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Performance-Determining Variables of a Simulated Skimo Sprint Competition in Elite Junior Skimo Athletes

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Abstract: This study aimed to investigate the variables determining performance in a simulated on-snow Skimo sprint competition, and how their relationship with performance evolves from the individual time trial to the final. Fifteen national-level junior Skimo athletes (mean $\pm$ SD: age, 17.8 ± 2.5 years; maximal oxygen uptake, $66.8 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) underwent a comprehensive assessment, involving submaximal and maximal endurance tests, maximal strength assessments, and a maximal sprint to determine maximal glycolytic capacity. Subsequently, a simulated sprint competition, comprising an individual time-trial and three heats (quarterfinal, semifinal, final), was conducted. Whole-body and upper body aerobic power ($r = 0.69\text{--}0.93$), maximal speed and power ($r = 0.82\text{--}0.85$) during the maximal performance test, as well as fat-free mass ($r = 0.62\text{--}0.77$) and body fat ($r = -0.67\text{--}-0.77$), exhibited significant correlations with performance in the time-trial, quarterfinal and semifinal. Moreover, maximal strength ($r = 0.39\text{--}0.95$) and transition duration ($r = 0.52\text{--}0.85$) showed moderate to large correlations with sprint performance. Overall, aerobic power, maximal speed and power, as well as fat-free mass, and body fat emerged as crucial determinants of Skimo sprint performance, while dynamic strength and the ability to transition quickly between sections also proved to be relevant factors.

Keywords: fat-free mass; maximal oxygen uptake; one-repetition maximum; peak oxygen uptake; maximal speed; power; skimo; sprint; $\dot{V}L_{\text{max}}$



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1. Introduction

Alpine ski mountaineering (Skimo) is a winter endurance sport involving the ascent of steep snow-covered slopes on skis and descents on unprepared slopes. Skimo equipment features bindings that release the heel for uphill climbs, akin to traditional cross-country skiing technique, and locking it for downhill skiing [1,2]. Adhesive skins with directional fibers under the skis allow for forward gliding and provide adequate grip in uphill. Removing the skins at the top and locking the heels enables a transition to a downhill ski setup. Occasionally, skiers must hike steep sections carrying their skis on their backpacks.

Competitive Skimo includes various types of races, such as individual, team, vertical, relay, and sprint events [3]. The key differences between these events lie in the total elevation gain, the overall distance covered, and the distribution of downhill and uphill segments. Traditionally, individual races usually last between 1.5 and 2.5 h for the fastest racers [4]. The race requires covering a positive altitude difference of around 1500 m [3,5], meaning that more than 80% of the total time is spent on ascents [4].

Skimo sprint races involve multiple high-intensity efforts, each approximately three minutes long, with a maximum ascent of 70 m. The race includes two uphill sections on skis, separated by an uphill part on foot with skis attached to a backpack, followed by a

downhill section on skis. A sprint competition consists of an individual qualification time-trial (TT), followed by three elimination heats of six athletes as the competition progresses (quarterfinals [QF], semifinals [SF], and finals [F]). Altogether, a sprint competition lasts for a total duration of approximately 3–4 h, including warm-up, qualification and heats, and cool-down [3].

Long-distance Skimo performance is connected to performance-determining factors such as high maximal aerobic power ($\text{VO}_{2\text{max}}$) [4] and corresponding speed ($v\text{VO}_{2\text{max}}$) [6], the fraction of $\text{VO}_{2\text{max}}$ at ventilatory thresholds, while minimizing the energy cost of locomotion. Indeed, previous research revealed moderate-to-large correlations between Skimo race performance and physiological measures including $\text{VO}_{2\text{max}}$, $v\text{VO}_{2\text{max}}$ and VO_2 at the ventilatory thresholds [4,6,7]. The importance of $\text{VO}_{2\text{max}}$ was further emphasized in a comparison between elite and sub-elite athletes, where the former had 8% higher $\text{VO}_{2\text{max}}$ [6]. Depending on the race format, factors like anaerobic power, downhill skiing technique, low fat and body mass index, and effective equipment play crucial roles [5–8].

Nevertheless, the existing literature on competitive Skimo racing is relatively scarce, primarily concentrating on long-distance events. However, with the introduction of shorter sprint competitions in the upcoming 2026 Winter Olympics in Milano Cortina, greater attention will be directed towards this format. This underscores the need for additional research. Previous research has demonstrated that achieving higher average speeds on uphill sections (lasting for approx. 120–150 s) and optimizing transition times between sections are important determinants of Skimo sprint performance [9]. To date, no studies have explored the physiological variables linked to performance in Skimo sprint racing, nor how these dynamics evolve throughout the competition stages (e.g., from individual time-trial to finals).

Cross-country sprint skiing, which shares a similar format of repeated high-intensity efforts lasting around 2.5 to 3 min, highlights the critical importance of maximal aerobic capacity (i.e., both upper-body and whole-body) [10–13], skiing efficiency, and a robust anaerobic energy system [14–16]. Additionally, high speed skiing has been associated with strength and power, in both the upper and lower body [17,18]. Therefore, research suggests that heavier and more muscular cross-country skiers exhibit advantages on all terrain types except steep uphill [11,19,20]. However, as sprint skiing competitions progress, aerobic power has been shown of gradually greater importance [21]. Whether these findings apply to Skimo sprint requires further elucidation. However, one clear difference is that up to 80% of the total race time during Skimo sprint is spent on steep uphill. Accordingly, Skimo athletes may rely more on an effective power-to-weight ratio than absolute power capacities.

Therefore, the present study aimed to investigate performance-determining variables of an on-snow Skimo sprint competition in elite junior athletes and the evolution in their relationship with performance as the competition progresses from the time-trial to the final.

2. Methods

2.1. Participants

The study included fifteen national-level (Tier 3) [15] skimo athletes, comprising 11 men and 4 women, in the junior ($n = 10$) and U23 ($n = 5$) categories. All participants were members of the national youth Skimo team, participating in the World Cup ($n = 7$), Youth World Cup ($n = 6$), European Championships ($n = 4$), World Championships ($n = 4$), and Youth Olympic Games ($n = 3$). However, seven athletes did not complete any of the laboratory tests, resulting in a sample size of $n = 8$ (men, $n = 6$ and women, $n = 2$) for the conducted correlations. The mean $\pm$ standard deviation [SD] (confidence interval [CI]) characteristics of the group were as follows: age, 17.8 ± 2.5 (16.2–19.3) years; body height, 1.76 ± 0.07 (1.72–1.81) m; body mass, 61.8 ± 10.5 (55.1–68.4) kg; body mass index (BMI), 19.7 ± 2.2 (18.4–21.1) $\text{kg}\cdot\text{m}^{-2}$; body fat, 11.1 ± 5.8 (7.5–14.8) %; fat-free mass (FFM), 55.2 ± 11.5 (47.9–62.4) kg; $\text{VO}_{2\text{max}}$, 4157 ± 1025 (3184–5024) $\text{mL}\cdot\text{min}^{-1}$ and 66.8 ± 9.5 (60.8–72.9) $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. The mean training age in Skimo was 3.6 ± 1.8 (2.2–4.9) years. Table 1 provides an overview of the training characteristics of the group over the last

6 months prior to the intervention, presented as mean $\pm$ SD (CI). All participants and, for those under the age of 18, their parents, provided written informed consent to participate. The study was approved by the local university's institutional ethics committee (DHGS-EK-2023-004), and study procedures adhered to the principles outlined in the Declaration of Helsinki.

Table 1. Descriptive data of 6-month training volume and training intensity distribution in a group of male and female skimo athletes. Data are presented as mean $\pm$ SD (CI).

	Training	
	Hours	%
Total	278:58 $\pm$ 82:37 (202:33–355:23)	
Zone 1	193:01 $\pm$ 68:16 (129:53–256:10)	68.69 $\pm$ 11.75 (57.83–79.56)
Zone 2	67:15 $\pm$ 30:29 (39:03–95:26)	24.17 $\pm$ 9.39 (15.49–32.85)
Zone 3	11:20 $\pm$ 05:15 (06:28–16:11)	4.41 $\pm$ 2.81 (1.81–7.00)
Zone 4	05:23 $\pm$ 01:24 (04:05–06:41)	1.97 $\pm$ 0.26 (1.73–2.20)
Zone 5	01:37 $\pm$ 01:04 (00:37–02:36)	0.65 $\pm$ 0.49 (0.20–1.09)

Zone 1, 55–72% of HR_{max}; Zone 2, 72–82% of HR_{max}; Zone 3, 82–87% of HR_{max}; Zone 4, 87–92% of HR_{max}; Zone 5, 92–100% if HR_{max}. Based on the 5-Zone Intensity Scale used by the Norwegian Olympic Federation [22].

