a minority of the participants had LEA, which may have protected them from more severe health and performance consequences associated with long-term LEA. Protein and fat intake were within the recommended range providing adequate substrate for training adaptation and overall health.

2. Athletes showed periodization practises by increasing dietary intake during more intense training periods with increased fuel requirements. Nevertheless, more attention should be paid to achieving adequate CHO intake before KEY training sessions.

3. Lower EA and CHO intake during a 96-hour intensified training period were associated with decreased explosive strength (jump performance) and increased markers of under-recovery, such as lower lactate/RPE ratio. Therefore, higher EA and CHO intake may support training quality and intensity during hard training periods and enable higher overall training load without extensive fatigue and/or under-performance.

4. Better performing female XC skiers tended to have higher EA and macronutrient intake. Especially higher CHO intake was an important

factor explaining better competition performance and laboratory measured endurance performance. As dietary intake was not associated with year-to-year changes in performance, we suggest that the relationships between dietary practices and performance have developed over a longer period of time than investigated in the present study.

5. Athletes with higher FFM and lower FM and F% tended to perform better in competitions and laboratory measurements suggesting that dietary and training practices that lead to lean body composition may be beneficial for XC skiers' performance. Interestingly, higher CHO and protein intake were associated with lower F%, which suggest that, in the long-term, proper dietary intake may be more beneficial to optimize body composition compared to dietary restrictions.

6. Based on the LEAF-Q, approximately one third of the participants had an increased risk for LEA. A higher LEAF-Q score was associated with lower CHO intake in experiment II, which suggest that, in addition to LEA, the LEAF-Q may be effective tool to detect inadequate CHO availability.

7. Higher nutrition knowledge was associated with higher EA and CHO intake and may, therefore, prevent the negative health and performance consequences associated with inadequate EA and CHO intake. The role of adequate nutrition knowledge may be particularly important in young athletes who have recently moved away from their parental home and started to take more responsibility for the timing and content of their meals.

In conclusion, the results of the present dissertation indicate that young female XC skiers have difficulties to meet optimal EA and CHO intake, which may have a negative impact on their performance. Considering that better nutrition knowledge was associated with higher EA and CHO intake, our findings highlight the importance of enhanced high-quality nutrition education for young female XC skiers.

SUMMARY IN FINNISH

Maastohiihto on perinteinen kestävyyslaji, jossa menestyminen vaatii monipuolisia fyysisiä ominaisuuksia, teknistä ja taktista osaamista sekä kilpailukykyisiä varusteita. Maksimaalinen hapenottokyky on tärkein fysiologinen suorituskykyä selittävä tekijä, mutta yhteislähtöjen lisääntyminen ja kasvaneet kilpailuvauhdit ovat lisänneet myös anaerobisen kapasiteetin sekä nopeus- ja voimaominaisuuksien merkitystä. Lajin monipuolisiin vaatimuksiin vastatakseen suurin osa huippuhiihtäjistä harjoittelee vuosittain 750–950 tuntia, mikä voi yli kaksinkertaistaa energiantarpeen fyysisesti passiivisiin henkilöihin verrattuna. Tästä syystä hiihtäjillä on merkittävä riski liian vähäiseen energian ja ravintoaineiden saantiin, mikä puolestaan voi vaikuttaa negatiivisesti hiihtäjän terveyteen ja suorituskykyyn. Riski voi olla suuri etenkin nuorilla urheilijoilla, jotka ovat muuttaneet perheensä luota omilleen ja alkaneet ottaa enemmän vastuuta ruoanvalmistuksesta.

Kansallisten ja kansainvälisten arvokilpailujen kilpailumatkat vaihtelevat 2–3 minuuttia kestävien sprinttihiihtojen ja yli kaksituntisten 50 kilometrin kilpailujen välillä. Vaikka fysiologiset vaatimukset eroavatkin jonkin verran kilpailumatkojen välillä, suoritetaan ne kaikki teholla, jonka ylläpitäminen on vahvasti riippuvainen hiilihydraattien riittävyydestä energianlähteeksi. Suorituskykynsä optimoidakseen hiihtäjän tulee saada ravinnostaan runsaasti hiilihydraatteja, jotta ne riittävät kilpailusuoritusten ja kovatehoisten harjoitusten polttoaineeksi. Lisäksi hiihtäjän tulee huolehtia sopivasta proteiinin ja rasvan saannista tukeakseen palautumista, harjoitusadaptaatioita ja kokonaisvaltaista terveyttä.

Hiilihydraatin, proteiinin ja rasvan eli makroravintoaineiden saanti määrittää urheilijan kokonaisenergiansaannin, jonka riittävyys on tärkeä tekijä urheilijan kehittymisen ja terveenä pysymisen taustalla. Energiansaannin riittävyyden arviointiin voidaan käyttää termiä energiansaatavuus, jolla tarkoitetaan energiamäärää, joka jää harjoittelun jälkeen kehon käytettäväksi muihin energiaa kuluttaviin fysiologisiin toimintoihin. Mikäli energiansaatavuus on pitkään niukkaa, alkaa keho säästää energiaa perustoiminnoistaan, mikä voi ennen pitkää johtaa negatiivisiin terveysseuraamuksiin, kuten kuukautiskierron häiriöihin ja heikentyneeseen luun mineraalitiheyteen. Koska luusto kehittyy yleensä noin 18–20-vuotiaaksi asti, voi matala energiansaatavuus nuoruusiässä aiheuttaa korjaamatonta vahinkoa luuston kehittymiselle ja näkyä täten suurentuneena murtumariskinä loppuelämän ajan. Matalan energiansaatavuuden riski on erityisen suurta maastohiihdon kaltaisissa lajeissa, joissa sekä harjoittelun aiheuttama korkea energiankulutus että kevyemmän kehonpainon mahdolliset suorituskykyedut altistavat riittämättömälle energiansaannille.

Tämän väitöskirjatutkimuksen päätavoitteena oli selvittää ravitsemuksen ja suorituskyvyn yhteyksiä nuorilla naismaastohiihtäjillä. Toisena tavoitteena oli selvittää, oliko hiihtäjien ravitsemus kestävyysurheilijoiden suositusten mukaista ja mikä oli matalaan energiansaatavuuteen liittyvien fysiologisten oireiden esiintyvyys. Lisäksi tutkittiin ravitsemusosaamisen, kehonkoostumuksen, veren hormonipitoisuuksien ja harjoitusmäärien vaikutusta ravitsemukseen ja suorituskykyyn.

Väitöskirjan ensimmäisessä osatutkimuksessa tutkittiin Suomen Hiihtoliiton alle 18-vuotiaiden maajoukkueryhmän hiihtäjien ravitsemusta tavanomaisen harjoitusjakson ja intensiivisen maajoukkueleirin aikana. Lisäksi selvitettiin ravitsemusosaamisen vaikutusta ravinnonsaantiin koti- ja harjoitusleiriolosuhteissa. Tutkimukseen osallistui 19 naismaastohiihtäjää, jotka täyttivät 48-tunnin ruoka- ja harjoituspäiväkirjat vapaavalintaisina päivinä 2–12 vuorokautta ennen harjoitusleiriä sekä harjoitusleirin toisena ja kolmantena päivänä. Lisäksi urheilijat osallistuivat hyppytesteihin, submaksimaaliseen juoksutestiin, verikokeisiin ja kehonkoostumusmittaukseen harjoitusleirin ensimmäisenä ja viimeisenä aamuna sekä täyttivät ravitsemusosaamista ja matalan energiansaatavuuden riskiä kartoittavat kyselylomakkeet.

Väitöskirjan toisessa osatutkimuksessa tutkittiin lukioikäisten naismaastohiihtäjien ravitsemusta harjoituskauden eri vaiheissa. Lisäksi selvitettiin vuoden aikaisen ravitsemuksen yhteyttä suorituskykyyn, kehonkoostumukseen, veren hormonipitoisuuksiin sekä kyselylomakkeilla määritettyyn ravitsemusosaamiseen ja matalan energiansaatavuuden riskiin. Tutkimukseen osallistui 27 Vuokatti-Ruka Urheiluakatemiassa opiskelevaa ja harjoittelevaa naispuolista maasto- tai ampumahiihtäjää. Tutkittavista 64 % kuului maasto- tai ampumahiihdon maajoukkueryhmiin. 16 kuukauden seurantajakson aikana urheilijat täyttivät viisi kertaa kolmen vuorokauden ruoka- ja harjoituspäiväkirjat. Ensimmäiset päiväkirjat täytettiin peruskuntokaudella, toiset kilpailuun valmistavalla kaudella, kolmannet kilpailukaudella, neljännet siirtymäkaudella ja viidennet jälleen peruskuntokaudella noin vuosi ensimmäisten päiväkirjojen jälkeen. Lisäksi urheilijat osallistuivat suorituskykytesteihin, kehonkoostumusmittaukseen ja verikokeisiin ensimmäisen peruskuntokauden, kilpailuun valmistavan kauden, kilpailukauden ja jälkimmäisen peruskuntokauden päätteeksi. Kyselylomakkeet täytettiin tutkimuksen alussa ja lopussa. Urheilijoiden kilpailusuorituskykyä arvioitiin nuorten Suomen mestaruushiihdoista Kansainvälisen Hiihtoliiton pistejärjestelmää (FIS-pisteitä) hyödyntäen.

Väitöskirjan ensimmäisessä osatutkimuksessa havaittiin, että nuoret maastohiihtäjät kasvattivat energian ja makroravintoaineiden saantiaan kotoa harjoitusleirille kasvaneen energiankulutuksen mukaisesti. Siitä huolimatta keskimääräinen energiansaatavuus ja hiilihydraattien saanti jäivät molemmissa olosuhteissa alle optimisuosituksen. Erityisesti haasteita oli hiilihydraattien saannissa pääharjoitusten ympärillä, mikä näytti korostuvan urheilijoiden kotiharjoittelun yhteydessä. Harjoitusleirin seurauksena havaittiin ylikuormittuneisuuteen viittaavaa laskua urheilijoiden hyppytesteillä mitatussa räjähtävässä voimatuottokyvyssä, nousua juoksutestin koetussa kuormittavuudessa suhteessa veren laktaattipitoisuuteen (laktaatti/RPE-suhde) sekä muutoksia useiden hormonien pitoisuuksissa. Suurempi energiansaatavuus ja hiilihydraattien saanti olivat yhteydessä räjähtävän voimantuottokyvyn ja laktaatti/RPE-suhteen ylläpitoon osoittaen, että riittävä energian ja hiilihydraattien nauttiminen kuormittavan harjoitusjakson aikana voi auttaa välttämään suorituskyvyn laskua ja ylikuormitusoireita. Lisäksi tutkimuksessa havaittiin, että ravitsemusosaaminen oli yhteydessä runsaampaan hiilihydraattien saantiin sekä koti- että leiriolosuhteissa osoittaen riittävän osaamisen merkityksen suorituskykyä tukevan syömiskäyttäytymisen taustalla.

Myös toisessa osatutkimuksessa havaittiin, että urheilijat mukauttivat energian ja makroravintoaineiden saantiaan harjoitusjakson energiantarpeen mukaan. Ensimmäisen osatutkimuksen tapaan energiansaatavuus ja hiilihydraattien saanti olivat myös toisessa osatutkimuksessa suositellun alapuolella. Parempi suorituskyky oli yhteydessä suurempaan energiansaatavuuteen ja makroravintoaineiden saantiin. Erityisesti hiilihydraattien saanti oli merkittävä kilpailutuloksia ja laboratoriossa mitattua suorituskykyä selittävä tekijä. Myös kehonkoostumus oli voimakkaasti yhteydessä kestävyyssuorituskykyyn. Urheilijat, joilla oli pienempi rasvaprosentti, suoriutuivat paremmin sekä kilpailuissa että laboratoriotesteissä. Pienempi rasvaprosentti oli kuitenkin yhteydessä myös runsaampaan hiilihydraattien ja proteiinin saantiin osoittaen, että syömisen rajoittaminen pitkällä aikavälillä ei välttämättä ole toimiva tapa kehonkoostumuksen optimointiin nuorilla naismaastohiihtäjillä. Kyselylomakkeen perusteella noin kolmannes naismaastohiihtäjistä osoitti matalan energiansaatavuuden riskiin viittaavia fysiologisia oireita, mikä on yli puolet vähemmän kuin aiemmin havaittu nuorilla naisjuoksijoilla. Kyselylomakkeella määritetty matalan energiansaatavuuden riski oli yhteydessä vähäisempään ruokapäiväkirjojen perusteella määritettyyn hiilihydraatinsaantiin, mikä osoittaa, että matalan energiansaatavuuden lisäksi myös hiilihydraatinsaannin riittävyys voi vaikuttaa matalaan energiansaatavuuteen yhdistettyjen fysiologisten oireiden esiintyvyyteen.

Kokonaisuudessaan tämän väitöskirjatutkimuksen tulokset osoittavat, että nuoret maastohiihtäjät saavat ravinnostaan suositeltua vähemmän energiaa ja hiilihydraatteja, mikä voi vaikuttaa negatiivisesti heidän suorituskykyynsä ja terveyteensä. Koska ravitsemusosaaminen vaikuttaisi olevan yhteydessä suurempaan energiansaatavuuteen ja hiilihydraattien saantiin, tämä tutkimus korostaa laadukkaan ravitsemuskoulutuksen merkitystä nuorille naismaastohiihtäjille.

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ORIGINAL PAPERS

I

NUTRITION KNOWLEDGE IS ASSOCIATED WITH ENERGY AVAILABILITY AND MACRONUTRIENT INTAKE AROUND TRAINING IN YOUNG FEMALE CROSS-COUNTY SKIERS

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Nutrition Knowledge Is Associated with Energy Availability and Carbohydrate Intake in Young Female Cross-Country Skiers

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Abstract: The aim of this study was to provide information on energy availability (EA), macronutrient intake, nutritional periodization practices, and nutrition knowledge in young female cross-country skiers. A total of 19 skiers filled in weighted food and training logs before and during a training camp. Nutrition knowledge was assessed via a validated questionnaire. EA was optimal in 11% of athletes at home (mean 33.7 ± 9.6 $\text{kcal}\cdot\text{kgFFM}^{-1}\cdot\text{d}^{-1}$) and in 42% at camp (mean 40.3 ± 17.3 $\text{kcal}\cdot\text{kgFFM}^{-1}\cdot\text{d}^{-1}$). Most athletes (74%) failed to meet recommendations for carbohydrate intake at home (mean 5.0 ± 1.2 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$) and 63% failed to do so at camp (mean 7.1 ± 1.6 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$). The lower threshold of the pre-exercise carbohydrate recommendations was met by 58% and 89% of athletes while percentages were 26% and 89% within 1 h after exercise, at home and at camp, respectively. None of the athletes met the recommendations within 4 h after exercise. Nutrition knowledge was associated with EA at home ($r = 0.52$, $p = 0.023$), and with daily carbohydrate intake at home ($r = 0.62$, $p = 0.005$) and at camp ($r = 0.52$, $p = 0.023$). Carbohydrate intake within 1 and 4 h post-exercise at home was associated with better nutrition knowledge ($r = 0.65$, $p = 0.003$; $r = 0.53$, $p = 0.019$, respectively). In conclusion, young female cross-county skiers had difficulties meeting recommendations for optimal EA and carbohydrate intake. Better nutrition knowledge may help young athletes to meet these recommendations.

Keywords: endurance athlete; macronutrient; periodized nutrition; protein; sports nutrition; winter sport

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1. Introduction

Cross-country (XC) skiing is a demanding sport, where success requires high aerobic and anaerobic capacities, as well as the ability to produce high power and speed [1,2]. To reach these requirements XC skiers periodize high amounts of training by varying exercise type, volume, intensity, and frequency between single workouts, days, weeks, and months [3,4]. The aim of the periodized training is to first overload the trainee's physiological systems and then allow adequate recovery to develop training adaptations [5]. However, exercise-induced adaptations may be promoted or impaired by nutrition [6]. In fact, nutrition should be periodized to support the different goals of the training and to optimize competition performance [7,8]. Furthermore, XC ski training consumes high amounts of energy, which needs to be compensated for with high energy intake (EI) to maintain adequate energy availability (EA; the amount of dietary energy remaining after exercise for all other metabolic processes) and to avoid negative performance and health outcomes such as poor training response, hormonal dysfunction, impairment of bone health, and increased injury risk [9,10]. Notably, teenage female athletes may be at higher risk for stress fractures caused by low EA [11], and therefore adequate dietary intake is especially important among young female athletes.

XC skiers compete and perform most of their key training sessions at intensities that are highly dependent on carbohydrate (CHO) based fuels for muscle metabolism [2,3,12]. Thus, pre-exercise meals should ensure adequate CHO availability in key training sessions, while this is less important before easy sessions [6,8,13]. As restoration of muscle CHO stores may take up to 24 h, the recovery process should be started as soon as possible after the high intensity training session in situations when recovery time between key training sessions is limited [14]. Meanwhile, performing part of the easy sessions with low CHO availability may increase the muscle adaptations to endurance training and therefore it might be beneficial to limit CHO intake before the training session where training intensity and quality are less important [6,8]. While CHO is an important macronutrient as a fuel, protein is needed for tissue repair and adaptation as it acts both as a trigger and substrate in anabolic processes [13,15]. Recovery and post-exercise muscle protein synthesis are optimized by ingesting adequate amounts of protein within two hours after the training session [13]. In addition to CHO and proteins, dietary fats are a vital component of the diet of XC skier as they are an important fuel during low intensity exercise and may help maintain adequate EA during hard training periods due to their high energy density [16]. Furthermore, dietary fats promote immune function and participate in the metabolism of fat-soluble vitamins [13]. Although timing macronutrient intake to support training goals is one of the key components of athletes' nutrition, to our knowledge only one study has explored the topic among XC skiers, which demonstrated that even elite skiers had difficulties meeting adequate CHO intake around training and competition [17].

