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# Performance-determining variables of a simulated sprint cross-country skiing competition

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# Abstract

**Purpose:** To investigate performance-determining variables of an on-snow sprint cross-country skiing competition and the evolvement in their relationship with performance as the competition progresses from the individual time trial (TT) to the final.

**Methods:** Sixteen national-level male junior skiers (mean [standard deviation]: age, 18.6 [0.8] years; peak oxygen uptake [$VO_{2peak}$], 67.6 [5.5] $mL \cdot min^{-1} \cdot kg^{-1}$) performed a simulated sprint competition (1.3-km) in the skating style, comprising a TT followed by 3 finals (quarterfinals [QF], semifinals [SF], and final [F]) completed by all skiers. In addition, sub-maximal and incremental roller-ski treadmill tests, on-snow maximal speed ($V_{max}$) tests, and strength/power tests were performed.

**Results:** $VO_{2peak}$ and peak treadmill speed during incremental testing, and relative heart rate ($\%HR_{max}$), rating of perceived exertion (RPE), blood lactate concentrations [$La^-$], and gross efficiency (GE) during sub-maximal testing were all significantly correlated with performance in the TT and subsequent finals (mean [range] r-values: 0.67 [0.53-0.86], all $p<0.05$). Relative $VO_{2peak}$ and sub-maximal $\%HR_{max}$ and [$La^-$] were more strongly correlated with performance in the SF and F compared to the TT (r-values: 0.74 [0-60-0.83] vs. 0.55 [0.51-0.60], all $p<0.05$). $V_{max}$ in uphill and flat terrain were significantly correlated with performance in the TT and subsequent finals (r-values: 0.63 [0.38-0.70], all $p<0.05$), while strength/power tests did not correlate significantly with sprint performance.

**Conclusions:** $VO_{2peak}$ and high-speed abilities were the most important determinants of sprint cross-country skiing performance, with an increased importance of $VO_{2peak}$ as the competition format progresses towards the final.



**Keywords:** maximal speed, one-repetition maximal strength, peak oxygen uptake, sub-maximal testing, XC skiing.

# Introduction

Sprint cross-country skiing involves repeated ~3 min high-intensity efforts separated by ~15-120 min recovery periods, starting with an individual qualifying time-trial (TT) followed by three knock-out heats as the competition format progresses (quarterfinals [QF], semifinals [SF], and final [F]).[1] Altogether, a sprint competition has a total duration of ~3-4 h, including warm-up, recovery between heats (active or passive), re-warm up, and cool-down. These competitive demands are unique to sprint cross-country skiing, which requires high aerobic and anaerobic turnover rates, technical and tactical abilities (e.g., positioning in the heats), as well as the ability to maintain performance over the repeated efforts throughout the competition day.[2]

There exists a rather large body of research investigating the physiological demands and corresponding performance-determining variables in sprint cross-country skiing, including physiological, biomechanical, strength, and power characteristics.[2] The most performance-differentiating variable seems to be a high aerobic energy turnover rate (i.e., peak oxygen uptake [$VO_{2peak}$ ]) [3,4] which may become increasingly important over the repeated efforts.[5] Complementary to the importance of high aerobic energy turnover, a well-developed anaerobic energy turnover rate (e.g., maximal accumulated oxygen deficit) is also regarded as a key variable for performance in sprint cross-country skiing.[6] Moreover, gross efficiency (GE) has been shown to differentiate world-class from national-class sprint skiers in the skating style,[4] and the ability to produce high maximal speeds ($V_{max}$) [4,7,8] has previously been correlated with sprint cross-country skiing performance. However, the literature on the importance of strength and power to sprint cross-country skiing performance are less clear.[2] For example, it has been shown that better performing skiers are able to produce greater upper-body power in custom-made double-poling ergometers, [9,10] while no differences in upper- and lower-body one-repetition maximal (1RM) strength have been found between world-class and national-class sprint skiers.[4]

Although the literature on performance-determining variables in sprint cross-country skiing is rather extensive, the different efforts of sprint cross-country skiing have so far been investigated in isolation[11] or by using laboratory-based designs.[2,5,7,12] Accordingly, there exists limited data on performance-determining variables and corresponding changes in their relationship with performance as the competition format progresses (e.g., from the individual TT to F) in an on-snow sprint cross-country skiing competition. Moreover, conflicting findings exists,[2] likely explained by differences in the methodology adopted, as well as the heterogeneity and performance level of the groups investigated.