2.2. Experimental Design

Conducted over three days, the study involved a series of tests evaluating both upper and lower body strength, along with various endurance parameters. These tests included double poling on an ergometer, running on a track, and uphill skiing on a treadmill. The assessment protocol comprised submaximal stages, incremental tests to exhaustion, and a maximal sprint to determine the participants' maximal glycolytic capacity.

One week after these laboratory tests, the skiers participated in a simulated on-snow skimo sprint competition (see Figure 1). The researchers analyzed overall performance and measured the time spent in seven specific sections of the competition. During these assessments, continuous monitoring was conducted using a heart rate (HR) monitor and a global navigation satellite system (GNSS). The combination of these tests aimed to provide comprehensive insights into the skiers' physiological capacities and performance characteristics. For the simulated sprint competition, participants used their personal skiing gear, including poles, boots, skis, and climbing skins. Standardized skins were provided during all laboratory skiing examinations. All participants were familiar with the testing protocols.

Testing Procedure

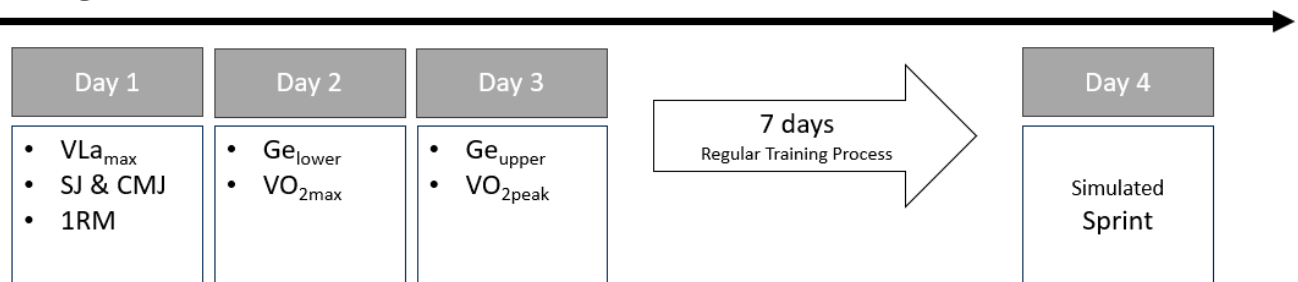


Figure 1. A schematic overview of the experimental protocol. Abbreviations: VLa_{max}, maximal glycolytic capacity test; SJ and CMJ, squat jump and counter movement jump tests; 1RM, one-repetition maximum tests; Ge_{lower}, gross efficiency test during treadmill skiing; VO_{2max}, maximal oxygen uptake test during treadmill skiing; Ge_{upper}, gross efficiency during upper body ergometry; VO_{2peak}, peak oxygen uptake during 3 min test on ski ergometer.

2.3. Laboratory Testing

Laboratory tests were carried out over 3 days under consistent environmental conditions, with a temperature range of 18–22 °C. To maintain comfort, a fan was utilized to circulate air around the participants. Throughout all tests, researchers provided strong verbal encouragement to ensure participants exerted maximal effort. To minimize potential confounding factors, participants were instructed to refrain from consuming caffeine and engaging in strenuous physical activity in the 24 h leading up to each laboratory test. Additionally, they were advised to consume their last meal at least two hours before testing.

2.4. Day 1

2.4.1. Assessment of Anthropometric Characteristics

Data collection procedures were conducted following previously described methods [23]. The participants were given specific instructions, including refraining from eating for 8 h prior to testing, minimizing fluid intake on the morning of the test, and emptying the bladder immediately before the test. Anthropometric characteristics were assessed using a measuring tape for standing body height (in meters). Body mass and body composition, including total and segmental lean body mass and fat mass, were analyzed using a bioelectrical impedance analysis device (InBody MC-780MA-N; InBody, Cerritos, CA, USA).

2.4.2. Maximal Strength

Maximal strength was assessed using the one-repetition maximum (1RM) in bench press, bench pull, and squat. Repetition maximum testing was conducted in accordance with the guidelines established by the National Strength and Conditioning Association [24]. The warm-up protocol included a 10 min warm-up on a cycle ergometer, followed by 3 sets with 2–5 repetitions at approximately 50–80% of 1RM for each exercise. The initial attempts for were performed with a load of approximately 90–95% of the estimated 1RM. After each successful attempt, the load was increased by 2–5% until participants failed to lift or pull the load with proper technique. The highest accepted attempt after two consecutive non-accepted attempts was registered as the 1RM. Rest periods of at least 5 min were provided between trials, and 1RMs were achieved within a maximum of 5 attempts. All 1RM testing was supervised by the same investigator and conducted on the same equipment with identical equipment positioning for each subject. The testing order for bench press, bench pull, and squat was the same in all testing sessions.

Bench press performance was tested in supine position on a bench. A 5-point body contact position (head, upper back, and buttocks firmly on the bench with both feet flat on the floor) were required to be graded proper form. During the eccentric phase of the exercise, a gentle contact of the barbell with the chest was permitted, although the attempt was considered unsuccessful if the chest movement helped the execution. The end position was determined by fully extended elbows at the end of the concentric movement [25].

Bench pull performance was tested in prone position on a bench. The examiner visually inspected whether the arms were straight as participants grabbed the barbell. The athletes performed a concentric arm flexion beginning from the extended position. The end position was determined by touching the bench with an elbow angle of $\leq 90^\circ$. Chest and lower extremities were required to stay in contact with the bench for a trial to be successfully performed [26].

During the squat attempts, participants were required to squat to a standardized depth, with the top of the thigh parallel to the ground. Squat depth was visually assessed and verbally reinforced by investigators. Squat attempts failed if participants could not stabilize the bar with their backs, lost the bar, or could not achieve the required depth.

The 1RMs were reported as both absolute values (kg) and relative strength (kg lifted/kg of body mass).

2.4.3. Maximal Glycolytic Capacity (VLa_{max})

An all-out 80 m running sprint test was conducted on an outdoor track. As part of a standardized warm-up, participants engaged in 5 min of low-intensity jogging at a self-paced velocity. Following the warm-up, participants performed two almost maximal starts for 5–10 m, starting every 90 s. Immediately before the 80 m sprint, participants rested for an additional 5 min in a sitting position. Time measurements were initiated when participants crossed the initial light barrier (specific device information is missing). Participants began the sprint autonomously, without a start signal, from a standing position. To prevent early triggering of the system by hand movement or a tilted upper body position, participants started 0.75 m ahead of the initial light barrier. After completing the sprint, participants sat down on a box and rested for another 10 min in a still position.

Blood samples were collected at various time points: at the arrival of the participants (1 sample), at the end of the warm-up (3 samples), immediately before and after the sprint, as well as every minute after exercise for 10 min. The samples were taken from the right earlobe using an enzymatic–amperometric sensor chip system (Biosen C-Line, EKF-diagnostic GmbH, Barleben, Germany).

VLa_{max} was calculated according to Equation (1) [27]:

$$VLa_{max} \text{ (mmol L}^{-1} \text{ s}^{-1}\text{)} = ([La^-]_{peak} - [La^-]_{rest}) \cdot (t_{exerc} - t_{alac}) \quad (1)$$

where $[La^-]_{peak}$ (mmol·L^{−1}) is the peak post-exercise lactate concentration, $[La^-]_{rest}$ (mmol·L^{−1}) is the resting lactate concentration, t_{exerc} (second) is the duration of exercise, and t_{alac} (second) is the period at the beginning of exercise in which no lactate formation is assumed. With reference to Heck, Schulz and Bartmus [27], t_{alac} was set to 3.5 s for all participants, since all sprint times fell in within the time span of 10 to 15 s.

2.4.4. Jump Performance

Squat jumps (SJ) and countermovement jumps (CMJ) were tested using a portable contact mat [ALGE, Lustenau, Austria]. The contact mat operates as a switch. It sent information to a computer regarding whether the mat was loaded. From this information, the flight time and the jump height were determined for all jumps. The jump height was calculated from the flight time ($gt^2/8$; g = the gravitational acceleration [9.81 m·s^{−2}] and t = flight time). ICCs of 0.87–0.98 and 0.94 have been reported for squat jumps and countermovement jumps, respectively [28,29]. To ensure adequate familiarization, the participants were given three test trials for each jump type. After the familiarization, the participants completed as many attempts as needed, with a 1 min rest in between, until two consecutive jumps were lower than the previous best. All jumps were performed with hands fixed on the hips throughout the entire measurement. The best result from these attempts was used for statistical analysis.

