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Resting metabolic rate and exercise energy expenditure in Swiss elite biathletes

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1 Abstract

Background

Low Energy Availability (LEA) and Relative Energy Deficiency in Sport (REDs) are common among the endurance disciplines, negatively impacting affected athletes' long-term health and performance. Several indicators are currently used to diagnose LEA and REDs, including body composition, scores from validated questionnaires, performance and energy balance. The objectives of the current investigation were to 1) assess the resting metabolic rate (RMR) and to explore potential cases of RMR suppression and 2) establish the exercise energy expenditure (EEE) profiles and associations with power output and heart rate in elite biathletes.

Methods

Thirteen elite biathletes from the Swiss National Team (seven women and six men, age: 27.5 ± 3.9 and 26 ± 2.8 years, $\dot{V}O_2max$: 56.1 ± 3.6 and 69.2 ± 3.7 ml·kg^{-1}·min^{-1}, respectively) underwent an RMR and EEE assessment in addition to their routine National team performance testing in June 2023. Measured (mRMR) and predicted (pRMR) RMR were used to determine RMR_{ratio} as a surrogate marker of LEA. Furthermore, the athletes completed a submaximal graded exercise test protocol in the skating technique, which included 4 x 3 x 4 min of skiing (4 intensities, 3 sub-techniques, 4 min each) to determine EEE through indirect calorimetry. Linear regression analysis was performed to analyze the correlations between EEE scaled for body mass and power output, heart rate (HR), and rating of perceived exertion (RPE). These correlations were further differentiated by sex and sub-technique.

Results

mRMR varied from 1186 - 2062 kcal·24h^{-1} and RMR_{ratio} values ranged from 0.79 – 1.04, with inter-individual differences of up to 500 kcal·24h^{-1} observed among male and female athletes. Four out of thirteen athletes demonstrated suppressed RMR with RMR_{ratio} < 0.9. EEE_{rel} demonstrated a linear relationship with increasing intensity. Very large associations were found between EEE_{rel} and relative power output (R^2 = 0.88). Large correlations were observed between EEE_{rel} and HR (R^2 = 0.64) and RPE (R^2 = 0.58). Individual regressions demonstrated nearly perfect relationships between EEE_{rel} and HR (R^2 = 0.94 – 0.99). Large inter-individual differences were observed in gross efficiency (GE) across athletes ranging from 15 – 20%, with differences also observed between sub-techniques at around ~15.5% (G4), ~16.5% (G3), and 18% (G2).

Conclusion

This investigation explored the RMR and EEE profiles of thirteen elite biathletes. Our results demonstrated significant variations in RMR, with ~30% showing suppressed RMR as a potential surrogate indicator for LEA. This emphasizes the importance of tailoring nutrition strategies to each athlete's energy needs to support their bodily functions adequately. The strong relationships between EEE_{rel} and HR could be used to obtain accurate and individualized information on caloric expenditure during steady-state submaximal endurance training and optimize fueling during training and competition.

KEYWORDS: Nordic skiing, basal metabolic rate, cross-country skiing

2 Executive Summary

2.1 Description of research topic

In competitive endurance sports, issues surrounding eating disorders have long been a concern for the health and performance of athletes. The underlying conditions, namely low energy availability (LEA) and relative energy deficiency in sport (REDs) describe the difficulty for athletes to maintain adequate energy balance during training and competition. With studies reporting high prevalence in endurance athletes suffering from the negative long-term health impact of LEA and REDs as well as anecdotal evidence in regards to its presence in biathlon, it is imperative to evaluate effective tools to assess and manage these conditions and ensure proper fueling for training and competition.
In response to these growing concerns, Swiss-Ski has implemented a long-term interventional program called "FUEL", aiming to prevent REDs and eating disorders (ED) and to provide appropriate care for athletes. FUEL is based on a validated behavioral change protocol [1] and involves a four-month educational program aiming to increase the nutritional knowledge and behavior of athletes and staff, as well as providing proper one-on-one care for those affected by REDs and ED. FUEL will be conducted as a longitudinal project over a period of three years from 2023 – 2025 in the Swiss biathlon, ski jumping and cross-country skiing National Teams. The senior athletes in the biathlon team are completing the program in the current 2023/2024 season, while the U21 team biathletes will be included in the following season.
The FUEL intervention period is encapsulated by a comprehensive pre- and post-test diagnostic. The assessments include anthropometric characteristics, namely body fat content and bone mineral density (BMD), resting metabolic rate (RMR), exercise energy expenditure (EEE) profiles, performance, hormonal profiles and validated questionnaires. In addition, food intake and training will be recorded following the baseline assessment and two certified sport nutritionists will accompany the intervention. The content of this IBU research grant programme report has been slightly modified from its original proposal due to changes in the management of the ski federation and subsequent collaborations and has focused on the baseline assessments concerning energy balance.

2.2 Objectives

This investigation pursued the following objectives in regards to the energy profiling of thirteen Swiss senior National team biathletes:

1) Establish RMR profiles and identify athletes with suppressed RMR indicated by measured and predicted RMR (RMR_{ratio}) < 0.9.
2) Establish ski-specific individual EEE profiles via submaximal treadmill protocol in different skating sub-techniques to be used for the estimation of daily energy expenditure. This involves the analysis of individual relative caloric expenditure (EEE_{rel}) – heart rate (HR) relationships that allow for accurate evaluation of the energy expenditure for a given submaximal, steady-state training session.

2.3 Highlighting the main findings

RMR

- RMR among elite biathletes varied by up to 500 kcal·24h^{-1} (total range: 1186 - 2062 kcal·24h^{-1}) in both sexes, with RMR_{ratio} values ranging between 0.79 – 1.04

- 30% of athletes (three female and one male biathlete) demonstrated suppressed RMR ($RMR_{ratio} < 0.9$)

EEE

- Very large associations were found between EEE_{rel} and relative power output ($R^2 = 0.88$)
- Large correlations were observed between EEE_{rel} and the two internal load variables HR ($R^2 = 0.64$) and RPE ($R^2 = 0.58$)
- Individual regressions demonstrated nearly perfect relationships between EEE_{rel} and HR ($R^2 = 0.94 – 0.99$)
- Large inter-individual differences were observed in gross efficiency (GE) across athletes ranging from 15 – 20%. When separated by skating sub-techniques, GE showed varying values at ~15.5% (G4), ~16.5% (G3), and 18% (G2)

Conclusions

The inter-individual variations during the RMR assessment, translates into a considerable difference of up to 500 $kcal \cdot 24h^{-1}$ when comparing two athletes of the same sex. Although normalizing the caloric expenditure to body mass reduced the variability, a substantial difference remained. These data demonstrate the significance of tailoring daily fueling to each athlete independent of the energy demands of other daily activity, training, and competition. The meal size and frequency should not be judged based solely on an athlete's "size", but fit an individual's RMR. Coaches and support personnel may find it helpful to know that two people with the same height, weight, age, sex, and body composition can have different RMRs and therefore require different amounts of energy throughout the day. With four of thirteen athletes (30%) showing suppressed RMR_{ratio} in our analysis, potential issues surrounding LEA and REDs might be indicated.

There was a very strong linear relationship between EEE_{rel} and relative power. More importantly, EEE_{rel} and HR showed not only strong correlations on a group level, but very strong individual relationships, establishing a foundation for accurate calculation of EEE via HR monitoring during ski-specific training. When compared to data calculated from a sports watch, these individual HR-based regression equations are expected to provide more exact information on the energy requirements for a given submaximal, steady-state endurance training session. In addition, GE results revealed a substantial inter-individual variance in our sample, with female biathletes appearing to have higher GE at higher power outputs than men. Individual GE profiles across different exercise intensities, could further give objective and relevant information for coaches' technique teaching.

Recommendations

The following recommendations could be concluded based on our results:

- Significant inter-individual variability in RMR of up to 500 $kcal \cdot 24h^{-1}$ underline the necessity for individual day-to-day fueling and support staff awareness of athletes' energy needs
- Using RMR during routine diagnostics has the potential to detect athletes with suppressed basal metabolic function, which, when combined with other diagnostic techniques (questionnaires, performance, hormonal profiles), could provide an objective surrogate marker for LEA and REDs.
- Individually calculated HR profiles may effectively estimate EEE during continual submaximal skiing exercise, allowing athletes and coaches to determine the energy requirements of a specific training session and hence optimize nutritional behavior

- EEE assessments performed with accurate measurement equipment (i.e., Douglas Bag method) could also be utilized for technique training by coaches to assess small changes in skiing efficiency between sub-techniques.