Optimizing nutrition is difficult without adequate knowledge. This may especially be the case among high school athletes, many of whom have moved away from their parental home and started to take more responsibility over purchasing and preparing food. Indeed, some [18,19], but not all [20], studies have shown that older athletes have better nutrition knowledge compared to younger ones. Although there is mild evidence to suggest a positive association between nutrition knowledge and dietary intake, a very limited number of studies have used valid tools to assess both nutrition knowledge and dietary intake [21].

Furthermore, to the best of our knowledge there are no studies reporting how nutrition knowledge is associated with timing and periodization of macronutrient intake in athletes. Therefore, the aim of the present study was to provide novel information on how CHO and protein intake were periodized around different training sessions, and then to clarify how nutrition knowledge affects dietary intake and periodization practices in young female XC skiers presenting at the top national level. In addition, we investigated how well recommendations for EA and macronutrient intake were met during different training situations.

2. Materials and Methods

2.1. Participants

A total of 31 female XC skiers from the Finnish Ski Association's under 18-year-old national team were invited to join the study. Of those, a total of 19 athletes (age 16.7 ± 0.7 years) participated in the study. The participants provided written informed consent prior to their involvement in the study and were allowed to drop out of the study at any time. The ethical board of the University of Jyväskylä approved the study and included procedures, and the study was conducted in accordance with the Declaration of Helsinki.

2.2. Experimental Overview

The study was carried out before and during a 5-day training camp in a specific preparation season in October. Participants filled in 48-hour food and training logs before and during the training camp. Nutrition knowledge questionnaires [22] and anthropometric measurements were completed at the beginning of the training camp.

2.3. Anthropometric Measurements

Anthropometric measurements were carried out in fasted state on the first morning of the training camp. The height of the participants was measured with a stadiometer. Body mass and body composition were measured following an overnight fast using a bioimpedance (Inbody 720, Biospace Co., Seoul, Korea) measurement.

2.4. Food and Training Logs

48-hour food and training logs were filled in twice during the study. The first logs were filled in between 12 and 2 days before the training camp (HOME) on self-selected days and the second logs were filled in during the second and third day of the 5-day training camp (CAMP). At CAMP, participants had three prescheduled meals in the restaurant of the local sport institute. Participants selected the contents of their meals from a buffet, which included salad and bread tables, several main course options, and dessert. Most ingredients were produced in Finland, and sport institute food is not highly processed. Typical drinks included juice from fruits, milk, and water. The energy and macronutrient contents of the dishes were obtained from the chef. Participants were allowed to have their own snacks between meals. Participants recorded the type, amount, and timing of foods and fluid consumed, measuring intake using kitchen scales. Written and verbal instructions were given for accurate record keeping. The food logs were analyzed using Aivodiet-software (version 2.0.2.3, Mashie, Malmö, Sweden), which employs the national food composition database Fineli Release 16 (2013). Energy and macronutrient intake were recorded as daily intake, as well as at pre- and post-exercise time points, and expressed in relation to body weight.

Training logs were analyzed for exercise energy expenditure (EEE) using equations by Charlot et al. [23]. Participants' average heart rate (HR), the duration of each training session, the subject's body mass, self-reported maximal oxygen uptake, resting HR, and maximum HR were used for calculations. Resting energy expenditure was estimated using the Cunningham equation [24]. Resting energy expenditure that would have occurred during exercise regardless of exercise was subtracted from EEE so that only the additional energy cost of the exercise is included in the EEE. EA was estimated as EI minus EEE and expressed in kcal·kg fat-free mass $(\text{FFM})^{-1}$·day $(\text{d})^{-1}$ and compared with cut-off values for low (<30 kcal·kgFFM^{-1}·d^{-1}) and optimal EA (>45 kcal·kgFFM^{-1}·d^{-1}), as specified by Loucks et al. [10]. Sessions that involved over 30 min duration were divided into KEY or EASY sessions, as described in detail by Heikura et al. [25]. Briefly, KEY sessions were defined as speed or strength training, high intensity work (above aerobic threshold [26]) or duration of exercise over 150 min, and all other trainings were categorized as EASY sessions. The amount of ingested CHO was recorded in the 4-hour pre-exercise period as well as in 1- and 4-hour post-exercise periods, while protein intake was recorded in the 2-hour post-exercise period to compare intake with current consensus statement recommendations [13]. Mean CHO and protein intake around KEY and EASY exercises were calculated for each athlete separately at HOME and at CAMP. Thus, every athlete had single values describing her intake around different training situations (KEY at HOME; EASY at HOME; KEY at CAMP; EASY at CAMP).

2.5. Nutrition Knowledge

A validated nutrition knowledge questionnaire for young endurance athletes [22] was completed on paper at the beginning of the training camp. The questionnaire included 79 statements in true/false format, divided into five sections: (1) nutrition recommendations for endurance athletes, (2) dietary supplements, (3) fluid balance and hydration, (4) energy intake and recovery, and (5) the association between food choices and body image. Each correct answer yielded one point and each wrong answer zero points. Nutrition knowledge score refers to the proportion (percentage) of correct answers.

2.6. Statistical Analysis

Statistical analyses were conducted using SPSS Statistics 26 (IBM, Armonk, NY, USA). Results are reported as means ± SD. Normality was assessed via Shapiro–Wilk, and nonparametric tests were used with non-normally distributed data. Changes between HOME and CAMP as well as between different training situations were assessed using a repeated-measures analysis of variance, followed by a Student´s paired t test as a post hoc test to determine the p values in the pairwise comparisons. Wilcoxon signed rank test was used in the case of non-normally distributed variables. Effect sizes were calculated as Cohen's d with threshold values of <0.2 (trivial), 0.2–0.5 (small), 0.5–0.8 (moderate), and >0.8 (large) [27]. Pearson's (normally distributed data) or Spearman's (non-normally distributed data) correlation coefficient was used to analyze correlations between nutrition knowledge score and other variables. To test knowledge about nutrition recommendations more specifically, part one (44 questions) of the 79 question nutrition knowledge questionnaire [22] was used in the correlation analysis. Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Dietary Intake

Table 1 shows daily EI, EEE, EA, and macronutrient intake at HOME and at CAMP. Daily intake of energy ($p < 0.001$, d = 1.69), protein ($p = 0.002$, d = 0.84), and CHO ($p < 0.001$, d = 2.36), as well as EEE ($p < 0.001$, d = 2.21) were lower at HOME compared to CAMP, while an increased trend from HOME to CAMP was observed in EA ($p = 0.065$, d = 0.47). A high percentage, 89% and 58% of athletes, had suboptimal EA at HOME and at CAMP, respectively. Furthermore, five (26%) athletes had low EA at HOME and seven (37%) athletes at CAMP.

Table 1. Mean (± SD) daily training volume, energy and macronutrient intake, exercise energy expenditure, and energy availability in young female cross-country skiers (n = 19).

	HOME	%	CAMP	%	Recommendation [10,13]
Training (min·d^{-1})	120 ± 26	NA	214 ± 20 ***	NA	NA
EI (kcal·kg^{-1}·d^{-1})	43.1 ± 9.1	NA	60.4 ± 13.1 ***	NA	NA
EEE (kcal·kg^{-1}·d^{-1})	14.9 ± 4.5	NA	26.8 ± 4.3 ***	NA	NA
EA (kcal·kg^{-1}·d^{-1})	33.7 ± 9.6	11	40.3 ± 17.3	42	≥45
Protein (g·kg^{-1}·d^{-1})	2.1 ± 0.3	100	2.5 ± 0.5 **	100	1.2–2.0
CHO (g·kg^{-1}·d^{-1})	5.0 ± 1.2	26	7.1 ± 1.6 ***	37	6–10/8–12
Fat (% of EI)	30 ± 6	95	32 ± 7	100	20–35

EI = energy intake; EEE = exercise energy expenditure; EA = energy availability; CHO = carbohydrate; HOME = during home training; CAMP = during training camp; % = the percentage of athletes who met the lower threshold for recommended intake for optimal performance and recovery [10,13]; NA = Not Applicable. ** $p < 0.01$; *** $p < 0.001$ significant difference between HOME and CAMP.

EEE and macronutrient intake around KEY and EASY sessions are presented in Table 2. EEE was significantly higher in KEY sessions compared to EASY sessions at HOME and at CAMP ($p = 0.007$, d = 0.72; $p < 0.001$, d = 1.64, respectively). Furthermore, EEE in KEY sessions was lower at HOME than at CAMP ($p < 0.001$; d = 1.14). CHO intake during the 4-hour period before KEY sessions was lower at HOME than at CAMP ($p = 0.002$, d = 0.74), while CHO intake before EASY sessions remained similar ($p = 0.37$, d = 0.28). CHO intake both in 1 and 4 hours after exercise period was significantly lower at HOME compared to CAMP after KEY ($p < 0.001$, d = 1.17; $p < 0.001$; d = 1.40, respectively) and EASY ($p = 0.002$, d = 1.04; $p < 0.001$; d = 1.09, respectively) sessions. Protein intake was higher after KEY sessions at CAMP compared to EASY sessions at CAMP ($p = 0.033$, d = 0.41) and KEY sessions at HOME ($p = 0.018$, d = 0.59). Many athletes failed to meet the lower end of the recommended CHO intake on a daily basis as well as around KEY exercises while the percentages were higher at HOME compared to CAMP. All athletes met the minimum recommendations for protein intake.

Table 2. Mean (± SD) daily training volume, energy and macronutrient intake, exercise energy expenditure, and energy availability in young female cross-country skiers (n = 19).

	HOME			**CAMP**			**Recommendation [13]**
	EASY	**KEY**	**%**	**EASY**	**KEY**	**%**	
EEE (kcal·kg^{-1}·d^{-1})	7.3 ± 3.5	$10.8 \pm 3.6\ ^{\dagger\dagger}$	NA	8.3 ± 3.3	$14.6 \pm 1.8\ ^{***,\dagger\dagger\dagger}$	NA	NA
Protein POST2 (g·kg^{-1})	0.6 ± 0.3	0.6 ± 0.2	100	0.7 ± 0.3	$0.8 \pm 0.1\ ^{*,\dagger}$	100	0.25–0.30
CHO PRE4 (g·kg^{-1})	1.2 ± 0.8	1.0 ± 0.3	58	1.7 ± 1.2	$1.3 \pm 0.3\ ^{**}$	89	1–4
CHO POST1 (g·kg^{-1})	0.5 ± 0.5	0.8 ± 0.5	26	$1.7 \pm 1.0\ ^{***}$	$1.7 \pm 0.7\ ^{***}$	89	1.0–1.2
CHO POST4 (g·kg^{-1})	1.5 ± 0.7	1.6 ± 0.7	0	$2.7 \pm 1.2\ ^{***}$	$2.7 \pm 0.8\ ^{***}$	5	4.0–4.8

EEE = exercise energy expenditure; CHO = carbohydrate; PRE4 = within four hours before exercise; POST1 = within an hour after exercise; POST2 = within two hours after exercise; POST4 = within four hours after exercise; HOME = during home training; CAMP = during training camp; KEY = key training sessions; EASY = non-KEY training sessions; % = the percentage of athletes who met the lower threshold for recommended intake for optimal performance and recovery [13] around key sessions; NA = Not Applicable. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ significant difference between HOME and CAMP; † $p < 0.05$; †† $p < 0.01$; ††† $p < 0.001$ significant difference between EASY and KEY.

3.2. Nutrition Knowledge

Mean total nutrition knowledge score was 76.0 ± 7.3%. The scores from the different parts were 73.4 ± 8.4% (Part 1), 67.4 ± 19.1% (Part 2), 92.5 ± 10.0% (Part 3), 71.8 ± 14.6% (Part 4), and 87.1 ± 11.3% (Part 5).

3.3. Nutrition Knowledge, Exercise Energy Expenditure and Dietary Intake

Figure 1 demonstrates that a higher nutrition knowledge score was associated with higher EI, EA, and CHO intake at HOME (r = 0.59, $p = 0.008$; r = 0.52, $p = 0.023$, r = 0.62, $p = 0.005$, respectively), as well as with higher CHO intake at CAMP (r = 0.52, $p = 0.023$). EI, EA, and protein intake at CAMP were positively associated with nutrition knowledge, but correlations were not statistically significant (r = 0.44; $p = 0.062$; r = 0.32; $p = 0.19$; r = 0.44, $p = 0.063$, respectively). Daily EEE did not correlate with nutrition knowledge at HOME (r = 0.22; $p = 0.36$) or at CAMP (r = 0.12; $p = 0.62$).

3.4. Nutrition Knowledge, Exercise Energy Expenditure and Dietary Intake

There was a positive trend between nutrition knowledge score and CHO intake before KEY exercises at HOME (r = 0.44, $p = 0.058$, Figure 2A) and at CAMP (r = 0.45, $p = 0.053$, Figure 2B). In addition, nutrition knowledge score was positively associated with CHO intake during 1-hour (r = 0.65, $p = 0.003$, Figure 2C) and 4-hour (r = 0.53, $p = 0.019$, Figure 2D) periods after KEY sessions at HOME but not at CAMP (r = −0.01, $p = 0.97$; r = 0.16; $p = 0.49$, respectively). Post-exercise protein intake and EEE during KEY exercises were not associated with nutrition knowledge at HOME (r = −0.08, $p = 0.76$; r = 0.04, $p = 0.86$, respectively) or at CAMP (r = 0.33, $p = 0.18$; r = 0.17, $p = 0.49$, respectively).

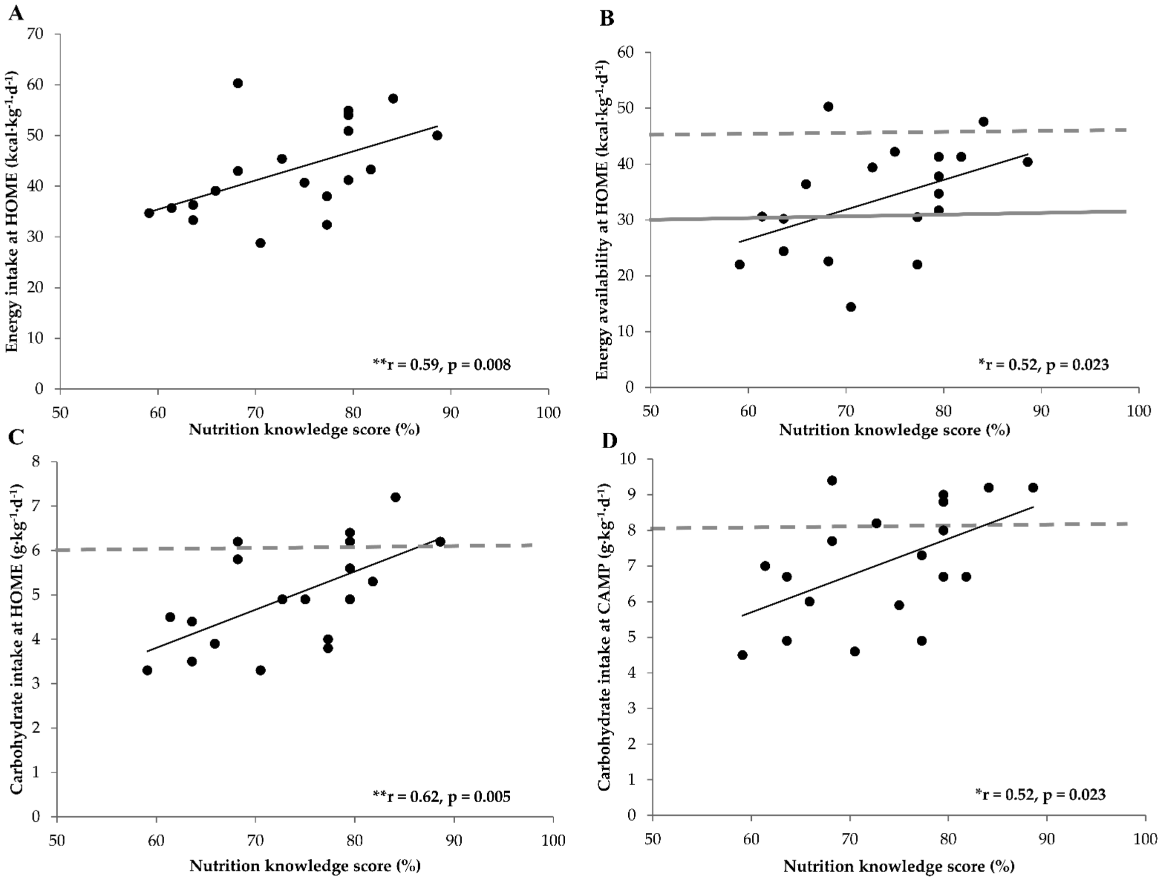

Figure 1. Associations between nutrition knowledge score and daily energy intake (**A**), energy availability (**B**), and carbohydrate intake (**C**,**D**). The gray horizontal dotted line denotes the consensus statement recommendations for optimal energy availability and carbohydrate intake [10,13]. The gray horizontal line denotes the threshold for low energy availability [10]. HOME = during home training; CAMP = during training camp; * $p < 0.05$; ** $p < 0.01$ significant correlation.

