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Energetic Demands and Nutritional Strategies of Elite Cross-Country Skiers During Tour de Ski: A narrative review

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Abstract

The Tour de Ski (TDS: 6–9 sprint and distance races across 9–11 days) represents the most intense competition series of the cross-country (XC) ski season and is characterized by accumulated stress from consecutive days of high-intensity (~85–160% VO_2max) racing, travel, cold temperatures and low to moderate altitude (500–1500 m above sea level). Here, nutritional strategies play a key supportive role for optimized health, recovery and performance. This narrative review aims to provide an evidence-based discussion on the energetic demands of the TDS and recommendations for nutritional strategies to optimize health and performance of XC skiers during and following the TDS. We highlight several challenges that may arise during the TDS, including: poor energy availability (EA) due to decreased appetite or a pressure to maintain a low body weight, suboptimal carbohydrate availability due to a failure to replenish muscle glycogen stores across consecutive-day racing, and increased risk of illness due to a combination of factors including high-intensity racing, poor nutrition, sleep, travel and hygiene. We encourage XC skiers to maintain optimal overall EA across the ~1.5-week period, ensure high daily carbohydrate availability, as well as the use of strategies to maintain a healthy immune system. In addition, we include practical guidelines on the management of nutrition support prior to and during the TDS. We recognize that many nutritional questions remain unanswered both in the context of elite XC ski racing and specifically for extreme demands such as the TDS that should be addressed in future investigations.

Keywords: nutrition, winter sports, cross-country skiing, ski tour, carbohydrates, recovery, performance

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1. Introduction

The Tour de Ski (TDS) is a cross-country (XC) skiing event organized by the International Ski Federation (FIS) as part of the annual World Cup. Spanning 9–11 days (6–9 stages consisting of sprint and distance events) held across Central Europe (Table 1), it represents the most intense competition period of the season. The skier is challenged by the accumulated stress from consecutive days of racing, travel, cold temperatures (typically ranging from +4 °C to −10 °C), low to moderate altitude (500–1500 m above sea level), as well as the psychological pressure of competition. Furthermore, the event is held in the middle of the competition season (i.e. end of December/early January) and on most years, precedes the World Championships or the Olympic Games. Therefore, the skier must maintain health and performance not only during, but also following, the tour. Nutritional strategies play a key supportive role in managing optimal health and performance throughout and following the tour but have been relatively poorly described in the current literature. While similarities to other endurance sports exist in terms of physiological requirements during competition, XC skiing and especially the TDS pose several unique challenges meriting special attention. Therefore, the purpose of this review is to provide an evidence-based discussion on the energetic demands faced by XC skiers during and following the TDS as well as nutritional strategies to optimize health and performance of the XC skiers. Although the information in this review can be applied to ski tours in general, this review will focus on the TDS specifically.

2. Performance demands of TDS

XC skiing is a demanding endurance sport that requires a variety of physiological, technical and tactical capacities to perform at a high level (Sandbakk et al. 2016a; Tonnessen et al. 2014). Although ski-specific aerobic capacity seems to be the major factor distinguishing world-class skiers from national-class skiers (Sandbakk et al. 2016a), increased race speeds during the last decades have augmented the role of speed and strength for success (Losnegard 2019; Sandbakk and Holmberg 2017). Furthermore, anaerobic capacity and tactical knowledge have an important role in XC skiing races, especially in sprint skiing and mass start competitions that cover a large part of the current international competition schedule (Haugnes et al. 2019; Losnegard 2019; Sandbakk and Holmberg 2017). Finally, an efficient skiing technique (Haugnes et al. 2019) and competitive skiing equipment (Sandbakk and Holmberg 2017) are needed for optimal locomotion.

Success in the TDS relies on successful performance across the sprint, mass starts and distance time-trial races as well as the capacity to recover in-between competitions during an intensive competition program. Over the last 5 years, the races have ranged from 1.2–1.5 km (sprint competitions, including up to 4 heats in one day) to distance races of 5–15 km for women and 10–30 km for men, which translate into competition times of ~3–75 min [Table 1 and Svendsen et al. (2015)]. Importantly, recent years have seen a trend towards shorter race distances, where the last three tours (2017-18, 2018-19, and 2019-20) have been characterized by maximum race distances of 10 and 15 km for females and males, respectively, translating into a maximum race duration of ~30 to 40 min, respectively. Aerobic metabolism is a key factor determining XC skiing performance

(Sandbakk et al. 2016a) as it covers ~85–95% of total energy expended during distance competition while corresponding values in sprint skiing vary between 75–85 % (Sandbakk and Holmberg 2017); the rest of the energy needs must be covered with anaerobic systems (Losnegard 2019).

Only one study has explored training and competition loads during the TDS. Svendsen et al. (2015) reported increased training loads during, compared with six weeks before and after the TDS. The researchers hypothesized that the increase in load together with other stressors (travelling, cold climate, moderate altitude, psychological pressure) would cause overreaching. This was confirmed with the observations of increased incidence of self-reported symptoms of infection and impaired race performance later in the season among athletes participating in the TDS (Svendsen et al. 2015). Thus, the recovery capacity of the athletes appears to be extremely challenged during and after the TDS and may be crucial for performance in the last races of the tour as well as dictating the success of the skier during the remainder of the competitive season.

Taken together, the TDS is characterized by the requirement to perform well in races ranging from ~3–75 minutes in duration, as well as the ability to recover quickly between the competitions. These factors have important implications for the immediate success during the TDS, but are also likely to have carry-over effects on the health and performance of the XC skier during the remainder of the season. An evidence-based review of the best nutrition strategies to address these challenges will be covered in detail in the following sections.

