PHYSIOLOGICAL DEMANDS OF ELITE CROSS-COUNTRY SKIING DURING A REAL COMPETITION

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ABSTRACT

Gonzalez-Millan, C, Perez-Brunicardi, D, Salinero, JJ, Lara, B, Abián-Vicen, J, Areces, F, Ruiz-Vicente, D, Soriano, L, and Del Coso, J. Physiological demands of elite cross-country skiing during a real competition. *J Strength Cond Res* 31(6): 1536–1543, 2017—The aim of this study was to assess different physiological variables before and after a 5-km (women) and 10-km (men) cross-country skiing competition to determine potential mechanisms of fatigue. Fourteen elite-level skiers competed in an official cross-country skiing competition using the classical style (9 men and 5 women). Instantaneous skiing velocity was measured during the race by means of 15-Hz global positioning system devices. Before and after the race, a sample of venous blood was obtained to assess changes in blood lactate and serum electrolyte and myoglobin concentrations. Prerace to postrace changes in blood oxygen saturation, forced vital capacity during a spirometry test, jump height during a countermovement jump, and handgrip force were also measured. Mean race speed was 15.8 ± 2.5 and 15.4 ± 1.5 $km \cdot h^{-1}$, whereas mean heart rate was 171 ± 6 and 177 ± 3 $b \cdot min^{-1}$ for men and women, respectively. There were no significant prerace to postrace changes in jump height, handgrip force, and forced vital capacity in men and women. Blood oxygen saturation was reduced from prerace to postrace in men (95.9 ± 2.1% to 93.1 ± 2.3%, $p = 0.02$) and women (97.8 ± 1.1% to 92.4 ± 2.1%, $p < 0.01$), whereas blood lactate concentration increased at the end of the race in men (1.4 ± 0.5 to 4.9 ± 2.1 $mmol \cdot L^{-1}$, $p < 0.01$) and women (1.9 ± 0.1 to 6.9 ± 3.2 $mmol \cdot L^{-1}$, $p < 0.01$). After the race, blood markers of muscle damage were at low concentrations, whereas serum electrolytes remained unchanged. Fatigue in 5- and 10-km cross-country skiing competitions was related to a reduced blood oxygen carrying capacity and presumably increased muscle and blood acidosis, whereas the influence of exercise-induced muscle damage on fatigue was minor.

KEY WORDS blood lactate concentration, performance, endurance athlete, myoglobin, lung ventilation

INTRODUCTION

Race times in cross-country skiing competitions may vary from several minutes (for 1.5-km sprint competitions) to several hours (for ski marathons) (13). Unlike other endurance events, such as endurance running in which the course of the race is predominantly flat, cross-country skiing competitions are held over courses with continuous changes of slope that demand near-maximum efforts on uphill and flat sectors combined with downhill sectors mainly used for recovery (2). Despite this "intermittent" nature, the length and duration of official cross-country competitions makes aerobic metabolism crucial for performance, although the contribution of anaerobic pathways might be noteworthy in sprint modalities or during short and steep uphill sectors.

According to the physical demands of the competition, maximal oxygen uptake ($\dot{V}O_2max$) has been identified as one of the main factors for success in cross-country skiing races (12,25,29). Still, a high $\dot{V}O_2max$ does not necessarily guarantee success at the elite level because $\dot{V}O_2max$ cannot be maintained during the whole cross-country skiing race (33). Perhaps, the maintenance of a high proportion of $\dot{V}O_2max$ is likely a better indicator of physiological performance in cross-country skiing because it is typically related to the ability to exercise without net accumulation of blood lactate (a high lactate threshold; (16,33)). In fact, although blood lactate concentration increases progressively during a race, especially after uphill sectors (33), blood lactate concentration ranges from 7 to 14 $mmol \cdot L^{-1}$ after a race (15,20,21).