3 Report

3.1 Research Subject

Competitive biathletes and cross-country skiers have long been in the spotlight regarding body mass, body image and associated eating disorders. While efforts to pull athletes preemptively out of training and competition on the World Cup stage have served as cautionary tales in recent years, young athletes remain to be at risk of developing disorders caused by a lack of energy balance throughout their career [2]. Especially elite female athletes in weight-dependent disciplines are known to be frequently affected by disordered eating behaviors [3]. The International Olympic Committee and other sport governing bodies have proposed the term Relative Energy Deficiency in Sport (REDs) to describe the decline in physiological functioning induced by a caloric deficit that leads to a variety of symptoms, including impairments of metabolic rate, menstrual function, bone health, immunity and cardiovascular health [4]. Low energy availability (LEA) is the underlying mechanism that causes REDs [5] and refers to the state of insufficient energy intake (EI) by an individual relative to their energy expenditure [6]. Energy availability (EA) is hereby the energy remaining for physiological functions once the exercise energy expenditure (EEE) has been taken into account (EA = EI – EEE) [4]. Diagnosis is most often performed by combining specific questionnaires, bone density assessments and recordings of energy intake (EI) [7,8].

Approximately 25% of athletes are at moderate to high risk of LEA and subsequent development of REDs [7,9] with some estimations suggesting a prevalence of up to 60% in certain cohorts [10]. Athletes in sports where a higher power-to-body-mass ratio is beneficial are at an increased risk of LEA [4,11]. Although this certainly applies to competitive biathletes and cross-country skiers, scientific evidence on prevalence of LEA and REDs in these populations are limited. Recent studies have shown that up to 70% of young female cross-country skiers fail to meet recommended energy intake [12], with even more pronounced occurrence of impaired EA in elite cross-country skiers [13]. While deliberate LEA might be appropriate for some athletes to achieve optimal body mass for performance, unintentional failure to consume sufficient energy, i.e., inadvertent LEA, is more often the case and has compromising consequences on the body’s ability to adapt to a given training load. Aside from a decrease in athletic performance, a prolonged state of LEA is associated with lower estrogen levels in females and lower testosterone in males [7], lower resting metabolic rate (RMR) [14], increased percentage of body fat and muscle breakdown [4], lower bone mineral density (BMD) and subsequent risks for stress fractures [15,16]. Thus, LEA is not only of concern as contributor to poor athletic performance due to associated detrimental endocrine effects, but entails potential long-term damages to physiological development incurred from unfavorable metabolism and a shift in hormone profile.

The most effective approach to limit the adverse impact of REDs on performance and health outcomes remains adequate nutrition [2]. However, while awareness and guidance represent the cornerstone of nutritional interventions in sport, there is still a lack of knowledge regarding the methods to assess EA [10], especially in regards to sport and sex-specific exercise energy expenditure during training. In this context, individual profiles of metabolic rate during rest and exercise can improve the quality and data-based approach during the nutritional counselling. In the spring of 2023 Swiss-Ski has launched the FUEL project, to improve the nutritional knowledge behavior among athletes and staff.

3.2 Objectives

Within the FUEL project, this investigation aimed to 1) determine the resting metabolic rate as part of the clinical evaluation of risk factors for LEA and REDs and 2) establish ski-specific (EEE) profiles to estimate the HR-based caloric expenditure during endurance training for the senior Swiss National team biathletes. Results from both RMR and EEE, among other diagnostic measures, form the basis for screening and managing athletes at risk for LEA and REDs.

3.3 Material and Methods

3.3.1 Participants

Thirteen Swiss National Team biathletes (seven women and six men) volunteered to participate in this project as part of an extension to the regular performance testing (Table 1). Before participating, all skiers received a health assessment from the team physician and were found to be free of injury and disease. Participants were free to withdraw at any time during the project without having to provide a reason for their decision.

Table 1. Anthropometric and physiological characteristics of participants.

	Females	Males
n	7	6
Age (y)	27.5 ± 3.9	26.3 ± 2.8
Body height (cm)	167 ± 6.5	177 ± 3.8
Body mass (kg)	64.7 ± 8.1	70.7 ± 6.3
Body fat (%)	22.5 ± 1.8	12.8 ± 1.0
HR_{rest} (bpm)	52 ± 8	47 ± 8
RMR ($kcal \cdot 24h^{-1}$)	1468 ± 188	1779 ± 151
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	56.1 ± 3.6	69.2 ± 3.7

Data presented as mean ± standard deviation (SD). HR_{rest} = resting heart rate, $\dot{V}O_2max$ = maximum oxygen consumption.

3.3.2 Project design

The FUEL project involves three main components: counseling and education, diagnostics, and energy balance measurements (see Figure 1). The project involves an international collaboration with Prof. Monica Klungland Torstveit from the University of Agder, NOR and Prof. Anna Melin from Linnæus University (SWE), two renowned experts and members of the IOC consensus statement team on REDs. FUEL is embedded in the health management of Swiss-Ski and is accompanied by a PhD student and sport nutritionist. FUEL extends over three years, starting with the senior biathletes and ski jumpers in the first year, followed by junior athletes and other disciplines in year two (see Figure 2). The intervention consists of various online educational videos concerning sports nutrition and health and is accompanied by personal counseling sessions with a sports nutritionist (see Figure 3). The IBU research grant application focused on the part of the energy balance of senior biathletes.

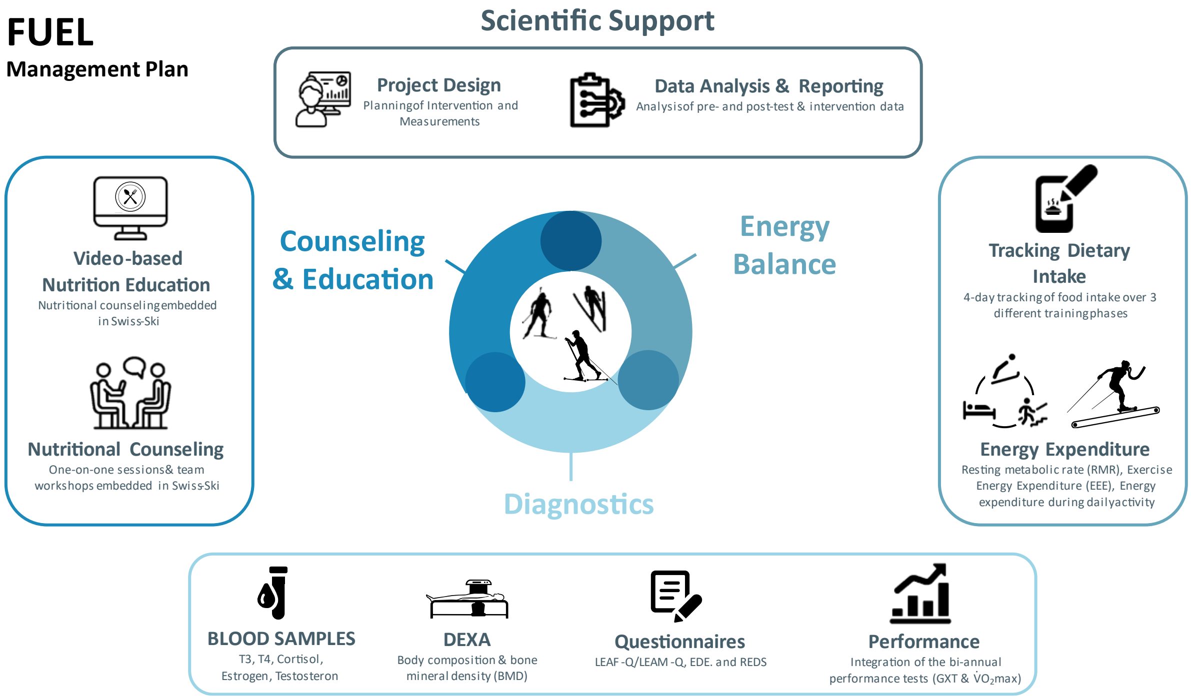

Figure 1. Overview of the FUEL project components, including counseling and education, diagnostics, and energy balance. A team of scientific experts in the domains of LEA and REDs, sports medicine, and performance accompany the project.