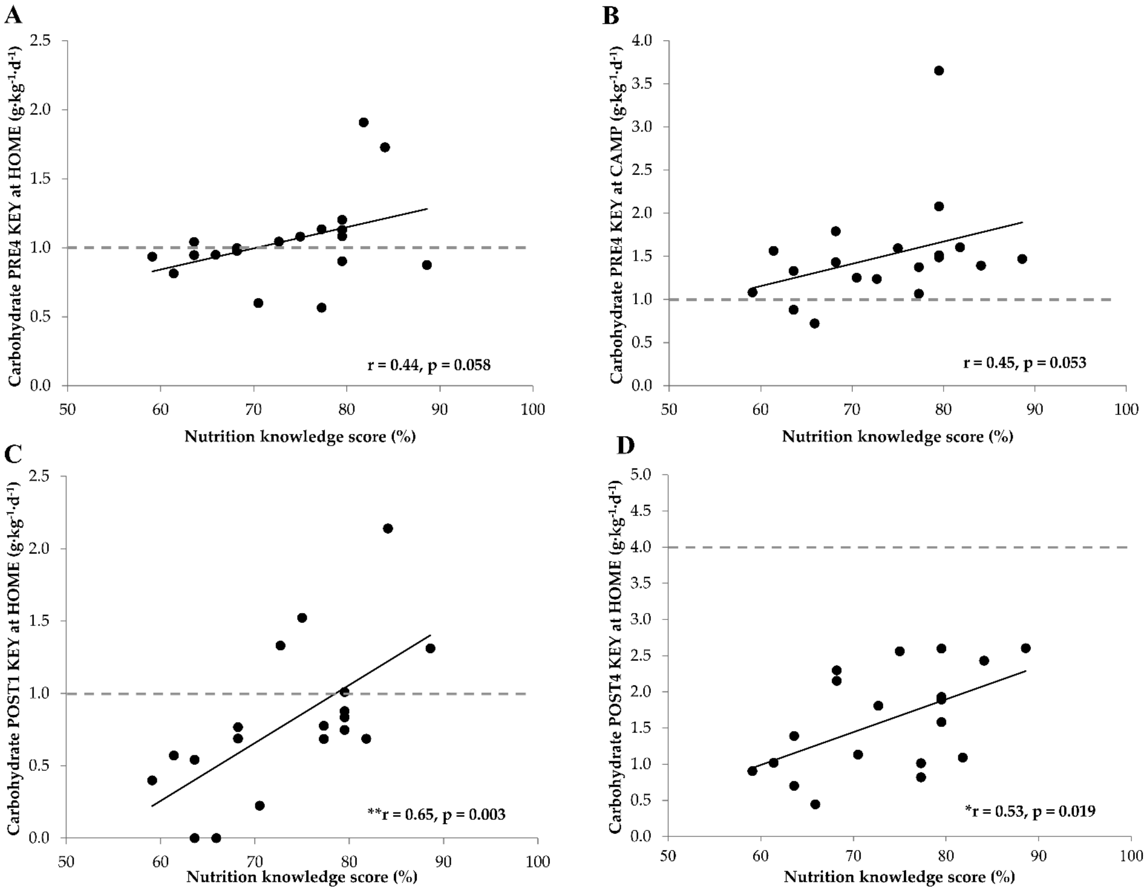

Figure 2. Associations between nutrition knowledge score and carbohydrate intake before (**A**,**B**) and after (**C**,**D**) KEY training sessions. The gray horizontal dotted line denotes the consensus statement recommendations for optimal carbohydrate intake [13]. PRE4 = within four hours before exercise; POST1 = within an hour after exercise; POST4 = within four hours after exercise; HOME = during home training; CAMP = during training camp; KEY = key training session; * $p < 0.05$; ** $p < 0.01$ significant correlation.

4. Discussion

The main findings of this study were that nutrition knowledge was positively associated with (i) daily EA, (ii) daily CHO intake, and (iii) CHO intake around exercise. It is notable that young female XC skiers had significant difficulties meeting the recommended CHO intake on a daily basis as well as during the 4-hour pre- and post-exercise periods. Detected difficulties may be limited with adequate nutrition knowledge and with arrangements that reduce an athlete's own responsibility for planning, scheduling, and preparing their own meals. It was also observed that young female skiers periodized their energy and macronutrient intake according to the energy requirements set by different EEE between training periods while dietary intake remained approximately similar before and after single training sessions with various intensities and durations.

The results demonstrated that young female XC skiers had suboptimal EA and CHO intake, especially during their typical home training. According to our observations, participants had about double the EEE during the CAMP compared to typical training at HOME as well as in KEY sessions compared to EASY sessions, which highlights the higher energy and macronutrient needs in these situations. Athletes increased their dietary intake from HOME to CAMP and therefore periodized their nutrition between normal and intensified training periods. In fact, the percentage of athletes who met the optimal level of EA and CHO intake was higher at CAMP than at HOME, which suggests that most athletes adjusted their diet to better support their performance and recovery during high load training camp. The scheduled and prepared buffet meals may also have supported athletes in meeting their energy and macronutrient requirements during the CAMP. Nevertheless, most athletes had inadequate CHO intake in both conditions despite dietary adjustments, which is a common observation among endurance athletes [17,25,28]. These findings are concerning, as inadequate CHO intake may lead to decreased glycogen stores that may impair training intensity and quality during intensive training [12,29] and increase the risk of illness [30].

Differences in periodization practices between EASY and KEY sessions were minor, and even the small differences that did occur (higher CHO intake before EASY sessions KEY sessions) actually goes against the principle of 'fuel for the work required' [31]. Indeed, almost half the athletes failed to meet pre-exercise CHO recommendations before KEY training sessions at HOME suggesting that training quality may be continuously compromised by fuel deficiencies. Another concerning finding was that 74% of athletes did not consume sufficient CHO during the first hour after KEY exercises at HOME, and almost all the athletes failed to meet recommendations within 4 hours post-exercise both at HOME and at CAMP. As restoration of muscle CHO stores may take up to 24 h, insufficient post-exercise CHO intake may have been particularly harmful at CAMP where the time between subsequent KEY sessions was limited [14]. It is not uncommon for female endurance athletes to have difficulties meeting post-exercise CHO recommendations, as only 40% of elite endurance runners met the recommendation within 1 hour of exersice [25] and only 31–54% of elite skiers did so within 4 hours of exercise [17]. Meanwhile, pre-exercise targets have been reported being met by 74–100% of elite female endurance athletes [17,25], which is a similar proportion to that observed in our participants at CAMP (89%) but higher than at HOME (58%).

The nutrition knowledge detected in this study was similar to previous studies that have used the same questionnaire for young endurance athletes [19,20]. As a novel finding, we detected that higher nutrition knowledge was associated with higher EA and CHO intake. When considering that 58–89% of athletes had suboptimal EA and 26–37% had low EA, the findings of this study highlight the importance of adequate nutrition knowledge to prevent the negative health and performance consequences associated with inadequate EA [9]. Furthermore, daily CHO intake was at a suboptimal level in 63–74% of athletes, which suggests that better nutrition knowledge may help to maintain adequate fueling for optimal performance and recovery [13].

In addition to daily intake, nutrition knowledge may significantly support recommended CHO intake around KEY training sessions. In the present study, athletes with higher nutrition knowledge were more likely to have higher CHO intake in pre- and post-exercise periods. This observation was pronounced at HOME, where athletes have more responsibility over the contents and timing of their meals, suggesting that enhanced nutritional education may be needed for athletes who have recently moved away from their parental home. Most athletes in this study belonged to sport high schools, which enabled them to have a higher training volume that they enjoyed in their earlier years in secondary school. However, inadequate post-exercise CHO intake may delay recovery from an increased training load [14,29], which may increase the risk of overtraining [32]. Suboptimal pre-exercise CHO intake, in turn, may decrease the quality of KEY training sessions [8,29,31], diminishing the desirable performance outcomes. Therefore, it is essential that athletes have adequate levels of nutrition knowledge to allow sufficient fueling around training sessions as well as adequate daily energy intake and availability to support training adaptations and overall health.

We found that young female XC skiers had slightly higher daily and more than twofold post-exercise protein intake compared to recommendations regardless of training type and nutrition knowledge. However, even higher protein intakes have been observed in elite female XC-skiers [17]. According to the current consensus statements, athletes have been recommended to consume 1.2–2.0 $g \cdot kg^{-1} \cdot d^{-1}$ and 0.25–0.30 $g \cdot kg^{-1}$ of protein during the 2-hour post-exercise period [13]. A recent investigation by Churchward-Venne et al. [33] found that 0.49 $g \cdot kg^{-1}$ protein is needed to maximize protein synthesis rate after 90 min of cycling at ∼60% VO_2peak, which suggests that ~50% higher protein intake may be needed after endurance workouts than earlier detected in the context of strength training [34]. Furthermore, Macnaughton et al. [35] found that a higher than currently recommended amount of protein is needed to maximize protein synthesis after a whole-body workout. In the case of our subjects, energy deficiency [36] and low CHO availability [37] may have further increased the requirements. While no studies exist specific to XC skiing, it is not baseless to suggest that protein requirements may be over current consensus statements for athletes who use their whole-body musculature during high load endurance training. It remains to be investigated whether as high as ~0.8 $g \cdot kg^{-1}$ post-exercise protein intake, which was detected in this study, has any benefits on recovery and adaptation.

Fat intake was observed to be ∼30% of daily EI at HOME and ∼32% at CAMP. Therefore, fat intake was within the recommended range of 20–35% of daily EI [13]. Adequate fat intake may have been an important component in supporting the health status of the athletes and may have aided in avoiding a more severe energy deficit [16]. These findings, in combination with previous studies [17], suggest that achieving the recommended level of fat intake is not a major challenge for XC skiers.

Limitations

Self-reported food logs may cause bias due to misreporting [38], and rather inaccurate methods used to assess EEE [23] and FFM, as well as the short recording period, may have further distorted EA assessment. Nevertheless, weighted food logs and highly motivated participants may have reduced bias related to misreporting. An additional limitation was that exercises were roughly divided into KEY and EASY sessions, and the exact loads of the exercises may have varied between subjects. However, EEE was significantly higher at KEY sessions compared to EASY sessions, and was not associated with nutrition knowledge. Finally, our research team took great care to continually interact with the participants to encourage their full compliance with the study protocols.

5. Conclusions

We found that young female XC skiers had suboptimal CHO intake and timing, both on a daily basis as well as around exercises, while protein intake was significantly higher than currently recommended [13]. Athletes periodized their dietary intake between training periods with different loads, as energy and macronutrient intake increased from normal training to an intensified training camp. Nevertheless, many athletes had suboptimal EA and CHO intake in both conditions that may have unfavorable performance and health outcomes. As a novel finding, we detected that adequate nutrition knowledge may help young athletes to meet recommended levels of EA and CHO intake. Thus, our findings highlight the importance of enhanced high-quality nutrition education for young endurance athletes.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon reasonable request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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II

ENERGY AVAILABILITY DURING TRAINING CAMP IS ASSOCIATED WITH CHANGES IN PERFORMANCE IN YOUNG FEMALE CROSS-COUNTRY SKIERS

by

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Energy availability during training camp is associated with signs of overreaching and changes in performance in young female cross-country skiers

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Abstract

Study aim: The aim of this study was to evaluate if young female skiers meet their energy and macronutrient requirements, and how energy availability (EA) and macronutrient intake affects their performance during an intensive training camp.
Material and methods: 19 female cross-country skiers (age 16.7 ± 0.7) filled in 48-hour food and training logs during a 5-day training camp. Fasting concentrations of hemoglobin, leptin, triiodothyronine (T3), insulin, insulin-like growth factor 1 (IGF-1), and glucose were measured before (PRE) and after (POST) the camp. Blood lactate (LA), heart rate (HR) and rating of perceived exertion (RPE) from a submaximal treadmill running test, jump height from counter movement jump (CMJ), and power from a reactive jump test (RJ) were also measured PRE and POST.
Results: Mean EA was 40.3 ± 17.3 kcal · kgFFM^{-1} · d^{-1}. 58% of the participants had suboptimal EA, 37% had low EA, and 53% had suboptimal carbohydrate intake. HR, HR/RPE ratio, LA/RPE ratio, CMJ, hemoglobin, leptin, T3, and insulin decreased from PRE to POST. RPE and glucose increased from PRE to POST. EA during the camp correlated with changes in LA ($r = 0.54$, $p = 0.018$), LA/RPE ($r = 0.65$, $p = 0.003$), and RJ ($r = 0.47$, $p = 0.043$).
Conclusions: Many athletes had difficulties in meeting their energy and carbohydrate requirements during a training camp. Furthermore, sufficient EA may help to avoid overreaching and to maintain performance during an intensive training period.

Key words: Carbohydrate – Female athlete – Macronutrient – Nutrition – Performance

Introduction

Cross-country (XC) skiing is a demanding sport that requires excellent aerobic and anaerobic capacities, adequate strength and ski-specific power, well-developed skiing technique, and the ability to attain and maintain high speeds [33]. To meet these demands, high and variable training loads are needed, which may, in turn, cause substantial challenges in optimizing energy and macronutrient intake, that are known to be among the key components when aiming to augment athletes´ performance, recovery, training adaptations, and health [39].

In XC skiing, low body weight may be an advantage on hilly courses and in poor gliding conditions, which may lead some skiers to restrict their eating in order to lose weight [29]. Combined with the high energy requirements of XC ski training [33, 35], weight control practises may lead to low energy availability (LEA) [31]. Long-term LEA, in turn, may lead to the so-called syndrome of Relative Energy Deficiency in Sport (RED-S) that can have detrimental effects on an athlete's performance and overall health [30]. Especially teenage female athletes may be at a higher risk for the negative health effects of RED-S, such as hormonal dysfunction, impairment of bone health, and increased risk of stress fractures [32]. Regrettably, little is known about the incidence of LEA related health problems among young female XC skiers.

Suboptimal energy and macronutrient intake during an intensive training period may decrease an athletes´ performance and impair recovery, ultimately leading to decreased training quality [39]. Furthermore, low EA and carbohydrate (CHO) intake have been suggested to increase the risk of illness, injury, and overreaching (OR, an

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accumulation of training and/or non-training stress resulting in short-term performance impairment), which, when not recognized, may lead to long-term impairment of athletic performance [25, 39]. There is no consensus regarding the early signs of OR, but changes in hormonal concentrations, vertical jump performance, heart rate (HR), blood lactate (LA), and rate of perceived exertion (RPE) have been reported after an overloading training period [6, 11, 16, 25, 38]. These changes may be severely compounded by inadequate energy and macronutrient intake, thus attention to nutrition may ultimately be an important factor for preventing the unnecessary negative effects of OR [25, 36].

Unfortunately, there is lack of sport-specific guidelines for energy and macronutrient intake for XC skiers, and thus more nutritional data collected from different training situations is required to provide specific recommendations to optimize XC skiers health, recovery, and performance, especially during high loads of training [8]. The aim of this study was to evaluate if young female XC skiers are meeting their individual energy requirements as well as the current recommendations for macronutrient intake for endurance athletes during a training camp, when the energy demand is high. Furthermore, we aimed to evaluate if EA and macronutrient intake during training camp is associated with training load induced changes in performance, and hormonal concentrations.

Materials and methods

Participants

Thirty-one (31) 15–17 year old female XC skiers from the Finnish Ski Associations´ under 18 year old national team were invited to join the study. Of those, a total of twenty-one (21) athletes were willing to participate. Two participants developed symptoms of respiratory infection before the first measurements, and thus the final number of participants was nineteen (19). Physical characteristics of the participants are presented in Table 1. The ethical board of the University of Jyväskylä approved the study and included procedures, and the study was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent to be involved in the study and were allowed to drop-out of the study at any time.

Table 1. Physical characteristics of the participants

n =19	Mean ± SD	Range
Age [years]	16.7 ± 0.7	15.8–17.6
Height [m]	1.67 ± 0.4	1.62–1.74
Weight [kg]	59.9 ± 6.6	50.6–75.1
Body Mass Index [$kg \cdot m^{-2}$]	21.5 ± 2.3	18.5–26.9
Body Fat [%]	15.9 ± 4.0	9.5–21.6

Experimental overview

This cross-sectional observation study was carried out during a 5-day training camp at sea level in October. Participants filled in 48-hour food, training, and activity logs during the second and third day of the training camp. Anthropometric measurements and the Low Energy Availability in Females Questionnaire (LEAF-Q) [26] were completed the first morning of the training camp. Fasting blood samples and performance tests were carried out on the first (PRE) and the last morning (POST) of the training camp. The training program during the 96 hours between the measurements included 11–12 hours of training that consisted of 8.5–9.5 hours of low intensity training (target blood LA < 2 $mmol \cdot L^{-1}$); 15–20 minutes of medium intensity training (target blood LA 2–4 $mmol \cdot L^{-1}$); 35–50 minutes of high intensity training (target blood LA > 4 $mmol \cdot L^{-1}$); and 100–110 minutes of speed, strength, and skill training.

Anthropometric measurements

Anthropometric measurements were completed in the morning after 12 hours of fasting and a visit to the bathroom. Height of the participants was measured with a wall-mounted stadiometer. Body mass and body composition were measured following an overnight fast using bioimpedance (Inbody 720, Biospace Co., Seoul, Korea) measurement.