Besides the necessity of extraordinary values of $\dot{V}O_2max$ and lactate threshold, cross-country skiing requires fast and dynamic muscle contractions–in both upper body and lower body–repeated for the duration of the race. Although muscle contractions during cross-country skiing competition

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represent only 10–20% of a skier's maximal strength, the requirement of muscle strength might be considerably greater in certain competitive situations, such as uphill and flat sectors (13). Poling force and cycle duration are reduced, whereas cycle frequency increases when skiers are fatigued (34), manifesting the importance of maintaining upper-body strength in this sport. In fact, recent research has provided evidence about improved cross-country skiing performance after a protocol of strength training (18,24). Other endurance sports that also involve continuous concentric and eccentric muscle contractions repeated over time, such as running or triathlon, lead to moderate-to-high levels of exercise-induced muscle damage that greatly limit performance (5–7). However, there is no information about muscle force reductions or the presence of exercise-induced muscle damage during cross-country skiing competitions.

Apart from these physiological aspects, lung function and arterial saturation have also been proposed as factors for success in cross-country skiing. Despite the extraordinary $\dot{V}O_2max$ values of elite cross-country skiers, lung function capacity was only 5–20% higher than in sedentary men while mild blood oxygen desaturation has been confirmed during maximal exercise intensity in elite cross-country skiers (14). In fact, those skiers with a higher $\dot{V}O_2max$ were the ones with a higher blood oxygen desaturation at maximal exercise intensity (14). Thus, there is the possibility that not all organs can adapt to the same extent with endurance training resulting in a mismatch between the blood O_2 transporting capacity and the O_2 diffusion system (9), ultimately affecting performance in endurance events such as cross-country skiing.

Most of the information about the physiological demands of cross-country skiing has been obtained by comparing the skating or double-pole technique (2,13,14,26,33). However, the mechanisms underlying fatigue in this type of competitions have not been properly investigated (36). Thus, the aim of this investigation was to assess different physiological variables before and after a 5-km (women) and 10-km (men) cross-country skiing competition to determine potential mechanisms of fatigue. We hypothesized that the 5- and 10-km competitions would produce significant decrements in upper- and lower-body muscle strength produced by decreased blood oxygen saturation and the presence of exercise-induced muscle damage.

METHODS

Experimental Approach to the Problem

The experimental design of this investigation included a pre-to-post analysis in elite male and female cross-country skiers to determine the physiological demands and the main cause (s) of fatigue in middle-distance competitions. This investigation was carried out in an ecological context–official competition–to reflect the true physiological challenges of 5- and 10-km cross-country skiing competitions with the final aim of improving the applicability of the results elite competitors. The rationale of this investigation was to assess different physiological variables before and after a real cross-country skiing competition to provide objective information about the training adaptations to seek in elite-level skiers.

Subjects

Nine male (18–43 years, 73.5 ± 5.1 kg) and 5 female (17–22 years, 65.8 ± 11.1 kg) well-trained and experienced cross-country skiers volunteered to participate in this study. Inclusion criteria involved previous cross-country skiing experience of at least 5 years, training routines for $\sim 2\ h \cdot d^{-1}$ on 4–5 $d \cdot wk^{-1}$ in the previous year and competing at elite or national level in their respective categories. Exclusion criteria included a history of serious muscle, cardiac or kidney disorders, taking any medication during the 2 weeks before competing, and bone, muscle, or tendon injuries in the 2 months before the experiments. Participants were fully informed of the benefits and the risks and discomforts associated with the experiments before signing an institutionally approved informed consent document to participate in the study. One female participant was underage (i.e., 17 years) and her parents received written and verbal information regarding the nature of the investigation and provided a written informed consent to participate in the investigation. The Camilo Jose Cela University Ethics Committee, in accordance with the latest version of the Declaration of Helsinki, approved the study.

Procedures

The experiment was carried out during the Spanish Cross-country Skiing Cup (February), at the Navafría Nordic Skiing Centre, Spain. This race was the most important competition of the season for most of the participants in the investigation and it was celebrated at the end of the competitive season. The day before the race, participants were encouraged to abstain from all dietary sources of alcohol and caffeine (e.g., coffee, cola drinks, chocolate) and to perform only light-intensity exercise. Participants had their habitual pre-competition breakfast at least 4 hours before the onset of the competition and they were encouraged to avoid stimulants containing nutritional supplements. Self-reported training and food or drink diaries confirmed the compliance of these standards.