For a successful squat jump, participants initiated the jump from a squat position (approximately 90° knee angle) after a 2 s hold without momentum. The countermovement jump utilized the momentum of a preceding squat movement (to approximately 90° knee angle) to initiate an immediate jump. Correct movement execution was visually assessed, and participants received verbal reinforcement from the investigators while performing the jumps.

2.5. Day 2

2.5.1. Gross Efficiency (GE)

Physiological responses in connection with submaximal exertion were monitored during 5 min stages of treadmill skiing at a 15% inclination, with a 1 min rest between stages and a 0.2 m·s^{−1} increase in speed for each successive stage. The initial speeds were 1.0 m·s^{−1} for both men and women. The test was terminated when a blood lactate concentration ($[La^-]$) of (close to) 4 mmol·L^{−1} or higher was measured. Blood samples were taken on the right earlobe during the 30 s break between each 5 min period and

were analyzed for whole blood [la-] using an enzymatic–amperometric sensor chip system (Biosen C-Line, EKF-diagnostic GmbH, Barleben, Germany).

Pulmonary oxygen consumption (VO_2) and carbon dioxide production (VCO_2) were determined by calculating the average of the final minute. Immediately after the test, [la-] was measured. GE was calculated by dividing work rate by metabolic rate. To calculate the submaximal work rate (P_{sub}), power used against gravity (P_g) was calculated as the increase in potential energy per unit time: $P_g = m \cdot g \cdot \sin(a) \cdot v$, where v represents the belt speed and a represents the angle of incline. The metabolic rate was computed as the aerobic metabolic rate calculated by multiplying VO_2 with the oxygen energetic equivalent, using measurements of respiratory exchange ratio (RER) and standard conversion tables [30].

Respiratory parameters (VO_2 , VCO_2) were measured (10 s sampling time) using a computerized metabolic unit with mixing chamber (K5, Cosmed, Rome, Italy). The flow turbine was calibrated with a 3L calibration syringe. The metabolic system was calibrated with known concentrations of certified calibration gases before each test according to the specifications of the manufacturer. The spiroergometric system used for the upper-body capacity tests was identical.

2.5.2. Maximal Oxygen Uptake Test

After the submaximal GE test, participants had a 10 min passive recovery before undergoing an incremental test to determine $\text{VO}_{2\text{max}}$ and HR_{max} . The test began with a starting speed of $1.4 \text{ m} \cdot \text{s}^{-1}$ at a 15% inclination, and the speed was increased by $0.2 \text{ m} \cdot \text{s}^{-1}$ every minute until exhaustion. Skiers were verbally encouraged to continue as long as possible, and the test required fulfilling two out of three criteria: (1) achieving a 30 s VO_2 plateau while increasing exercise intensity, (2) RER above 1.10, and (3) exceeding [la-] of $8 \text{ mmol} \cdot \text{L}^{-1}$. [10] Continuous VO_2 measurements were taken, and $\text{VO}_{2\text{max}}$ was determined from the average of the three highest 10 s consecutive measurements. The start of the VO_2 plateau was defined as the time point corresponding to $\text{VO}_{2\text{peak}}$ minus 150 mL VO_2 , and the end of the VO_2 plateau was determined at the time of exhaustion. HR_{max} was the highest 10 s value recorded using electrode belts (Polar H10, Polar, Kempele, Finland). Peak [la-] was measured 1.5 min after completing the test. Peak treadmill speed (V_{max}) was calculated using the formula: $V_{\text{max}} = v_{\text{COM}} + (t/60) \cdot S$, where v_{COM} is the speed of the last completed stage, t is the number of seconds completed in the last uncompleted stage, and S is the change in velocity of the last uncompleted stage.

2.6. Day 3

2.6.1. Assessment of Upper-Body Capacity

A specially designed double poling ergometer (SkiErg; Concept 2, Morrisville, VT, USA) was used for all double poling capacity tests. Power was generated by pulling cords spinning a wind resistance flywheel, with the damper setting at 100% of body mass for all performance tests. Participants sat on a saddle-shaped stool adjusted to their height, minimizing variations in joint positions and imitating the body position for double-poling technique. Straps secured participants at the hip level, allowing a wide range of motion for the upper body, and additional straps around the ankles reduced leg contribution. This setup aimed to isolate upper-body movements during double poling.

Gross efficiency.

Physiological responses during submaximal exertion were monitored in three stages with low, moderate, and high steady-state 5 min workloads (approximately 60%, 70%, and 80% peak heart rate), with 30 s rest between stages. Blood samples were taken on the right earlobe during the 30 s breaks and analyzed for [la-] using an enzymatic–amperometric sensor chip system (Biosen C-Line, EKF-diagnostic GmbH, Barleben, Germany).

Steady-state conditions were considered if the respiratory exchange ratio remained below 1.0. Additionally, in accordance with the study by Nilsson et al. [31], a difference of less than 2.5% between two consecutive measurements was defined as the criterion for a steady-state VO_2 at a given power output. In general, blood lactate concentration

above 4 mmol L⁻¹ indicated a deviation from steady state, and only values below this are considered. However, since upper body work could differ in lactate production versus removal, we have included a few values that deviated from this criterion but where rate of perceived exertion and $\dot{V}O_2$ indicated aerobic steady state.

$\dot{V}O_2$ and $\dot{V}CO_2$ were determined by calculating the average of the final minute. Immediately after the test, [la-] was measured. GE was calculated by dividing work rate (average wattage of the submaximal stage) by aerobic metabolic rate. The aerobic metabolic rate was calculated by multiplying $\dot{V}O_2$ with the oxygen energetic equivalent, using measurements of RER and standard conversion tables [30].

2.6.2. Peak Oxygen Uptake Test

After the gross efficiency test, participants had a 5 min passive rest. Then, they performed a 3 min maximal effort bout, instructed to maintain an even maximal pace until exhaustion. Each skier received continuous visual and verbal feedback on the elapsed time, but remained blinded to other skiers' performances. Cardiorespiratory variables were continuously monitored, and the highest average $\dot{V}O_2$ during a continuous 30 s period was defined as $\dot{V}O_{2peak}$. The highest 10 s heart rate was defined as peak heart rate. Peak [la-] was measured 1.5 min after completing the test, and the average power output during the 3 min test was used to assess performance.

2.7. Day 4

2.7.1. Simulated Sprint Competition

The sprint competition was simulated on a racecourse that adhered to the ISMF sprint rules (see Figure 2) [3]. The race consisted of four technical sections (Section 1 on skis, S1S; Section 2 on foot, S2F; Section 3 on skis, S3S; Section 4 downhill, S4D) and three transitions (T1-2-3), with specified distances and climbs for each section.

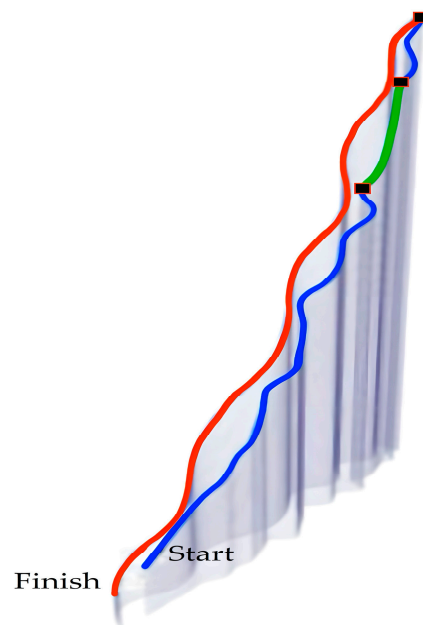


Figure 2. Three-dimensional profile of the racecourse. In accordance with ISMF sprint rules [3], the simulated sprint event took place on a 645 m course, which included both uphill (338 m) and downhill (307 m) sections, resulting in a total climb of 67 m. The average slopes for uphill and downhill were 21.1% and 23.2%, respectively. The blue line marks uphill skiing sections; the green line marks the uphill running section; the red line marks the downhill section; black squares with red outlines mark transition areas between sections; Start marks the race start; Finish marks the race finish.