Blood samples

Fasting blood samples were obtained from an antecubital vein for analysis of hemoglobin, cortisol, leptin, triiodothyronine (T3), insulin, insulin-like growth factor 1 (IGF-1), and glucose. PRE and POST samples from each subject were collected at the same time of day between 7am and 9am. Blood was drawn into EDTA tubes (Greiner-Bio-One GmbH, Kremsmünster, Austria) for analyses of hemoglobin that were completed immediately with Sysmex XP300 analyzer (SysmexCo., Kobe, Japan). For the determination of serum hormone concentrations, blood was drawn into Vacuette gel serum tubes (Greiner-Bio-One GmbH, Kremsmünster, Austria) and centrifuged at 3600 rpm for 10 min to collect serum, which was frozen at –20ºC. Concentrations of cortisol, leptin, T3, insulin, and IGF-1 were analyzed by an immunometric chemiluminescense method (Immulite 2000 XPi, Siemens Healthcare, United Kingdom). The assay sensitivities were 5.5 $nmol \cdot L^{-1}$ (cortisol), 8.2 $ug \cdot L^{-1}$ (leptin), 1.5 $pmol \cdot L^{-1}$ (T3), 2 $U \cdot L^{-1}$ (insulin), 1.7 $nmol \cdot L^{-1}$ (IGF-1), and 2.0 $mmol \cdot L^{-1}$ (glucose). Reliabilities expressed as a coefficient of variation

(CV) were 7.7% (cortisol), 4.9% (leptin), 8.1% (T3), 5.2% (insulin), 4.4% (IGF-1), and 5.5% (glucose).

Performance tests

Jump tests on a force plate (HUR FP8, Kokkola, Finland) and a submaximal treadmill running test were performed 90–180 min after morning measurements. Participants were instructed to eat a breakfast (not controlled) during the ~3 hours break between fasting measurements and the performance tests. After a 15 min warm-up that consisted of easy running outside at a self-selected submaximal speed participants performed a counter movement jump (CMJ) test. Participants were instructed to stand with feet shoulder-width apart and hands on hips while flexing the knees and trying to jump as high as possible. The best jump height of three attempts was calculated from impulse [20] using Coachtech system (Vuokatti Sports Technology Unit, University of Jyväskylä, Finland). For the reactive jump (RJ) participants were instructed to jump ten times in a row with straight knees and as high as possible with the shortest possible contact time. Only a small downward knee flexion after landing was allowed. Participants performed 2 x 10 jumps and the average power of the two best jumps from a single trial was calculated using equations by Bosco et al. (1983) [4]. It has been shown that both vertical jumps (e.g. CMJ) and continuous jumps (e.g. RJ) have been reported to be valid tests for determining explosive power [5].

A submaximal treadmill running test (4 × 4 min) was performed after the jump tests. Participants ran with a constant 10.0 km $\cdot$ h^{-1} speed and the inclination was increased after each 4 min stage as follows: 0–4 min was 2%, 4–8min 4%, 8–12 min 7%, and 12–16 min 9%. Blood LA samples after each stage were obtained from the fingertip and collected into capillary tubes (20 µL), which were placed in a 1-mL hemolyzing solution and analyzed automatically after the completion of testing according to the manufacturer's instructions (EKF diagnostic, C-line system, Biosen, Germany). During the treadmill test, HR (Polar V800, Kempele, Finland) and RPE (Borg 6–20 scale [3]) were recorded from the final 15 seconds of each stage and values from the last stage were used in final analysis. HR/RPE and LA/RPE ratios were calculated. The test protocols described above were selected as they are the same that are generally used to monitor training status among Finnish XC skiers.

Food, training and activity logs

Participants filled in 48-hour food, training, and activity logs during the second and third day of the five-day training camp. During the training camp participants had three prescheduled meals in the restaurant of the local sport institute. Participants selected the contents of their meals from a buffet, and the energy and macronutrient contents of the dishes were obtained from the chef. Participants were allowed to have their own snacks between meals. Each participant recorded the timing, type and amount of foods and fluid consumed, quantifying intake using kitchen scales. Written and verbal instructions were given for accurate record keeping. In addition, a member of the research team took part to the meals to make sure that athletes were recording their food intake properly. A short recording period was selected to keep the subjects´ burden as small as possible.

The food logs were analysed for energy and macronutrient intake using Aivodiet-software (version 2.0.2.3, Mashie, Malmö, Sweden). Training logs were analysed for exercise energy expenditure (EEE) using equations by Charlot et al. (2014) [9]. The duration and average HR of each training session, participant body mass, and self-reported maximal oxygen uptake (the result from the most recent test completed at a sport institute), resting HR, and maximum HR were used for calculations. Total energy expenditure (TEE) was assessed from activity and training logs using MET values by Ainsworth et al. (2011) [1] and resting energy expenditure determined with the equation by Cunningham (1991) [12]. EA was estimated as EI minus EEE and expressed in kcal·kg fat-free mass $(FFM)^{-1}$ $\cdot$ day $(d)^{-1}$. EA was classified as low (<30 kcal $\cdot$ $kgFFM^{-1} \cdot d^{-1}$), moderate (30–45 kcal $\cdot$ $kgFFM^{-1} \cdot d^{-1}$), and optimal (>45 kcal $\cdot$ $kgFFM^{-1} \cdot d^{-1}$) according to cut-off values specified by Loucks et al. (2011) [22] Energy balance (EB) was calculated as TEE minus EI.

Questionnaires

Participants completed the Finnish version of LEAF-Q [26], which was used to assess the risk of low EA and prevalence of self-reported amenorrhea (absence of menstrual cycles for more than 90 d [31]). According to the Melin et al. (2014) a LEAF-Q-score of ≥8 indicates long-term energy deficiency risk [26].

Statistical analysis

Statistical analyses were conducted using SPSS Statistics 24 (IBM, Armonk, NY). Results are reported as means ± SD. Normality was assessed via Shapiro-Wilk. Differences between PRE and POST were analyzed either with a repeated-measures analysis of variance (normally distributed data) or Wilcoxon signed rank test (non-normally distributed data). Effect sizes were calculated as Cohen's *d* with threshold values of <0.2 (trivial), 0.2–0.5 (small), 0.5–0.8 (moderate), and >0.8 (large) [10]. Pearson's (normally distributed data) or Spearman's (non-normally distributed data) correlation coefficient were used to analyze correlations between variables. Statistical significance was defined as $p < 0.05$. Statistical trend was defined as $p < 0.100$.

Results

The mean total score on the LEAF-Q was 6 ± 4. Five of the 19 athletes (26 %) had a total score of ≥8 and were therefore categorized as being at risk for a long-term energy deficiency. Since including these athletes to the total sample did not cause any major differences to the results, the analysis were done with the whole group. In figure 1 they have, however, been marked as triangles and a supplementary table 4 has been included to show the results without these five athletes. Three of the participants (16%) had self-reported secondary amenorrhea.

Table 2 summarizes the analysed variables from the food, training, and activity logs. Mean EI was similar with mean TEE indicating that athletes were in energy balance, although individual variation was high (–1349–2468 kcal · d^{-1}). Mean EA (40.3 ± 17.3 kcal · kgFFM^{-1} · d^{-1}) was slightly below optimal level (>45 kcal · kgFFM^{-1} · d^{-1}). Based on calculations from food logs seven athletes (37%) were classified as having LEA, four (21%) moderate EA, and eight (42%) had optimal EA during the training camp. All (100%) of the amenorrheic and four (25%) of the eumenorrheic athletes were categorized to have LEA during the training camp.

PRE and POST values from the performance and blood tests are presented in table 3. HR, HR/RPE, LA/RPE, and CMJ decreased while RPE increased from PRE to POST. Also statistical trends for the decrease of LA and RJ were detected. Hemoglobin, leptin, T3, and insulin decreased while glucose increased from PRE to POST. No changes in cortisol and IGF-1 were detected.

Correlations

EA correlated with PRE to POST changes in LA (r = 0.54, p = 0.018), LA/RPE (r = 0.65, p = 0.003,

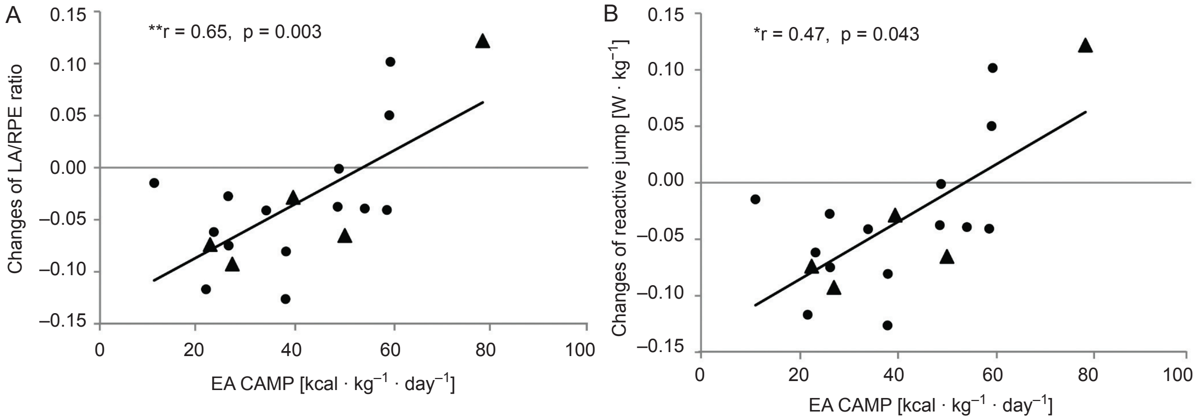

Figure 1. Associations of EA CAMP and PRE to POST changes of LA/RPE ratio (A) and reactive jump (B). Five athletes with LEAF-Q score ≥ 8 are marked with triangles. EA CAMP = energy availability during the training camp; PRE = performance tests before the training camp; POST = performance tests after the training camp; LA = blood lactate; RPE = rate of perceived exertion

Table 2. Mean (± SD) energy and macronutrient intake, energy expenditure, energy balance and energy availability during the training camp

n = 19	Mean ± SD	Range
Energy intake [kcal · d^{-1}]	3653 ± 1057	2508–6274
Total energy expenditure [kcal · d^{-1}]	3548 ± 287	3041–4006
Energy Balance [kcal · d^{-1}]	106 ± 933	–1349–2468
Exercise energy expenditure [kcal · d^{-1}])	1591 ± 213	1147–1971
Energy availability [kcal · kgFFM^{-1} · d^{-1}]	40.3 ± 17.3	11.1–78.4
Carbohydrate intake [g · kg^{-1} · d^{-1}]	7.1 ± 1.6	4.5–9.4
Protein intake [g · kg^{-1} · d^{-1}]	2.5 ± 0.5	1.6–3.5
Fat intake [g · kg^{-1} · d^{-1}]	2.2 ± 0.8	1.2–4.3

Table 3. Mean (± SD) values from the last stage of the submaximal treadmill running test, force plate jumps, and blood analysis before the training camp (PRE) and after the training camp (POST)

n = 19	PRE	POST	p value	Effect size
Heart rate [bpm]	189 ± 10	183 ± 10***	< 0.001	1.51
Lactate [mmol · L^{-1}]	5.0 ± 1.6	4.6 ± 1.9	0.120	0.37
RPE [6–20]	15.8 ± 1.4	16.4 ± 1.3*	0.030	0.54
HR/RPE	12.0 ± 1.0	11.2 ± 1.0**	0.001	0.90
LA/RPE	0.31 ± 0.08	0.28 ± 0.08*	0.041	0.52
Counter movement jump [cm]	32.0 ± 3.7	31.2 ± 3.2*	0.036	0.52
Reactive jump [W · kg^{-1}]	44.6 ± 8.1	43.1 ± 8.0	0.065	0.45
Hemoglobin [g · L^{-1}]	145 ± 6	139 ± 5***	< 0.001	1.50
Cortisol [nmol · L^{-1}]	506 ± 70	499 ± 49	0.586	0.13
Leptin [ug · L^{-1}]	31.6 ± 22.5	22.9 ± 13.6**	0.004	0.61
T3 [pmol · L^{-1}]	5.5 ± 1.1	5.2 ± 0.7*	0.020	0.59
Insulin [U · L^{-1}]	7.7 ± 4.5	5.9 ± 2.9*	0.018	0.55
IGF-1 [nmol · L^{-1}]	40.7 ± 6.3	37.9 ± 7.1	0.086	0.42
Glucose [mmol · L^{-1}]	5.3 ± 0.3	5.5 ± 0.4*	0.047	0.49

RPE = rate of perceived exertion; HR = heart rate; LA = blood lactate; T3 = triiodothyronine; IGF-1 = insulin-like growth factor 1. *p < 0.05, **p < 0.01, ***p < 0.001 significant difference between PRE and POST.

Table 4. Mean (± SD) values from the last stage of the submaximal treadmill running test, force plate jumps, and blood analysis before the training camp (PRE) and after the training camp (POST) when subjects with LEAF-Q score ≥ 8 have been excluded

n = 14	PRE	POST	p value	Effect size
Heart rate [bpm]	187 ± 10	182 ± 11***	< 0.001	1.29
Lactate [mmol·L^{-1}]	5.2 ± 1.7	4.8 ± 1.9	0.148	0.41
RPE [6-20]	16.1 ± 1.4	16.6 ± 1.3	0.058	0.49
HR/RPE	11.7 ± 0.8	11.0 ± 1.0*	0.010	0.81
LA/RPE	0.32 ± 0.09	0.28 ± 0.10*	0.046	0.59
Counter movement jump [cm]	32.7 ± 3.3	32.1 ± 2.7	0.157	0.40
Reactive jump [W·kg^{-1}]	45.5 ± 8.2	44.7 ± 7.8	0.065	0.25
Hemoglobin [g·L^{-1}]	144 ± 5	138 ± 5***	< 0.001	1.87
Cortisol [nmol·L^{-1}]	504 ± 76	495 ± 52	0.581	0.15
Leptin [ug·L^{-1}]	37.1 ± 23.7	26.1 ± 13.6**	0.009	0.69
T3 [pmol·L^{-1}]	5.6 ± 0.9	5.2 ± 0.7**	0.005	0.88
Insulin [U·L^{-1}]	8.0 ± 5.1	5.8 ± 3.1*	0.041	0.57
IGF-1 [nmol·L^{-1}]	40.6 ± 4.8	38.9 ± 6.3	0.080	0.51
Glucose [mmol·L^{-1}]	5.3 ± 0.3	5.5 ± 0.4*	0.012	0.78

RPE = rate of perceived exertion; HR = heart rate; LA = blood lactate; T3 = triiodothyronine; IGF-1 = insulin-like growth factor 1. *p < 0.05, **p < 0.01, ***p < 0.001 significant difference between PRE and POST.

Figure 1A), and RJ (r = 0.47, p = 0.043, Figure 1B). There was also a positive trend between EA and changes of HR (r = 0.38, p = 0.11) and CMJ (r = 0.42, p = 0.071). CHO intake correlated with PRE to POST changes of RJ (r = 0.48, p = 0.038). No statistically significant correlations between blood parameter changes and nutrition were detected.

Discussion

We aimed to evaluate if young female XC skiers meet their energy and macronutrient requirements and how EA and macronutrient intake affected their performance during an intensive training camp. Our results indicated that more than half of the young female XC skiers had suboptimal EA and CHO intake during a training camp. Lower EA and CHO intake were associated with signs of OR, including decreased muscular performance and submaximal LA/RPE ratio.

In the present study, 58% of young female XC skiers had suboptimal EA and negative EB during the training camp. Mean EI (3653 ± 1057 kcal · d^{-1}) was similar to that reported among Swedish female elite XC skiers during training and sprint competition days at 3541–3643 kcal · d^{-1} [8] but higher than the 2739–3142 kcal · d^{-1} reported among Finnish 16–20 years old male and female endurance athletes including XC skiers [17]. Although mean EI was adequate to keep mean EB and mean EA near optimal values, individual variation was high. Ultimately, most (58%) of the athletes had suboptimal EA and seven (37%) athletes had LEA suggesting that most athletes did not achieve an adequate EI during the training camp. Even transient LEA may compromise performance, training quality, recovery, and training adaptation [34, 39]. Furthermore, if LEA persists for a long time, it may lead to RED-S associated health and performance problems, such as hormonal dysfunctions, menstrual disorders, and impaired bone health [30]. Taking these health and performance consequences in to account, it is concerning that over one third of the participants had LEA during the training camp. This finding indicates that it is essential to ensure that young athletes and their coaches understand the significance of sufficient EI during hard training periods.

According to the LEAF-Q five (26 %) athletes were considered to be at risk for long-term energy deficiency while incidence of self-reported current secondary amenorrhea was 16% (n = 3). Although these findings are somewhat more positive than the 50 % of self-reported amenorrhea detected in Finnish endurance runners [18], all (100%) of the amenorrheic athletes in the present study had LEA, while the incidence of LEA was lower (25%) among eumenorrheic participants. This supports the notion that LEA may be a risk factor for menstrual disorders [23, 30]. Although many studies have failed to find an association between menstrual disorders and real-world dietary EA at a group level [e.g. 18, 27], our findings suggest that food and training logs may be effective tools to help detect LEA and RED-S associated health and performance concerns when working with individuals.