3. Energetic demands and energy availability during TDS

The TDS is an intense racing period, where the management of energy availability [EA; i.e. the balance between energy intake (EI) and exercise energy expenditure (EEE) across the day] is an important consideration for both health and performance outcomes during and following the TDS.

3.1. Daily energy expenditure in XC skiers

Several reports exist on total daily energy expenditure in other endurance sports such as road cycling, These studies report total daily energy expenditures of up to 6071 and 7815 kcal·d^{-1} in male cyclists during an average stage and a mountain stage of a cycling grand tour (Rehrer et al. 2010), respectively; meanwhile race energy expenditures of up to 5184 kcal were reported in male cyclists during single-day classic (Heikura et al. 2019). On the contrary, few studies have attempted to quantify energy expenditure and EI in elite XC skiers. Sjödin et al. (1994) measured total daily energy expenditure (via doubly labelled water) and EI (self-report) during a week of training in elite Swedish female (n = 4) and male (n = 4) XC skiers. The mean daily EI was 4350 and 7218 kcal·d^{-1} in women and men, respectively. Meanwhile, doubly labelled water estimates of total daily energy expenditure averaged 4374 and 7218 kcal·d^{-1}, in women and men, respectively.

3.2. Energy cost of locomotion during XC skiing

Very little information exists on the energy cost of various XC skiing disciplines at the elite level. There are several layers of complexity that challenge the measures or estimates of EEE during XC skiing events, including but not limited to: 1) varying terrain (flat, downhill, uphill sections); 2) varying skiing techniques;

and 3) environmental conditions. It is also important to consider the energy cost of activity outside the race itself (warm-up and cool-down as well as a possible low-intensity session on the morning/evening of race days) as well as on non-competition days; indeed, it is not uncommon for skiers to complete an evening recovery session on days of racing [for example, (Govus et al. 2018)] as well as varying amounts of light to intense exercise on the days in-between (*personal communication with athletes*). These factors increase the energy requirements of the athlete but are difficult to factor in due to lack of reported data.

Compared to other endurance sports, direct reports of EEE during XC skiing are scarce. Early work by Rusko (2003) reported EEE over 1 km, 10 km and 15 km races of 95 kcal, 717 kcal and 1076 kcal, respectively. Of course, the size and sex of the athlete will affect these values which remain estimates. Despite these gaps in the literature, back-of-the-envelope calculations of EEE can be made indirectly from oxygen update data (VO_2) (Weir 1949). Here, 1 L of O_2 consumed requires ~5 kcal [although it should be noted that a fuel-mix specific value based on measured respiratory exchange ratio (RER) should be used where available for higher accuracy of estimates]. Therefore, EEE can be estimated as follows:

Equation: $$EEE = VO_2\ (L{\cdot}min^{-1}) * (RER * 1.1 + 3.9) * t$$

where EEE is exercise energy expenditure, VO_2 is the mean oxygen cost (L per minute of exercise), RER is the measured respiratory exchange ratio, and *t* denotes exercise duration in minutes.

Reports of VO_2 in national or elite level female and male skiers completing various distances of training/racing in classic or skating ski techniques range from 150–194 $mL{\cdot}kg^{-1}{\cdot}km^{-1}$ (Fabre et al. 2015; Gloersen et al. 2020). Based on equations above, these values translate into EEE of 0.75-0.97 $kcal{\cdot}kg^{-1}{\cdot}km^{-1}$, or specifically, 450–582 kcal in a 10 km race for a 60 kg woman and 844–1091 kcal in a 15 km race for a 75 kg man. Due to the complexity of estimates of EEE across a sprint ski race as well as lack of peer reviewed reports, we have decided to defer from estimating EEE for sprint racing and encourage further research around this topic.

3.3. Energy availability in XC skiers

Energy availability reflects the difference between dietary EI and EEE, expressed relative to fat-free mass (FFM). It therefore describes the energy left after energy cost of exercise for other energy-consuming physiological processes in the body (Mountjoy et al. 2018). Although no absolute cutoff value exists nor should be utilized in the field, low EA (LEA) has often been defined as <30 $kcal{\cdot}kg\ FFM^{-1}{\cdot}d^{-1}$ (Loucks et al. 2011) based on laboratory investigations in sedentary women; notably though, these cutoffs have never been tested in elite athletes. LEA has more recently been recognized to underpin the development of Relative Energy Deficiency in Sport (RED-S) – a syndrome consisting of at least 10 health and 10 performance impairments in female and male athletes (Mountjoy et al. 2018).

While the time-course of changes as a result of LEA remains somewhat unknown and is likely to vary between various body systems, laboratory studies have shown impairments in as little as 4–5 days (Loucks et al. 2011). On the contrary, a recent report in professional male cyclists showed that very brief (<24 h) exposures to extreme LEA (<15 kcal·kg $FFM^{-1}·d^{-1}$) over an 8-day single-day racing period did not impair sex and metabolic hormone concentrations when alternated with days of >45 kcal·kg $FFM^{-1}·d^{-1}$ EA (Heikura et al. 2019). While the (male) endocrine system might be more resilient to acute and brief changes in EA, emerging evidence suggests that brief periods of LEA can impair sports performance indirectly as a result of decreased glycogen stores (Kojima et al. 2020) and increased risk for illness (Drew et al. 2018), which will have residual effects beyond the success during the TDS.

Due to the high energetic demands of the TDS, the skiers are at risk for developing LEA as a consequence of the inability to compensate for extreme EEE via adequate EI due to suppression of appetite and/or low meal and snack variation/availability. As XC skiing is a weight-sensitive sport where success depends on gravitational factors, LEA can also develop from restrictive eating behavior as a means to maintain a light physique throughout the competition. For example, a recent study reported signs of long-term energy deficiency in 4 out of 13 elite female XC skiers (Carr et al. 2019).