Therefore, this study was designed to investigate performance-determining variables of an on-snow sprint cross-country skiing competition and the evolvement in their relationship with performance as the competition progresses from the TT to the F.

# Methods

## Participants

Eighteen national-level (Tier 3)[13] male junior skiers from a Norwegian sport high school volunteered to take part in the study. Two skiers did not complete any of the laboratory tests (i.e., correlations are performed for n=16) and four more skiers did not perform the strength and power tests (i.e., correlations are performed for n=12). The mean (standard deviation [SD]) characteristics of the group were: age, 18.6 (0.8) years; body mass, 75.4 (7.7) kg; body height 181.6 (5.4) cm; body-mass-index (BMI), 22.8 (1.7); $VO_{2peak}$ roller skiing, 5098 (652) $mL \cdot min^{-1}$ and 67.6 (5.5) $mL \cdot min^{-1} \cdot kg^{-1}$; International Ski and Snowboard Assosiation (FIS) points, 181.1 (50.5). The study followed the institutional requirements and approval for data security and handling was obtained from the Norwegian Center for Research Data in front of the study. All skiers signed a written informed consent before participation and parental consent was obtained for the skiers aged <18 years.

## Overall design

The skiers performed a simulated on-snow sprint competition in the skating style. A promotion-relegation system was used instead of the regular knock-out system and all skier completed all finals. The skiers were continuously monitored by a heart rate (HR) monitor and a global navigation satellite system (GNSS). After the F, the skiers performed maximal speed ($V_{max}$) tests both in uphill and flat terrain. Within 3 weeks prior to the competition, the skiers completed laboratory roller-ski tests of performance and physiological variables, including sub-maximal stages and an incremental test to exhaustion, as well as upper- and lower-body strength/power tests on two separate days.

## Simulated sprint competition

**Methodology.** The competition was performed on a FIS-regulated 1311 m racecourse (height difference, 23 m; total climb, 48 m) used in previous World-cup sprint cross-country skiing competitions. The racecourse was divided into different terrain sections based on position and altitude along the racecourse (Figure 1). The racecourse constituted five different sections: S1, uphill; S2, downhill; S3, uphill; S4, downhill; S5, flat (final sprint). The weather conditions were stable throughout the competition with the following mean (range) values: ambient air temperature, -2.1◦C (-1.7 to -3.7◦C); snow temperature, -2.8◦C (-1.7 to -3.7◦C) and relative humidity, 78% (77-79%). The skiers were equipped with a combined GNSS and inertial measurement unit (IMU) (Optimeye S5, Catapult Sports, Melbourne, Australia) that was taken on and off between the different finals. The methodology used has previously been described [14] and the GNSS sensors validated against higher-accuracy GNSS sensors.[15] The skiers wore Garmin Forerunner 920XT/935 watches (Garmin Ltd., Olathe, USA) with electrode belts to monitor HR, and used their own ski equipment including poles, boots, and skis during the simulated competition. The skiers were instructed to prepare their skis with the same fluorine-free glide wax before the competition. In the morning of the competition day, the skiers had ~1 h available for self-selected warm-up. Thereafter, the individual TT was performed, in which TT rank was further used to separate the skiers into 3 subsequent QF heats (A-B-C-heat). In contrast to the official knock-out system used in sprint cross-country skiing,[1] the system included a promotion and relegation of the two fastest (rank 1-2) and slowest skiers (rank 5-6) in each heat, while the skiers ranked 3-4 remained in the same heat for the subsequent final. The recovery times between the TT, QF, SF, and F were set to 75, 50 and 35 min, respectively, adopted from the official FIS competition rules, with minor modifications due to the logistics of performing the promotion-relegation system and collecting all data. The time between the TT and QF was shorter (normally 90-120 min) and the time between the SF and F longer (normally 15-20 min). After the F, the skiers were allowed ~20-min recovery before performing two 20-m $V_{max}$ tests in both uphill (G2/V1 sub-technique) and flat terrain (G3/V2 sub-technique) in a “semi-fatigued state” with ~5-min recovery in between.[16] The average speed of the two attempts was used for analyses.