The weather during the competition remained stable, characterized by partly cloudy and foggy conditions. The mean (range) values for ambient air temperature, relative humidity, and snow temperature were -3.1°C (-2.75 to -3.5°C), 84% (83–85%), and -4°C , respectively. No wind was observed on the course, and the snow comprised older layers with new snow from previous days.

The skiers were equipped with a combined GNSS, inertial measurement unit (IMU), and barometric pressure sensor (Naos, Archinisis GmbH, Düringen, Switzerland), which was replaced between different finals. The methodology used has been previously described [32]. To enhance GPS accuracy, all sensors were activated at least 45 min before testing. Archinisis software (0.1.3 ANAVS) improved precision by computing an average reference course with a defined course and elevation profile using data from 10 segments. The sensor automatically detected movement cycles and their corresponding sub-techniques, utilizing trunk inclination peaks as cycle indicators. It applied a Gaussian mixture model to classify these cycles into sub-techniques, considering metrics like cycle distance, lateral excursion, and trunk inclination consistency within each cycle [33].

Participants wore electrode belts to monitor heart rate (Polar H10, Polar, Kempele, Finland), and used their own ski equipment, including poles, boots, skis, and skins during the simulated competition. Athletes had an hour for individual warm-up routines. Subsequently, they participated in an individual time trial to determine quarterfinal heats based on their TT rank. The two fastest skiers (rank 1–2) from each quarterfinal advanced to the semifinal heats, while the four slowest skiers (two withdrew after TT) competed in the Lucky Loser Final (LLF). The two fastest skiers from each SF advanced to the big final, whereas the two slowest skiers from each SF competed in the small final. Recovery times between TT, QF, SF, and F were set to 45–60 min, 30 min, and 30 min, respectively, to avoid potential impacts on subsequent performance. Rate of perceived exertion (RPE) was assessed utilizing the 6–20 Borg scale [34].

2.7.2. Statistics

All statistical analyses were conducted using SPSS 29.0 (SPSS Inc, Chicago, IL, USA), with data presented as mean $\pm$ SD. Additionally, the 95% confidence intervals (95% CI) for means were reported. The Shapiro–Wilk test was used to assess the normality of the data, and the homogeneity of variances was verified using the Levene’s test. Two separate one-way repeated measures ANOVA were employed to compare performance across the TT and heats. One was calculated for all participants from TT to SF (LLF included). The second was calculated only for the finalists from TT to F. Where global differences were observed, Scheffe’s post hoc analyses were conducted to pinpoint the specific locations of these differences. The relationship between physiological characteristics and sprint performance (speed in the different sections) was analyzed using the non-parametric Kendall’s Tau rank correlation coefficients. Additionally, 95% CI for correlation coefficients were reported.

3. Results

Table 2 presents the time, speed, transition time, and cycle characteristics, along with the corresponding physiological responses during the time-trial and heats of the simulated on-snow sprint skimo competition. The Lucky Loser Final lasted for a total average duration of 333.2 ± 59.0 [257.0–403.4] seconds, with an average speed of 2.1 ± 0.4 [1.7–2.5] $\text{m}\cdot\text{s}^{-1}$, and a total transition duration of 72.6 ± 7.8 [62.9–82.3] seconds. The evaluation of the performances across the time-trial and heats showed no significant differences for most of the measures ($F = 0.064$ – 2.028 , $\eta^2 = 0.006$ – 0.225 , $p = 0.26$ – 0.96). The only observed differences in performance between heats was found in Section 1 on skis, with all participants included from TT to SF ($F = 4.880$, $p = 0.02$, $\eta^2 = 0.307$). Post hoc testing pointed out significant performance differences between prolog and quarterfinal ($d = 0.28$, $p < 0.05$), as well as prolog and semifinal ($d = 0.35$, $p < 0.05$), but no differences between quarterfinal and semifinal ($d = 0.07$, $p < 0.05$).

Table 2. Descriptive data of time, speed, transition time, cycle characteristics, and related physiological responses during a simulated on-snow sprint skimo competition in a group of male and female skimo athletes. Data are presented as mean $\pm$ SD (CI).

Total						
	Time-Trial (<i>n</i> = 15)	Quarterfinal (<i>n</i> = 13)	Semifinal (<i>n</i> = 8)	Final (<i>n</i> = 8)	Average (<i>n</i> = 15)	* <i>p</i>
Overall Time (s)	284.4 $\pm$ 55.9 [252.1–316.7]	282.8 $\pm$ 49.7 [252.7–312.8]	262.6 $\pm$ 29.9 [237.6–287.6]	253.8 $\pm$ 27.4 [230.9–276.7]	275.1 $\pm$ 45.8 [261.5–288.6]	<i>p</i> = 0.49; 0.64
Overall Speed (m·s ^{−1})	2.4 $\pm$ 0.4 [2.2–2.7]	2.4 $\pm$ 0.4 [2.2–2.7]	2.6 $\pm$ 0.28 [2.4–2.8]	2.7 $\pm$ 0.3 [2.4–2.9]	2.5 $\pm$ 0.4 [2.4–2.6]	<i>p</i> = 0.45; 0.74
Transition Times (s)	68.7 $\pm$ 10.6 [62.6–74.9]	69.2 $\pm$ 8.0 [64.4–74.1]	67.5 $\pm$ 7.6 [61.1–73.9]	64.5 $\pm$ 6.5 [59.1–69.9]	67.9 $\pm$ 8.5 [65.3–70.4]	<i>p</i> = 0.75; 0.70
Overall Time w/o Transition (s)	215.7 $\pm$ 48.3 [187.8–243.6]	213.5 $\pm$ 42.5 [187.9–239.2]	195.1 $\pm$ 26.5 [173.0–217.3]	189.3 $\pm$ 24.5 [168.8–209.8]	206.3 $\pm$ 39.8 [194.4–218.2]	<i>p</i> = 0.52; 0.74
Overall Speed w/o Transition (s)	3.2 $\pm$ 0.6 [2.9–3.6]	3.3 $\pm$ 0.5 [2.9–3.6]	3.5 $\pm$ 0.4 [3.2–3.]	3.6 $\pm$ 0.5 [3.2–4.0]	3.4 $\pm$ 0.5 [3.2–3.5]	<i>p</i> = 0.64; 0.66
Ascent						
	Time-Trial	Quarterfinal	Semifinal	Final	Average	* <i>p</i>
Overall Time (s)	250.7 $\pm$ 52.4 [220.5–281.0]	250.5 $\pm$ 47.2 [222.0–279.0]	230.2 $\pm$ 28.9 [206.1–254.3]	222.2 $\pm$ 27.9 [198.9–245.6]	241.5 $\pm$ 43.62 [228.5–254.6]	<i>p</i> = 0.59; 0.66
Overall Speed (m·s ^{−1})	1.5 $\pm$ 0.3 [1.3–1.6]	1.5 $\pm$ 0.2 [1.3–1.6]	1.6 $\pm$ 0.2 [1.4–1.7]	1.6 $\pm$ 0.2 [1.5–1.8]	1.5 $\pm$ 0.2 [1.5–1.6]	<i>p</i> = 0.38; 0.6
Transition Times (s)	41.5 $\pm$ 19.6 [30.2–52.8]	41.5 $\pm$ 18.2 [30.5–52.5]	35.9 $\pm$ 8.7 [28.60–43.1]	31.2 $\pm$ 7.7 [24.8–37.6]	38.5 $\pm$ 15.9 [33.8–43.3]	<i>p</i> = 0.88; 0.5
Overall Time w/o Transition (s)	209.2 $\pm$ 34.6 [189.3–229.2]	209.0 $\pm$ 32.7 [189.3–228.8]	194.4 $\pm$ 22.8 [175.3–213.4]	191.1 $\pm$ 23.8 [171.2–210.9]	203.0 $\pm$ 30.4 [193.9–212.1]	<i>p</i> = 0.58; 0.96
Overall Speed w/o Transition (s)	1.7 $\pm$ 0.3 [1.6–1.9]	1.8 $\pm$ 0.2 [1.6–1.9]	1.9 $\pm$ 0.2 [1.7–2.0]	1.9 $\pm$ 0.2 [1.7–2.1]	1.8 $\pm$ 0.2 [1.7–1.9]	<i>p</i> = 0.40; 0.67
Sections						
	Time-Trial	Quarterfinal	Semifinal	Final	Average	* <i>p</i>
Speed S1S (m·s ^{−1})	2.1 $\pm$ 0.3 [1.9–2.3]	2.0 $\pm$ 0.3 [1.8–2.2]	2.1 $\pm$ 0.3 [1.9–2.3]	2.1 $\pm$ 0.3 [1.9–2.4]	2.1 $\pm$ 0.3 [2.0–2.2]	<i>p</i> = 0.02; 0.44
Speed S2F (m·s ^{−1})	1.0 $\pm$ 0.1 [1.0–1.1]	1.1 $\pm$ 0.2 [1.0–1.]	1.1 $\pm$ 0.1 [1.0–1.2]	1.2 $\pm$ 0.1 [1.1–1.3]	1.1 $\pm$ 0.1 [1.0–1.1]	<i>p</i> = 0.94; 0.3
Speed S3S (m·s ^{−1})	1.3 $\pm$ 0.2 [1.2–1.4]	1.4 $\pm$ 0.2 [1.3–1.5]	1.5 $\pm$ 0.2 [1.3–1.6]	1.5 $\pm$ 0.2 [1.3–1.7]	1.4 $\pm$ 0.2 [1.3–1.5]	<i>p</i> = 0.52; 0.14
Speed S4D (m·s ^{−1})	9.6 $\pm$ 1.2 [8.9–10.3]	10.0 $\pm$ 0.9 [9.4–10.5]	9.9 $\pm$ 0.9 [9.2–10.7]	10.0 $\pm$ 0.4 [9.7–10.4]	9.9 $\pm$ 0.9 [9.6–10.1]	<i>p</i> = 0.30; 0.58
Cycle Characteristics						
	Time-Trial	Quarterfinal	Semifinal	Final	Average	* <i>p</i>
S1S Cycle Duration (s)	0.8 $\pm$ 0.1 [0.8–0.9]	0.9 $\pm$ 0.1 [0.8–0.9]	0.8 $\pm$ 0.1 [0.8–0.9]	0.8 $\pm$ 0.1 [0.8–0.9]	0.8 $\pm$ 0.1 [0.8–0.9]	<i>p</i> = 0.64; 0.12
S1S Cycle Cadence (c·min ^{−1})	74.4 $\pm$ 4.4 [70.7–78.1]	71.8 $\pm$ 3.5 [68.9–74.7]	79.1 $\pm$ 4.2 [69.6–76.6]	73.2 $\pm$ 5.1 [68.9–77.5]	73.0 $\pm$ 4.2 [69.5–76.5]	<i>p</i> = 0.40; 0.06
S1S Cycle Speed (m·s ^{−1})	2.4 $\pm$ 0.2 [2.2–2.5]	2.2 $\pm$ 0.2 [2.1–2.3]	2.3 $\pm$ 0.2 [2.1–2.5]	2.3 $\pm$ 0.2 [2.1–2.5]	2.3 $\pm$ 0.2 [2.1–2.5]	<i>p</i> = 0.40; 0.06
S1S Cycle Length (m)	1.9 $\pm$ 0.1 [1.8–2.0]	1.9 $\pm$ 0.1 [1.8–2.0]	1.9 $\pm$ 0.1 [1.8–2.0]	1.9 $\pm$ 0.1 [1.8–2.0]	1.9 $\pm$ 0.1 [1.8–2.0]	<i>p</i> = 0.83; 0.53
HR in %HR _{max} (%)	87.9 $\pm$ 4.2 [82.8–93.1]	88.0 $\pm$ 5.1 [81.8–94.3]	87.9 $\pm$ 3.3 [82.7–93.1]	87.9 $\pm$ 3.7 [82.0–93.9]	88.0 $\pm$ 0.1 [87.9–88.1]	<i>p</i> = 0.12; 0.19
RPE (6–20)	15.9 $\pm$ 1.7 [14.9–16.9]	15.2 $\pm$ 1.8 [14.1–16.2]	15.9 $\pm$ 1.3 [14.9–17.0]	16.1 $\pm$ 2.2 [14.3–18.0]	15.8 $\pm$ 0.4 [15.1–16.5]	<i>p</i> = 0.29; 0.35