Taken together, while brief periods of LEA across the TDS may be inevitable and harmless (Heikura et al. 2019), residual effects are likely to have implications for the elite XC skier who faces the challenge of maintaining optimal health and performance during and following TDS. Therefore, XC skiers are encouraged to avoid extreme LEA during the TDS and aim to maintain an EA that averages optimal levels over the period of the TDS to support health and performance during and beyond the tour (Table 2).

4. Macronutrient demands around TDS

This section will discuss the role of dietary carbohydrates (CHO) and proteins as key nutrients in support of recovery, health and performance across consecutive days of high-intensity racing during the TDS. While dietary fats are an important part of a healthy diet in XC skiers, their role in performance success in this context is minimal (Hawley and Leckey 2015) and therefore, the reader is referred published recommendations (Thomas et al. 2016) on dietary fat intake in endurance athletes.

4.1. Carbohydrates

XC ski racing is completed at around 90–95 % VO_{2max} (10 km and 15 km) (Gloersen et al. 2020) with uphill sections and sprint racing requiring supramaximal (~100-160% VO_{2max}) intensities (Losnegard 2019). Uphill sections are the most important section of the race course as performance over these sections has been shown to explain 95.5% of the variance in overall performance (Sandbakk et al. 2016b). Therefore, racing and the key sections determining competition success are characterized by high intensities that are almost exclusively reliant on CHO based fuels from blood glucose and muscle glycogen (Hawley and Leckey 2015). This is evident from reports of Fabre et al. (2015) who showed RER values of 0.98–1.02 (94–100% of energy from CHO oxidation) in elite skiers over a simulated 6 km skiathlon race. Similarly, unpublished data by Rusko (2003) reported the relative contribution of CHO to total EEE for the 1 km, 10 km and 15 km ski races at around 99%, 90% and 80%, respectively.

The importance of CHO based fuels is explained by the findings of recent studies associating low muscle glycogen concentrations with impaired Ca^{2+} release from the skeletal muscle, which may contribute to fatigue (Ortenblad et al. 2011). Although muscle glycogen concentrations are unlikely to become a rate-limiting factor for performance success over a single XC event of <15 km in a XC skier who commences the race with adequate muscle glycogen stores, the skiers can still experience a significant depletion of muscle glycogen stores during racing. For example, Rusko (2003) reported a 42-46% decrease in muscle glycogen content during the 15 km (men) and 10 km (women) events, respectively. More recently, Ortenblad et al. (2018) reported a 71% and 31% reduction in arm and leg muscle glycogen concentration, respectively, in elite XC skiers following a 20 km classical ski race. The sprint event is also associated with a substantial decrease in muscle glycogen concentration. Indeed, a single 1.3 km (~4 min) simulated XC ski sprint resulted depleted muscle glycogen by around 15–55% depending on glycogen localization and fiber type (Gejl et al. 2017). Sprint races in XC skiing involve several (up to 4) rounds of racing within a small (<2 h) time frame, which further emphasizes the reliance on adequate CHO based fuels both in-between sprints rounds and on a daily basis. Overall, a failure to replenish muscle glycogen stores after a single event will have a carry-over effect on the subsequent days of racing. Therefore, adequate daily CHO intake is required to maintain optimal concentration of muscle glycogen across the TDS.

The main nutritional strategy to replenish and maintain optimal muscle and liver glycogen stores is the ingestion of CHO from a combination of foods sources, which in the case of the TDS can be done without aggressive approaches to CHO loading. The best protocol is likely to be a combination of a high-CHO (~7–12 $g \cdot kg^{-1} \cdot d^{-1}$) diet and optimized pre- and post-race meal timing and content (Burke et al. 2011). Adequate total CHO intake is important as low CHO intakes can lead to decreased muscle glycogen content, impaired economy and increased fatigue even during a period of moderate training loads. For example, Sherman et al. (1993) showed that a diet providing 10 $g \cdot kg^{-1} \cdot d^{-1}$ CHO during 7 d of running or cycling training (1 h at 75% VO_{2max} followed by 5 x 1 min sprints at 100% VO_{2peak}) maintained muscle glycogen stores while lower intakes (5 $g \cdot kg^{-1} \cdot d^{-1}$) reduced them by 36%. As restoration of muscle glycogen stores may take up to 24 h, and as skiers are likely to experience daily depletion to some extent, the recovery process should be started as soon as possible after the race and continued by consuming CHO rich meals at a rate of 1.0–1.2 $g \cdot kg^{-1} \cdot h^{-1}$ for the remainder of the day for rapid replenishment of muscle and liver glycogen stores (Burke et al. 2017). Pre-race meal and snacks (1–4 $g \cdot kg^{-1} \cdot h^{-1}$ CHO 1–4 h pre-race) are especially important in restoring liver glycogen stores that have likely become depleted overnight (Thomas et al. 2016). While the race distances in TDS do not require the ingestion of CHO for improved race performance (Thomas et al. 2016), the ingestion of CHO during racing will benefit rapid recovery in-between racing. Meanwhile, in-between sprint races, CHO drinks or mouth rinsing (Thomas et al. 2016) may be useful.

In summary, the skiers should aim at a CHO intake of around 7–12 $g \cdot kg^{-1} \cdot d^{-1}$ including optimized pre- and post-race meal timing and content (~1.0 $g \cdot kg^{-1} \cdot h^{-1}$) to support high-intensity performance, high training and racing loads and subsequent recovery (Table 2). Men may have slightly higher relative requirements for energy and CHO due to longer race distances as opposed to women. Although single days of racing during the TDS are unlikely to fully deplete muscle glycogen stores, special attention should be given to a high CHO diet to maintain performance across successive days of competition.