**Figure 1 around here**

**Laboratory tests**

**Methodology.** Performance and physiological variables were derived from treadmill (Forcelink S-mill, Motekforce Link, Amsterdam, Netherlands) roller-ski skating using the G3/V2 sub-technique.[16] The same pair of skating roller skis with standard category 2 wheels (IDT Sports, Lena, Norway) was used for all tests. Initially, the skiers performed 4x5-min sub-maximal stages (2.2, 2.8, 3.3, and 3.9 $m \cdot s^{-1}$, respectively) at a 2.9° fixed incline with 2-min recovery in between. The stages at 2.8 and 3.9 $m \cdot s^{-1}$ were used for further analyses. Respiratory variables and HR were collected over the last two minutes, whereas rating of perceived exertion (RPE) and blood lactate [$La^-$] were determined directly after completing each stage. GE was defined as the ratio of work and metabolic rate as previously described by Sandbakk et al.[3] After 5 min of recovery, an incremental test to exhaustion was completed to determine $VO_{2peak}$ and peak treadmill speed according to Sandbakk et al.[3] The test was performed at a 4.0º fixed incline and starting speed of 3.3 $m \cdot s^{-1}$. Thereafter, the speed was increased by 0.3 $m \cdot s^{-1}$ every minute until exhaustion. Respiratory variables were collected using open-circuit indirect calorimetry with mixing chamber (Vyntus CPX, Vyaire Medical, Mettawa, USA). HR was continuously measured with a Garmin Forerunner 920XT watch with a HR electrode belt and [$La^-$] measured using the Biosen C-Line lactate analyser (Biosen, EKF Industrial Electronics, Magdeburg, Germany). RPE was determined using the 6-20 Borg scale.[17] These protocols are used for regular performance and physiological profiling of cross-country skiers in our laboratory and where therefore most convenient to employ in the study.

On a separate day, the skiers performed tests of strength/power and anaerobic characteristics consisting of the exercises seated pull down, triceps press, leg press, and a 30-sec double-poling ergometer test. Initially, the skiers completed a 10-min low-intensity warm-up running (60-72% of maximal heart rate [$HR_{max}$]) before 1RM strength in seated pull down and triceps press were determined with protocols previously described by Losnegard et al.[18] These exercises were performed in a cable pulley apparatus (Multi Pulley, Pulse Fitness, Cheshire, UK) using a customized handle to simulate double-poling. The first attempt was performed with a load approximately 5-8% below expected 1RM. After each successful attempt, the load was increased by 5-8% until two consecutive failed attempts were reached. Recovery time between each attempt was set to 2 min. For both exercises, the movement started with the handle positioned at the same height as the forehead and the skiers then pulled the handle down to the hip bone with the elbows held slightly lateral to simulate a double-poling pull. For 1RM to be accepted, the handle had to be pulled completely down in one continuous motion with the hands in parallel. Leg press was performed using a Keiser machine (A300 leg press with A420 computer display, Keiser, Fresno, USA) locked to bilateral movement with a built-in incremental power profile consisting of a single trial of 9-13 repetitions. The protocol included standardized increases in load (40 kg to 250-350 kg depending on 1RM) until failure with standardized 10-90 s recovery periods in-between, increasing correspondingly to the increases in load. During all repetitions, the skiers sat with the knees flexed at 90° and the hips flexed at 45° and were instructed to exert maximal effort. The maximal successful load (1RM) was registered, while peak power was extracted from the accompanied software. For the 30-sec double-poling ergometer test (i., proxy for anaerobic energy turnover) the skiers completed a 1-min re-warm up at a self-selected intensity before performing the 30-sec test using protocols according to those described by Talsnes et al.[19] The 30-sec double-poling test was performed on a double-poling ergometer (SkiErg, Concept2, Morrisville, USA) with the damper positioned at drag factor 10 (1-10).

**Statistical analyses**

All statistical analyses were carried out using SPSS 26.0 (SPSS Inc, Chicago, IL, United States) and data are presented as mean (SD). A one-way repeated measures ANOVA was used to compare performance across the TT and heats. In cases of any global differences, Fisher LSD post-hoc analyses were applied to assess where the differences occurred. Relationship between the performance-determining variables and sprint performance (speed in the different efforts and related sections) was assessed using the parametric Pearson's or non-parametric Spearman's rank correlation coefficients when data deviated from normal distribution. while the strength (r-values) of the correlations were interpreted according to Hopkins [20] (<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). To statistically compare the strength of different correlations, the hypothesis test for comparisons of correlations according to Williams was applied.[21] Williams t-test for dependent correlations allows assessment of whether two dependent correlations significantly differ from each other and involves transforming correlations into a common scale, calculating test statistics and performing a hypothesis test to determine significance level.[21] In cases of multiple correlations between performance-determining variables and sprint performance, r-values are presented as mean (range). Alpha values <0.05 determined the level of statistical significance.