On arrival at the ski center, each participant filled out an ad hoc questionnaire about age, previous cross-country skiing experience, and training routines. Participants then rested for 5 minutes in a chair and a 7-ml venous blood sample was withdrawn. Blood lactate concentration at rest was measured from capillary blood with a portable lactate analyzer (Lactate Pro; Arkray Inc, Kyoto, Japan). After this, participants performed a maximal exhalation after a maximal inspiration (Spirobank G; Medical International Research, Roma, Italy), following guidelines for standardized spirometry (19). For this maneuver, participants performed the maximal exhalation with an anatomical mouthpiece between their teeth while the lips firmly sealed the mouthpiece, allowing the air to pass freely from the mouth to the spirometer and a nose clip was used to avoid any air leakage through the nostrils. Participants performed 2 repetitions of the spirometry test, with a 3-minute rest period between repetitions, and forced vital capacity and forced expiratory flow were measured. The repetition with the highest value of forced vital capacity was chosen for the statistical analysis.

Participants then completed a 15-minute warm-up consisting of ski routines at submaximal intensity and practice jumps. After that, participants performed 2 countermovement vertical jumps for maximal height on a force platform (Quattrojump; Kistler, Winterthur, Switzerland) to assess prerace leg power output. There was 1 minute of rest between attempts, and the jump with the highest vertical height was chosen for the statistical analysis. For this measurement, participants began stationary in an upright position with their weight evenly distributed over both feet. Each participant placed their hands on their waist to remove the influence of the arms on the jump. On command, the participants flexed their knees and jumped as high as possible while keeping the hands on the waist and landed with both feet. During the jumps, 2 experienced experimenters checked the correct execution of each jump (neither arm nor trunk movements during the impulse and landing phases) while jumps executed incorrectly were repeated. The precompetition jumps were performed with the clothes and ski boots used during the race to replicate the conditions of the jump after the race. Handgrip maximal strength production in both hands was also measured using a handgrip dynamometer (Grip-D; Takei, Niigata, Japan). For this measurement, participants were encouraged to grip the dynamometer as hard as possible during 4 seconds. Participants performed 2 attempts with each hand with a 30-second resting period between repetitions; the highest value obtained with each hand was chosen for the statistical analysis. The handgrip test was performed with participants in an upright position, with the elbows extended, the arms parallel to the body, and the wrist in neutral position. After this, participants continued with their precompetition routines.

Ten minutes before the onset of the race, participants were weighed in their competition clothes (±50 g scale; Radwag, Radom, Poland), and blood oxygen saturation was measured for 30 seconds by means of pulse oximetry (Oxym2001; Quirumed, Valencia, Spain). At this time, a global positioning system (GPS) or heart rate device (SPI-PRO-X; GPSports, Canberra, Australia) was inserted into a custom-made harness, and a heart rate monitor (T34; Polar, Oulu, Finland) was attached to their chest. The GPS obtained data at 15 Hz, whereas the heart rate monitor obtained data at 1 Hz. Heart rate during the race was normalized by individual's maximal heart rate, obtained during an incremental running test until volitional fatigue on a treadmill measured on a different day. After that, participants headed to the start line without instructions about pace or other indications related to the race.

The race consisted of 5 km of cross-country skiing for women and 10 km of cross-country skiing for men with an individual time-trial racing format. The competition was carried out in a circuit at ~1750 m of altitude with a length of 5 km (180 m of net positive elevation), and participants used the classical style during the race. The competition course was mapped with a GPS and a barometer to provide a valid course and elevation profile. The course was set in an open area with minimal tree cover, thus there were minimal interferences for the GPS data collection process. Female participants completed one lap of the circuit and male participants completed 2 laps (Figure 1). Conditions during the race were mean ± *SD* dry temperature of 3 ± 1° C with a relative humidity of 73 ± 8%. Pole length, boot style, and ski base preparation (grinds, structure, and waxing) were individualized to the specific athlete's preferences. A machine prepared the track of the evening before the competition while the snow was hard-packed on the day of the competition. Within 15 seconds of the end of the race, blood oxygen