4.2. Proteins

Dietary protein is an essential nutrient acting both as a substrate for recovery and trigger for adaptation after exercise (Phillips and Van Loon 2011). During the TDS the main function of protein intake is to maximize recovery between the competitions and to help to maintain performance despite intensive race schedule. Endurance athletes have increased protein requirements compared to the healthy non-exercising adults (Kato et al. 2016). This may be due to the need to replace oxidative losses of amino acids during exercise (Tarnopolsky 2004) and to provide substrates for the repair and rebuilding of body proteins after exercise (Moore et al. 2014). If exercise is performed with low CHO availability, the contribution of protein to EEE may be as high as ~10% (Lemon and Mullin 1980). Given that XC skiers may fail to maintain high CHO availability on race days, protein catabolism during racing may exceed the values estimated above. According to the most recent consensus statements, athletes should consume 1.2–2.0 $g \cdot kg^{-1} \cdot d^{-1}$ protein (Thomas et al. 2016), where the upper range may be required during periods of higher-volume/intensity training/racing (Phillips and Van Loon 2011). For example, Kato et al. (2016) reported an average and recommended protein requirements of 1.65 and 1.83 $g \cdot kg^{-1} \cdot d^{-1}$, respectively, in male endurance athletes completing an acute 20 km run at race pace. Thus, the daily protein requirements during TDS may be elevated towards the upper end of the reference range due to the characteristics of the tour (intensive consecutive-day training and racing loads). The requirements are unlikely to pose nutritional challenges to elite skiers who reportedly consume 2.8–3.3 $g \cdot kg^{-1} \cdot d^{-1}$ protein during a simulated sprint competition day (Carr et al. 2019). However, special attention should be paid to the skiers who do not meet the energy requirements of daily competition.

In addition to daily recommendations, timing of protein intake should be considered. According to current evidence, protein intake should be divided in 4–6 equal portions throughout the day to optimize post-exercise adaptations (Areta et al. 2013; Thomas et al. 2016). Maximal rates of muscle protein synthesis are achieved with a single bolus of 20 g or 0.25–0.30 $g \cdot kg^{-1}$ protein (Moore et al. 2014; Thomas et al. 2016), although a recent investigation reported maximal myofibrillar protein synthesis rates with the ingestion of 30 g (0.49 $g \cdot kg^{-1}$) protein after 90 min of cycling at ~60% VO_{2peak} in the overnight fasted state (Churchward-Venne et al. 2020). Additional factors such as LEA (Areta et al. 2014) and the need for rapid replenishment of glycogen stores in the absence of adequate CHO intake (Jentjens et al. 2001) may further increase protein requirements post-exercise.

Current evidence on the effects of post-exercise protein intake for subsequent exercise performance is contradictory. Some studies have shown accelerated recovery of muscle function (Davies et al. 2018; Hoffman et al. 2010), high intensity interval performance (Rowlands et al. 2008; Thomson et al. 2011), and endurance capacity (Witard et al. 2011) following protein ingestion during the recovery period between exercise bouts. While conflicting reports exist (Roberson et al. 2018), the benefits of post-exercise protein intake on subsequent performance via enhanced glycogen synthesis in the absence of adequate post-exercise CHO intake are clear (Jentjens et al. 2001). Meanwhile, the ingestion of protein before or during endurance exercise appears to provide no benefit on subsequent performance (Phillips and Van Loon 2011).

In summary, we encourage the skiers to focus on optimal protein intake between (daily total intake) and within (timing of meals in relation to exercise and throughout the day) days across the tour to maintain optimal health and support rapid recovery between races (Table 2). For most skiers, daily intakes between 1.6 and 2.0 $g \cdot kg^{-1} \cdot d^{-1}$ are recommended, with special focus on spreading the meals evenly across the day, with appropriate dose [0.25 to up to 0.50 $g \cdot kg^{-1}$ (or 20 to 30 g), per meal] and an optimal timing (within 2 h) post-exercise. Higher intakes may be considered for athletes with inadequate energy and CHO intakes to prevent negative health and performance outcomes. However, it should be emphasized that excess protein intakes will increase satiety and likely impair the athlete's ability to ingest adequate energy and CHO. Therefore, while protein intake is important for recovery purposes, the key considerations of the XC skier during the TDS are around adequate EA and CHO.

4.3 Dietary fats

While dietary fats play a negligible role in fuel oxidation during high-intensity exercise (and thus, the majority of the current TDS events), they become an important fuel source during lower intensity portions of the overall tour (warm up, cool down) and may contribute to the fuel oxidation during the latter stages of longer races of the tour, especially in the case of compromised muscle glycogen stores (Romijn et al. 1993). Furthermore, intramuscular triglycerides (IMTG) appear to contribute to energy metabolism especially at the onset of high-intensity exercise. For example, Type I fiber IMTG content decreased by 27 % (along with a 23-44 % decrease in type I, IIa and IIx fibers) after a 45 min resistance exercise session (Koopman et al. 2006). In addition, 3 h of cycling at ~63 % VO_{2max} resulted in a 76-78% reduction in type I fiber IMTG content (and thus, ~20 % contribution to fuel utilization during exercise) regardless of whether exercise was completed with or without CHO (Stellingwerff et al. 2007). Nevertheless, CHO remain the main fuel source for high intensity exercise and therefore, adequate CHO is crucial for optimized performance during the TDS.

In addition, dietary fats are an energy dense option to increase energy intake during intense training and competition periods, thus assisting in maintaining optimal EA. For example, professional male cyclists participating in single-day racing with daily EE of ~5184 kcal reported consuming up to 3.3 g/kg/d fat (Heikura et al. 2019). Finally, adequate fat intake is obviously an important component of a healthy diet of the XC skier, where effects are seen in fat-soluble vitamin metabolism and immune function (Thomas et al. 2016). We recommend that XC skiers maintain an adequate fat intake (minimum of 20% of total energy) based on their individual overall energy needs.