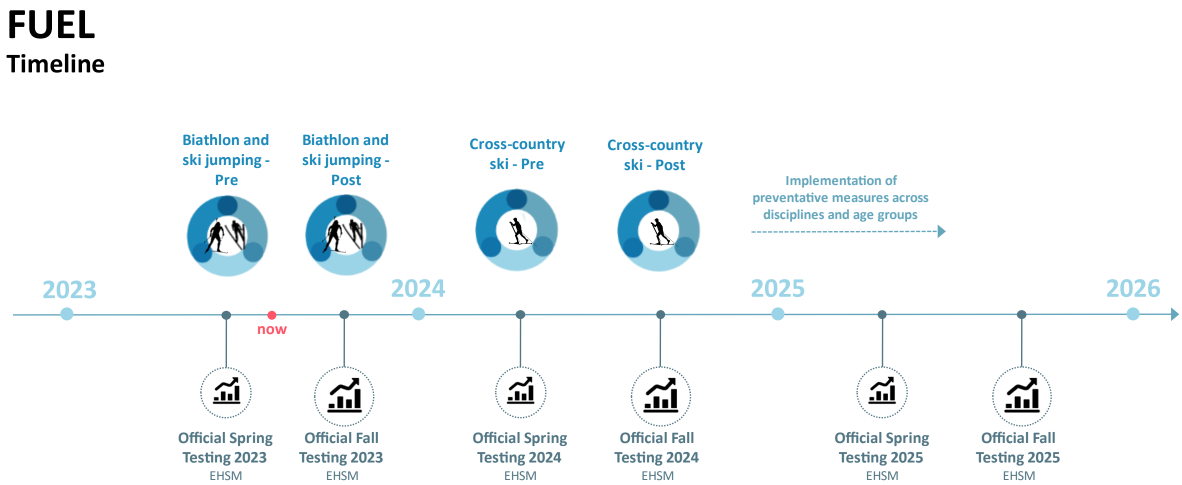

Figure 2. Timeline of the data collection for the three Nordic disciplines biathlon, ski jumping and cross-country skiing during the project.

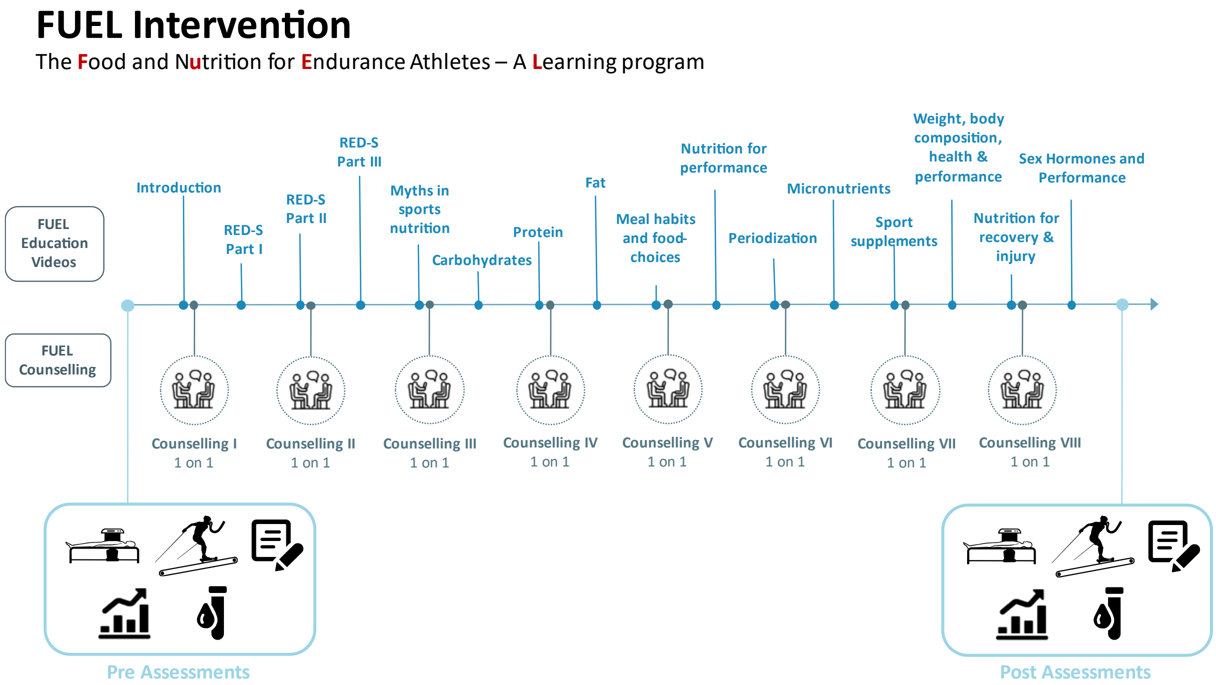

Figure 3. Timeline of the dual interventional content of the FUEL project, involving educational videos on sports nutrition and health, and individual counseling sessions with a sports nutritionist. The complete diagnostic and energy balance components are measured before and after the intervention.

3.3.3 Test preparation and anthropometrics

Participants were instructed to adopt the same pre-competition preparation before both testing sessions, including dietary intake, hydration state, and caffeine consumption. The skiers were required to refrain from strenuous exercise within 24 h before the trial. Standardized laboratory conditions were maintained and controlled throughout the study period (air temperature: 23.1 ± 1.2 °C; relative humidity: 50.0 ± 8.0%). Body mass, lean body mass, and fat mass were determined in a fasted state during a 10-min measurement in the supine position using dual-energy X-ray absorptiometry (DXA; Lunar iDXA, GE Medical Systems, Chicago, IL, USA). Trained medical personnel conducted these examinations at the Swiss Olympic medical facility on the morning of the first trial during each measurement period.

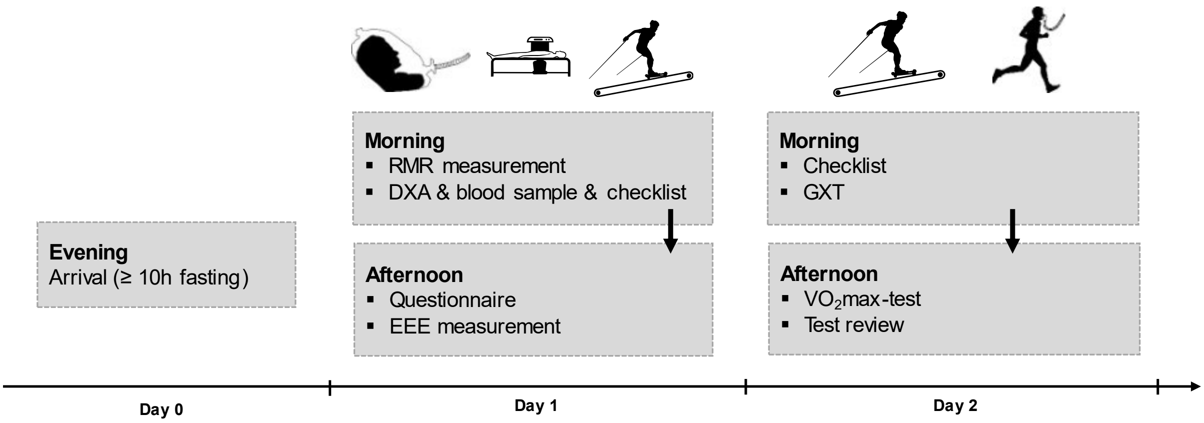

Figure 4. Timeline of the two-day diagnostics with the metabolic assessments performed on day 1 and performance measures on day 2. RMR = resting metabolic rate, DXA = dual-energy X-ray absorptiometry, EEE = exercise energy expenditure, GXT = graded exercise test, $\dot{V}O_2max$ = maximal oxygen uptake.