## Results

Time and speed in the TT and heats, as well as related physiological responses are shown in Table 1. The skiers were faster in the SF than both the TT (-2.1 [2.5]%, p=0.006), QF, and F (-1.5 [1.8]% and -3.9 [5.2]%, respectively, both P<0.05). Performance-determining variables including sub-maximal and incremental roller-ski skating tests, as well as upper- and lower-body strength/power tests can be found in Table 2.

**Table 1 and Table 2 around here**

Correlations between performance-determining variables and sprint performance are shown in Table 3. HR in $\%HR_{max}$, RPE, $[La^-]$, and GE derived from sub-maximal testing demonstrated large to very large inverse correlations with performance in the TT and heats (all p<0.05). However, HR in $\%HR_{max}$ and $[La^-]$ were more strongly correlated with speed in the SF and F compared to the TT (all p<0.05, Table 3, Figure 2) and speed in S3 and S4 compared to S2 and S5 in all finals (r-values: -0.73 [0.69-0.81] vs. -0.55 [0.47-0.61], all p<0.05). Both absolute and relative $VO_{2peak}$, and peak treadmill speed derived from incremental testing demonstrated large to nearly perfect positive correlations with speed in the TT and heats (all p<0.05). However, relative $VO_{2peak}$ was more strongly correlated with speed in the SF and F compared to the TT (both p<0.05, Table 3, Figure 2). Moreover, relative $VO_{2peak}$ and peak treadmill speed were more strongly correlated with speed in S3 and S4 compared to S2 and S5 in all finals (r-values: 0.78 [0.74-0.82] vs. 0.58 [0.52-0.64], all p<0.05).

** Table 3 and Figure 2 around here**

The skiers' $V_{max}$ in uphill and flat terrain were 5.1 (0.3) $m \cdot s^{-1}$ and 8.4 (0.3) $m \cdot s^{-1}$, respectively. $V_{max}$ both in uphill and flat terrain showed large to very large positive correlations with speed in the TT and heats (r-values: 0.63 [0.38-0.70], all $p<0.05$, Figure 3). Moreover, $V_{max}$ in flat terrain was more strongly correlated with speed in S5 (final sprint) compared to all other sections (average r-values: 0.72 vs. 0.50 [0.46-0.54], all $p<0.05$), while $V_{max}$ in uphill terrain was more strongly correlated with speed in S3 compared to S1-S2 (r-values: 0.75 [0.70-0.80] vs. 0.59 [0.57-0.60], all $p<0.05$).

**Figure 3 around here**

Except for 1RM in triceps-press, no significant correlations were found between anthropometric characteristics, the upper- and lower-body strength and power tests and sprint performance. However, 1RM in seated pull-down, as well as peak and average power output in the 30-sec double-poling ergometer test was more strongly correlated with speed in the TT, QF, and SF compared to the F (r-values: 0.58 [0.47-0.66] vs. 0.23 [0.01-0.31] all $p<0.05$, Figure 4). Further, both 1RM and peak power in leg-press were more strongly correlated with speed in S5 (final sprint) compared to S1-S3 (r-values: 0.78 vs. 0.54 [0.40-0.67], all $p<0.05$).

**Figure 4 around here**

# Discussion

This study investigated performance-determining variables of an on-snow sprint cross-country skiing competition and the evolvement in their relationship with performance as the competition format progresses. The main findings were that $VO_{2peak}$ and GE from roller-ski tests in the laboratory as well as on-snow high-speed abilities were all strong determinants of sprint performance. However, $VO_{2peak}$ and physiological cost during sub-maximal testing showed increasing correlations with performance as the competition format progressed while strength/power tests correlated less strongly with performance as the competition progressed.

**Performance and physiological variables.** $VO_{2peak}$ and peak treadmill speed during incremental testing, as well as GE and $\%HR_{max}$, RPE, and $[La^-]$ during sub-maximal testing were all strongly correlated with performance both in the individual TT and subsequent finals. Although there exist conflicting literature on the relationship between GE and cross-country skiing performance,[2] large correlations between GE and sprint performance were found in the current study, supporting previous findings by Sandbakk et al.[4] and Seeberg et al.[22] Therefore, also physiological and perceptual responses/cost at sub-maximal speeds were associated with sprint performance. Altogether, these findings are consistent with previous literature investigating relatively heterogenous groups of skiers,[3-5,11] and verifying that aerobic energy turnover (i.e., $VO_{2peak}$) and skiing efficiency (i.e., GE) are important performance-determining variables in sprint cross-country skiing.[2]