5. Nutrition to support immunity, iron balance, and sleep during TDS

5.1. Immune function

Intense periods of competition and training are associated with an increased risk of respiratory viral infection (Valtonen et al. 2019). Participating in the TDS increases the risk to ~3-fold during or 10 days after the tour when compared to athletes who are not participating (Svendsen et al. 2015). In addition to the physiological stress related to training and competing, psychosocial stress in high level athletes may increase the susceptibility to illness in these athletes (Walsh and Oliver 2016). Furthermore, travel, human crowding, housing with other athletes, and concurrent viral epidemics all increase the risk of viral transmission among athletes and staff during the tour (Svendsen et al. 2015; Valtonen et al. 2019).

Although a large body of research supports the beneficial effects of nutritional strategies in preventing respiratory infections, strong evidence is still lacking (Williams et al. 2019). Current guidelines on daily CHO and protein requirements in athletes, as outlined by Thomas et al. (2016) and as described in the context of the TDS in section 4, are likely sufficient to support immune health during the TDS (Williams et al. 2019). A low vitamin D status has been associated with susceptibility to respiratory infections. In athletes, He et al. (2013) reported a significantly higher prevalence of respiratory tract infection symptoms during winter in those with vitamin D deficiency compared with those within the normal range. A large meta-analysis of 11,321 patients in 25 randomized controlled trials showed that vitamin D supplementation protected against acute respiratory infections with increased efficacy in those with lower baseline vitamin D status (Martineau et al. 2017). In addition to supporting a healthy immune system, vitamin D plays a pivotal role across a range of body systems including bone health, skeletal muscle function and recovery from injury (de la Puente Yague et al. 2020). Recent evidence suggests that vitamin D is also involved in the regulation of iron balance. Here, vitamin D appears to downregulate the body's master iron regulatory hormone, hepcidin (Bacchetta et al. 2014). For example, a single dose of 100,000 IU vitamin D2 resulted in a concomitant increase in serum 25D-hydroxyvitamin D (from ~27 to ~44 ng/mL) as well as a 34% decrease in circulating hepcidin within the following 24 hours (Bacchetta et al. 2014). Thus, athletes are recommended to monitor their serum vitamin D concentration and individually modify the vitamin D supplementation to maintain serum 25(OH)D levels >75 nmol/l (Williams et al. 2019).

Maintaining a healthy iron balance is important for the athletes because iron plays key roles in support of optimal immune function as well as acts as an essential nutrient in the production of oxygen carrying hemoglobin. Indeed, iron deficiency is known to impair cell-mediated immunity (Beard 2001; Castell et al. 2019), thereby increasing the risk of illness. Several factors affect iron balance including but not limited to dietary intake, poor bioavailability, environmental stressors (high-altitude), exercise training, excess iron need due to rapid growth, and in female XC skiers, menstrual blood loss (Maughan et al. 2018). Vitamin C is obviously required for optimal absorption of dietary (or supplemental) iron. Overall, given the essential role of iron status on performance and the possible negative effects of iron supplementation (for example, on the composition of gut microbiota) (Rusu et al. 2020; Zoller and Vogel 2004), routine monitoring of iron status in XC skiers is recommended (Maughan et al. 2018). Supplementation may be required in cases of iron deficiency, nevertheless, nutritional strategies (e.g. "food first" approach) to increase iron intake are recommended to prevent future iron deficient episodes (Pedlar et al. 2018). Nutrient supplements should not be used without a specific medical or nutritional reason (Maughan et al. 2018).

High intensity exercise exaggerates the rate of reactive oxygen and nitrogen species (RONS) production which is coupled with weakened enzymatic and nonenzymatic antioxidants systems, eliciting increased oxidative stress (Wadley et al. 2016). Exogenous antioxidants including vitamins E and C, carotenoids, as well as flavonols (e.g., quercetin) have been suggested to be beneficial in illness prevention. Although some studies have found lower incidence of respiratory infections with antioxidant supplementation (Bermon et al. 2017), the efficacy of antioxidants in the prevention of respiratory infections remains unclear. Therefore, we recommend a food-first approach over supplementing with individual antioxidants during the TDS (Heaton et al. 2017) with the exception for vitamin C which may be efficient in preventing and treating respiratory infections (Carr and Maggini 2017).

Heavy exercise influences gut microbiome (Mailing et al. 2019), which appears to play a key role in immunity (Spencer et al. 2019). Probiotics are live micro-organisms that may transiently alter the gut microbiome and which, according to Jäger et al. (2019), have a likely positive and beneficial effect on the immune system of the athlete. Therefore, probiotics may be used to support immune function during the TDS. It is important to note though that the clinical effectiveness of probiotics in the prevention of viral infection episodes during high loads of training and competition in elite athletes remains unclear (Leite et al. 2019).

Zinc is an essential trace element that has implications for immunity, energy metabolism and antioxidative processes. Indeed, zinc supplementation may be beneficial in treating respiratory infection symptoms. A recent meta-analysis showed that zinc lozenges (75 $mg \cdot day^{-1}$ of elemental zinc) reduced respiratory infection duration by ~3 days when taken <24 h after the onset of symptoms, and for the duration of the illness (Hemila 2017).

Based on current evidence we encourage XC skiers to consume a nutrient-dense, fiber-rich, diet with a variety of fresh fruit and vegetables, to enhance the diversity of gut microbiome and to maintain immune health. In some cases, vitamin D and vitamin C supplementation may be considered to support the immune system during the TDS (Table 2).