3.3.4 Resting metabolic rate (RMR)

The RMR test was conducted between 7 am and 11 am using a ventilated hood system (Moxus, AIE Technology, Inc., Bastrop, TX, USA), measuring O_2 consumption and CO_2 production through indirect calorimetry. The participants were housing in the facilities of the Swiss Federal Institute of Sport Magglingen and arrived at the laboratory by bus, with the instruction to avoid any physical activity after waking up. They were in a fasted state for at least 10 hours before the test. A plastic sheet was placed over the participant's upper body to form a seal between the air inside and outside the hood. The test was conducted according to the manufacturer's guidelines in a quiet room with dim lighting and a thermoneutral environment. The athletes were in a supine position for 15 minutes prior to the RMR measurement and were instructed to breathe normally, not talk, fidget, or sleep throughout the 30-minute measurement period. The flow calibration was performed using a 3-L calibration syringe and gas analyzers were calibrated using two standard gas concentrations before every measurement. RMR was derived from the O_2 consumption and CO_2 production using the Weir formula [17]. A 5-minute steady-state period was identified with a CV of less than 10% to determine the measured RMR (mRMR) with a custom-made Excel template [18]. The predicted RMR was derived from Cunningham [19], and the RMR_{ratio} was derived from mRMR/pRMR. Suppressed RMR was defined as $RMR_{ratio} < 0.90$, and normal RMR was defined as $RMR_{ratio} > 0.90$ [20].

3.3.5 Exercise energy expenditure (EEE)

The test to determine EEE was performed on a treadmill using skating roller skis based on a modified protocol by Nordhoof et al. [21] and was preceded by a standardized 10-min warmup on a cycle ergometer at 1.50 $W \cdot kg^{-1}$ for women and 1.7 $W \cdot kg^{-1}$ for men. The biathletes completed four interval blocks consisting of 3 x 4 min with increasing intensity corresponding to approximately the first four intensities in a five-zone endurance intensity model (see Figure 5). In each intensity block, the three skating sub-techniques G4, G3 and G2 were used based on the treadmill incline (1.1, 2.9, 6.8°) and speed in a randomized order. Passive rest was 120 s between consecutive bouts for the first two interval blocks and 150 s for two remaining blocks. Female and male biathletes started at different velocities, with three overlapping intensity blocks. Expired air was collected during the last minute of each 4-min interval via a two-way non-rebreathing valve (Hans Rudolph Inc., Shawnee, KS, USA) and plastic tubing into 100 L Douglas bags (Cranlea Human Performance Ltd, Birmingham, United Kingdom). Expiratory gas concentrations and volume were analyzed after each test using a custom-built Douglas bag metabolic cart. Before a series of bags was analyzed, high-precision O_2 and CO_2 dry gas analyzers (S-3A/I and CD-3A, AEI Technologies, Inc., Bastrop, TX, USA) were calibrated using two-point calibration with precision-analyzed gas mixtures. $\dot{V}O_2$ and $\dot{V}_E$ were calculated using F_EO_2, F_ECO_2, and bag volume, considering ambient O_2 and CO_2 concentrations, air temperature, relative humidity, and barometric pressure. EEE was calculated based on the formular from Frayn [22] and expressed in absolute and relative (EEE_{rel}, $kJ \cdot min^{-1} \cdot kg^{-1}$) terms. GE was determined as power output divided by the metabolic rate. HR was continuously measured and averaged over the last 60 s of each stage. During the breaks, the test instructor collected a capillary blood sample to determine the BLa, while the skiers reported their rating of perceived exertion on a 6 – 20 Borg scale [23].

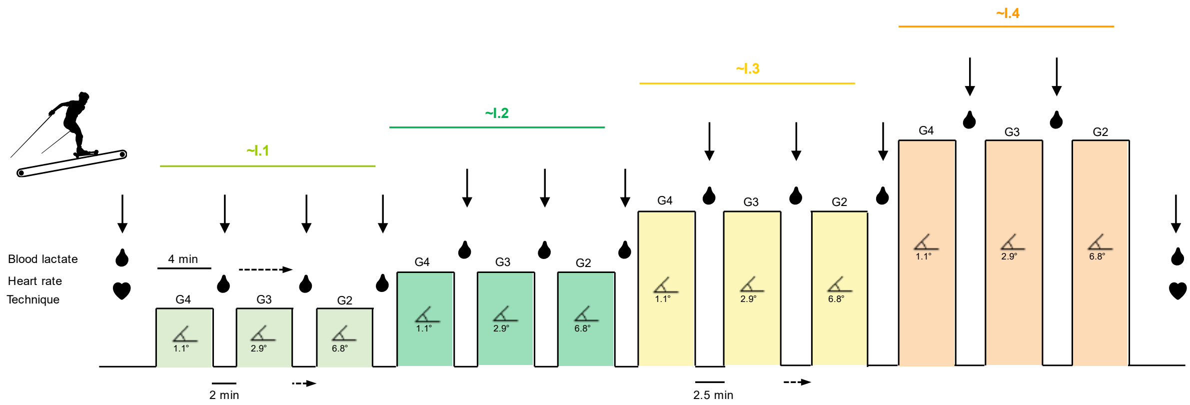

Figure 5. Roller ski skating test protocol to determine exercise energy expenditure across different intensities. G4, G3 and G2 refer to the incline-appropriate sub-techniques (gears). Order of sub-technique and appropriate treadmill velocity and incline were randomly assigned.

3.3.6 $\dot{V}O_2max$ test

$\dot{V}O_2max$ was determined while running on the treadmill. Before the test, skiers completed a 20-min warmup with progressive intensity. The $\dot{V}O_2max$ test started at an incline of 6° and a treadmill velocity of 2.50 $m{\cdot}s^{-1}$ for men and 1.90 $m{\cdot}s^{-1}$ for women, with a stepwise velocity increase every 60 s of 0.30 $m{\cdot}s^{-1}$ until task failure. Task failure was defined as the moment when the athlete could not maintain a position within 2 m of the front of the treadmill, marked by an elastic cord stretched across the treadmill. Expired air was collected at 30-s intervals with the same equipment described above. The filling of bags started approximately 3 min before the anticipated test termination. $\dot{V}O_2max$ was defined as the highest oxygen uptake measured in one bag, meeting the criteria of 1) a filling time of > 25 s and 2) an increase in $\dot{V}O_2$ from the previous bag of < 150 $mL{\cdot}min^{-1}$ [24].

3.3.7 Materials and equipment

All treadmill tests were conducted on a large motorized treadmill (3 × 4.5 m, Poma, Porschendorf, Germany) using skating roller skis (Marwe Skating 610 A, wheel type US6, Marwe OY, Hyvinkää, Finland). Skiers used XC ski poles (Triac 3, Swix, Lillehammer, Norway) equipped with custom-made pole tips for treadmill use. The roller skis were warmed up for a minimum of 10 min before each test [25]. The average power output for the EEE test was calculated as the sum of power against gravity and rolling friction:

$$P_t = P_g + P_f \tag{1}$$

$$P_g = m \cdot g \cdot v \cdot \sin(\alpha) \tag{2}$$

$$P_f = m \cdot g \cdot v \cdot \cos(\alpha) \cdot \mu \tag{3}$$

where P_t is the total power output, P_g the work against gravity, P_f the work against rolling friction, m the mass of the skier including equipment, g the gravitational constant, v the treadmill velocity, α the inclination of the treadmill, and μ the coefficient of friction. μ for the roller ski was determined before and after the test period via the tow test on the treadmill by the same investigator as previously described [26]. The μ value (mean ± SD) for the roller ski was 0.02388 ± 0.00075. All HR measures were monitored using a chest belt and analyzed with Firstbeat Sports (Firstbeat Technologies Oy, Jyväskylä, Finland). BLa was determined via capillary blood collected from a 20-μL sample taken from the skier's ear lobe, hemolyzed in a pre-filled micro-test tube, and analyzed in a lactate analyzer (Biosen C-Line, EKF Diagnostics, Barleben, Germany).

3.3.8 Statistical analysis

Test data are reported as mean ± SD unless otherwise indicated. The normal data distribution was assessed visually using quantile-quantile (Q-Q) plots and Shapiro-Wilk test statistics. A three-way repeated measures ANOVA was performed to evaluate the effects of intensity, technique, and sex on EEE_{rel} during the treadmill test. Linear regression analysis was conducted to explore the relationships between EEE_{rel} and power output, HR, RPE and GE. All analyses were performed using R v.4.0.2 [27].

3.4 Results

3.4.1 Resting metabolic rate

The mRMR ranged from 1186 kcal·24h^{-1} to 2062 kcal·24h^{-1} in the participants, with RMR_{ratio} values ranging between 0.79 – 1.04 (see Table 2). The inter-individual differences of up to 500 kcal·24h^{-1} were observed in both men and women (see Figure 2). Three female and one male biathlete demonstrated suppressed RMR based on RMR_{ratio}. The differences were reduced when RMR was normalized for fat free mass (see Figure 6).