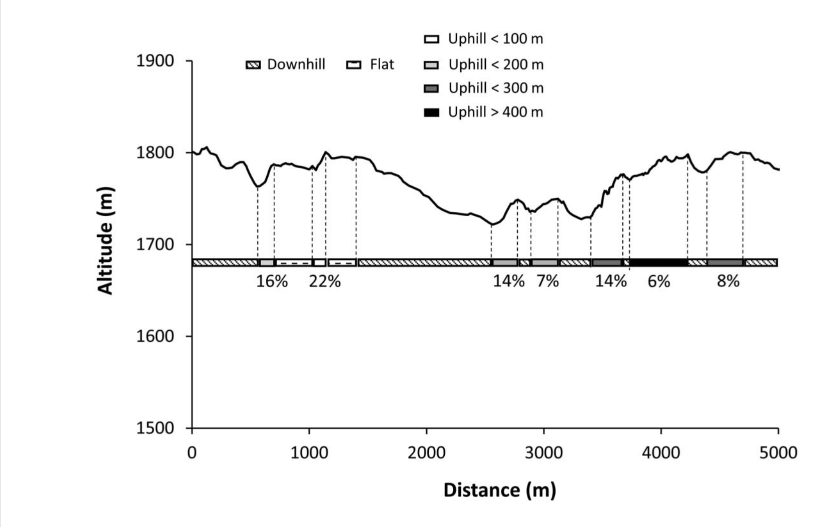

Figure 1. Profile of the ski trail. Female skiers performed 1 lap of this trail (5 km) and male skiers performed 2 laps of this trail (10 km). This profile included downhill, flat, and uphill sectors. The distance (from shorter than 100 m to longer than 400 m) and the gradient (from 6 to 22%) have been included for each uphill sector.

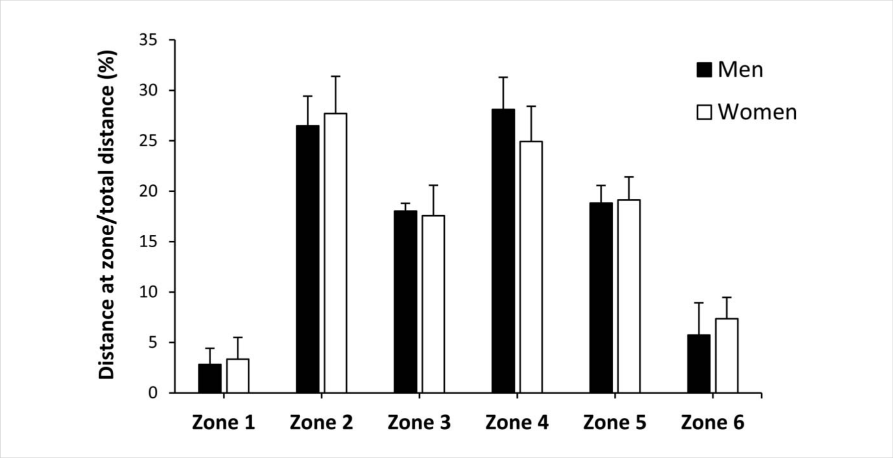

Figure 2. Percentage of distance covered at different speeds during a cross-country skiing competition in elite female (5 km) and male participants (10 km). The skiing velocity during the competition was measured by means of 15-Hz GPS devices. Zone 1 = from 0 to 4.99 km·h^{-1}. Zone 2 = from 5.0 to 9.9 km·h^{-1}. Zone 3 = from 10.0 to 19.9 km·h^{-1}. Zone 4 = from 20.0 to 29.9 km·h^{-1}. Zone 5 = from 30.0 to 39.9 km·h^{-1}. Zone 6 = >40 km·h^{-1}.

saturation and blood lactate concentration were obtained as previously described. After this, participants performed 2 countermovement jumps and the handgrip strength test, as previously described. Then, the spirometry test was executed following the methodology described above and the individual's body mass was measured. The body mass change attained during the race was calculated as a percent reduction in body mass (prerace to postrace). Although the postrace body mass measurement included the sweat trapped in the clothing, this represents an error of less than 10% for the calculation of true hydration status (3). Participants then rested for 5 minutes and a venous blood sample was obtained. After that, participants were provided with fluid (water and sports drinks) and finished their participation in the study.