Data are presented as mean (standard deviation). S1S, Section 1 on skis; S2F, Section 2 on foot; S3S, Section 3 on skis, S4D, Section 4 downhill; HR, heart rate; HR_{max}, maximal heart rate; RPE, rating of perceived exertion. * One-way repeated-measures ANOVA (main effects).

Table 3 presents physiological characteristics, including strength and jump tests, anaerobic capacity tests, submaximal and incremental treadmill tests, as well as submaximal and maximal upper body ergometer tests.

Table 3. Descriptive data of performance and physiological indices during strength and jump tests, anaerobic capacity test, sub-maximal and incremental skimo treadmill tests, as well as upper-body submaximal and maximal endurance ski ergometer tests in a group of male and female skimo athletes ($n = 8$). Data are presented as mean $\pm$ SD (CI).

Strength and Jump Tests			
1RM Back Squat (kg)	63.8 ± 18.6 (48.2–79.3)		
1RM·BM ⁻¹ Back Squat (kg·kg ⁻¹)	1.1 ± 0.2 (0.9–1.2)		
1RM Bench Pull (kg)	51.6 ± 15.5 (38.6–64.5)		
1RM·BM ⁻¹ Bench Pull (kg·kg ⁻¹)	0.9 ± 0.2 (0.7–1.0)		
1RM Bench Press (kg)	45.0 ± 14.1 (33.2–56.8)		
1RM·BM ⁻¹ Bench Press (kg·kg ⁻¹)	0.7 ± 0.2 (0.6–0.9)		
SJ (cm)	34.3 ± 5.6 (29.5–39.0)		
CMJ (cm)	31.6 ± 7.5 (25.4–37.4)		
Anaerobic capacity test			
Sprint time (s)	11.5 ± 0.7 (10.9–12.1)		
VLa _{max} (mmol·L ⁻¹ ·s ⁻¹)	0.7 ± 0.2 (0.6–0.9)		
Sub-maximal test lower body			
	(1.2 m·s ⁻¹)	(1.4 m·s ⁻¹)	(1.6 m·s ⁻¹)
VO ₂ (mL·min ⁻¹)	2326 ± 268 (2102–2550)	2694 ± 241 (2472–2917)	3205 ± 252 (2892–3518)
HR (bpm)	153 ± 22 (135.1–171)	166 ± 19 (149–184)	174 ± 12 (159–188)
RER	0.9 ± 0.1 (0.9–1.0)	1.0 ± 0.0 (0.9–1.0)	1.0 ± 0.0 (0.9–1.1)
GE (%)	13.7 ± 1.1 (12.8–14.6)	14.1 ± 0.6 (13.6–14.6)	13.7 ± 0.8 (12.9–14.4)
[la-] (mmol·L ⁻¹)	3.0 ± 1.6 (1.7–4.4)	2.8 ± 1.1 (1.8–3.7)	3.2 ± 1.0 (2.0–4.5)
Incremental test lower body			
VO _{2max} (mL·min ⁻¹)	4104 ± 1100 (3184–5024)		
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	67.88 ± 11.1 (58.6–77.2)		
HR _{max} (bpm)	203.4 ± 6.5 (198.0–209)		
O ₂ Pulse (mL·beat ⁻¹)	21.4 ± 4.8 (17.4–25.4)		
TTE (s)	350.0 ± 94.9 (270.7–429.3)		
V _{max} (m·s ⁻¹)	2.3 ± 0.4 (2.1–2.6)		
Sub-maximal test upper body			
	60% HR _{max}	70% HR _{max}	
VO ₂ (mL·min ⁻¹)	1008 ± 1535 (880–1136)	1228 ± 243 (1025–1432)	
HR	120 ± 8 (113–126)	141 ± 17 (127–155)	
RER	1.0 ± 0.1 (0.9–1.0)	1.0 ± 0.1 (1.0–1.0)	
Power (W)	33.4 ± 6.3 (28.1–38.6)	42.6 ± 11.4 (33.1–52.2)	
Power (W·kg ⁻¹)	0.6 ± 0.1 (0.5–0.6)	0.7 ± 0.1 (0.6–0.8)	
Stroke frequency (SPM)	38.5 ± 4.5 (34.7–42.3)	39.0 ± 4.5 (35.2–42.8)	
GE (%)	9.5 ± 1.0 (8.7–10.4)	9.8 ± 1.3 (8.7–10.9)	
[la-] (mmol·L ⁻¹)	2.3 ± 0.4 (2.0–2.7)	3.2 ± 0.8 (2.45–4.0)	

Table 3. Cont.