Table 2. Measured and predicted resting metabolic rates in male and female biathletes.

Participant	Sex	HR_{rest} (bpm)	mRMR (kcal·24h^{-1})	pRMR (kcal·24h^{-1})	RMR_{ratio}
1	f	42	1718	1811	0.948
2	f	55	1702	1631	1.044
3	f	54	1542	1659	0.929
4	f	62	1482	1692	0.876
5	f	62	1367	1519	0.900
6	f	41	1281	1516	0.845
7	f	47	1186	1406	0.843
8	m	49	2062	2064	0.999
9	m	48	1815	1785	1.017
10	m	60	1798	1769	1.016
11	m	37	1764	1769	0.997
12	m	49	1643	1818	0.904
13	m	37	1589	2005	0.792

Data presented for each participant. HR_{rest} = resting heart rate, mRMR = measured resting metabolic rate, pRMR = predicted RMR according to Cunningham, RMR_{ratio} = ratio derived by dividing mRMR by pRMR.

3.4.2 Exercise Energy Expenditure

EEE_{rel} demonstrated a linear relationship with increasing intensity (see Figure 8). There was no statistically significant three-way interaction between intensity level, sub-technique and sex on EEE_{rel} $F(4,99) = 0.193$, $p = 0.941$. Pairwise comparison between sub-techniques across intensity levels demonstrated higher EEE_{rel} in the G3 and G2 technique compared to the G4 technique ($p < 0.01$, Figure 9). Very large associations were found between EEE_{rel} and relative power output ($R^2 = 0.88$, Figure 10A), with small differences in the regression between male and female biathletes (Figure 10B). Within a given sub-technique, the relationships were stronger ($R^2 = 0.95 – 0.98$) compared to the non-stratified data.

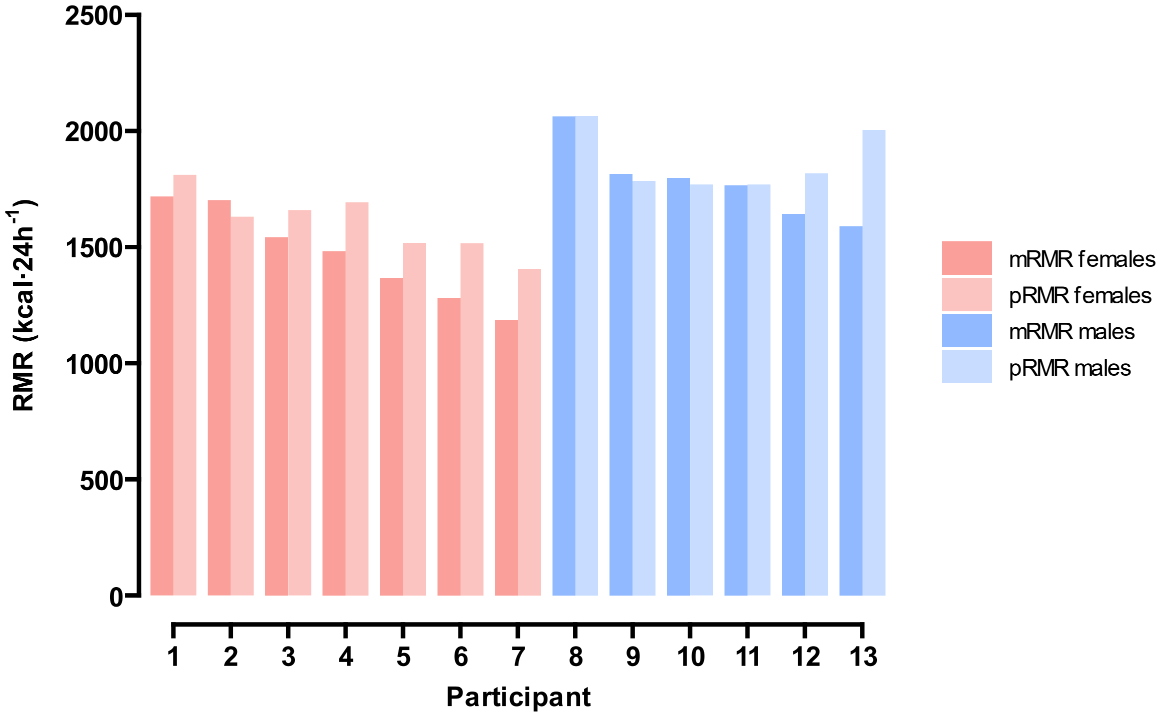

Figure 6. Measured (dark) and predicted (light) resting metabolic rates in female and male biathletes. mRMR = measured metabolic rate, pRMR = predicted metabolic rate.

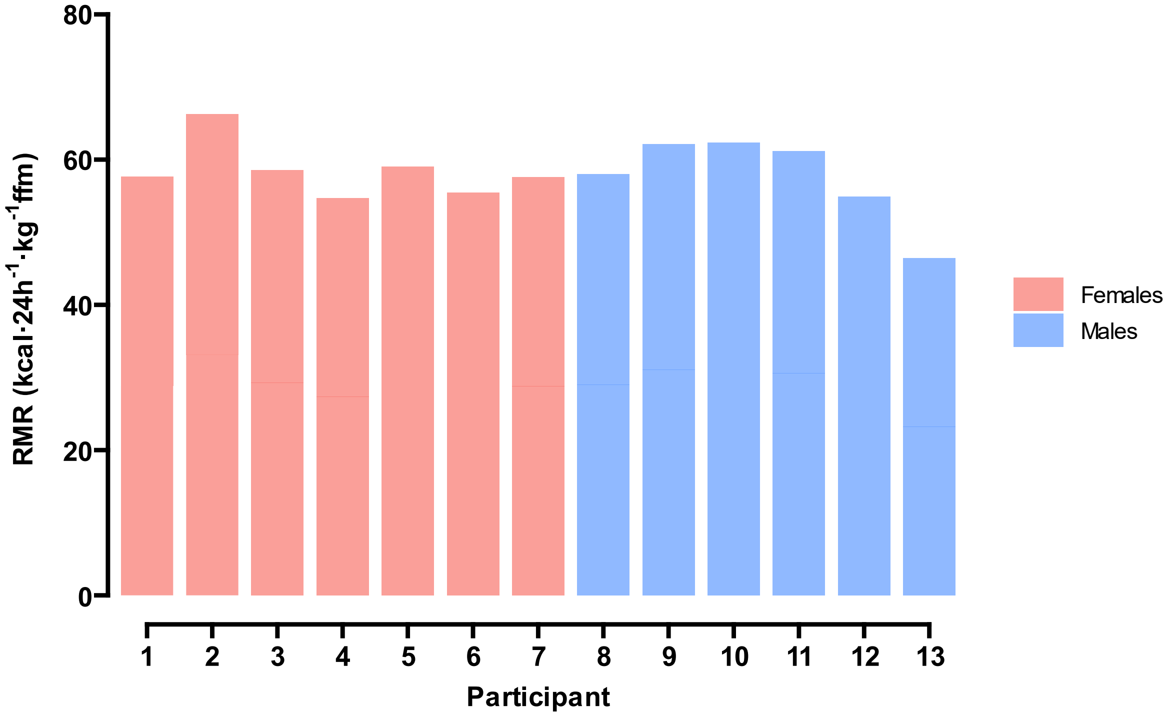

Figure 7. Resting metabolic rates normalized for fat free mass in female and male biathletes. ffm = fat free mass.