A portion of each whole blood sample was used to determine glucose concentration (Accu-chek; Roche, Basel, Switzerland), hemoglobin concentration (Coulter ACT5 Diff CP; Beckman-Coulter Instruments, Brea, CA, USA), and hematocrit (microcentrifugation). Blood volume and plasma volume changes during the race were calculated using the equations outlined by Dill and Costill (10). The remaining blood was allowed to clot in serum-separating tubes (BD Vacutainer Rapid Serum Tube, Becton Dickinson, Franklin Lakes, NJ, USA) and then serum was separated by centrifugation (10 minutes at 5,000*g*) and frozen at −80° C within the following 10 minutes. Forty-eight hours after the end of the race, the serum portion was analyzed for sodium, potassium, and chloride concentrations (Nova 16; NovaBiomedical, Boston, MA, USA). In addition, myoglobin and creatine kinase concentrations were measured as blood markers of muscle damage (AU5400; Beckman Coulter, Brea, CA, USA).

Statistical Analyses

Data are presented as mean ± *SD* for male and female participants, and the alpha level for significance in paired

Table 1. Prerace to postrace changes in handgrip maximal strength during a handgrip dynamometer test, jump height during a countermovement jump, and forced vital capacity during a spirometry test, in a cross-country skiing competition in elite female (5 km) and male (10 km) participants.

Variable (units)	Group	Pre	Post	*p*
Right handgrip force (N)	Men	434 ± 75	423 ± 82	0.76
	Women	325 ± 129	309 ± 102	0.83
Left handgrip force (N)	Men	432 ± 62	412 ± 46	0.44
	Women	295 ± 141	285 ± 83	0.89
Countermovement jump height (cm)	Men	29.8 ± 4.8	31.8 ± 2.7	0.31
	Women	24.6 ± 3.8	26.2 ± 3.6	0.51
Countermovement jump peak power (W·kg^{-1})	Men	24.0 ± 3.6	24.9 ± 4.1	0.61
	Women	20.5 ± 3.5	22.2 ± 5.1	0.56
Forced vital capacity (L)	Men	5.2 ± 0.8	5.2 ± 0.8	0.88
	Women	4.0 ± 0.6	3.8 ± 0.3	0.60
Force expiratory volume in 1 s (L)	Men	4.5 ± 0.6	4.6 ± 0.6	0.86
	Women	3.7 ± 0.4	3.6 ± 0.4	0.99

comparison was set at $p \le 0.05$. Because of the difference in the competition distances, there were no comparisons between male and female participants. Normality was tested with the Shapiro-Wilk test, with all the variables presenting a normal distribution. Prerace to postrace changes in the variables measured twice in this investigation were analyzed with the Student's *t*-tests for paired samples. The data were analyzed with the statistical package SPSS version 20.0 (SPSS Inc., Chicago, IL, USA).

RESULTS

Total race time was 38.2 ± 3.6 minutes for male skiers (10 km) and 19.7 ± 2.0 minutes for female skiers (5 km). Mean race speed was 15.8 ± 2.5 $\text{km}\cdot\text{h}^{-1}$ for men and 15.4 ± 1.5 $\text{km}\cdot\text{h}^{-1}$ for women, whereas the maximal speed achieved during the race was very similar (46.0 ± 2.7 and 46.4 ± 3.6 $\text{km}\cdot\text{h}^{-1}$, respectively). Figure 2 depicts the distribution of distances covered at different speeds. The distance in zones 1, 2, and 3 was covered mostly during uphill sectors, whereas the distance in zones 4, 5, and 6 was covered during flat and downhill sectors. For both male and female skiers, the distance covered in zones 2 and 4 were higher than the remaining zones ($p \le 0.05$), although a considerable distance was covered at a speed higher than 30 $\text{km}\cdot\text{h}^{-1}$. The distribution was very comparable for men and women despite the difference in the distance covered during the race. Mean heart rate (171 ± 6 $\text{b}\cdot\text{min}^{-1}$, 89 ± 4% of maximal heart rate for men and 177 ± 3 $\text{b}\cdot\text{min}^{-1}$, 87 ± 3% of maximal heart rate for women) and peak heart rate during the competition (189 ± 5 $\text{b}\cdot\text{min}^{-1}$, 98 ± 5% of maximal heart rate for men and 189 ± 3 $\text{b}\cdot\text{min}^{-1}$, 95 ± 1% of maximal heart rate for women) were similar between men and women.