According to current recommendations, endurance athletes should consume 6–10 g · kg^{-1} · d^{-1} CHO when training 1–3 h·d^{-1} and 8–12 g · kg^{-1} · d^{-1} CHO when training 4–5 h · d^{-1} [39]. Since the average training volume in the present study was between 3–4 h · d^{-1} the amount of consumed CHO (~7 g · kg^{-1} · d^{-1}) was at the lower end of the recommendations. At an individual level, many athletes (53%) consumed <7 g · kg^{-1} · d^{-1} CHO, which may be considered as the minimum recommendation for the current training volume. Suboptimal CHO intake among endurance athletes has been reported in many studies [e.g. 8, 17, 18] and may negatively impact XC skiing performance, training quality, immune function, and recovery [8, 33, 39]. In our study, lower CHO intake was associated with decreased muscular performance as the jump height in CMJ and power in RJ were impaired more in participants who had lower CHO intake during the training camp. Thus, adequate CHO intake should be emphasized and communicated to young athletes aiming to maximize their volume of high-quality training sessions while supporting their normal physiological growth and development [13].

As in previous studies [8, 17], we found that mean protein intake of young female XC skiers (2.5 g · kg^{-1} · d^{-1}) exceeded the currently recommended level (1.2–2.0 g · kg^{-1} · d^{-1}) for athletes [39]. Whole-body training [24] and high volume endurance training [19], may increase XC skiers´ protein needs compared to studies that have been used as a basis for the current recommendations [39]. Fat intake was within recommended 20–35% of total energy intake [39] in our study as well as in previous studies exploring XC skiers [8, 17]. Therefore, inadequate protein and fat intake does not seem to be major concern among female XC skiers, and more attention should be paid to ensure adequate CHO intake in these athletes, especially during intensive training periods.

There are several potential pathways through which LEA can lead to impaired sports performance [21, 30, 34]. In the present study, jump performance and submaximal HR, HR/RPE ratio and LA/RPE ratio decreased with increased training load, which could be interpreted to indicate that the recovery capacity of the athletes was exceeded. Although reduced submaximal HR and LA levels are traditionally considered to be a result of effective endurance training [15], short-term changes may also be an indicator of an increased level of fatigue or even OR after an intensive training period [16, 28, 36, 37]. Mean LA levels did not change significantly between PRE and POST but an association was observed between EA and LA changes.

Decreased LA response was associated with lower EA, which may be explained by depleted glycogen stores [36]. Furthermore, the observed decrease in the LA/RPE ratio was greater when EA was lower. While earlier studies have associated decreased LA/RPE ratio with OR [14, 37], our results show that the risk of OR may be greater when EA during intensified training period is insufficient. Although OR may be a natural and even desirable result of an intensified training period [25], our results support the idea that adequate EA may enable higher training intensity during the training camp and allow athletes to have higher overall training load before they need a recovery period.

Inadequate EA and CHO intake may negatively affect muscular performance. In line with the previous findings [2, 11], we detected that a training period with high load led to decreased vertical jump performance. Interestingly, a greater decrease of RJ was associated with lower EA and CHO intake and there was a negative trend between CMJ and EA. Although previous studies have reported decreased CMJ height after harder training [2, 11], this study gives novel information about how nutrition may also be related to decreases in jump performance. A recent study by Tornberg et al. (2017) [40] found that amenorrheic athletes had lower neuromuscular performance than eumenorreic athletes suggesting that long term LEA may decrease neuromuscular performance. Our results suggest that already short-term inadequate energy and CHO intake may compromise muscular performance. CHO is a key fuel for the brain and central nervous system [39] and thus diminished CHO stores may explain why jump performance decreased more in participants with lower EA and CHO intake. Since high speed and strength capacities are vital for success in today´s XC skiing [33], it is important that athletes have adequate energy and CHO availability to maintain muscular performance in key training sessions.

Both high training load and energy deficiency affect the endocrine system [25, 30]. We detected small but statistically significant decreases in mean hemoglobin, T3, insulin, and leptin from PRE to POST while resting glucose increased and cortisol remained unchanged. Although the mentioned decreases were statistically significant, their clinical significance may be minimal and these results should be interpreted with caution. Indeed, we did not find any significant associations between hormonal and nutritional variables and thus, intensified training may have affected the endocrine system more than nutrition status did.

The primary limitation of present study is accuracy of the methods used to assess energy intake, expenditure, and availability. Self-reported food logs typically underreport the nutritional intake of athletes [7], and HR based equations used in this study have not been validated in XC skiing and may have poor accuracy on an individual level [9]. In addition, measuring FFM with bioimpedance may have influenced EA values. Nevertheless, we used weighted food logs and athletes were highly motivated to get proper feedback on their nutrition and filled their logs as precisely as possible, which may have reduced bias related to misreporting. The second remarkable limitation was that we gathered nutrition and training data for only two days and thus made the assumption that athletes had similar nutritional intake throughout the training camp. Furthermore, including athletes with amenorrhea and LEAF-Q score ≥8 to the analysis may have influenced the results we observed during the camp (see minor influences in figure 1 and supplementary table 4). However, it is important to note that the study aim was to evaluate how EA and macronutrient intake affects performance during an intensive training camp regardless of the situation before the camp. Therefore, all of the athletes who followed the study protocol appropriately were included in analyses. Finally, our subject number and follow-up time were limited and we lacked a control group, which reduces the generalizability of the results. We acknowledge these short-comings in our work, but do want to emphasize the strengths of our study. Our research team took great care to continually interact with our participants throughout the study and to encourage their full and complete compliance with the standardized study protocols. Lastly, the athletes that participated did represent the best young female XC skiers in Finland and the association between EA and OR in the present population is a relatively exciting and novel finding which needs to be further investigated.

Conclusions

It was shown that many young female XC skiers had suboptimal EA and CHO intake during an intensive training camp. Moreover, lower EA and CHO intake during this training camp were associated with the signs of OR and the deterioration of muscular performance as demonstrated by RJ and CMJ. Therefore, more attention should be paid to ensure that young female XC skiers meet their energy and macronutrient, particularly CHO, requirements to support performance and recovery. Finally, our results highlight the importance of young athletes and their coaches understanding the significance of sufficient EA and CHO intake for health and performance.

Conflict of interest: Authors state no conflict of interest.

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III

CARBOHYDRATE INTAKE IN YOUNG FEMALE CROSS-COUNTRY SKIERS IS LOWER THAN RECOMMENDED AND AFFECTS COMPETITION PERFORMANCE

by

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Carbohydrate intake in young female cross-country skiers is lower than recommended and affects competition performance

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Purpose: (1) To evaluate if energy availability (EA), macronutrient intake and body composition change over four training periods in young, highly trained, female cross-country skiers, and (2) to clarify if EA, macronutrient intake, body composition, and competition performance are associated with each other in this cohort.
Methods: During a one-year observational study, 25 female skiers completed 3-day food and training logs during four training periods: preparation, specific preparation, competition, and transition periods. A body composition measurement (bioimpedance analyzer) was performed at the end of the preparation, specific preparation, and competition periods. Competition performance was determined by International Ski Federation (FIS) points gathered from youth national championships.
Results: EA (36–40 kcal·kg FFM^{-1}·d^{-1}) and carbohydrate (CHO) intake (4.4–5.1 g·kg^{-1}·d^{-1}) remained similar, and at a suboptimal level, between training periods despite a decrease in exercise energy expenditure ($p = 0.002$) in the transition period. Higher EA ($r = -0.47$, $p = 0.035$) and CHO intake ($r = -0.65$, $p = 0.002$) as well as lower FM ($r = 0.60$, $p = 0.006$) and F% ($r = 0.57$, $p = 0.011$) were associated with lower (better) FIS-points. CHO intake was the best predictor of distance competition performance ($R^2 = 0.46$, $p = 0.004$).
Conclusions: Young female cross-country skiers had similar EA and CHO intake over four training periods. Both EA and CHO intake were at suboptimal levels for performance and recovery. CHO intake and body composition are important factors influencing competition performance in young female cross-country skiers.

KEYWORDS

endurance sport, energy availability, body composition, FIS points, female athlete, macronutrient, nutrition, periodization

1. Introduction

The annual training plan of most athletes is periodized into macrocycles (training periods), which have their own specific training and performance goals (1). The typical training year for cross-country (XC) skiers consists of a one- to three-part training period between May and November, a competition period from November to April, and a few weeks long transition period from April to May to allow for recovery before a new training year (2–5). The aim of this periodized training plan is to develop a variety of physiological, technical, and tactical capabilities that, together with competitive equipment, are needed for successful XC skiing performance (3).

Due to the variable training load and goals across training periods, nutritional needs may change. Therefore, to promote and support training goals, nutrition should also be periodized (6, 7). Periodized nutrition means that macronutrient intake is modified between training periods to support the specific training goals while maintaining adequate micronutrient intake and energy availability (EA) and avoiding negative health and performance consequences (6, 8, 9). In particular, carbohydrate (CHO) requirements may vary significantly depending on the intensity, volume and goals of the training (6). In XC skiing, most competitions and key training sessions are performed at intensities that are highly dependent on CHO based fuels (3, 10). Consequently, inadequate CHO intake may impair training intensity and competition performance, delay recovery, and increase the risk of lost training days due infection or injury (9–11).

In young athletes, the main goal of nutrition is to ensure optimal energy and nutrient availability to promote performance, recovery, training adaptations, overall health, and normal physical development (12). Physical maturation also induces changes in nutritional needs and performance capabilities, especially for young female athletes, who typically gain more body fat during adolescence between the ages of 8 and 20 years (13). As previous findings suggest that leaner body composition may confer a competitive advantage in young female XC skiers (14), more knowledge is needed, on how nutrition affects performance and body composition.

A recent study by Kettunen et al. (15) found that most young female XC skiers had suboptimal CHO intake and EA during normal training days and during an intensified 5-day training camp, despite some nutritional periodization practices. As research regarding the nutritional practices across the training year is still limited, the aim of this study was to evaluate if EA, macronutrient intake, and body composition change over four macrocycles in young female XC skiers. In addition, the study aimed to clarify how EA, macronutrient intake, body composition, and competition performance are associated with each other.

2. Materials and methods

2.1. Participants

A total of 27 female XC skiers and biathletes from a local high school sport academy (age 15–19 years) provided written informed consent to participate in this observational study. Two participants dropped out due personal reasons and thus the final number of the participants was 25. The proportion of the participants, who belonged to the youth XC or biathlon national team was 64%. Due to some missing data, the number of the participants varies between analyses, and therefore *n* values are presented in tables.

2.2. Design

Data were prospectively collected for one training year from the beginning of May to the end of April (**Figure 1**). The participants completed four 3-day food and training logs, one for each training period (macrocycle) of the training year as follows: preparation (Log_1), specific preparation (Log_2), competition (Log_3), and transition period (Log_4). Laboratory measurements were performed at the end of the preparation (M_1), specific preparation (M_2), and competition periods (M_3). M_3 was performed 12 ± 5 days after the Finnish Youth Championships in XC skiing, which was the main goal of the year for most of the participants. Total training volume (total hours) was recorded daily using an electronic training log (eLogger, eSportwise Oy, Finland). Competition performance was determined by International Ski Federation (FIS) points gathered from Finnish Youth National Championships. The study was approved by the ethical board of the University of Jyväskylä (20.3.2020) and conducted in accordance with the Declaration of Helsinki.

2.3. Anthropometric measurements (M_1, M_2, M_3)

Anthropometric measurements were completed in the morning following an overnight fast. The height of each participant was measured with a wall-mounted stadiometer. Body mass (BM), fat mass (FM), fat free mass (FFM), and fat percent (F%) were measured using bioimpedance analyzer (Inbody 720, Biospace Co., Seoul, Korea). Participants were barefoot and in their underwear during the measurement, which was performed in a private room.

2.4. Race performance

The level of XC skier performance can be evaluated by FIS points (16, 17). FIS point calculations are based on competition

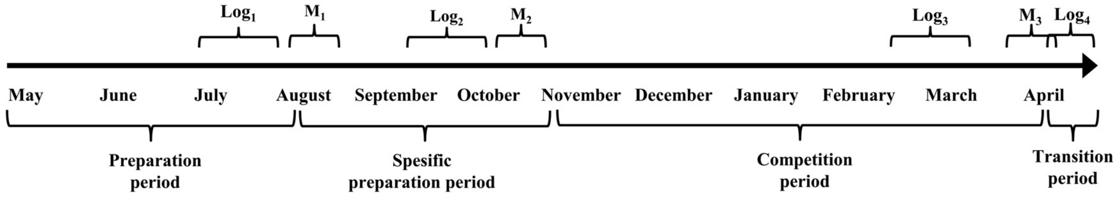

FIGURE 1
The timing of the training periods, food, and training logs (Log_1–Log_4), and measurements (M_1–M_3) during a one-year follow-up study.

performance as presented by Jones et al. (14) and lower FIS points indicate a better performance (17). As many FIS level competitions were canceled due to the COVID-19 pandemic, competition performance was evaluated by FIS points earned from Youth National Championships to which both XC skiers and biathletes took part. The best points from three distance competitions and one sprint competition were recorded separately. A total of 20 participants competed in at least one distance race and 14 participants competed in the sprint race.

2.5. Food and training logs

Three-day food and training logs were collected at four time points (Log_1–Log_4). Participants selected three subsequent days for each log from a 4-week period and were asked to select days that reflect their normal life and training as well as possible. Participants recorded the timing, type, and weight of foods and fluid consumed, quantifying their intake using kitchen scales (Idéale+, Tokmanni Oy, Mäntsälä, Finland). Verbal and written instructions were given to ensure a more accurate record keeping. Participants were instructed to take at least two photographs of the weighed portions, and whenever the scales were not available (e.g., in a restaurant) to validate what was recorded. The timing, type, and average heart rate (HR) of all exercises performed were recorded in training logs. Written and verbal instructions were given for accurate record keeping. Food logs were analyzed for energy intake (EI) and macronutrient intake using Aivodiet-software (version 2.0.2.3, Mashie, Malmö, Sweden). Although there are significant challenges in the validity of food logs, they are the best available tool for assessing dietary intake of the athletes (18).

2.6. Assessment of exercise energy expenditure and energy availability

The exercise energy expenditure (EEE) assessments were based on the individual relationships between HR, oxygen uptake (VO_2) and energy expenditure (EE). An incremental exercise test was performed by walking with ski poles on a treadmill (Telineyhtymä, Kotka, Finland) during M_1, M_2, and M_3. The test started at an inclination of 3.5° with a speed of $5.0\,\text{km}^{-1}\cdot\text{h}^{-1}$. The inclination and/or speed of the treadmill was increased every third minute so that oxygen demand calculated using the equation by Balke & Ware (19) increased $6\,\text{kcal}\cdot\text{kg FFM}^{-1}\cdot\text{d}^{-1}$ every stage. The treadmill was not stopped between the stages. Breathing gases were measured continuously using Medikro 919 Ergospirometer (Medikro Oy, Kuopio, Finland). The average VO_2 and respiratory exchange ratio (RER) from the last 60 s of each stage were recorded. Heart rate (HR) was monitored continuously throughout the tests using a Polar H10 HR belt (Polar Electro Oy, Kempele, Finland), and the average HR from the last 60 s of each stage was recorded. The protocol was selected as it is commonly used at local Olympic Training Center to monitor participants' performance in a similar way as was done in the present study. Therefore, participants were familiar with the protocol.

The first five stages of the treadmill test were utilized to form an individual regression line for each participant as described by Tomten & Hostmark (20). EE during each stage was calculated as (21):

$$EE = VO2 \times (1.1 \times RER + 3.9)$$

HR was strongly linearly correlated with calculated EE at increasing workloads ($r = 0.99$ at each measurement point) (21). EEE for each training session was calculated from the duration and mean HR of the training session using the regression line. The resting EE during exercise was calculated using the Cunningham equation (22) and subtracted from EEE in line with the latest definition of EA (23). Laboratory-based measures where HR is plotted against indirect calorimetry are regarded as the best methods to assess EEE in field conditions (24). Importantly, the mean intensity of most training sessions recorded were performed at an intensity between the first and fifth stage of the treadmill test.

Daily EA was calculated as (25):

$$EA = \frac{EI - EEE}{FFM}$$

where FFM is fat free body mass obtained from the bioimpedance measurement (25).

As FFM and relationship between HR and EE may change within a year, M_1 was used to analyze Log_1, M_2 to analyze Log_2, and M_3 to analyze Log_3 and Log_4.

2.7. Statistical analyses

Statistical analyses were performed with IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY). All data were checked for normality with a Shapiro-Wilk test and nonparametric tests were used with non-normally distributed data. The changes in variables between different parts of the training year were analyzed using a one-way analysis of variance for repeated measurements followed by the Bonferroni *post-hoc* test. Wilcoxon signed rank test was used for nonparametric variables. Results are reported as means ± SD. Correlations for normally distributed data were analyzed by using Pearson's correlation coefficient (r) and nonparametric data were analyzed using Spearman's correlation coefficient (r_s). Stepwise linear regression analysis was used to determine which variables were the best predictors FIS points. The relative importance of predictors was calculated based on R Square (R^2). A p-value <0.05 was defined statistically significant.