Strength and Jump Tests	
Maximal test upper body	
VO _{2peak} (mL·min ^{−1})	2051 ± 700 (1465–2636)
VO _{2peak} (mL·kg ^{−1} ·min ^{−1})	37.0 ± 8.9 (25.9–48.1)
HR _{max} (bpm)	184 ± 8 (178–191)
Power (W)	78.3 ± 31.0 (52.3–104.2)
Power (W·kg ^{−1})	1.3 ± 0.4 (1.0–1.6)
Stroke frequency (SPM)	47.9 ± 9.2 (40.2–55.6)
[la-] (mmol·L ^{−1})	9.9 ± 3.8 (6.7–13.1)

1RM, one-repetition maximum; SJ, squat jump; CMJ, counter movement jump; VLa_{max}, maximal glycolytic capacity; VO₂, oxygen uptake; HR, heart rate; RER, respiratory quotient; GE, gross efficiency; [la-], blood lactate concentration; VO_{2max}, maximal oxygen uptake; HR_{max}, maximal heart rate; O₂ pulse, oxygen pulse; TTE, time to exhaustion; V_{max}, maximal treadmill speed; VO_{2peak}, peak oxygen uptake; Power, average power during 3 min test.

Table 4 displays the correlations between physiological characteristics and sprint performance. The measurements showing the highest correlations with performance were upper and whole-body VO_{2peak}, maximal speed, power, and anthropometric variables (see Figure 3). These variables tended to show stronger correlations with speed in time-trial, quarterfinals, and semifinals than in finals.

Table 4. Correlations (r-values) between different performance-determining variables and performance (speed during total race) in a sprint Skimo competition in a group of male and female Skimo athletes.

	Time-Trial (n = 8)	Quarterfinal (n = 8)	Semifinal (n = 8)	Final (n = 5)	Average
Anthropometrics					
Body mass (kg)	0.52 *	0.40	0.54 *	0.95 *	0.59 *
BMI	0.22	0.11	0.23	0.32	0.30
Body fat (%)	−0.67 *	−0.76 **	−0.77 **	−0.11	−0.67 *
FFM (kg)	0.74 **	0.62 *	0.77 **	0.52	0.82 **
Sprint time (s)	−0.15	−0.04	−0.23	−0.32	−0.22
VLa _{max} (mmol·L ^{−1} ·s ^{−1})	0.15	0.04	0.15	0.32	0.22
Sub-maximal test lower body					
GE1 (%)	0.49 *	0.37	0.43	0.11	0.49 *
GE2 (%)	0.32	0.16	0.23	0.44	0.32
GE3 (%)	0.37	0.21	0.39	0.89 *	0.47
Incremental test					
VO _{2max} (mL·kg ^{−1} ·min ^{−1})	0.89 **	0.91 **	0.93 **	0.32	0.82 *
VO _{2max} (mL·min ^{−1})	0.82 **	0.69 **	0.85 **	0.53	0.89 **
O ₂ Pulse (mL/beat)	0.89 **	0.76 **	0.93 **	0.32	0.96 *
V _{max} (m·s ^{−1})	0.82 **	0.84 **	0.85 **	0.11	0.74 **
Sub-maximal test upper body					
GE 60% (%)	0.52 *	0.55 *	0.54 *	−0.53	0.45
GE 70% (%)	0.34	0.37	0.35	−0.32	0.26
Maximal test upper body					
Power (W)	0.74 **	0.62 *	0.77 **	0.74 *	0.82 **
VO _{2peak} (mL·min ^{−1})	0.96 **	0.91 **	0.93 **	0.32	0.96 **
VO _{2peak} (mL·kg ^{−1} ·min ^{−1})	0.67 *	0.69 **	0.69 *	0.11	0.59 *

Table 4. Cont.

	Time-Trial (<i>n</i> = 8)	Quarterfinal (<i>n</i> = 8)	Semifinal (<i>n</i> = 8)	Final (<i>n</i> = 5)	Average
Strength and power tests					
1RM BS (kg)	0.49 *	0.44	0.59 *	0.53	0.57 *
1RM/BM BS (kg·kg ^{−1})	0.59 *	0.62 *	0.70 *	0.38	0.63 *
1RM Bpull (kg)	0.39	0.26	0.48	0.67	0.46
1RM/BM Bpull (kg·kg ^{−1})	0.08	0.04	0.16	0.22	0.15
1RM Bpress (kg)	0.54 *	0.42	0.64 *	0.95 *	0.62 *
1RM/BM Bpress (kg·kg ^{−1})	0.43	0.31	0.53 *	0.83 *	0.51 *
SJ (cm)	0.23	0.19	0.28	0.22	0.31
CMJ (cm)	−0.23	−0.26	−0.20	−0.22	−0.15
Cycle Characteristics					
	(<i>n</i> = 15)	(<i>n</i> = 13)	(<i>n</i> = 13)	(<i>n</i> = 8)	
Duration (s)	−0.56 **	−0.22	−0.44 *	0.12	−0.42 *
Cadence	0.54 **	0.19	0.42 *	0.04	0.42 *
Speed (m·s ^{−1})	0.78 **	0.51 **	0.56 **	0.04	0.8 **
Length (m)	0.81 **	0.32	0.44 *	0.04	0.65 **
Transition Duration					
1 (s)	−0.51 **	−0.5 *	0.42 *	−0.19	−0.42 *
2 (s)	−0.34 *	−0.67 **	−0.53 **	−0.54 *	−0.63 **
3 (s)	0.63 **	−0.67 *	−0.82 **	−0.42	−0.78 **
Total (s)	−0.52 **	−0.85 **	−0.55 **	−0.57 *	−0.54 **

BM, body mass; BMI, body mass index; FFM, fat-free mass; VLa_{max} , maximal glycolytic capacity; GE, gross efficiency; VO_{2max} , maximal oxygen uptake; V_{max} , maximal treadmill velocity; VO_{2peak} , peak oxygen uptake; 1RM, one-repetition maximum; BS, back squat; Bpull, bench pull; Bpress, bench press; SJ, squat jump; CMJ, countermovement jump. R-values interpreted as: <0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; 0.9, nearly perfect; 1.0, perfect. * $p < 0.05$. ** $p < 0.01$.

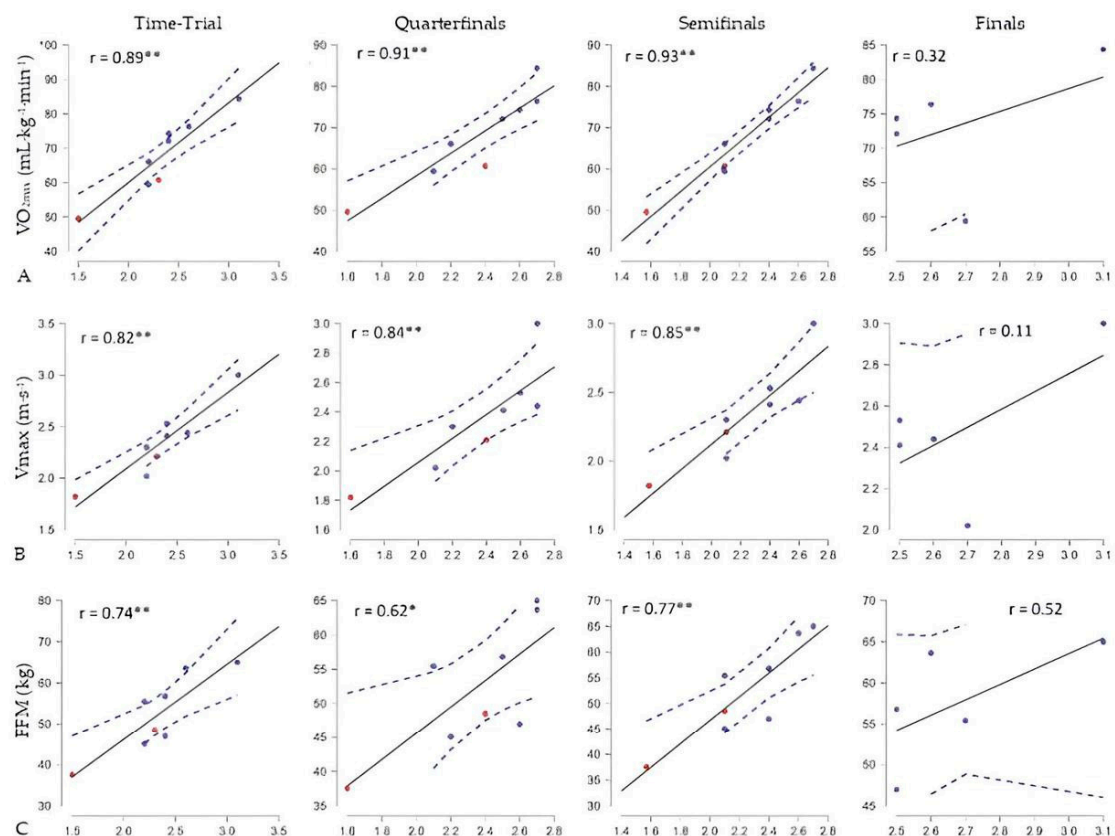


Figure 3. Cont.