In men and women, handgrip force was similar before and after the race in the right hand and in the left hand (Table 1). Jump height and peak power during a countermovement jump were also similar before and after the race in both men and women. During the spirometry test, there were no prerace to postrace changes in forced vital capacity or forced expiratory volume in male and female skiers.

Body mass was significantly reduced by 1.1 ± 1.1% in men and by 0.5 ± 0.5% in women during the competition ($p \le 0.05$). Blood volume and plasma volume were significantly reduced during the race (Table 2; $p < 0.01$) in both men and women. Blood oxygen saturation was also reduced from prerace to postrace in both groups ($p \le 0.05$), whereas blood lactate concentration significantly increased after the race ($p < 0.01$). Blood glucose concentration increased during the race only in female participants ($p < 0.01$), whereas a tendency was observed in male skiers ($p = 0.09$). Serum myoglobin and creatine kinase concentrations were higher after the race in men ($p < 0.01$) but only serum creatine kinase concentration was significantly increased after the race in

TABLE 2. Prerace to postrace changes in blood and plasma volume, oxygen saturation, glucose and lactate concentration, and serum triglycerides, myoglobin, creatine kinase, and electrolytes concentration, in a cross country skiing competition in elite female (5 km) and male (10 km) participants.

Variable (units)	Group	Pre	Post	p
Blood volume change (%)	Men	–	−1.8 ± 1.8	<0.01
	Women	–	−1.8 ± 2.0	<0.01
Plasma volume change (%)	Men	–	−3.2 ± 3.1	<0.01
	Women	–	−3.2 ± 3.2	<0.01
Blood oxygen saturation (%)	Men	95.9 ± 2.1	93.1 ± 2.3	0.02
	Women	97.8 ± 1.1	92.4 ± 2.1	<0.01
Blood glucose concentration ($\text{mg}\cdot\text{dL}^{-1}$)	Men	96.0 ± 8.2	112.0 ± 32.7	0.09
	Women	74.4 ± 12.4	171.0 ± 12.0	<0.01
Blood lactate concentration ($\text{mmol}\cdot\text{L}^{-1}$)	Men	1.4 ± 0.5	4.9 ± 2.1	<0.01
	Women	1.9 ± 0.1	6.9 ± 3.2	<0.01
Serum triglyceride concentration ($\text{mg}\cdot\text{dL}^{-1}$)	Men	87.7 ± 34.4	71.3 ± 25.3	<0.01
	Women	60.6 ± 23.4	69.4 ± 18.1	0.11
Serum myoglobin concentration ($\mu\text{g}\cdot\text{L}^{-1}$)	Men	27.6 ± 10.0	109.6 ± 48.9	<0.01
	Women	24.2 ± 7.2	27.4 ± 9.9	0.32
Serum creatine kinase concentration ($\text{U}\cdot\text{L}^{-1}$)	Men	193.9 ± 80.7	264.7 ± 111.1	<0.01
	Women	201.6 ± 99.7	224.8 ± 115.6	0.02
Serum sodium concentration ($\text{mmol}\cdot\text{L}^{-1}$)	Men	140.4 ± 1.7	140.1 ± 1.2	0.14
	Women	139.8 ± 1.5	138.8 ± 0.8	0.04
Serum chloride concentration ($\text{mmol}\cdot\text{L}^{-1}$)	Men	95.2 ± 1.5	93.8 ± 1.7	0.01
	Women	96.4 ± 0.5	93.0 ± 1.4	<0.01
Serum potassium concentration ($\text{mmol}\cdot\text{L}^{-1}$)	Men	4.3 ± 0.3	4.2 ± 0.5	0.29
	Women	4.3 ± 0.6	3.7 ± 0.2	0.01

women ($p = 0.02$). In women, serum sodium, chloride, and potassium concentrations were reduced during the race ($p \leq 0.05$), whereas only serum sodium concentration was reduced in men skiers ($p \leq 0.05$).