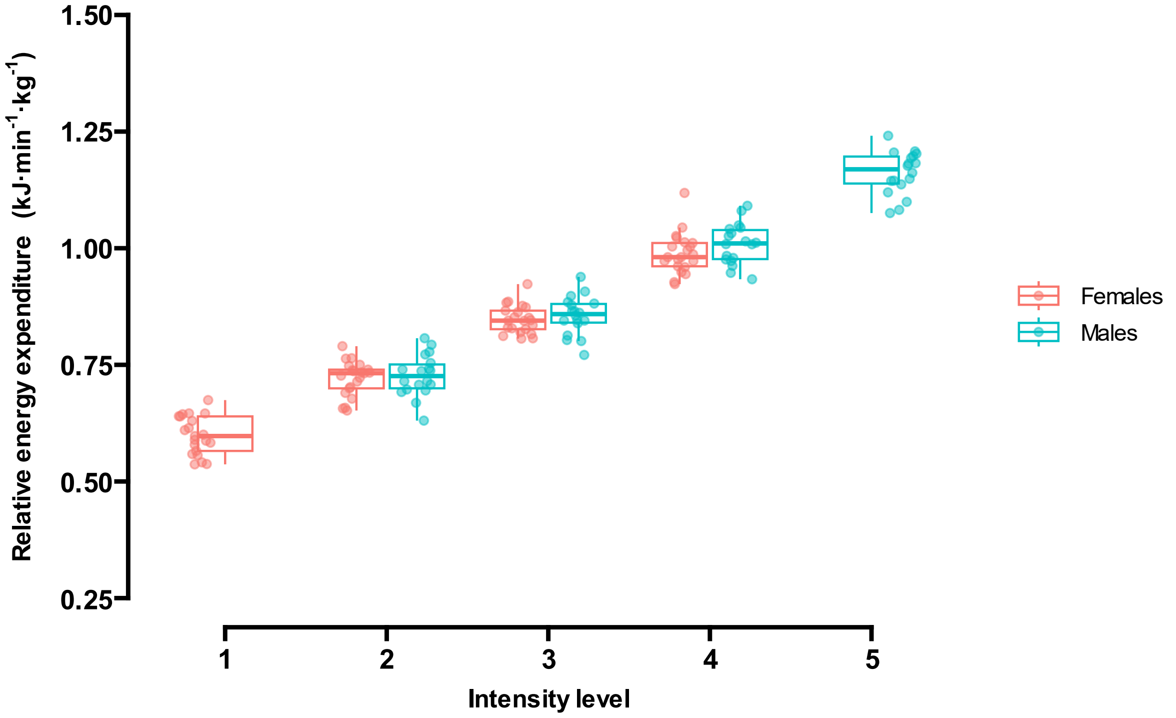

Figure 8. Relative exercise energy expenditure during an incremental exercise protocol for female and male biathletes.

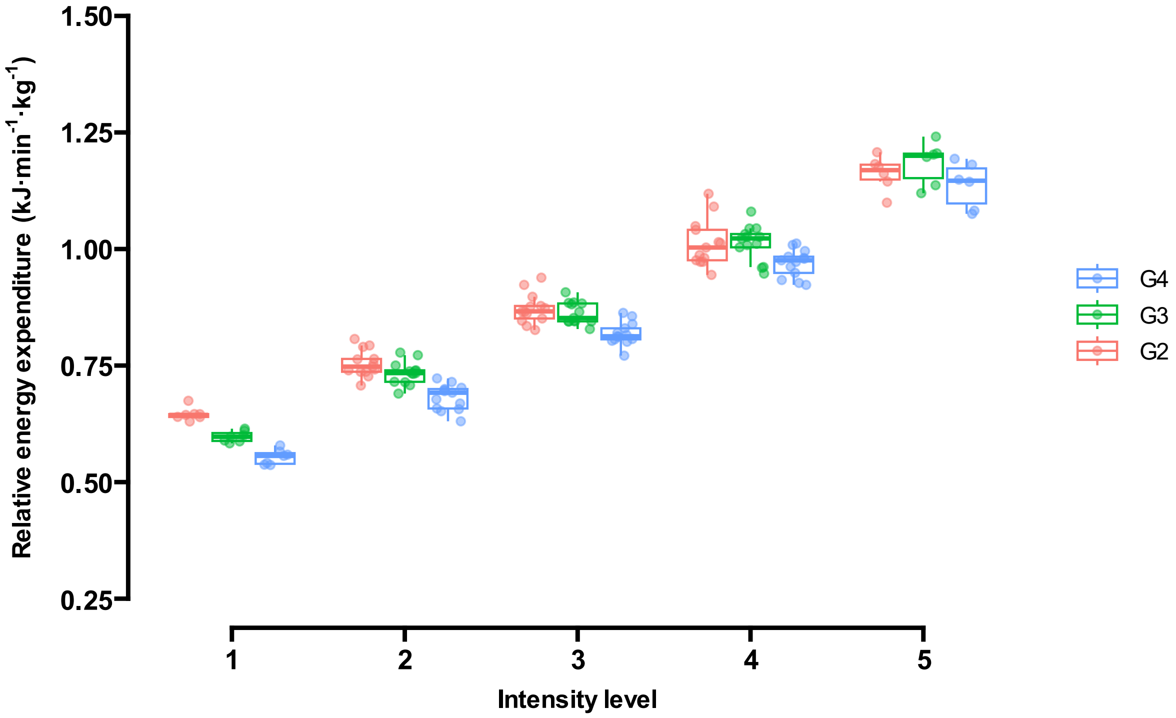

Figure 9. Relative exercise energy expenditure separated by skiing technique during an incremental exercise protocol in female and male biathletes.

Large correlations were observed between EEE_{rel} and HR (R^2 = 0.64, Figure 11A). For a given HR, men showed higher EEE_{rel} compared to women (Figure 11B), with similar strength in the association (R^2 = 0.81 and 0.77, respectively). No significant differences were observed in the associations across different sub-techniques (Figure 11C). All individual regressions demonstrated nearly perfect relationships between EEE_{rel} and HR (R^2 = 0.94 – 0.99, Figure 11D).

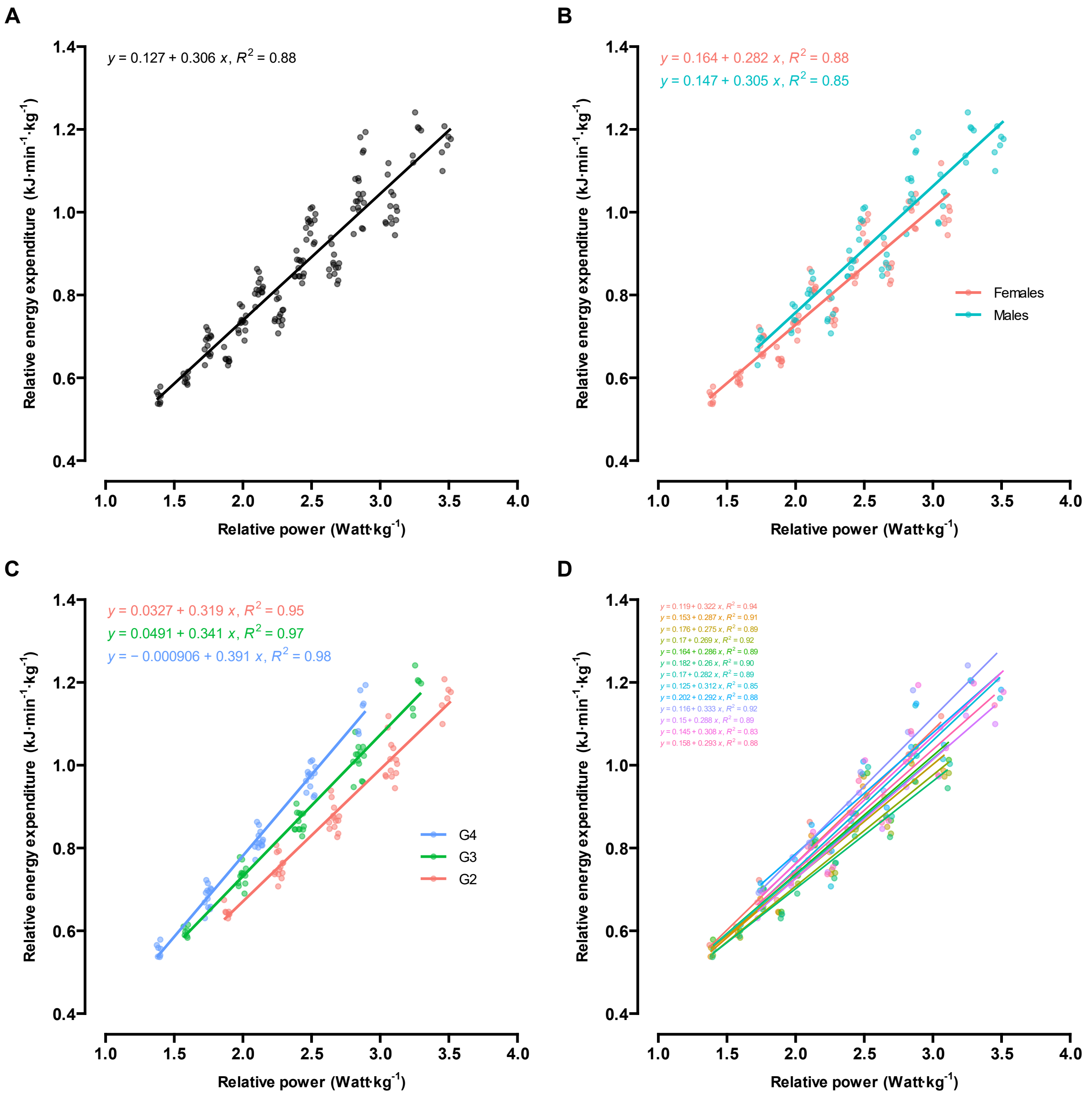

Figure 10. Association between relative exercise energy expenditure and relative power output across all intensities and sub-techniques (A), separated by sex (B), sub-technique (C), and individual athlete (D) during an incremental exercise protocol in female and male biathletes.