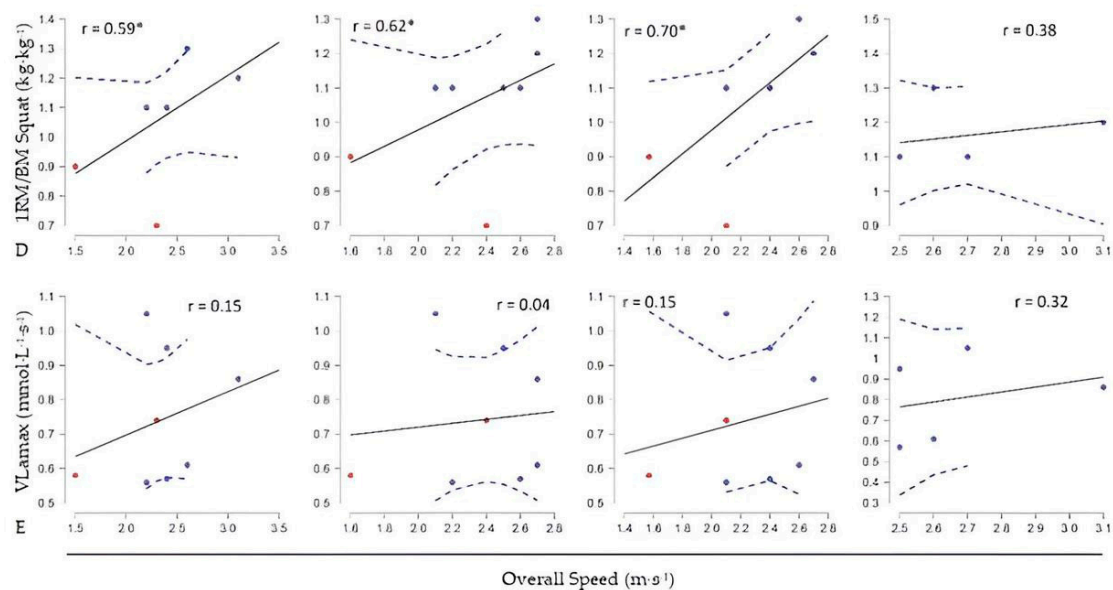


Figure 3. Relationship between Skimo sprint performance and (A) $\text{VO}_{2\text{max}}$, maximal oxygen uptake, (B) V_{max} , peak treadmill speed, (C) FFM, fat-free mass, (D) 1RM, one-repetition maximal strength in back squat standardized to body mass, and (E) VLa_{max} , maximal glycolytic capacity in a group of male and female skimo athletes ($n = 8$ for TT to SFs; $n = 5$ for F). Dashed lines represent 95%CI. Red dots represent female athletes. Blue dots represent male athletes. * $p < 0.05$. ** $p < 0.01$.

In contrast, except for GE1, GE tended to show higher correlations with F (0.44–0.89) compared to TT, QF, and SF (0.16–0.39). Similarly, although non-significant, VLa_{max} had higher correlation coefficients with F compared to TT, QF, and SF. Throughout the entire competition, both absolute and relative 1RM for back squats and bench presses showed good correlations with performance ($r = 0.31$ – 0.95). Compared to the previous measurements, the correlation coefficients remained stable also during F ($r = 0.38$ – 0.95). However, bench pull, SJ, and CMJ only showed non-significant correlations with performance. On average, all cycle characteristics showed a significant correlation with performances. However, no significant correlations were found between cycle characteristics and F. The correlations with physiological indices showed the highest correlations between all cycle characteristics and upper and whole-body aerobic capacity ($r = 0.14$ – 0.8 and 0.2 – 0.91 , respectively), as well as maximal speed during treadmill running ($r = 0.29$ – 0.91). Furthermore, fat-free mass, power, as well as 1RM back squat and bench press, both absolute and relative, showed good correlations with cycle characteristics, especially during TT. The total transition duration showed significant correlations with all heats during the competition ($r = -0.52$ to -0.85 , all $p < 0.001$, and $r = -0.57$, $p < 0.05$).

4. Discussion

This study investigated the variables determining performance in a simulated on-snow Skimo sprint competition in elite junior athletes, and how their relationship with performance evolves from the individual time-trial to the final. The main findings reveal that upper and whole-body aerobic power, maximal speed and power, as well as fat-free mass and body fat, are all strong determinants of Skimo sprint performance. Notably, the ability to transition quickly between sections also proved to be a relevant factor in Skimo sprint performance.

Most anthropometric measurements, except for BMI, demonstrated significant correlations with sprint performance. These findings align with the literature on the role of anthropometrics in Skimo, where BMI and body fat, both in percent of body mass and in kilograms, were significantly correlated with performance in vertical races [5,7]. Lasshofer et al. [6] reported a non-significant correlation between BMI and vertical race

performance, highlighting potential variation across studies. None of the previous studies in Skimo investigated the role of FFM on (sprint) performance. Drawing parallels with cross-country sprint skiing, where total lean mass—both as a percentage of BM and in kilograms—has exhibited correlations with sprint performance indices (e.g., peak and mean velocity, performance in sprint prologue) [35–37], the observed associations may be elucidated by the relationships between muscle size, force-generating potential, and anaerobic energy stores [37–42]. The literature suggests that heavier and more muscular cross-country skiers exhibit advantages on various terrains, except in steep uphill, where their relative advantage diminishes [11,19]. However, considering that the majority of Skimo race duration involves steep uphill, the emphasis shifts to the importance of an effective power-to-weight ratio over absolute power capacities.

Absolute and relative $\text{VO}_{2\text{max}}$ demonstrated robust correlations with performance in both individual time trial and subsequent heats, consistent with existing literature on the interplay between $\text{VO}_{2\text{max}}$ and Skimo race performance. Specifically, there were strong correlations between relative $\text{VO}_{2\text{max}}$ and individual, and vertical race performance [4,6]. Conversely, absolute $\text{VO}_{2\text{max}}$ demonstrated non-significant correlations with individual race performance [4]. These findings are consistent with previous literature in the realm of $\text{VO}_{2\text{max}}$ and cross-country sprint skiing, a similar competition format consisting of repeated high-intensity efforts of approximately 2.5 to 3 min, showing significant and substantial correlations between sprint performance (skating and classical technique) and both absolute and relative $\text{VO}_{2\text{max}}$ [13,43,44]. This trend extended to the relationships between sprint uphill performance, and both absolute and relative $\text{VO}_{2\text{max}}$ [43]. Sandbakk et al. [44] identified the strongest correlation between cross-country sprint performance and absolute values of $\text{VO}_{2\text{max}}$ compared to relative values. Their argument, asserting the greater relevance of absolute values due to the high speed and relatively flat terrain in sprint competitions, contrasts with the skimo context, where the majority of the race involves uphill segments. Consequently, it could be posited that higher relative $\text{VO}_{2\text{max}}$ values serve as more effective predictors of Skimo sprint performance. In contrast, Stoggl et al. [45] only found a non-significant correlation between relative $\text{VO}_{2\text{max}}$ and simulated sprint performance. The authors contended that, within a homogenous group of elite cross-country skiers, aerobic capacity establishes a foundational role, with neuromuscular characteristics such as V_{max} assuming greater significance for success in sprint competitions. This interpretation may elucidate the lower correlation coefficients between $\text{VO}_{2\text{max}}$ and performance in the final, as the physiological indices of the participants were more homogenous than with all participants included in time-trial, quarterfinal, and semifinal.