3. Results

As presented in **Table 1**, EI, EEE, and macronutrient intake remained similar between Log_1, Log_2, and Log_3 while EI, EEE,

TABLE 1 **Food and training log data between four training periods in young female XC skiers ($n = 23$).**

	Preparation period (Log_1)	Specific preparation period (Log_2)	Competition period (Log_3)	Transition period (Log_4)
Energy intake ($kcal \cdot kg\ FFM^{-1} \cdot d^{-1}$)	50.8 ± 10.6	52.5 ± 9.3	53.3 ± 8.9	$46.2 \pm 10.7^{bb,\ cc}$
Exercise energy expenditure ($kcal \cdot kg\ FFM^{-1} \cdot d^{-1}$)	14.1 ± 5.5	14.2 ± 5.3	13.3 ± 5.7	$7.7 \pm 6.9^{aa,\ bbb,\ cc}$
Energy availability ($kcal \cdot kg\ FFM^{-1} \cdot d^{-1}$)	36.7 ± 11.0	37.8 ± 10.7	40.0 ± 9.6	38.5 ± 11.2
Carbohydrate intake ($g \cdot kg^{-1} \cdot d^{-1}$)	5.0 ± 1.0	5.0 ± 1.1	5.1 ± 1.0	4.4 ± 1.1
Protein intake ($g \cdot kg^{-1} \cdot d^{-1}$)	2.0 ± 0.5	2.1 ± 0.4	2.0 ± 0.4	$1.6 \pm 0.4^{aaa,\ bbb,\ ccc}$
Fat intake ($g \cdot kg^{-1} \cdot d^{-1}$)	1.5 ± 0.5	1.5 ± 0.4	1.5 ± 0.4	1.3 ± 0.5
Training (food diaries) ($h \cdot d^{-1}$)	2.1 ± 0.7	2.1 ± 0.7	1.9 ± 0.7	$1.1 \pm 0.7^{aaa,\ bb,\ cc}$
Training (eLogger) ($h \cdot d^{-1}$)	1.9 ± 0.3	1.8 ± 0.3	$1.5 \pm 0.5^{aa,\ bb}$	$0.5 \pm 0.4^{aaa,\ bbb,\ ccc}$

^{aa}Significantly different from preparation period (Log_1) $p < 0.01$.
$^{aaa}p < 0.001$.
^{b}Significantly different from specific preparation period (Log_2) $p < 0.05$.
$^{bb}p < 0.01$.
$^{bbb}p < 0.001$.
^{c}Significantly different from competition period (Log_3) $p < 0.05$.
$^{cc}p < 0.01$.
$^{ccc}p < 0.001$.

and protein intake were lower in Log_4 than in Log_1, Log_2, and Log_3. Nevertheless, EA remained statistically similar between the logs. Yearly training volume was 610 ± 89 h and ranged between 450 and 815 h. There were no significant differences between the daily training volume reported in the food and training logs compared to the mean training volume reported in the electronic training diaries during each training period.

As presented in **Table 2**, BM and body mass index (BMI) increased from M_1 to M_2 and further from M_2 to M_3. In addition, FM and F% increased from M_2 to M_3.

Mean FIS distance points for participants from the Youth National Championships were 171.6 ± 52.0 ($n = 20$, range 101.0–274.6) and mean FIS sprint points were: 186.2 ± 32.0 ($n = 14$, range 127.2–239.6).

As presented in **Table 3**, better success in XC distance races, indicated by lower FIS distance points, was associated with higher EA and macronutrient intake as well as with lower FM and F%. FIS sprint points were negatively associated with training volume. In addition, athletes with higher FM and F% tended to eat less CHO, protein, and fat in relation to their BM (**Table 3**). When stepwise linear regression was performed using the variables presented in **Table 3**, CHO intake explained 46% of the variance in FIS distance points ($R^2 = 0.46$, $p = 0.004$). Training volume was the best predictor for FIS sprint points ($R^2 = 0.34$, $p = 0.036$).

TABLE 2 **Anthropometric variables in the end of three macrocycles in young female XC skiers.**

	n	M_1 (August)	M_2 (November)	M_3 (April)
Body mass (kg)	24	61.8 ± 6.8	63.1 ± 6.8^{aaa}	$64.7 \pm 7.3^{aaa,\ bb}$
Height	24	168.2 ± 5.2	168.5 ± 5.3	168.6 ± 5.2
BMI ($kg \cdot m^{-2}$)	24	21.8 ± 2.2	22.2 ± 2.2^{aaa}	$22.7 \pm 2.7^{aaa,\ bb}$
Fat free mass (kg)	23	51.0 ± 5.2	51.9 ± 5.0	51.5 ± 4.9
Fat mass (kg)	23	10.6 ± 3.6	10.9 ± 4.0	$13.0 \pm 4.3^{aaa,\ bbb}$
Fat percent (%)	23	17.0 ± 4.8	17.1 ± 5.2	$20.0 \pm 5.0^{aaa,\ bbb}$

^{a}Significantly different from M_1 $p < 0.05$.
$^{aa}p < 0.01$.
$^{aaa}p < 0.001$.
^{b}Significantly different from M_2 $p < 0.05$.
$^{bb}p < 0.01$.
$^{bbb}p < 0.001$.

4. Discussion

The present study assessed the changes in nutritional intake and body composition during a training year in young female XC skiers. The results showed that athletes had similar EEE, EI, EA, and macronutrient intake during preparation, specific preparation, and competition periods. However, athletes decreased EI during the transition period, where they also experienced lower EEE, thus maintaining EA. Unfortunately, in most athletes, CHO and EA were lower than recommended for performance and training adaptations (9). The second aim of the study was to assess the relationships between nutrition, body composition, and competition performance. Interestingly, better performance in XC distance competitions was associated with higher EA and macronutrient intake as well as with lower FM and F%. CHO intake was the best predictor for FIS distance points.

The EEE and training volume between preparation (Log_1), specific preparation (Log_2), and competition periods (Log_3) remained similar but decreased significantly in the transition period (Log_4). Also nutritional requirements of the training remained quite similar during the first three training periods, where athletes had similar EI, EA, and macronutrient intake. Nevertheless, during the transition period, athletes adapted to smaller energy needs by consuming less energy. Therefore, athletes seemed to periodize their EI between transition period and other training periods. Indeed, EA remained stable despite the variation in energy needs, which is in line with periodized nutrition recommendations (6). This finding is also in line with the findings of Ihalainen et al. who found that young female runners had similar EA in different parts of their training year

TABLE 3 Correlation coefficients (r_s for BM, r for others) between FIS points, EA, and macronutrient intake (the mean of Log_1, Log_2 and Log_3), anthropometrics in the end of the competition season, and yearly training volume.

	FIS_d	FIS_s	EA	CHO	Protein	Fat	BM	FFM	FM	F%	Training
FIS_d	1										
FIS_s	0.36	1									
EA	−0.47*	−0.23	1								
CHO	−0.65**	0.01	0.69***	1							
Protein	−0.51*	0.22	0.53**	0.75***	1						
Fat	−0.53*	0.31	0.82***	0.69***	0.65**	1					
BM	0.42	−0.02	−0.23	−0.28	−0.08	−0.27	1				
FFM	0.28	−0.13	−0.38	−0.16	0.11	−0.17	0.83***	1			
FM	0.60**	0.09	−0.37	−0.60**	−0.60**	−0.49*	0.77***	0.28	1		
F%	0.57*	0.17	−0.20	−0.55**	−0.64**	−0.43*	0.51*	−0.06	0.93***	1	
Training	−0.27	−0.58*	−0.31	−0.29	−0.31	−0.09	0.07	−0.02	0.13	0.11	1

FIS_d, FIS distance points; FIS_s, FIS sprint points; EA, energy availability (kcal·kg $\text{FFM}^{-1}\cdot\text{d}^{-1}$); CHO, carbohydrate intake ($\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$); BM, body mass; FFM, fat free body mass (kg); FM, fat mass (kg); F%, fat percent.

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.001$.

(26). Unfortunately, the data of the present study does not reveal whether the lower EI during transition period was intentional or spontaneous.

The mean EA of athletes during the present one-year follow-up varied between 36 and 40 kcal·kg $\text{FFM}^{-1}\cdot\text{d}^{-1}$, which is considered suboptimal for performance and training adaptations but adequate to maintain normal physiological functions (25). The EA detected in the present study is similar to that reported in young female XC skiers at home and training camp conditions (15) and in young female distance runners during different parts of the training year (26). Notably, the individual variation was high, and six athletes had low EA (<30 kcal·kg $\text{FFM}^{-1}\cdot\text{d}^{-1}$) in Log_1, while four had low EA in Log_2, two in Log_3, and five in Log_4. In the long term, these individuals may be at risk to develop deleterious health and performance consequences related to low EA such as hormonal disturbances, decreased bone health, and increased risk of injury (8, 27).

When comparing the results from the first three food logs to the nutrition recommendations for endurance athletes training 1–3 $\text{h}\cdot\text{d}^{-1}$, protein intake (2.0–2.1 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$) was in the upper limits (1.2–2.0 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$), fat intake (1.5 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ i.e., ∼31% of total EI) was in the recommended range (20%–35% from total EI), and CHO intake (5.0–5.1 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$) was less than recommended (6–10 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$) (9). These findings are similar to those previously reported in Swedish national team XC skiers (28) and in Finnish Youth National Team XC skiers (15). Thus, it seems that consuming adequate CHO is a notable challenge for female XC skiers of different ages and nationalities.

BM and F% increased significantly over the training year and especially during the competition period, which is against the body composition periodization principles that are used to optimize performance in elite athletes (29). Importantly, an increase in BM, FM, and F% is also a normal physiological phenomenon during adolescence (13), which may explain, at least partly, why BM, FM, and F% increased as the study progressed. BM increased evenly from M_1 to M_3, while the increase from M_1 to M_2 was mostly explained by the increase in FFM while the increase from M_2 to M_3 is explained by an increase in FM, which led to a simultaneous increase in F%.

Better competition performance in distance events at the Youth National Championships was associated with higher EA and macronutrient intake as well as with lower FM and F%. CHO intake was the best predictor for FIS distance points. The present results indicate that adequate CHO intake across the training year may have an important role in optimizing competition performance. This finding is logical, as inadequate CHO intake may impair training intensity and competition performance, delay recovery and increase the risk of lost training days due infection or injury (9–11).

In addition to the findings that nutritional intake and body composition were associated with performance, we found that anthropometric and nutritional variables correlated with each other. Interestingly, higher FM and F% were associated with lower intake of all macronutrients. Because of the observational study setting, reliable causal relationships cannot be determined. One potential explanation may be that athletes with higher body fat restricted their eating to lose BM without desired results. Another explanation may be that higher body fat is an adaptation to chronic low EA as long-term low EA leads to energy conserving metabolic changes that, over the long term may become detrimental to training adaptations and sport performance (8, 27). It is also possible that athletes who have adopted proper eating practices that support their training, have succeeded in developing their performance from year to year whereby their body composition has adapted to the demands of their sport due to successful training and/or genetics. It is worth noting, that the macronutrient intake in the present study and current nutritional recommendations (9) are expressed in relation to BM. Athletes with higher FM and F% have higher amount of metabolically inactive tissue and therefore, it is possible that they do not need as much fuel in relation to their BM as their leaner counterparts.

FIS sprint points were predicted by yearly training volume but were not associated with any other variables. Similar results were reported by Jones et al. (14) who did not find any predictors for

FIS sprint points. In contrast, Carlsson et al. (30) found that lean body mass predicted XC sprint performance in elite female skiers. It is difficult to assess why training volume predicted sprint but not distance performance in present study. Nevertheless, it is important to note that only 14 participants took part in the sprint race at Youth Nationals, which increases the risk of error in FIS sprint point analyses, thus these results should be interpreted with caution.

The present study has some limitations. One of the major limitations is that the methods used to assess dietary intake and EA in field conditions are prone to errors (24, 31). To minimize these errors, we selected methods that are considered the most valid to assess EEE and dietary intake in field conditions (24). Food and training logs were completed during different parts of the training year, which gave more reliable information regarding overall practices. Notably, training logs reflected the training volume expected from each training period suggesting that training logs reflected actual training completed. Finally, FIS points were recorded only from single races instead of a yearly score. Nevertheless, we believe that this gave the best possible description of the competition performance as many races were cancelled due to the COVID-19 pandemic and the Youth National Championships were among the most important competitions for our participants. Importantly, it should be recognized that non-physiological factors such as ski selection, waxing, and environmental factors may have affected competition performance and FIS points.

4.1. Conclusions

Young female XC skiers maintained similar, but suboptimal, EA and carbohydrate intake between four training periods. EEE remained similar between preparation, specific preparation, and competition periods suggesting similar dietary requirements during these macrocycles. Nevertheless, athletes experienced lower EEE during the transition period, but maintained EA by decreasing EI. CHO intake across the training year seems to be an important predictor for XC distance competition performance in young female XC skiers. Furthermore, lower BM, FM, and F% may be beneficial for distance competition performance. Based on our results, however, restricting dietary intake may not be an optimal way to modify body composition in young female athletes. Therefore, based on the findings of present study, young female XC skiers should aim to maintain adequate EA and CHO intake throughout the training year to promote long-term development in competition performance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethical board of the University of Jyväskylä. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization and methodology: OK, VL, and JI; investigation: OK; statistical analysis: OK and JM; original draft preparation: OK; Writing—review and editing: OK, RM, VL, JM, and JI; supervision: RM, VL, and JI. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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IV

NUTRITIONAL INTAKE AND ANTHROPOMETRIC CHARACTERISTICS ARE ASSOCIATED WITH ENDURANCE PERFORMANCE AND MARKERS OF LOW ENERGY AVAILABILITY IN YOUNG FEMALE CROSS-COUNTRY SKIERS

by

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Nutritional intake and anthropometric characteristics are associated with endurance performance and markers of low energy availability in young female cross-country skiers

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ABSTRACT

Background: Low energy availability (LEA) can have negative performance consequences, but the relationships between LEA and performance are poorly understood especially in field conditions. In addition, little is known about the contribution of macronutrients to long-term performance. Therefore, the aim of this study was to evaluate if energy availability (EA) and macronutrient intake in a field-based situation were associated with laboratory-measured performance, anthropometric characteristics, blood markers, training volume, and/or questionnaire-assessed risk of LEA in young female cross-country (XC) skiers. In addition, the study aimed to clarify which factors explained performance.

Methods: During a one-year observational study, 23 highly trained female XC skiers and biathletes (age 17.1 ± 1.0 years) completed 3-day food and training logs on four occasions (September–October, February–March, April–May, July–August). Mean (±SD) EA and macronutrient intake from these 12 days were calculated to describe yearly overall practices. Laboratory measurements (body composition with bioimpedance, blood hormone concentrations, maximal oxygen uptake (VO_{2max}), oxygen uptake (VO_2) at 4 $mmol{\cdot}L^{-1}$ lactate threshold (OBLA), double poling (DP) performance (time to exhaustion), counter movement jump (height) and the Low Energy Availability in Females Questionnaire (LEAF-Q)) were completed at the beginning (August 2020, M_1) and end of the study (August 2021, M_2). Annual training volume between measurements was recorded using an online training diary.

Results: The 12-day mean EA (37.4 ± 9.1 $kcal{\cdot}kg\ FFM^{-1}{\cdot}d^{-1}$) and carbohydrate (CHO) intake (4.8 ± 0.8 $g{\cdot}kg^{-1}{\cdot}d^{-1}$) were suboptimal while intake of protein (1.8 ± 0.3 $g{\cdot}kg^{-1}{\cdot}d^{-1}$) and fat ($31 \pm 4$ E%) were within recommended ranges. Lower EA and CHO intake were associated with a higher LEAF-Q score ($r = 0.44$, $p = 0.042$; $r = 0.47$, $p = 0.026$). Higher CHO and protein intake were associated with higher VO_{2max} ($r = 0.61$, $p = 0.005$; $r = 0.54$, $p = 0.014$), VO_2 at OBLA ($r = 0.63$, $p = 0.003$; $r = 0.62$, $p = 0.003$), and DP performance at M_2 ($r = 0.42$, $p = 0.051$; $r = 0.44$, $p = 0.039$). Body fat percentage

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(F%) was negatively associated with CHO and protein intake (r = -0.50, p = 0.017; r = -0.66, p = 0.001). Better DP performance at M_2 was explained by higher training volume (R^2 = 0.24, p = 0.033) and higher relative VO_{2max} and VO_2 at OBLA at M_2 by lower F% (R^2 = 0.44, p = 0.004; R^2 = 0.47, p = 0.003). Increase from M_1 to M_2 in DP performance was explained by a decrease in F% (R^2 = 0.25, p = 0.029).

Conclusions: F%, and training volume were the most important factors explaining performance in young female XC skiers. Notably, lower F% was associated with higher macronutrient intake, suggesting that restricting nutritional intake may not be a good strategy to modify body composition in young female athletes. In addition, lower overall CHO intake and EA increased risk of LEA determined by LEAF-Q. These findings highlight the importance of adequate nutritional intake to support performance and overall health.

1. Introduction

The relationship between energy availability (EA) and performance is not yet fully understood, although the negative consequences of low energy availability (LEA) on health are quite well documented, especially with females [1]. Most importantly, there is a significant gap in knowledge between short-term laboratory studies and long-term field-based studies examining LEA [2]. Although actual cutoff values are individual, LEA is often defined as < 30 kcal·kg $FFM^{-1}·d^{-1}$ based on laboratory studies in sedentary women [3]. LEA may suppress endocrine function, impair bone health, and increase the risk of illness while leaving inadequate amounts of energy for recovery and training adaptations, which all have negative consequences for performance development [1,2,4]. Changes in hormone levels, menstrual disturbances, and increased incidence of bone stress injuries are typical symptoms and signs of LEA [1,2,4]. Regrettably, relatively little is known about EA in cross country (XC) skiers who are prone to several LEA risk factors such as high exercise energy expenditure (EEE) [5] and the performance benefits of lean body composition (i.e. more fat free mass (FFM) and less fat mass (FM)) [6].