The relationship between EEE_{rel} and RPE demonstrated a large R^2 (0.58, Figure 12A), with stronger associations found when separated by sex (R^2 = 0.65 and R^2 = 0.73 for female and male biathletes, respectively, Figure 12B). The correlation between gross efficiency and relative power output showed a moderate association (R^2 = 0.22, Figure 13A). No significant correlations were observed between gross efficiency and relative power output when stratified by sub-technique (R^2 < 0.16, Figure 13C).

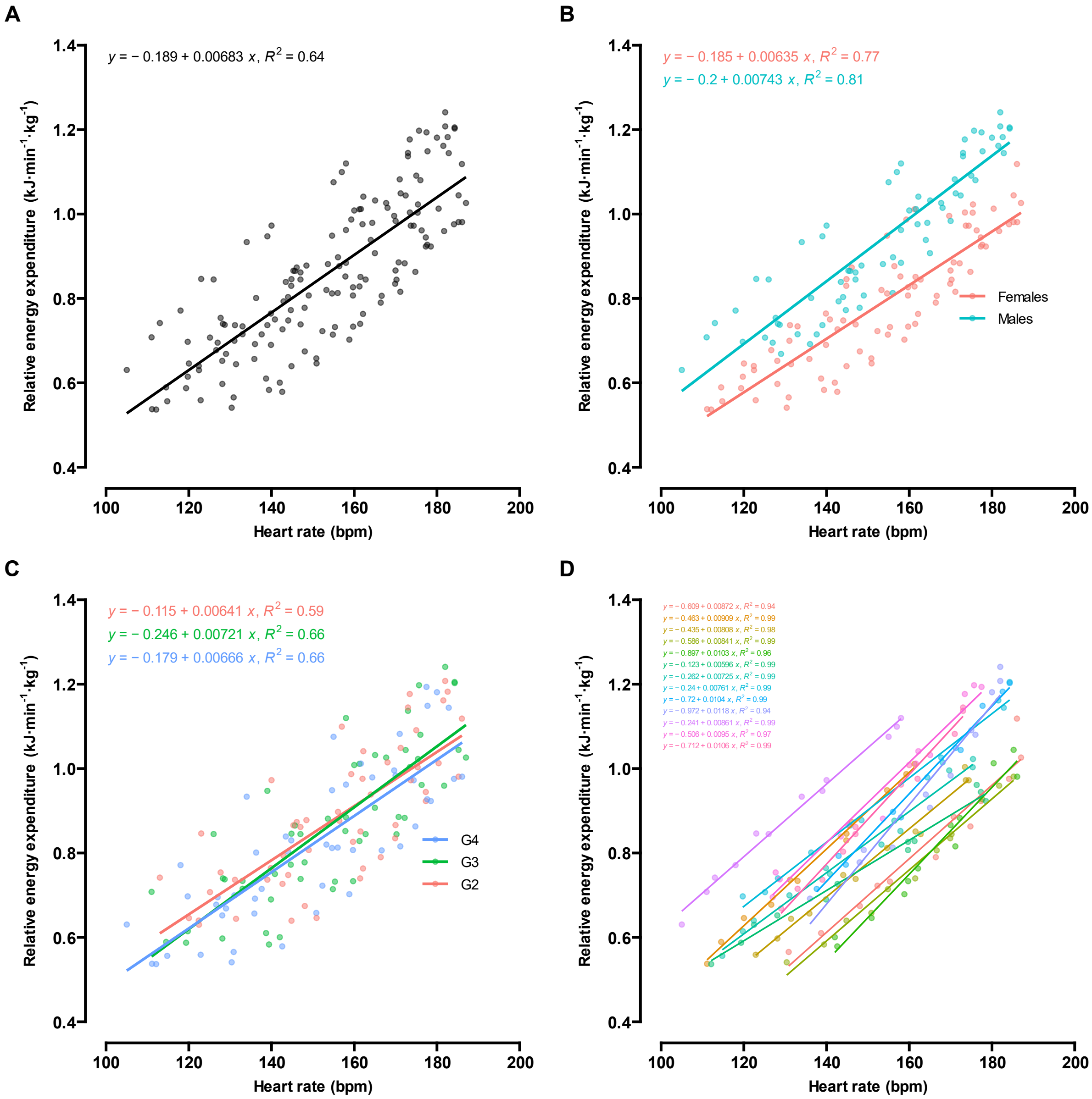

Figure 11. Association between relative exercise energy expenditure and heart rate across all intensities and sub-techniques (A), separated by sex (B), sub-technique (C), and individual athlete (D) during an incremental exercise protocol in female and male biathletes.

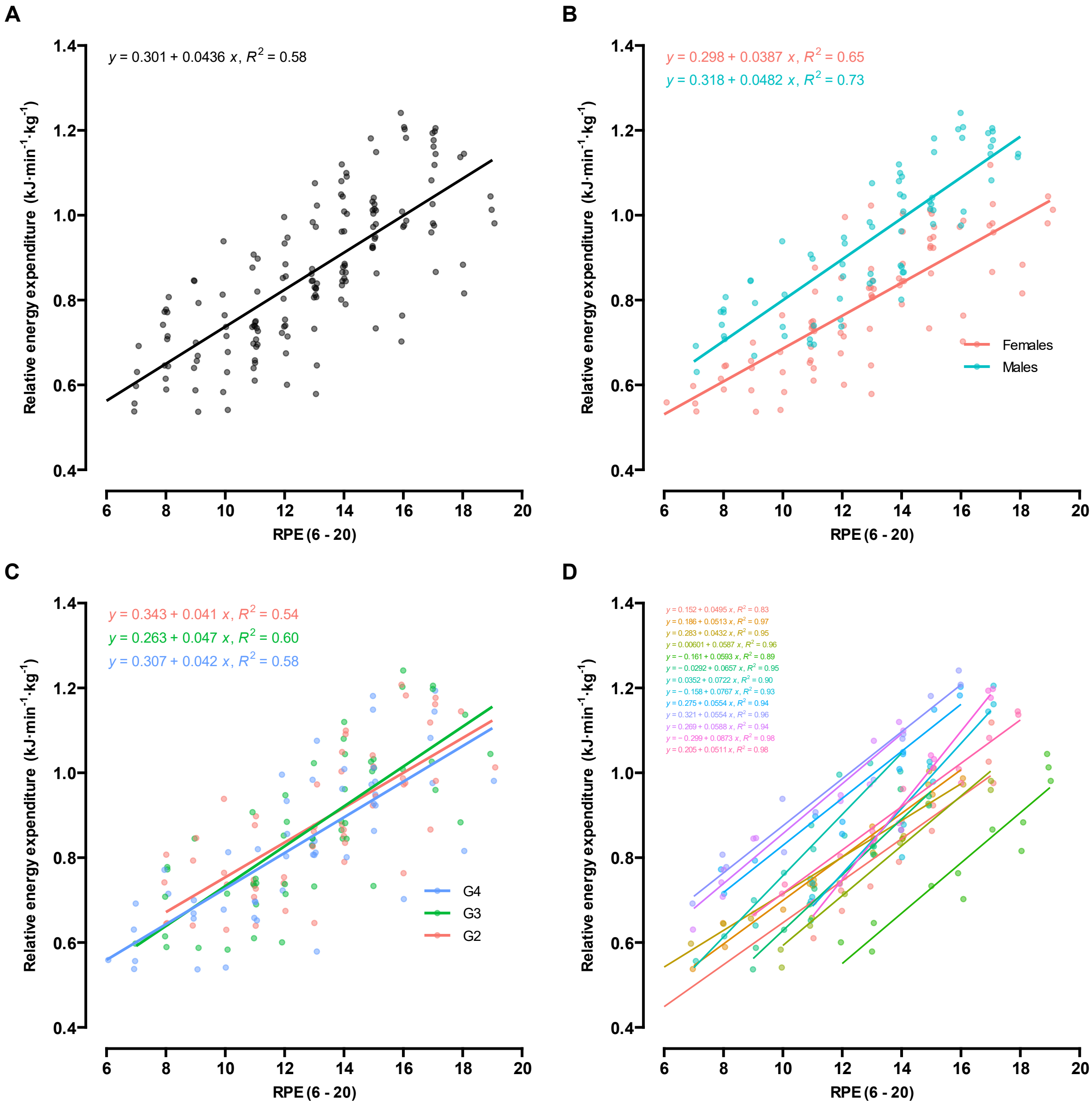

Figure 12. Association between relative exercise energy expenditure and rating of perceived exertion across all intensities and sub-techniques (A), separated by sex (B), sub-technique (C), and individual athlete (D) during an incremental exercise protocol in female and male biathletes.