Although Vesterinen et al.[5] showed that skiers with high $VO_{2peak}$ were better able to recover and thereby maintain speed over four 850-m repeated efforts in an experimental trial roller skiing on a tartan track, this is the first study to demonstrate increasing correlations between $VO_{2peak}$ and sprint performance as the competition format progresses in an on-snow simulated sprint competition. These findings are further supported by the increasing correlations found between the sub-maximal physiological cost and performance from the TT to F. Moreover, $VO_{2peak}$ and peak treadmill speed were more strongly correlated with performance in the terrain sections in the latter part of the racecourse (S3-4) both in the TT and heats, as comparable to the findings of Andersson et al.[23] Taken together, the relatively long-time span of the competition day (~3-4 h in total), as well as the ability to perform repeated high-intensity efforts including supra-maximal intensities in uphill sections, likely explains the increasing importance of $VO_{2peak}$ as the competition format progresses in sprint cross-country skiing.

Although not thoroughly investigated in this study, the role of anaerobic energy turnover as well as the ability to repeat supra-maximal exercise intensities, both in uphill sections within heats and across the subsequent finals should be acknowledged as important features of sprint cross-country skiing.[6] The correlations found between peak and average power in the 30-sec double-poling ergometer test (i.e., proxy for anaerobic energy turnover) is also consistent with previous studies demonstrating that better performing skiers produce greater upper-body power.[9,10] On average, the total anaerobic energy contribution has been reported to be 20-25% across repeated efforts in sprint cross-country skiing, that are values comparable to those reported in middle-distance running (i.e., 800 m).[24] However, the ability to recover from, and repeat these high-intensity efforts separates sprint cross-country skiing from most endurance sports. Interestingly, the recovery from supra-maximal exercise intensities is also an aerobic process dependent on oxygen availability,[25] which further supports the above-mentioned importance of a high aerobic energy turnover in sprint cross-country skiing.

**Speed, strength, and power tests.** The skiers' $V_{max}$ on-snow in a "semi-fatigued state" showed large to very large positive correlations with sprint performance, in which $V_{max}$ on flat and uphill terrain was most strongly correlated with performance in the final sprint and the uphill sections in the latter part of the racecourse, respectively. These findings shows that terrain-specific $V_{max}$ tests are particularly relevant for performance in corresponding terrains during a simulated sprint competition and extend upon existing literature on the general importance of high-speed abilities to sprint cross-country skiing performance.[4,7,8] Still, it should be noted that these tests were performed after the competition, in a "semi-fatigued" state, and therefore might differ in their relationship to sprint performance compared to high-speed abilities obtained in a "fresh-state".

Most of the upper- and lower-body strength and power tests demonstrated moderate to large, but insignificant correlations with sprint performance. However, the relatively low number of skiers performing these tests led to reduced statistical power and may have influenced significance levels. Accordingly, our findings are in line with the less clear literature on the role of strength and power to sprint cross-country skiing performance.[2] The strongest correlations were found between 1RM strength in triceps-press and performance in the QF and SF, an exercise that has previously shown relevance to cross-country skiing performance.[18] Furthermore, peak power and 1RM in leg press showed significant correlations with sprint performance in some finals in addition to demonstrating stronger correlations with performance in S5 (final sprint) compared to S1-3. Although no differences in 1RM lower-body strength have been found between world-class and national-class sprint skiers,[4] our study is done in a more heterogenous group of junior skiers and indicate that adequate leg strength and power is relevant to sprint cross-country skiing performance and particular to final-sprint abilities in the skating style.

The strength of the correlations between 1RM in seated pull-down, as well as power output in the 30-sec double-poling ergometer test (i.e., proxy for anaerobic energy turnover) and sprint performance were reduced as the competition progressed. The reason for these findings is not known, particularly considering that adequate strength previously has been shown beneficial for maintaining GE and performance throughout long-lasting endurance competitions.[26] However, these changes might reflect the increasing correlations between performance and aerobic characteristics throughout the competition and not necessary decreased impact of strength and power *per se*.