5.2. Sleep

Sleep is an essential aspect of recovery and performance improvement in athletes (O'Donnell et al. 2018). While physical exercise has generally a positive effect on sleep, high training loads (a key characteristic of TDS) may impair sleep quantity and quality (Roberts et al. 2019). Sleep deprivation in athletes has been associated with increased errors, impaired decision making, reduced maximal power, increased fatigue as well as reduced ability to perform maximal exercise (Reilly and Edwards 2007) and increased risk of illness (Halson 2014). From the nutritional perspective, CHO, tryptophan, valerian, and melatonin have been investigated as potential sleep enhancers in athletes (Halson 2014). However, it appears that adequate intake of energy, CHO and proteins remain the key underpinning factors behind optimal sleep (Halson 2014).

6. Environmental challenges of TDS: Altitude, cold and travel

6.1. Altitude and cold

The TDS is carried out in cold weather (typically +4 °C to −10 °C), at low-moderate altitudes (~500–1500 m above sea level). The exposure to moderate altitudes can have a substantial effect on performance outcomes, with a possible advantage for those who are acclimatized to these altitudes (Chapman et al. 2010). While high-altitude exposure has implications for the hydration and fuel requirements of an athlete, the effects of low-moderate altitudes met during the TDS are likely to be less meaningful (Stellingwerff et al. 2019). The effects of cold ambient temperatures on fuel utilization patterns appear to depend on exercise intensity. Although unlikely to occur in competitive level XC skiers during competition due to high metabolic rates of exercise, shivering at 5 and 10 °C has been shown to increase CHO oxidation at rest (Haman et al. 2005). Meanwhile,submaximal exercise at 0 vs 22 °C appears to increase reliance on fat-based fuels (Gagnon et al. 2013), and results in no difference in muscle glycogen utilization at 9 vs 21 °C (Jacobs et al. 1985). In the absence of reports of cold exposure and fuel utilization during maximal intensity racing typical of the TDS, we propose that due to high exercise intensities, CHO remain the main fuel source during racing.

6.2. Travel considerations

Teams organise their own stage-to-stage transportation during the TDS that incorporates heavy travel schedules .Travelling exposes the athletes to a higher risk of illness. Svendsen et al. (2016) reported that international air travel was the single biggest risk factor for infection. In addition to respiratory symptoms, gastrointestinal infections related to travelling are frequent among athletes (Halson et al. 2019). Other risks involved with frequent travel include inadequate nutrient intake and hydration status (Halson et al. 2019). Thus, careful planning and organization is required to minimize such issues. Halson et al. (2019) have published a thorough listing of the nutritional recommendations for travelling athletes.

7. Ergogenic aid use during the TDS

Ergogenic aids can be used to improve performance capacity during the TDS. In this review, we shortly introduce nutritional supplements that have the potential to enhance performance and/or rapid recovery during the TDS. However, all ergogenic aids should be evaluated on an individual basis, as some supplements have been found to carry contaminants that could lead to a positive drug test (Maughan et al. 2018).

Caffeine is a widely used ergogenic aid with well documented, positive performance effects in a range of sports events (Grgic et al. 2019). A meta-analysis by Ganio et al. (2009) concluded that pre-exercise caffeine resulted in a mean performance improvement of ~2.3%, whereas ingestion before and during exercise resulted in a ~4.3% improvement. In XC skiing, reports have shown enhanced all out double poling performance on two consecutive days despite higher muscle soreness, with no difference between 3 vs 4.5 $mg \cdot kg^{-1}$ (Stadheim et al.

2014). In general, low-to-moderate doses (3–6 $mg \cdot kg^{-1}$) are recommended for athletes due to the increased risk for side effects such as headaches or GI tract problems associated with the use of higher doses (Goldstein et al. 2010). We caution XC skiers against the use of higher caffeine doses especially later in the day as caffeine can negatively affect sleep latency and quality (Pickering and Grgic 2019). For example, 400 mg of caffeine 6 h before sleep impaired sleep quality and duration, as well as increased sleep latency (Drake et al. 2013). These effects are likely to translate into poor recovery and potentially impaired performance over a multi-stage ski tour.

Acute and chronic supplementation with dietary nitrate, usually in the form of concentrated beetroot, has been reported to reduce oxygen cost of submaximal exercise and improve continuous maximal exercise performance over durations of 5–30 min in recreationally active participants (Jones 2014). However, studies in XC skiers have failed to observe performance improvements following nitrate ingestion (Nyback et al. 2017; Peacock et al. 2012; Sandbakk et al. 2015). According to Jones (2014), there appears to be a blunted physiological response to nitrate supplementation in elite/well-trained endurance athletes. Current evidence does not support the use of nitrate for performance support during TDS.

Fatigue resistance is to some extent dependent upon the intracellular and extracellular buffering systems. This is highly important during short (1–10 min) duration high-intensity exercise bouts. To counteract the performance limiting effects of a low muscle and blood pH, orally ingested ergogenic strategies including the ingestion of sodium bicarbonate ($NaHCO_3$) to improve the body's buffering capacity have been investigated. McNaughton et al. (2016) concluded that 300 $mg \cdot kg^{-1}$ $NaHCO_3$ can improve high-intensity exercise performance and recovery from repeated high intensity exercise bouts. However, we are unable to conclusively recommend the use of $NaHCO_3$ during the TDS, notably due to the risk of GI upset and fluid retention (leading to increased BM) following supplementation. Therefore, we conclude that while $NaHCO_3$ might have some potential to support XC sprint racing performance, more research is needed to find optimized and individualized dosing and timing protocols to avoid adverse symptoms with supplementation.

Accordingly, we conclude that there is ample evidence to support the use of caffeine in optimizing performance during the TDS. Meanwhile, the evidence to support the use of other ergogenic aids in enhancing the performance of the XC skier is limited. Therefore, the decisions on the use of any ergogenic supplement should be individualized to each skier and trialled (dosage and timing) prior to competition for optimized supplementation protocols (Table 2).