In addition to EA, the macronutrient composition of a diet can also have a significant impact on performance and health. Carbohydrates (CHO), in particular, are known to be a critical macronutrient for performance in endurance sports such as XC skiing [5,7]. Indeed, XC ski races and key training sessions are conducted at intensities that mostly depend on CHO based fuels [5,8]. To maintain capacity for high working intensities between hard training sessions and competitions, consumption of high amounts of CHO is necessary [9]. Unfortunately, previous studies have shown that both elite [10] and young female skiers [11] struggle to meet the current CHO recommendations for endurance athletes. In contrast, the recommendations for protein and fat intake are met by most XC skiers [10,11], which supports recovery, training adaptations, and normal body functions [12].

Females, and especially females under 20 years of age, who compete in endurance and/or lean sports (e.g. running, XC skiing), are especially prone to LEA associated health and performance problems [1,13]. Regrettably, most studies that have focused on the macronutrient requirements in athletes have been conducted with male participants resulting in a significant gap in knowledge about macronutrient needs in female athletes

[14]. Therefore, the aim of this study was to investigate whether EA and macronutrient intake in field-based conditions are associated with the changes in performance, anthropometric characteristics, blood markers, training volume, and/or questionnaire-determined risk for LEA. In addition, the study aimed to clarify which of the abovementioned variables explained maximal oxygen uptake (VO_{2max}), lactate threshold, upper body endurance performance, and lower limb explosive performance, i.e. the factors that contribute to performance in XC skiing [15].

2. Materials and methods

2.1. Participants

A total of 27 female XC skiers and biathletes (age 17.1 ± 1.0 years, VO_{2max} 54.1 ± 3.8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) participated in the study. All participants provided informed consent after receiving comprehensive oral and written details of the protocol. The participants were members of the sport academy of a local high school. Four participants dropped out due to personal reasons and thus the final number of the participants was 23. Altogether 64% of the participants belonged to Youth National Teams. The Ethical Board of the University of Jyväskylä approved the study procedures (No. 380/13.00.04.00/2020), and the study was conducted in accordance with the Declaration of Helsinki.

2.2. Design

The one-year follow-up study was performed from August 2020 (M_1) to August 2021 (M_2) to examine whether 12-day mean EA and macronutrient intake assessed from four 3-day food and training logs in different phases of the training year were associated with changes in performance, anthropometric characteristics, and serum hormone concentrations in young female XC skiers. The Low Energy Availability in Females Questionnaire (LEAF-Q) [16] and laboratory measurements including performance tests, anthropometric measurements, and blood samples were completed at the beginning (M_1) and at the end of the study (M_2). In addition, anthropometric measurements and aerobic performance tests were performed twice during the follow-up (November and the following April) to refine EA assessment (see calculations). Annual training volume was recorded using an online training diary (eLogger, eSportwise Oy, Finland).

2.3. Anthropometric measurements

Anthropometric measurements were completed in the morning following an overnight fast. Height of the participants was measured with a wall-mounted stadiometer. Body mass (BM), FFM, FM, and fat percentage (F%) were measured using bioimpedance (Inbody 720, Biospace Co., Seoul, Korea).

2.4. Blood samples and analysis

Fasting blood samples were obtained from the antecubital vein for analysis of serum hormone concentrations. M_1 and M_2 samples from each participant were collected at the same time of day between 7 a.m. and 9 a.m. Blood was drawn into Vacuette gel serum tubes (Greiner-Bio-One GmbH, Kremsmünster, Austria). The tubes were centrifuged at 3600 rpm for 10 min to collect serum, which was frozen at -20°C. Concentrations of insulin, cortisol, insulin-like growth factor 1 (IGF-1), free triiodothyronine (T3), free thyroxine (T4), thyroid-stimulating hormone (TSH), leptin, and testosterone were analyzed by an immunometric chemiluminescence method (Immulite 2000 ×Pi, Siemens Healthcare, United Kingdom). The assay sensitivities were 2.0 $U{\cdot}L^{-1}$ for insulin, 5.5 $nmol{\cdot}L^{-1}$ for cortisol, 2.6 $nmol{\cdot}L^{-1}$ for IGF-1, 1.5 $pmol{\cdot}L^{-1}$ for free T3, 1.4 for free T4, 0.004 $mU{\cdot}L^{-1}$ for TSH, 0.2 $ug{\cdot}L^{-1}$ for leptin, and 0.5 $nmol{\cdot}L^{-1}$ for testosterone. Reliabilities expressed as a coefficient of variation were 8.8% for insulin, 7.7% for cortisol, 4.4% for IGF-1, 10.3% for free T3, 6.6% for free T4, 9.2% for TSH, 4.9% for leptin, and 10.9% for testosterone.

2.5. Jump performance

The counter movement jump (CMJ) test [17] was performed on a force plate (HUR FP8, Kokkola, Finland) after a self-selected warm-up. Participants were instructed to stand with feet shoulder-width apart and hands on hips while flexing the knees and trying to jump as high as possible. The best jump height of three attempts was calculated from impulse [18].

2.6. Aerobic capacity and lactate threshold

The incremental aerobic capacity test, which was familiar to the participants, was performed by walking or running with poles on a treadmill (Telineyhtymä, Kotka, Finland) ~15 min after CMJ. The test started at 3.5° inclination with a speed of 5.0 $km{\cdot}h^{-1}$. The inclination and/or the speed of the treadmill was increased every third minute so that predicted oxygen uptake (VO_2) calculated according to the equation by Balke & Ware [19] increased by 6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ in every stage.

Respiratory variables were measured continuously using a mixing chamber system (Medikro 919 Ergospirometer, Medikro Oy, Kuopio, Finland). Volume and gas calibration of the ergospirometer was done prior to every measurement. VO_2 and respiratory exchange ratio (RER) from the last 60 s of each stage, and the highest 60 s average (VO_{2max}) were recorded. Heart rate was monitored continuously throughout the tests using a heart rate belt (Polar H10, Polar Electro Oy, Kempele, Finland), and the average heart rate from the last 60 s of each stage was recorded. Blood lactate samples at the end of each stage were obtained from a fingertip and collected into capillary tubes (20 μL), which were placed in a 1-mL hemolyzing solution and analyzed using Biosen C-line analyzer (EKF diagnostics, Barleben, Germany). In addition to VO_{2max}, the VO_2 at 4 $mmol{\cdot}L^{-1}$ lactate (Onset of Blood Lactate Accumulation, OBLA) was recorded.

2.7. Double poling performance

A maximal double poling test was performed by roller skiing on a treadmill (Rodby Innovation AB, Vänge, Sweden). All skiers used the same pair of Marwe 800 ×C roller skis (Marwe Oy, Hyvinkää, Finland) equipped with prolink bindings (Salomon Group, Annecy, France) and standard 6C6 wheels (Marwe Oy, Hyvinkää, Finland). Poles (Swix Triac 3.0, BRAV, Lillehammer, Norway) were selected based on the length of the participants´ classic poles and were equipped with a tip customized for treadmill roller skiing. After a self-selected warm-up outside the laboratory, participants performed a 10 min warm-up at the same workload as the first stage of the subsequent submaximal test including two ~15 s sprints at the workload equal to the fourth to sixth stage of the test. Following the warm-up, athletes performed an incremental treadmill test double poling at an incline of 2°, starting at 10 $km{\cdot}h^{-1}$ and followed by an increase of 1 $km{\cdot}h^{-1}$ every minute until volitional exhaustion. Time to exhaustion was also recorded.

2.8. Food and training logs

Food and training logs were collected at four time points (September–October, February–March, April–May, July–August) for a 3-day period. Athletes selected three subsequent days for each log from a 4-week period, and the mean values from 12 days were calculated to describe yearly overall practices. Participants were asked to select days that described their typical daily dietary and training routines as well as possible. Timing, amount, and type of food as well as fluid consumed were recorded in the food logs while calibrated kitchen scales were used to weigh servings. If the scales were not available (i.e. in a restaurant), participants took photos of their portions. They were also asked to take at least two photos of the weighted portions to validate what was recorded. Timing, type, and average heart rate of exercises performed were recorded in training logs. Written and verbal instructions were given to ensure more accurate record keeping. Food logs were analyzed for energy intake (EI) and macronutrient intake using Aivodiet-software (version 2.0.2.3, Mashie, Malmö, Sweden). All dietary records were analyzed by the same researcher. Despite limitations in validity of food logs, they are currently the best available tool to assess dietary intake of the athletes in the field conditions [20].

2.9. Calculations

The EEE assessments were based on the individual relationship of energy expenditure (EE), oxygen uptake, and heart rate during the aerobic capacity test. EE during the first five stages of the test was calculated as follows:

$EE = VO_2 * (1.1 * RER + 3.9)$ [21]

Calculated EE and heart rate from the five first stage of the test were used to form an individual regression line for each subject as described by Tomten & Hostmark [22]. EEE of each exercise was calculated from the mean heart rate and duration of the training session using this regression line. As the relationship between EE and heart rate may change within a year, the aerobic capacity test was performed four times during the study (August, November, April, August) to update the regression line. The Cunningham equation [23], utilizing FFM from the bioimpedance measurement, was used to calculate resting EE, which was subtracted from EEE to follow the latest definition of EA [24]. Laboratory-based measurements, where heart rate is plotted against indirect calorimetry are among the most valid methods to assess EEE in field conditions [2].

Daily EA was calculated as:

$EA = (EI - EEE) / FFM$ [3],

where FFM is obtained from bioimpedance measurement performed within ~a month of the logs.

To enable a comprehensive understanding of the nutritional practices during the whole training year, the 12-day mean EI, EEE, EA, and macronutrient intake was used in the analysis.

2.10. Questionnaires

Participants completed the LEAF-Q [16] at the beginning and at the end of the study, which was used to assess the risk of LEA (≥8 points [16]) and the prevalence of self-reported amenorrhea (absence of menstrual cycles for more than 90 d [25]). The LEAF-Q consist of questions regarding physiological symptoms linked to energy deficiency, such as injuries, gastrointestinal symptoms, and menstrual dysfunction [16].

2.11. Statistical analysis

IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY) was used for statistical analysis. A Shapiro–Wilk test was performed to check the normality of the data. Nonparametric tests were used to analyze non-normally distributed data (FFM at M_1, BM at M_2, FM at M_2). The significance of the changes from M_1 to M_2 were analyzed either with Student´s paired t-test (normally distributed data) or Wilcoxon signed rank test (non-normally distributed data). Results are reported as means ± SD. The effect size of differences was expressed as Cohen’s *d* [26]. Correlations for normally distributed data were analyzed by using Pearson’s correlation coefficient (*r*) while nonparametric data was analyzed using Kendall’s tau b (τ_b). Stepwise linear regression analysis was used to determine which of the nutritional, anthropometric, and training volume variables presented in Table 3 explained performance variables in the end of the follow-up period (M_2). BM and FM were excluded from the regression analyses because the normality of the variables was violated. The method selected the best variables to explain the dependent variable. In the analysis of year-to-year changes in the performance variables, the changes in body composition, instead of absolute values, were used as independent variables. Homoscedasticity was tested by estimating Pearson and Spearman’s correlations between the standardized predicted values and the absolute standardized residuals and was not violated in any of the analyses. The relative importance of contributing variables was calculated based on R Square (R^2). The statistical significance was defined as $p < .05$.

3. Results

Table 1 presents the mean EI, EEE, EA, and macronutrient intake from the food and training logs (the mean of 12 d). The mean EA (37.4 ± 9.1 kcal·kg FFM^{-1}·d^{-1}) and CHO (4.8 ± 0.8 g·kg^{-1}·d^{-1}) intake were below the recommendation while protein (1.8 ± 0.3 g·kg^{-1}·d^{-1}) and fat intake (1.4 ± 0.4 g·kg^{-1}·d^{-1}) were at recommended range.

BM, height, body mass index (BMI), FFM, FM, and F% increased significantly during the follow-up year (Table 2), while VO_{2max} in relation to BM decreased (Table 2). The results of other performance variables and blood hormone concentrations remained similar between M_1 and M_2. Nine athletes had LEAF-Q score ≥ 8 at both measurement points. Five of the athletes had score of ≥ 8 at both M_1 and M_2, four athletes only in

Table 1. The 12-day means for energy intake, exercise energy expenditure, energy availability, and macronutrient intake in young female cross-country skiers.

$n = 23$	Mean ± SD	Range	Recommendation [12]
Energy intake (kcal·kg $FFM^{-1}·d^{-1}$)	50.3 ± 7.7	32.2–63.0	NA
Exercise energy expenditure (kcal·kg $FFM^{-1}·d^{-1}$)	12.8 ± 4.5	7.5–20.9	NA
Energy availability (kcal·kg $FFM^{-1}·d^{-1}$)	37.4 ± 9.1	12.4–49.0	≥45
Carbohydrate intake ($g·kg^{-1}·d^{-1}$)	4.8 ± 0.8	2.8–6.4	6–10
Protein intake ($g·kg^{-1}·d^{-1}$)	1.8 ± 0.3	1.2–2.4	1.2–2.0
Fat intake (E%)	31 ± 4	24–37	20–35 E%

M_1, and four athletes only in M_2. One subject had self-reported amenorrhea at both M_1 and M_2. This participant had LEA (26.4 kcal·kg $FFM^{-1}·d^{-1}$), a high LEAF-Q score (12 at M_1 and 15 at M_2), and her concentrations of several metabolic hormones were below the lower limit of 95% confidence interval (CI) for the group mean. Namely, concentrations of insulin at M_1 (4.0, CI: 5.8–11.5) free T3 at M_1 (3.7 $pmol·l^{-1}$, CI: 4.2–5.2 $pmol·l^{-1}$) and at M_2 (3.0 $pmol·l^{-1}$, CI: 4.2–5.1 $pmol·l^{-1}$), free T4 at M_1 (10.0 $pmol·l^{-1}$, CI: 12.5–14.5 $pmol·l^{-1}$) and at M_2 (8.2 $pmol·l^{-1}$, CI: 12.5–14.0 $pmol·l^{-1}$), TSH at M_1 (0.9 $mU·l^{-1}$, CI: 1.9–3.1) and at M_2 (1.1 $mU·l^{-1}$, CI: 2.0–2.8 $mU·l^{-1}$), and leptin at M_2 (14.2 $ng·L^{-1}$, CI: 23.2–37.0 $ng·L^{-1}$) were below 95% CI.

On average, participants trained 601 ± 101 (454–811) hours during the follow-up year. Training volume was not associated with anthropometric or nutritional variables. Participants who had higher training volume generally performed better in the DP test at M_2 ($r = 0.49$, $p = 0.033$) and had higher absolute VO_{2max} ($L·min^{-1}$) at M_2 ($r = 0.57$, $p = 0.18$). In addition, training volume showed a statistical trend toward higher relative VO_{2max} ($ml·kg^{-1}·min^{-1}$) at M_2 ($r = 0.42$, $p = 0.092$), and toward increase in DP test time ($r = 0.43$, $p = 0.069$) and relative VO_{2max} ($r = 0.40$, $p = 0.11$) from M_1 to M_2.

Table 3 shows the correlations between performance, nutrition, body composition, and training volume. Athletes with higher relative VO_{2max} and VO_2 at OBLA at M_2 tended to consume more macronutrients, particularly CHO (Figure 1a) and protein, in relation to their BM. In addition, CHO and protein intake were positively associated with the DP test time, but in the case of CHO, this association did not reach statistical significance ($p = 0.051$). The only positive association between performance changes and nutrition was the positive association between protein intake and the change from M_1 to M_2 in relative VO_2 at OBLA ($r = 0.55$, $p = 0.013$). As shown in Table 3, absolute VO_{2max} and VO_2 at OBLA were positively associated with BM, BMI, and FFM while relative VO_{2max} and VO_2 at OBLA were negatively associated with BM, FM, and F% (Figure 1b). DP test time did not correlate with anthropometric variables. CMJ was negatively associated with BMI. Training volume was positively associated with absolute VO_{2max} and DP test time (Table 3).

BM at M_2 was negatively associated with CHO intake ($\tau_b = 0.33$, $p = 0.036$), FM at M_2 with protein intake ($\tau_b = 0.43$, $p = 0.006$) and F% at M_2 with both CHO (Figure 1c) and protein intake ($r = -0.50$, $p = 0.017$; $r = -0.66$, $p = 0.001$, respectively). There were no associations between nutritional intake and changes in anthropometric characteristics or between nutritional intake and hormone concentrations. In contrast, EA and CHO intake were negatively associated with the LEAF-Q score at M_2 ($r = 0.44$, $p = 0.042$; $r = 0.47$, $p = 0.026$, respectively).