**Methodological considerations**

In this study, a promotion-relegation system was used instead of the regular knock-out system in official sprint cross-country skiing to allow all skiers to complete three finals. This organization might have led to decreased effort and speed in the latter part of the finals among skiers who were not positioned to qualify for a "better" heat. However, the high ecological validity of including positioning and tactics when simulating sprint cross-country skiing could be seen more as a strength in comparison to previous laboratory-based designs with standardized and constant speeds across the repeated efforts.[2,7,12] Moreover, potential individual differences between skis and ski-snow friction could have slightly influenced the results although the snow and weather conditions on this test-day were considered optimal for field measurements in cross-country skiing. Also, considering the relatively young age (18 years) and heterogeneity of the participants, performance-determining variables found here might differ from more homogenous groups of elite- to world-class senior cross-country skiers.

## Practical applications

The findings of this study confirm practical observations from the field where skiers with high "aerobic profiles" seems to improve their performance as the competition format progresses in sprint cross-country skiing whereas a decline in performance is often seen among typical "sprinter profiles". Accordingly, becoming a successful sprint cross-country skier involves a "trade-off" between having and/or developing "high-speed, "explosive" and "aerobic" characteristics. Sprint cross-country skiers should attain a necessary level of strength and power but, thereafter, further improvements in performance are likely more dependent on the development of aerobic endurance, including the ability to recover from and repeat the high-intensity efforts throughout the competition day.

## Conclusions

$VO_{2peak}$ and high-speed abilities were overall the strongest determinants of sprint cross-country skiing performance, although the influence of $VO_{2peak}$ increased and the influence of strength and power characteristics decreased as the competition format progressed.

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**Figure legends**

Figure 1. Three-dimensional profile of the racecourse used divided into five different sections (S1-5). The uphill sections are displayed in red (S1 and S3, flat sections in grey (S5), and downhill sections in green (S2 and S4).

Figure 2. Relationship between sprint cross-country skiing performance and (A) sub-maximal (3.9 $m \cdot s^{-1}$) HR in $\%HR_{max}$, (B) [$La^-$], (C) peak speed, and (D) $VO_{2peak}$ during roller-ski skating in a group of male junior skiers (n=16). TT indicates individual time trial; QF, quarterfinals; SF, semifinals; F, final; HR in $\%HR_{max}$, heart rate in percentage of maximal heart rate; [$La^-$], blood lactate; $VO_{2peak}$, peak oxygen uptake. *Significant different from relationship (r-value) with TT performance.

Figure 3. Relationship between sprint cross-country skiing performance and maximal speed tests in (A) uphill (G2/V1) and (B) flat (G3/V2) terrain in a group of male junior skiers (n=16). TT indicates individual time trial; QF, quarterfinals; SF, semifinals; F, final; $V_{max}$, maximal speed. *Significant different from relationship (r-value) with TT performance.

Figure 4. Relationship between sprint cross-country skiing performance and one-repetition maximal strength in (A) seated pull-down, (B) leg press, (C) average, and (D) peak power output in a 30-sec double-poling ergometer test in a group of male junior skiers (n=12). TT indicates individual time trial; QF, quarterfinals; SF, semifinals; F, final; 1RM, one-repetition-maximal; DP, double-poling. *Significant different from relationship (r-value) with F performance.

Table 1. Descriptive data of time, speed, and related physiological responses during a simulated on-snow sprint cross-country skiing skating competition in a group of male junior skiers (n=16).

| | **TT** | **QF** | **SF** | **F** | **Avg** | ***p** |
|---|---|---|---|---|---|---|
| Overall time (s) | 176.4 (6.9) | 175.3 (8.1) | 172.7 (7.7) | 179.4 (12.5) | 176.1 (7.9) | p=0.008 |
| Overall speed ($m \cdot s^{-1}$) | 7.4 (0.3) | 7.4 (0.4) | 7.6 (0.3) | 7.4 (0.3) | 7.5 (0.3) | p=0.005 |
| Speed S1 ($m \cdot s^{-1}$) | 5.2 (0.3) | 4.6 (0.4) | 4.8 (0.4) | 4.6 (0.4) | 4.8 (0.3) | p<0.001 |
| Speed S2 ($m \cdot s^{-1}$) | 11.8 (0.4) | 12.5 (0.5) | 12.4 (0.3) | 12.4 (0.4) | 12.3 (0.2) | p<0.001 |
| Speed S3 ($m \cdot s^{-1}$) | 5.2 (0.3) | 5.8 (0.3) | 5.9 (0.3) | 5.7 (0.4) | 5.7 (0.3) | p=0.005 |
| Speed S4 ($m \cdot s^{-1}$) | 11.3 (0.4) | 11.8 (0.5) | 11.9 (0.3) | 12.0 (0.4) | 11.8 (0.3) | p=0.008 |
| Speed S5 ($m \cdot s^{-1}$) | 8.4 (0.4) | 8.7 (0.6) | 8.5 (0.6) | 8.8 (0.4) | 8.6 (0.4) | p=0.057 |
| HR in %$HR_{max}$ (%) | 90.5 (2.3) | 90.0 (5.0) | 89.0 (6.0) | 88.0 (1.8) | 89.4 (2.8) | p=0.341 |
| RPE (6-20) | 17.7 (0.9) | 15.5 (1.7) | 16.6 (1.2) | 16.8 (1.8) | 16.6 (0.8) | p=0.004 |
| [$La^-$] ($mmol \cdot L^{-1}$) | 9.8 (1.6) | 9.1 (2.1) | 8.8 (1.8) | 10.9 (1.4) | 9.6 (1.1) | p=0.002 |