8. Practical recommendations for the preparation, implementation and finalization of nutrition support during the TDS

This review has outlined the scientific evidence for the use of several nutrition strategies to support the health and performance of the XC skier during the TDS. However, several factors must be considered to enable successful implementation of nutrition support in the field. These factors have been discussed below, along with recommendations and solutions to these challenges based on the real-life experience of providing nutrition support for the Norwegian XC ski team during the TDS.

- Contact the hotel in advance for information on the menu and timing of main meals: Ensure that main meals meet the overall requirements of a high energy- and CHO diet. To avoid misunderstandings, use the local language for communication.
- If you plan to bring your team-chef, make sure to check that the hotel is positive to let the chef use parts of the kitchen and bring his/her own food.
- Prepare individual meal plans for each XC skier to ensure daily requirements are met for optimized competition performance and recovery across TDS. Pictures of nutrition plates for days requiring more CHO, or recovery days may be useful. Prepare a specific plan for athlete experiencing loss of appetite and GI issues, making sure that different solutions are available.
- Plan a day to day meal structure and discuss this with the chef. Sometimes the athletes may need to postpone the dinner, for example, due to logistics, so different solutions must be offered.
- Familiar foods and sports products are handy when the appetite is challenging during the TDS, check which food items you are legally allowed to bring into the country and pre-pack accordingly.
- Use the necessary transportation between race locations as an opportunity to focus on recovery: Make an individual recovery bag for each athlete with specific needs.
- It may be a good idea to have one room with a TV, games, foods and snacks for the athletes. They can use the room as a social place, or just pick up some recovery snacks before going to bed. The ingestion of snacks in-between main meals seems to be important to facilitate the replenishment of glycogen stores during successive days of racing.
- If possible, request for a separated area in the restaurant for the team. Here, the team will be able to gather, socialise and debrief. In addition, this lowers the risk of infections or illness from crowded areas. Athletes should be educated on the basics of maintaining good personal hygiene during TDS to avoid illness (e.g., wash hands with soap and water, change of wet clothes).
- In the context of the TDS, the athletes are encouraged to weigh themselves daily to ensure daily energy, CHO and fluid balance is met. Promote a comfortable environment for athletes to discuss about nutrition, weight-control and energy-consumption to avoid accumulation of challenges during the tour. Outside the TDS, daily weighing is not necessary and may pose more risks than rewards in terms of the psychology of physique.
- For the athletes using ergogenic supplements during competition, a well-tested protocol should be prepared for each athlete and each race.
- A high caffeine intake can affect sleeping patterns, and should be periodized, when competition lasts several days. Pinpoint the most important races; the protocol should be based on the smallest dose with the best effect. The skier should be familiar with the regime in competitions, to experience eventual side effects.

- Other members of the support team can have a significant role in making food, snack and drinks readily available for the athletes before, during and after the race.
- A good sleeping hygiene is important during competitions lasting more than one day. Recovery days should be individually optimized with short naps, snacking, social gaming or other relaxing activities.
- Transport to and from the competition arena is also a good time for short naps. Due to a lot of travelling, athletes may find it useful to bring their own headset and pillow, for example, to facilitate short naps during transportation (flights and driving).

9. Summary and future research considerations

The performance demands and energetic requirements of the individual competitions in a TDS can be outlined from previous research, but the consequences of repeated efforts in challenging environments for performance, recovery and health are less clear. While a single day of high-intensity racing during the TDS is unlikely to pose significant nutritional challenges to the recovery and health of the XC skier, successive days of racing and the requirement to maintain peak performance during and in the weeks after the TDS present a considerable nutritional challenge for the health and performance of these athletes. Here, the main challenges include the accumulated effects of frequent racing on the muscle glycogen concentrations, poor EA due to high EEE and/or decreased appetite as well as suppressed immunity due to a combination of stressors. We propose that the XC skiers should aim to maintain adequate energy and CHO availability across the ski tour for optimal performance, recovery and success in the future races following the tour. Optimal protein and micronutrient intakes, adequate sleep and maintenance of good hygiene practices are important for maintenance of health and recovery throughout the tour. We advise caution with the use of ergogenic supplements as most are unlikely to provide benefits during the TDS but pose a threat of contamination and adverse side-effects. Future research should focus on the nutritional requirements of elite XC skiers in training and racing, with a special consideration on the additional effects of environmental challenges and frequent training/racing protocols on the health and performance of the skiers.

Table 1. An example program of the 2019-20 Tour de Ski (TDS). The reader should keep in mind that each year's program varies slightly in terms of the race locations, the number of race and rest days, race distances and techniques.

Stage	Venue	Event	Technique	Distance (F) / winning time (min:ss) in 2019-20	Distance (M) / winning time (min:ss) in 2019-20
1	*Lenzerheide, SUI (1473 m a.s.l.)*	Distance, mass start	Free	10 km / 28:12	15 km / 33:19
2		Sprint	Free	1.5 km / 3:06	1.5 km / 2:55
3	*Toblach, ITA (1256 m a.s.l.)*	Distance, interval start	Free	10 km / 23:52	15 km / 31:03
4		Distance, pursuit	Classic	10 km / 26:52	15 km /38:15
5	*Val Di Fiemme, ITA (~880-1280 m a.s.l.)*	Distance, mass start	Classic	10 km / 29:08	15 km / 39:51
6		Sprint	Classic	1.3 km / 3:03	1.5 km / 3:04
7		Final climb, mass start	Free	10 km / 34:22	10 km / 30:56

Table 2. Recommendations for nutrition around Tour de Ski (TDS) to address the special challenges that arise from this type of racing.