In the stepwise linear regression analysis, DP test time at M_2 was explained by training volume ($R^2 = 0.24$, $p = 0.033$), absolute VO_{2max} by BMI and training volume ($R^2 = 0.71$, $p < .001$), relative VO_{2max} ($ml·kg^{-1}·min^{-1}$) by F% ($R^2 = 0.44$, $p = 0.004$), absolute VO_2 at OBLA

Table 2. Anthropometric characteristics, performance variables, hormone concentrations, blood lipids, and questionnaire scores in young female cross-country skiers in two measurement point (M_1, M_2) with one year interval (Mean ± SD). Significance of the differences between M_1 and M_2 is presented in *p* values and effect sizes (Cohen's d.).

	n	M_1	M_2	*p*	*d*
Anthropometrics					
Body mass (kg)	22	61.8 ± 7.1	64.5 ± 7.7	<.001	0.90
Height	22	168.4 ± 5.1	169.1 ± 5.1	.024	0.52
BMI (kg·m^{-2})	22	21.8 ± 2.2	22.4 ± 2.3	.001	0.78
Fat free mass (kg)	22	51.2 ± 5.2	52.6 ± 4.9	<.001	0.75
Fat mass (kg)	22	10.6 ± 3.4	11.9 ± 4.3	.038	0.44
Fat percentage (%)	22	17.0 ± 4.3	18.1 ± 4.9	.10	0.37
Performance					
VO_{2max} (L·min^{-1})	20	3.3 ± 0.3	3.3 ± 0.3	.41	0.18
VO_{2max} (ml·kg^{-1}·min^{-1})	20	54.1 ± 3.8	52.1 ± 4.3	.006	0.70
VO_2 at OBLA (L·min^{-1})	20	2.9 ± 0.3	2.9 ± 0.3	.45	0.17
VO_2 at OBLA (ml·kg^{-1}·min^{-1})	20	47.1 ± 3.4	46.4 ± 4.2	.26	0.24
DP (s)	22	492 ± 68	494 ± 70	.91	0.03
CMJ (cm)	21	30.9 ± 3.8	30.7 ± 4.1	.69	0.09
Hormone concentrations					
Insulin (mU·L^{-1})	23	8.9 ± 6.6	7.9 ± 4.3	.44	0.17
Cortisol (nmol·L^{-1})	23	554 ± 150	591 ± 161	.21	0.27
IGF-1 (nmol·L^{-1})	23	34.6 ± 10.0	36.0 ± 12.1	.57	0.12
Free T3 (pmol·L^{-1})	23	4.7 ± 1.1	4.6 ± 1.0	.50	0.14
Free T4 (pmol·L^{-1})	23	13.5 ± 2.4	13.2 ± 1.8	.66	0.09
TSH (mU·L^{-1})	23	2.5 ± 1.4	2.4 ± 0.9	.73	0.07
Leptin (ng·L^{-1})	23	24.3 ± 13.8	30.1 ± 15.9	.21	0.26
Testosterone (nmol·L^{-1})	23	0.8 ± 0.4	0.7 ± 0.3	.47	0.15
Questionnaires					
LEAF-Q	22	5.5 ± 3.6	7.3 ± 4.5	.08	0.40

BMI, body mass index; VO_{2max}, maximal oxygen uptake; VO_2 at OBLA, oxygen uptake in 4.0 mmol·l^{-1} lactate level; DP time from double poling test; CMJ, counter movement jump on the force plate; IGF-1, insulin-like growth factor 1; T3, triiodothyronine; T4, thyroxine; TSH, thyroid-stimulating hormone; LEAF-Q, The Low Energy Availability in Females Questionnaire. Statistically significant *p* values are bolded.

Table 3. Correlation coefficients (r or τ_b) between EA, macronutrient intake, and performance variables at the end of the follow-up period ($M_{2.}$).

	VO_{2max} ($L \cdot min^{-1}$)	VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	VO_2 at OBLA ($L \cdot min^{-1}$)	VO_2 at OBLA ($ml \cdot kg^{-1} \cdot min^{-1}$)	DP (s)	CMJ (cm)
EA ($kcal \cdot kg\ FFM^{-1} \cdot d^{-1}$) (*r*)	-0.36	0.31	-0.27	0.32	.27	0.22
CHO ($g \cdot kg^{-1} \cdot d^{-1}$) (*r*)	-0.21	**0.61****	-0.10	**0.63****	.42	0.39
Protein ($g \cdot kg^{-1} \cdot d^{-1}$) (*r*)	0.02	**0.54***	0.15	**0.62****	**.44***	0.29
Fat ($g \cdot kg^{-1} \cdot d^{-1}$) (*r*)	-0.24	0.42	-0.07	**0.53***	.26	0.23
Body mass (kg) (τ_b)	**0.41***	**-0.46****	**0.42****	**-0.41***	-.09	-0.28
Body mass index ($kg \cdot m^{-2}$) (*r*)	**0.74*****	-0.40	**0.64****	-0.40	.13	**-0.50***
Fat free body mass (kg) (*r*)	**0.76*****	-0.37	**0.72*****	-0.31	.09	-0.27
Body fat mass (kg) (τ_b)	0.15	**-0.52****	0.20	**-0.45****	-.23	-0.27
Fat percentage (%) (*r*)	0.24	**-0.67****	0.21	**-0.61****	-.38	-0.37
Training volume ($h \cdot y^{-1}$) (*r*)	**0.57***	0.43	0.39	0.22	.41*	0.04

EA, energy availability; CHO, carbohydrate intake; VO2max, maximal oxygen uptake; VO2 at OBLA, oxygen uptake in 4.0 $mmol \cdot l^{-1}$ lactate level; DP, time from double poling test; CMJ, counter movement jump on the force plate; r, variable analyzed using Pearson´s r; τb, a nonparametric variable that is analyzed by using Kendall's tau-b; * significant correlation $p < .05$; ** $p < .01$. Statistically significant correlations are bolded.

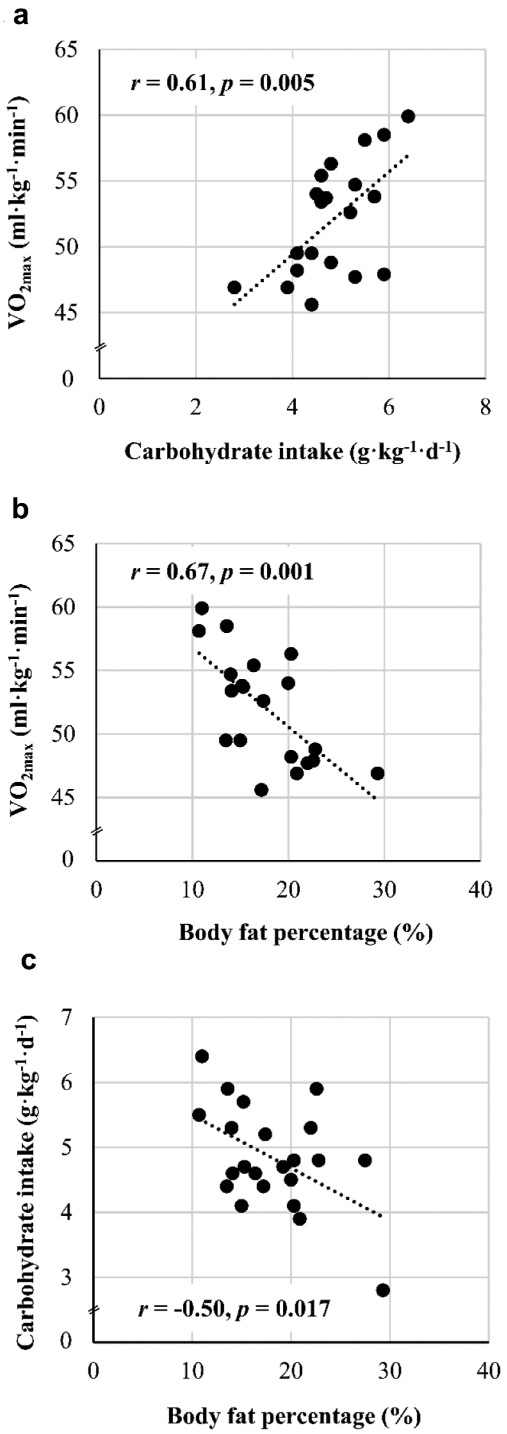

Figure 1. Associations between carbohydrate intake and maximal oxygen uptake (VO_{2max}) (A), body fat percentage and VO_{2max} (B), and body fat percentage and carbohydrate intake.

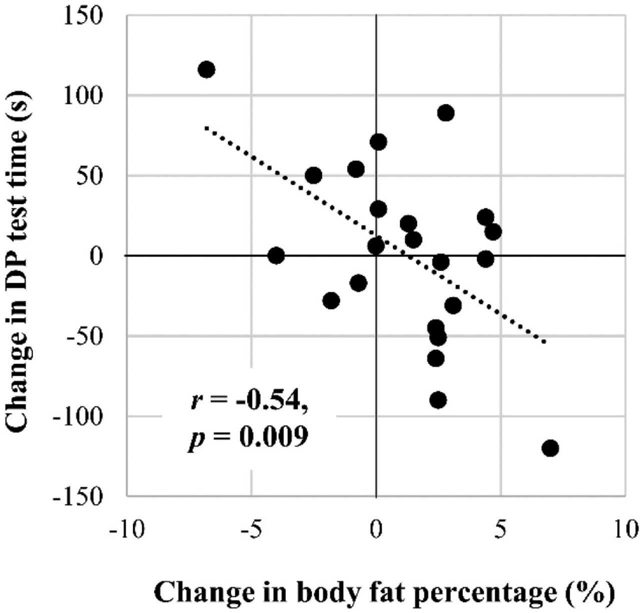

Figure 2. Association between changes in body fat percentage and double poling (DP) test time.

by FFM ($R^2 = 0.64$, $p < .001$), and relative VO_2 at OBLA by F% ($R^2 = 0.47$, $p = 0.003$). Changes from M_1 to M_2 in the DP test time were explained by changes in F% ($R^2 = 0.25$, $p = 0.029$, Figure 2). Changes in VO_{2max}, VO_2 at OBLA, or CMJ were not explained by training volume, nutrition, or anthropometric characteristics.

4. Discussion

The present study aimed to clarify how 12-day mean EA and macronutrient intake in field-based situations are associated with performance, anthropometric characteristics, hormonal concentrations, LEAF-Q points, and/or training volume. The results indicated that young female XC skiers with higher CHO and protein intake had higher VO_{2max} and VO_2 at OBLA in relation to their BM as well as better DP performance. Nevertheless, anthropometric characteristics and higher training volume seemed to be the most important factors explaining endurance performance. The results also indicated that lower EA and CHO intake were associated with higher LEA risk (high LEAF-Q score).

The 12-day mean EA (37.4 ± 9.1 kcal·kg $FFM^{-1}·d^{-1}$) was at a suboptimal level in light of the EA recommendation for female athletes [3]. In addition, four (17 %) of the participants had LEA. These values are comparable to those previously reported from a shorter follow-up period [11]. On average, the young female XC skiers appear to have EA that is above the "historical" LEA threshold of 30 kcal·kg $FFM^{-1}·d^{-1}$ [3]. Notably, this threshold is based on the short-term laboratory interventions, that showed impaired endocrine [27] and bone turnover markers [28]. Unfortunately, the minimum EA level that can be maintained over longer periods (weeks, months, or years) without negative effects on health and performance is currently unknown and likely individual [2]. Therefore, we do not know with certainty whether the mean EA observed in the present study ultimately affects long-term health and/or performance.

EA assessment in field conditions have several methodological challenges that can reduce the validity of the observations [2,29]. Consequently, researchers have recommended the use of surrogate markers of LEA (i.e. blood parameters and/or questionnaires) for screening purposes [2,29]. As such, the assessment of LEAF-Q scores and blood hormone analyses were included in the study protocol. As expected, lower EA was associated with a higher risk of LEA determined by LEAF-Q score, and indeed, all of the athletes with LEA, as determined by food diaries, had a LEAF-Q score ≥ 8 at the end of the follow-up period. These findings suggest that food and training logs may provide important information regarding the risk of LEA if the recording period is long enough.

Blood hormone concentrations remained similar from M_1 to M_2 and were not associated with other variables. This could be due to the fact that hormonal disturbances are typically reported as a result of LEA [27,30], which was avoided by most participants in the present study. Indeed, the only amenorrheic athlete had insulin, free T3, free T4, TSH, and leptin concentrations that were among the lowest of the entire group (below the lower limit of 95% CI). Previous studies have shown decreased insulin, free T3, and leptin are associated with LEA and amenorrhea, while the results for free T4 and TSH are variable [30]. In addition to decreased levels of metabolic hormones, the amenorrheic participant was identified as having LEA determined by food and training logs and was classified as high risk for LEA based on LEAF-Q. This case suggests that food and training logs, LEAF-Q, and measurement of specific hormones could all be successfully used for screening purposes in athletes with long-term LEA. Nevertheless, this conclusion is limited because we did not perform a clinical diagnosis to exclude other possible causes of amenorrhea. In addition, CVs of the hormone concentrations were relatively high and thus the interpretations should be made with caution.

As in previous studies in female XC skiers [10,11], CHO intake ($4.8 \pm 0.8\ g \cdot kg^{-1} \cdot d^{-1}$) was lower than recommended for endurance athletes training 1–3 h per day ($6–10\ g \cdot kg^{-1} \cdot d^{-1}$ [12]), while protein ($1.8 \pm 0.3\ g \cdot kg^{-1} \cdot d^{-1}$), and fat intake (31 ± 4 of total EI) were within the recommended range (protein $1.2–2.0\ g \cdot kg^{-1} \cdot d^{-1}$; fat 20–35% of total EI [12]). Interestingly, athletes with higher CHO and protein intake tended to have better relative VO_{2max}, VO_2 at OBLA, and DP test time in the end of the follow-up period, which suggest that eating practices that include higher amounts of these macronutrients might be beneficial for long-term performance adaptations. This finding is not surprising as the intensities used in XC skiing competitions and key training sessions are reliant on CHO based fuels [5,8], and relatively high CHO intake is needed to replenish muscle glycogen stores between training sessions [9]. In addition, adequate CHO intake is important to minimize the risk of illness [31] and overtraining [32]. Protein, in turn, plays an essential role as a substrate for recovery and trigger for adaptation after exercise [33], thus adequate amount of protein is needed for recovery and training adaptation. Given that high load endurance training [34], whole body training [35], adolescence [36], energy deficiency [37] and low CHO availability [38] may increase protein requirements, a protein intake in the upper range or slightly above current recommendations [12] may have been beneficial for the participants in the present study.

Despite the associations between nutrition and performance, the strongest factors explaining better performance were related to leaner body composition and higher training volume. Training volume during the one-year follow-up explained 24% of the variation in the DP test time at the end of the study, while 25% of the annual changes of the DP test time were explained by changes in F%. This is consistent with the findings of Jones et al. (2021), who reported that changes toward leaner body composition favor the development in XC ski performance [6]. In particular, increased upper-body strength and lean mass can lead to improved DP performance [6,39]. In addition, it is known that a higher training volume is an important factor that differentiates elite XC skiers from national level athletes [40], which highlights the importance of high training volume for performance development.

Lower F% was beneficial for relative VO_{2max} and explained 44% of the variation, while F% alone explained 47% of the variation in relative VO_2 at OBLA. Although mean relative VO_{2max} and VO_2 at OBLA decreased and BM, FM, and F% increased during the follow-up, changes in VO_{2max} and VO_2 at OBLA could not be explained by changes in anthropometric characteristics. Interestingly, lower BM, FM, and F% were associated with higher EA and macronutrient intake but there were no associations between nutrition and changes in anthropometric characteristics. Together these findings suggest that associations between nutrition, anthropometric characteristics, and maximal and submaximal aerobic performance have likely developed over a longer period of time than what was investigated. Nonetheless, the better performing athletes tended to have higher macronutrient intakes, which may have promoted their development over the years. Notably, the results of this study suggest that restricting EA or macronutrient intake is not an effective way to modify BM and/or body composition in young female endurance athletes. In addition, the results highlight that the adequacy of an athletes´ dietary intake cannot be determined based on BM or body composition [1,41,42].

Although problems with the validity and reliability of assessing dietary intake and EA in field conditions [2,29] can be considered as the main limitation of the present study, the methods used to minimize methodological errors were the strength of the study. As real-world EA assessment has been criticized as a short recording period only gives a snapshot of an athlete’s dietary and training practices [2,19], the present study aimed to provide an overall picture of nutritional and training practices by analyzing a total of 12 days of nutrition and training data from different parts of the training year. Although misreporting may limit the validity of the food logs, comprehensive written and verbal instructions, weighted food logs and highly motivated participants increased the validity of the present data. To increase the validity of EEE assessment, laboratory-based associations of EE, VO_2, and heart rate were utilized [2]. Unfortunately, for practical reasons, we could not measure body composition using the gold standard method DXA and the use of the less precise bioimpedance method is a minor limitation of the study. To minimize potential confounding factors, the measurement was always performed after an overnight fast and after the participants had visited the toilet. In addition, we were not able to standardize the phase of the menstrual cycle, which may have influenced on the bioimpedance analysis as well as on the other variables investigated. Additionally, while this study lacks assessment of competition performance, all performance parameters included are considered important for assessing XC skier development [15]. Furthermore, a recent study by Talsnes et al. (2021) showed that laboratory-based VO_{2max} incremental running test and roller ski performance tests have a strong positive correlation with competition performance [43].

5. Conclusions

Anthropometric characteristics, especially F%, and training volume appeared to be the most important factors explaining different indicators of a young female XC skier's performance. In addition, lower CHO and protein intake were associated with higher BM, FM, and F% as well as with lower VO_{2max} and DP performance. Taken together, these findings suggest that although lean body composition may be beneficial for endurance performance, it should not be sought by restricting dietary intake. Indeed, athletes with lower CHO intake and EA not only had poorer performance, but also an increased risk of self-reported physiological symptoms of LEA. These findings highlight the importance of adequate EA and macronutrient intake to support performance and overall health.

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Disclosure statement

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