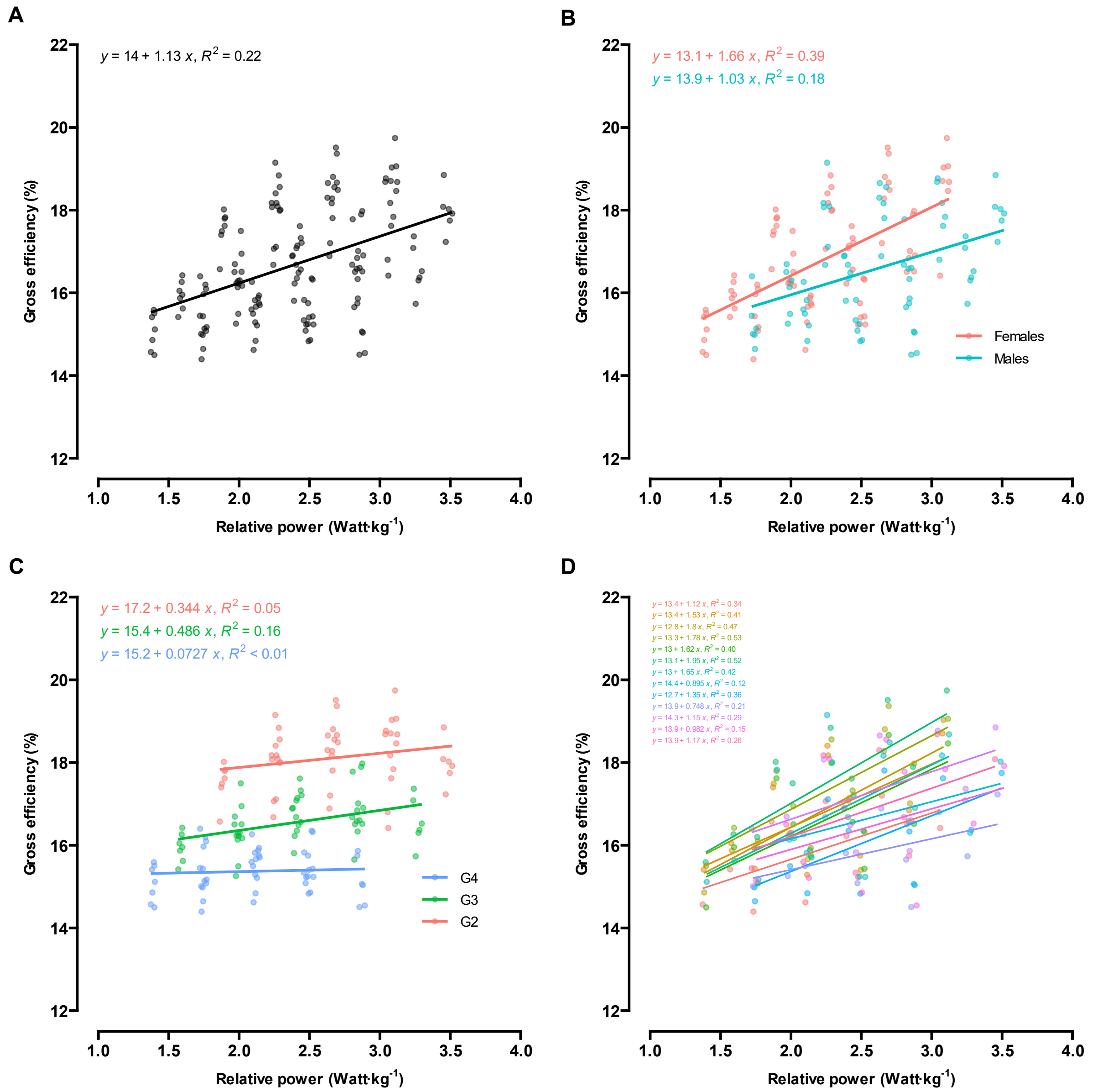

Figure 13. Association between relative power output and gross efficiency across all intensities and sub-techniques (A), separated by sex (B), sub-technique (C), and individual athlete (D) during an incremental exercise protocol in female and male biathletes.

3.5 Conclusion

In the present project, we investigated the RMR and EEE profiles of 13 Swiss National Team biathletes. In regards to RMR, our results showed large inter-individual differences of up to 500 kcal·24h^{-1}, with somewhat reduced differences when the values were normalized for fat free mass. At the same time, four out of thirteen athletes (~30%) showed suppressed RMR_{ratio}, indicating potential issues surrounding LEA. These findings indicate the importance to tailor the day-to-day fueling to the individual athlete irrespective of energy expenditure during daily activity and training and competition. As the considerable inter-individual variability is only reduced, but not completely removed when controlling for relevant variables such as FFM, meal size and frequency should not be judged simply by the "size" of an athlete. The finding that two people who are the same height, same weight, same age, same sex, and who have the same body composition could have RMR that differ considerably might be of interest for coaches and support staff and might help for proper fueling.

Regarding our EEE findings, a very strong linear relationship between EEE_{rel} and relative power was shown. Although this result was expected, the stratification by sub-technique data revealed differences between the three investigated skating techniques. But even more importantly, EEE_{rel} and HR demonstrated exceptionally strong correlations on the individual level, providing a basis for the accurate estimation of EEE via HR monitoring during ski-specific training in elite biathletes. These individual HR-based regression equations are expected to provide more precise information on the energy requirements for a given endurance training session compared to the data estimated from common sports watches. Surprisingly, the strength of the association between EEE_{rel} and RPE was only marginally lower compared to HR on the group level, and also demonstrated very high predictive value in some individuals. Although this could have potential implications for RPE as a low-cost tool to estimate EEE in the field, the potential bias of athletes providing RPE values in a fixed interval (e.g., 10 – 12 – 14 – 16) during laboratory-based incremental exercise protocols should be further explored. Furthermore, GE results revealed a relatively large inter-individual variation, and a small sex difference in our cohort, as the female biathletes appeared to show higher GE at higher power outputs compared to men. The sex difference in GE in cross-country skiing or biathlon is not supported by previous studies [28,29]. However, the small sample size and potential difference in the relative performance level might explain some of the difference. Nevertheless, individual GE profiles across different exercise intensities could provide valuable and objective information for the technique training for coaches.

3.6 Recommendations

The following recommendations could be concluded based on our results:

- Large inter-individual differences in RMR of up to 500 $kcal \cdot 24h^{-1}$ highlight the demand for individual day-to-day fueling and awareness of the supporting staff regarding the energy needs of athletes (see individual athlete sample report in appendix)
- The assessment of RMR during routine diagnostics has the potential to identify athletes with suppressed values and therefore, in combination with additional diagnostic tools (questionnaires, performance, hormonal profiles), could provide an objective surrogate marker for LEA and REDs.
- During constant submaximal skiing exercise, individually derived HR profiles can accurately predict EEE, allowing athletes and coaches to determine the energy requirements of a particular training session and hence improve fueling
- EEE protocols performed with accurate measurement equipment (i.e., Douglas Bag method) could additionally be used by coaches for technique training to assess subtle differences in skiing efficiency across skating sub-techniques.

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