Factors	Challenges during the TDS	Nutrition recommendations
EA	Low or suboptimal EA due to poor appetite, lack of food availability, or a pressure to maintain a low body weight throughout the tour.	Encourage the skiers to maintain an optimal overall EA over the TDS by focusing on frequent ingestion of high CHO/energy foods. It may not be necessary/possible to achieve an optimal EA on a daily basis; as long as the overall rolling average remains at an acceptable level (~35-45 kcal ·kg FFM $^{-1}$) this should be fine. The skiers at a high risk for low EA are those who struggle with reduced appetite; and those restricting energy intakes; encourage these individuals to consider the negative implications of low EA for performance, immunity and recovery during and following the TDS; special nutrition support should be provided to these high-risk individuals
CHO	Inadequate daily CHO to replenish muscle glycogen stores in-between consecutive days of racing.	Aim at a daily intake of 7-12 g·kg^{-1} CHO. Remind the skiers that while a single race is unlikely to fully deplete muscle glycogen stores, daily high-intensity racing is CHO-dependent; here, suboptimal recovery is likely to have a residual effect on the muscle glycogen stores, race performance and recovery on the subsequent day of racing. During race ingestion of CHO will not be ergogenic but may assist in maintaining an

	Inadequate CHO intake preceding and following the races.	overall high CHO availability and support recovery on a daily basis. The skiers are encouraged to consume 1-4 $g{\cdot}kg^{-1}$ on meals pre- and post-race for maximized performance and recovery.
Protein	Adequate protein is required for optimal recovery across an intense multi-day racing period. Athletes with suboptimal energy and CHO availability may require higher intakes. Over-emphasis on protein intakes will increase satiety and likely impair the athlete's ability to ingest adequate energy and CHO.	For most skiers, daily intakes between 1.6 and 2.0 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ are recommended. Focus on spreading the meals evenly across the day, with appropriate dose (0.25 $g{\cdot}kg^{-1}$ or 20 to 30 g per meal) and an optimal timing (within 2 h) post-exercise. Higher intakes may be considered for athletes with inadequate energy and CHO intakes to prevent negative health and performance outcomes. While protein intake is important for recovery purposes, the key considerations of the XC skier during the TDS are around adequate EA and CHO.
Fat	A secondary fuel source during TDS and mainly during lower intensity portions of the overall tour (warm up, cool down). Fats may also contribute to the fuel oxidation during the latter stages of longer races of the tour, especially in the case of compromised muscle glycogen stores. Some evidence for the role of IMTG during high-intensity exercise. An energy dense option to increase energy intake during intense training and competition periods, thus assisting in maintaining optimal EA.	Fat intakes should be individualized based on overall target energy intake and contribute to at least 20% of total energy intake to ensure optimal health and performance goals.

	An essential part of a healthy training and competition diet to maintain optimal health and immune function.	
Sleep	High-intensity exercise may impair sleep which has implications for performance, recovery and immune function.	Adequate intake of energy, CHO and proteins (see above) remain the key nutritional considerations for optimal sleep hygiene. XC skiers should avoid ingestion of large doses of caffeine within ~6 h of going to bed as this may impair sleep quality and latency.
Immunity	Intense periods of competition and training are associated with a 3-fold increased risk of a viral infection during the TDS. Further confounding risk factors for respiratory infections include psychological stress, travel, human crowding, housing with other athletes, and concurrent viral epidemics.	Ensure adequate daily energy, CHO and protein intake. Consume a nutrient-dense, fiber-rich, diet with a variety of fresh fruit and vegetables. Avoid deficiencies in especially iron, vitamin D and E status. Current evidence for the usefulness of probiotics remains controversial. In the case of symptoms of respiratory infections, athletes are encouraged to ingest zinc lozenges at a dose of $75\ mg \cdot day^{-1}$ of elemental zinc within 24 h of the onset of symptoms
Altitude	The TDS is competed at low to moderate altitudes (500-1500 m a.s.l.) which according to the current knowledge do not pose a special challenge in terms of nutrition.	Follow guidelines for adequate energy, CHO and protein intakes as outlines above and in sections 3 and 4 in this review.
Cold	The environmental temperatures during the various stages of the TDS typically range from +4 °C to −10 °C. While cold, these temperatures are not extreme and according to available limited evidence, do not have implications from the nutritional point of view.	Follow guidelines for adequate energy, CHO and protein intakes as outlines above and in sections 3 and 4 in this review.
Travel	The TDS incorporates heavy travel schedules which exposes the athlete to a higher risk of inadequate nutrient intake and hydration status, where special challenges include changes in meal timings and availability of foods and fluids required for optimal recovery and fueling in-between daily racing.	Contact the hotel and the kitchen staff before-hand to plan for the use of the team chef during the tour.

	Travelling also increases the risk of illness due to hygiene issues and frequent and close contact with other humans.	Check which foods you are allowed to bring into the country as customs rules and regulations may prohibit certain items. Plan ahead (individually per each athlete) and pack accordingly. Understand that at times plans may have to be adjusted; be prepared for these events. Use long transportation in-between race locations as an opportunity to refuel (there may be delayed access to main meals so ensure availability of appropriate snacks during this time) and recover (napping: have earplugs, sleeping masks etc available for the skiers). Ensure adequate hygiene practices (handwashing with soap and water, antibacterial wash, etc.) among the skiers and the staff.
Ergogenic supplements	Some events of the TDS and the performance of individual skiers may benefit from the use of ergogenic supplements. There is a risk for contamination.	Caffeine can be used at around 3-6 $mg{\cdot}kg^{-1}$ 60 min before competition. Supplement use should be Individualized and practiced beforehand to avoid adverse effects. The evidence behind the benefits of other supplements in the context of the TDS remains controversial. Only use supplements that have been third party batch tested.

EA, Energy availability; *FFM*, fat-free mass; *CHO*, carbohydrate

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