Data are presented as mean (standard deviation). TT, time trial; QF, quarterfinal; SF, semifinal; F, final; HR, heart rate; $HR_{max}$, maximal heart rate; RPE, rating of perceived exertion; [$La^-$], blood lactate. *One-way repeated-measures ANOVA (main effects).

Table 2**.** Descriptive data of performance-determining variables including sub-maximal and incremental roller-ski skating tests as well as upper- and lower-body strength and power tests in a group of male junior cross-country skiers.

| | | |
|---|---|---|
| **Sub-maximal test (n=16)** | | |
| | **(2.8 m·s$^{-1}$)** | **(3.9 m·s$^{-1}$)** |
| HR in %HRmax | 77.5 (5.4) | 88.5 (4.5) |
| RPE (6-20) | 10.9 (2.3) | 14.5 (2.1) |
| [La$^-$] (mmol·L$^{-1}$) | 1.8 (0.9) | 3.7 (2.0) |
| $VO_2$ (mL·min$^{-1}$·kg$^{-1}$) | 38.7 (1.5) | 51.0 (1.6) |
| GE (%) | 13.7 (0.5) | 14.4 (0.5) |
| **Incremental test (n=16)** | | |
| $VO_{2peak}$ (mL·min$^{-1}$) | 5098 (652) | |
| $VO_{2peak}$ (mL·min$^{-1}$·kg$^{-1}$) | 67.6 (5.5) | |
| Peak speed (m·s$^{-1}$) | 4.8 (0.4) | |
| TTE (s) | 376.9 (97.3) | |
| RPE (6-20) | 19.2 (0.7) | |
| [La$^-$] (mmol·L$^{-1}$) | 11.6 (1.6) | |
| $HR_{peak}$ (bpm) | 195 (9) | |
| **Strength and power tests (n=11)** | | |
| 1RM Pull down (kg) | 85.9 (6.4) | |
| 1RM Triceps press (kg) | 73.8 (7.5) | |
| 1RM Leg press (kg) | 295 (34) | |
| Peak power leg press (W) | 936 (144) | |
| Average power 30-sec DP (W) | 508 (52) | |
| Peak power 30-sec DP (W) | 601 (54) | |

Data are presented as mean (standard deviation). HR, heart rate; $HR_{max}$, maximal heart rate; RPE, rating of perceived exertion; [La$^-$], blood lactate concentration; $VO_2$, oxygen uptake; GE, gross efficiency; $VO_{2peak}$, peak oxygen uptake; TTE, time to exhaustion; $HR_{peak}$, peak heart rate; 1RM; one-repetition-maximal-strength; DP, double poling.

Table 3. Correlations (r-values) between different performance-determining variables and performance (speed) in a sprint cross-country skiing skating competition in a group of male junior skiers (n=16).