In contrast to observations in cross-country sprint skiing, where aerobic capacity tends to play a progressively influential role in subsequent heats [12,14,46], our study did not identify a growing correlation between $\text{VO}_{2\text{max}}$ and sprint performance as the Skimo competition unfolded. The absence of an escalating correlation strength throughout the competition may be attributed to the near-perfect correlations already evident from the initial runs. Notably, the individual trials in Skimo, especially the prolonged uphill sections, surpass the duration of those in traditional cross-country skiing. This extended duration likely constrains speeds to levels well within the aerobic system's capacity, setting it apart from the shorter, more intense bursts typically encountered in cross-country sprint skiing. Despite this distinctive dynamic, the emerging correlation between sub-maximal gross efficiency and performance from the individual time trial to the final. This echoes patterns documented in prior literature, suggests an increasing significance of $\text{VO}_{2\text{max}}$ as the Skimo sprint competition advances. This observation suggests a nuanced interplay between sub-maximal gross efficiency and the evolving demands of the competition format, highlighting the potential for $\text{VO}_{2\text{max}}$ to become even more important as the sprint competition progresses.

In accordance with the robust correlation observed for $\text{VO}_{2\text{max}}$, V_{max} also demonstrated very large correlation coefficients with performance in skimo sprint competitions. These findings highlight the general importance of the ability to generate high maximal

speed and extends upon the existing body of literature, encompassing both skimo (particularly in vertical races) [6] and cross-country sprint skiing [43,45,47] across various terrains, including flat and uphill sections [43]. The generation of high velocities is influenced by cardiovascular factors, as well as neuromuscular and anaerobic characteristics [48–51]. Accordingly, it has been suggested that the maximal velocity achieved during cross-country skiing diagonal striding may be limited not only by energy systems, but also by the rate of force development [52]. This is due to reported stride durations of approximately 200 ms per leg. During the simulated competition, the cycle duration lasted for approximately 800 ms, resulting in a stride duration of below 400 ms per leg. Although Skimo allows for a longer duration of force generation, the neuromuscular ability to produce the largest possible ground reaction force within short ground contact times may still limit skiing velocity. These results are further supported by the moderate to large correlations observed with strength measures, particularly highlighting the importance of lower body strength. Additionally, the increasing correlations found between VLa_{max} and superior performance in the finals reinforce the hypothesis that the relationship between V_{max} and the ability to sustain speed in sprint competitions may indicate a heightened anaerobic capacity [17,45,53].

While the previous literature emphasized the substantial role of anaerobic capacity, constituting approximately 20–30% of total energy expenditure during maximal efforts in cross-country sprint skiing [15,54,55], the present study underscores the pronounced significance of the aerobic energy system in Skimo sprint performance. Specifically, VO_{2max} emerges as a key determinant, particularly notable given the extended uphill section duration exceeding 3 to 4 min in this study. This aligns with prior research indicating that the relative importance of aerobic versus anaerobic energy expenditure becomes more evident in exercises lasting 100 s or more [16,56]. In this context, Andersson et al. [47] suggested that anaerobic capacity may be relatively more important during heats with tactical influence. However, in the current study, the group composition was heterogeneous and pacing patterns were more even, which may have reduced supra-maximal exercise intensities and consequently decreased anaerobic energy contributions. The increased correlation between VLa_{max} and performance in the finals could be explained by this insight. Participants displayed a more uniform performance level.

Both absolute and relative measures of 1RM back squat and 1RM bench press displayed moderate to large correlations with Skimo sprint performance, indicating an increase from the individual time trial to the semifinal. Conversely, 1RM bench pull, squat jump, and countermovement jump did not exhibit significant correlations with performance. Research on cross-country skiing has produced mixed results. Some studies have found significant correlations between sprint performance indices and 1RM measurements for both upper- and lower-body strength [21,46,57], while others have reported non-significant associations [21,57]. The discrepancies among studies may be primarily attributed to differences in strength testing methods, protocols, and performance variables. This complicates the synthesis of a cohesive understanding of the role of dynamic strength in skimo and cross-country sprint skiing performance. Hèrbert-Losier et al. [14] stated that elite skiers may reach a maximum strength threshold, beyond which further improvements may not necessarily lead to better performance. Similarly, Sandbakk et al. [17] found no significant differences in isometric lower-body strength and 1RM upper-body strength between world-class and national-class sprint skiers. However, this study, conducted on a group of junior skimo athletes with a more heterogeneous resistance training experience, supports the notion that elevating upper and lower body strength to an appropriate level is relevant to Skimo sprint performance. These findings contribute valuable insights into the relationship between strength capacities and Skimo sprint performance within the context of varying training backgrounds among athletes.

Although most cycle characteristics showed strong correlations with sprint performance, it is worth noting that these correlations became trivial during the finals. The reason for this shift remains unclear, especially since other factors that supposedly influence cycle

characteristics either maintained stable correlation coefficients or exhibited an increase in correlation strength, as was the case with 1RMs and GE3. The study by Lasshofer et al. [6] reported correlations between performance in a simulated Skimo vertical race and both average and maximal step length, along with cadence. These findings are consistent with results observed in cross-country sprint skiing, where cycle length was significantly correlated with classic sprint performance indices such as peak velocity and overall sprint performance [45]. Uphill skiing speed can only be increased by lengthening steps and/or increasing cadence. The results suggest that faster athletes may achieve both higher cadence and longer cycles. However, there is a point where increasing cadence becomes inefficient due to increased oxygen cost [58]. Therefore, superior uphill sprint performance is likely due to the generation of higher ground reaction forces, which propel the athlete's center of mass and increase cycle length. These findings align with previous research in both cross-country skiing and track and field [58,59].

The correlation found between transition times and overall competition performance highlights the crucial role of efficient transitions in Skimo sprints. This is particularly important, as the correlations remained significant even during the finals, emphasizing the lasting impact of effective transitions on overall race outcomes. Therefore, prioritizing training efforts to improve transition times is essential for achieving a more competitive performance in Skimo sprints.

While this study provides valuable insights, it is important to consider several limitations. The study intentionally included both male and female athletes. While this increased diversity in the sample, potential sex-differences were considered manageable within the given study design. Moreover, previous research emphasized the equal treatment of female physiological parameters alongside other confounding variables (i.e., maturation, temperature, nutrition, fatigue) [60], with the aim to address the existing sex data gap by promoting research on female athletes, especially considering the limited evidence-based recommendations for training individualization in this population [60,61]. It is noteworthy that no clusters that suggest clear sex-specific correlations were detected. However, it is important to consider the mixed-sex composition as a potential factor. This diversity could contribute to nuanced interpretations of the observed correlations. The participants were relatively young, with an average age of 17.8 ± 2.5 years, and had varying levels of experience. Therefore, the variables that determine performance identified in this study may not be applicable to more homogeneous groups of elite and world-class senior Skimo athletes. Furthermore, it is important to note the reduction in sample size as a limitation. Seven athletes did not participate in any laboratory testing, and an additional two athletes withdrew during the field tests. This reduction in the number of participants, particularly in the finals, not only diminished statistical power, but also introduces a potential source of bias in the generalizability of the findings. Future research endeavors should aim to address these limitations, perhaps by employing larger and more homogenous participant groups, to enhance the robustness and applicability of the results. Alongside the standard knock-out system in official Skimo sprint competitions, the study employed Lucky Loser Final. This deviation was made to ensure that all skiers completed at least three trials, which facilitated the inclusion of weaker athletes in later correlations (i.e., Semi-Finals, as LLF marked their third trial). This approach could have improved the relevance of positioning and tactics in more homogeneous heats (Quarterfinals vs. Semifinals, Finals). This has the potential to enhance the validity of the correlations compared to laboratory-based designs with standardized and constant speeds across repeated efforts. However, it is important to take into account potential individual differences between skis, skins, and skin-snow friction. Future research should consider these advantages and constraints.

5. Conclusions

In summary, this study provides a comprehensive understanding of the various factors that influence performance in Skimo sprint competitions. The findings highlight that success in Skimo sprint competitions is determined by a combination of factors, including

high maximal aerobic power at a relatively low body mass, and proficient technical abilities such as transitioning between sections. Additionally, the study highlights the importance of neuromuscular and anaerobic characteristics in determining success, as evidenced by the role of maximal speed. Therefore, it is crucial to have sufficient maximal strength, especially in the lower body, to achieve superior cycle characteristics, such as cycle length. Accordingly, success in Skimo sprint formats depends heavily on developing a robust aerobic capacity, which likely becomes increasingly important as the competition progresses. However, success at the elite competition level requires not only a high aerobic capacity but also sufficient strength to establish an optimal power-to-weight ratio for achieving the fastest possible climbing speed.

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