DISCUSSION

The main outcomes of this investigation were as follows: (a) For both male and female skiers, the values for upper-body (handgrip dynamometry) and lower-body (countermovement jump) muscle force or power production were similar before and after the race, which indicates that there was no quantifiable muscle fatigue during the competition. (b) Forced vital capacity and maximal expiratory flow remained unchanged from prerace to postrace, although blood oxygen saturation was significantly reduced in both sexes after the race. This suggests a reduced blood oxygen carrying capacity during the race despite insignificant fatigue in the respiratory muscles. (c) Blood lactate concentration increased during the race, whereas blood markers of exercise-induced muscle damage remained at very low levels. (d) Body mass loss, serum electrolyte concentration changes, blood and plasma volume reductions, and blood glucose concentration remained at values that correspond to minimal physiological consequences regarding fatigue during the cross-country skiing competition. Although we did not observe fatigue after 5-km (women) and 10-km (men) cross-country skiing races (as measured by upper-body strength and lower-body power changes), the accumulation of blood lactate coupled with a reduced blood oxygen saturation might be related to decreased physical performance in some sectors of the competition. Nevertheless, it is possible that dehydration, serum electrolyte imbalances, or exercise-induced muscle damage develop fatigue in cross-country skiing competitions of longer distances.

The physiological demands of cross-country skiing have been mostly determined by comparing classical and skating techniques in ecological contexts (2,13,14,20,22,33) or by using data obtained in the laboratory (13,14,25,26,30,31). From these previous investigations, it is clear that aerobic capacity, regarding $\dot{V}O_2max$, is a basic physiological condition for success in cross-country skiing, whereas factors such as quadriceps strength, body fat percentage, and heart volume are other parameters related to performance in this sport (16). However, there is a lack of information about the exact mechanism(s) related to fatigue in cross-country skiing. Although muscle strength reductions, exercise-induced muscle damage, or body water and electrolyte deficits and even hypoglycemia have been identified as limiting factors in other endurance sports (5–7,28), no study has been geared to determine the prevalence and degree of these factors in cross-country skiing.

Interestingly, the current investigation determined that there is no muscle fatigue after a cross-country skiing competition by comparing data on handgrip force and countermovement jump height and power before and after the race. These data coincide with the small, although statistically significant, declines in velocity found in men (from 6.8 to 6.5 $m \cdot s^{-1}$) and women (from 6.0 to 5.9 $m \cdot s^{-1}$) when comparing 5-km laps in 10- to 15-km competitions (17). A previous laboratory investigation determined a significant reduction in poling force during a submaximal cross-country trial performed after a test to exhaustion on a treadmill (34). However, the "fatigue" induced in this laboratory setting did not reflect the physiological challenges of a cross-country competition with continuous uphill and downhill sectors.

Despite carefully setting the performance tests just at the end of the competition and the fact that the time between the race finishing and the measurements was less than 2 minutes, data on these variables remained unchanged after the race (Table 1). Besides, the concentrations of serum creatine kinase and myoglobin at the end of the race indicated mild-to-insignificant exercise-induced muscle damage in both male and female competitors. Interestingly, postcompetition values of serum myoglobin and creatine kinase were higher in men than in women, which might indicate a progressive effect of the competition distance rather than a sex effect on the development of exercise-induced muscle damage during cross-country skiing. In any case, these values are much lower than the ones found after a marathon (1,5) or after a half-ironman (6,7), where muscle damage was one of the main causes for the development of muscle fatigue and reduced overall performance. All this information, merged together, suggests that the capacity to produce force in the active skeletal muscle fibers remained unchanged during the cross-country competition, at least in these 5- and 10-km races. This finding contrasts with the causes of fatigue found in other sprint-based cross-country competitions (32,35,36).

Exercise-induced hypoxemia has been found in several endurance sports, such as running, cycling, and rowing, and it has been linked to ensuing fatigue during endurance-based exercise (23). Cross-country skiers may be more prone to suffering exercise-induced hypoxemia than participants in other sports because of the high muscle mass involved (11) and the concurrence of competitions and race courses at certain levels of altitude. Holmberg et al. (14) found mild blood oxygen desaturation in elite skiers exercising at maximal intensity on a treadmill. The current investigation confirms this finding but increases the ecological validity because we measured a reduction in blood oxygen saturation during a real competition (Table 2), although the hypoxemia values could have been influenced by the altitude of the race course (~1,750 m of altitude). In contrast, the exercise-induced hypoxemia found in the current cross-country skiers was not related to respiratory muscle fatigue because forced vital capacity and peak expiratory flow during the first second remained unchanged prerace to postrace. The exercise-induced hypoxemia in cross-country skiing could be related to the 1:1 locomotor respiratory coupling typically used in the classical style that leads skiers to use higher tidal volumes for increased mechanical ventilation instead of a higher respiratory frequency. Thus, the use of respiratory muscle training strategies to increase tidal volume could be a reasonable recommendation to avoid or reduce blood oxygen desaturation during a cross-country skiing competition.

The average speeds obtained in this investigation were very similar to the ones reported in previous investigations with skiers of similar characteristics and using the same classical style (4,20,33) but they were slightly slower than the speed reported in world-class cross-country skiers (2). The average heart rate during the competition was also comparable with previous investigations (2,20,33), although the pattern is highly dependent on the racecourse profile. Although the race in the current investigation finished after a downhill sector, blood lactate concentration after the race (Table 2) was similar to previous data obtained in similar conditions (15,20,21,33). Welde et al. (33) established that junior cross-country skiers do not exercise close to their $\dot{V}O_2max$; instead, the exercise intensity maintained during a ~25-minute competition was similar to the onset of blood lactate accumulation, as measured in laboratory testing. Thus, it seems that cross-country skiers regulate speed during uphill and downhill sectors to limit the accumulation of blood lactate. It is likely that the muscle and blood accumulation of H^+ represents a major mechanism for fatigue in this sport.

In summary, during a cross-country skiing competition in elite-level skiers (5 km for women and 10 km for men), there was a significant accumulation of blood lactate and a reduction of blood oxygen saturation induced by the race despite upper- and lower-body muscle strength and power remained unchanged. Thus, the accumulation of H^+ in the active muscle and into the blood, as a result of the engagement of anaerobic pathways, joined to a reduced blood oxygen-carrying capacity, seem to be the mechanisms related to reduced performance in some sectors of the cross-country skiing competition. In contrast, other fatiguing mechanism, predominantly present in other endurance disciplines, such as upper- and lower-body muscle fatigue, respiratory muscle fatigue, hypoglycemia, exercise-induced muscle damage, or body water and electrolyte deficits, were not present during this cross-country competition, at least over the distances used in this investigation.

Practical Applications

The present study extends earlier knowledge regarding the possible cause(s) of fatigue in cross-country competitions, by specifically addressing fatiguing mechanism related 5- and 10-km competitions. Although skiers did not present decrements in upper-body strength (handgrip dynamometry) and lower-body power (countermovement jump), there was a significant accumulation of blood lactate and a reduced blood oxygen saturation after the race. These data were evident despite the competition finished after a downhill sector that likely allowed the recovery of the participants during this last period of the race. In any case, these values suggest that blood and muscle acidosis and a reduced blood oxygen-carrying capacity might be related to fatigue in some parts of the cross-country skiing race. Thus, as a practical application, the current investigation suggests the necessity of using high-intensity training routines to improve H^+ regulation and to increase muscle and blood buffer capacity that ultimately would lead to a higher skiing speed during this type of competition (27). To this respect, the selection of training protocols that combine repeated bouts of high-intensity interspersed with low-intensity and prolonged recovery periods might be necessary to obtain adaptations related to improved lactate removal and reduced muscle acidosis (8). Besides, legal physical and physiological strategies to increase the blood oxygen-carrying capacity can also improve cross-country performance in this competition distances. This manuscript is unique because it offers the assessment of different physiological variables during real cross-country skiing competitions, thus providing valuable information of potential mechanisms of fatigue and training adaptations to seek in elite-level skiers.

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