| | **TT** | **QF** | **SF** | **F** | **Avg** |
|---|---|---|---|---|---|
| **Anthropometrics** | | | | | |
| Body mass (kg) | 0.41 | 0.41 | 0.36 | 0.13 | 0.33 |
| BMI | 0.28 | 0.33 | 0.36 | 0.10 | 0.28 |
| Age (years) | 0.58* | 0.50* | 0.56* | 0.30 | 0.49 |
| **Sub-maximal test (2.8 $m \cdot s^{-1}$)** | | | | | |
| HR in $\%HR_{max}$ | -0.53* | -0.64* | -0.60* | -0.77** | -0.73** |
| RPE (6-20) | -0.68** | -0.58* | -0.65** | -0.55* | -0.67** |
| $[La^-]$ ($mmol \cdot L^{-1}$) | -0.60* | -0.73** | -0.73** | -0.66** | -0.84** |
| $VO_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | -0.56* | -0.44 | -0.51 | -0.68* | -0.60 |
| GE (%) | 0.58* | 0.48 | 0.55* | 0.63* | 0.63* |
| **Sub-maximal test (3.9 $m \cdot s^{-1}$)** | | | | | |
| HR in $\%HR_{max}$ | -0.58* | -0.63** | -0.67** | -0.73** | -0.74** |
| RPE (6-20) | -0.71** | -0.68** | -0.69** | -0.60* | -0.74** |
| $[La^-]$ ($mmol \cdot L^{-1}$) | -0.60* | -0.74** | -0.79** | -0.83** | -0.84** |
| $VO_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | -0.49 | -0.49 | -0.60* | -0.22 | -0.45 |
| GE (%) | 0.52* | 0.59* | 0.66** | 0.37 | 0.57* |
| **Incremental test** | | | | | |
| $VO_{2peak}$ ($mL \cdot min^{-1}$) | 0.62* | 0.74** | 0.73** | 0.60* | 0.73** |
| $VO_{2peak}$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | 0.51* | 0.68** | 0.73** | 0.77** | 0.77** |
| Peak speed ($m \cdot s^{-1}$) | 0.73** | 0.80** | 0.82** | 0.86** | 0.90** |
| **Strength and power tests** | | | | | |
| 1RM Pull down (kg) | 0.50 | 0.53 | 0.55 | 0.16 | 0.37 |
| 1RM Triceps press (kg) | 0.44 | 0.73* | 0.85** | 0.59 | 0.76** |
| 1RM Leg press (kg) | 0.34 | 0.67* | 0.57 | 0.56 | 0.64* |
| Peak power leg press (W) | 0.52 | 0.61 | 0.56 | 0.56 | 0.66* |
| Average power 30-sec DP (W) | 0.42 | 0.53 | 0.53 | 0.01 | 0.41 |
| Peak power 30-sec DP (W) | 0.52 | 0.59 | 0.71* | 0.19 | 0.56 |

TT, time trial; QF, quarterfinal; SF, semifinal; F, final; Avg, average; HR, heart rate; $HR_{max}$, maximal heart rate; RPE, rating of perceived exertion; $[La^-]$, blood lactate; $VO_2$, oxygen uptake; GE, gross efficiency; $VO_{2peak}$, peak oxygen uptake; 1RM; one-repetition-maximal strength; DP, double poling. 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 1

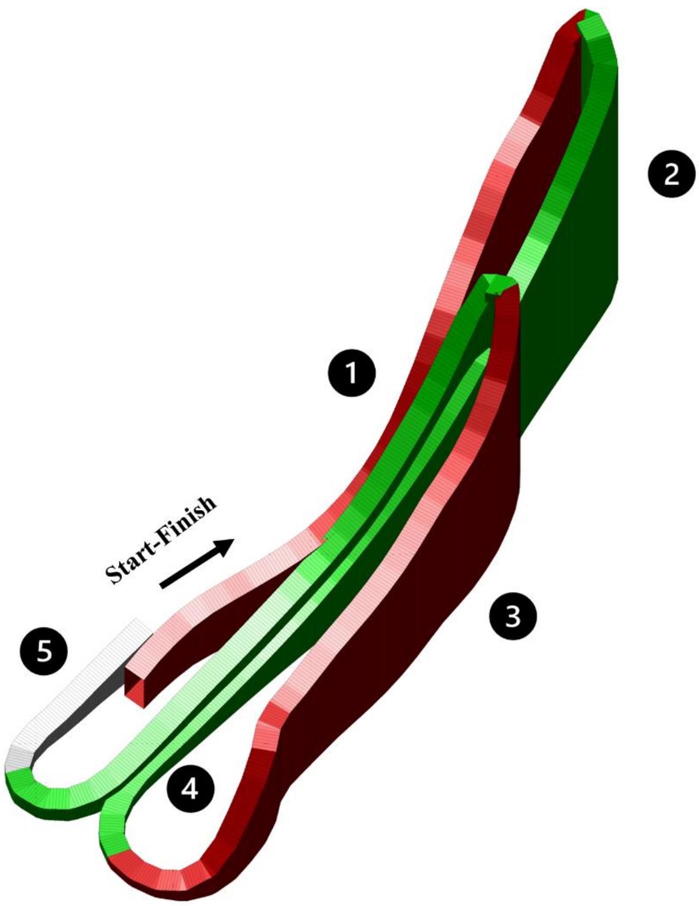
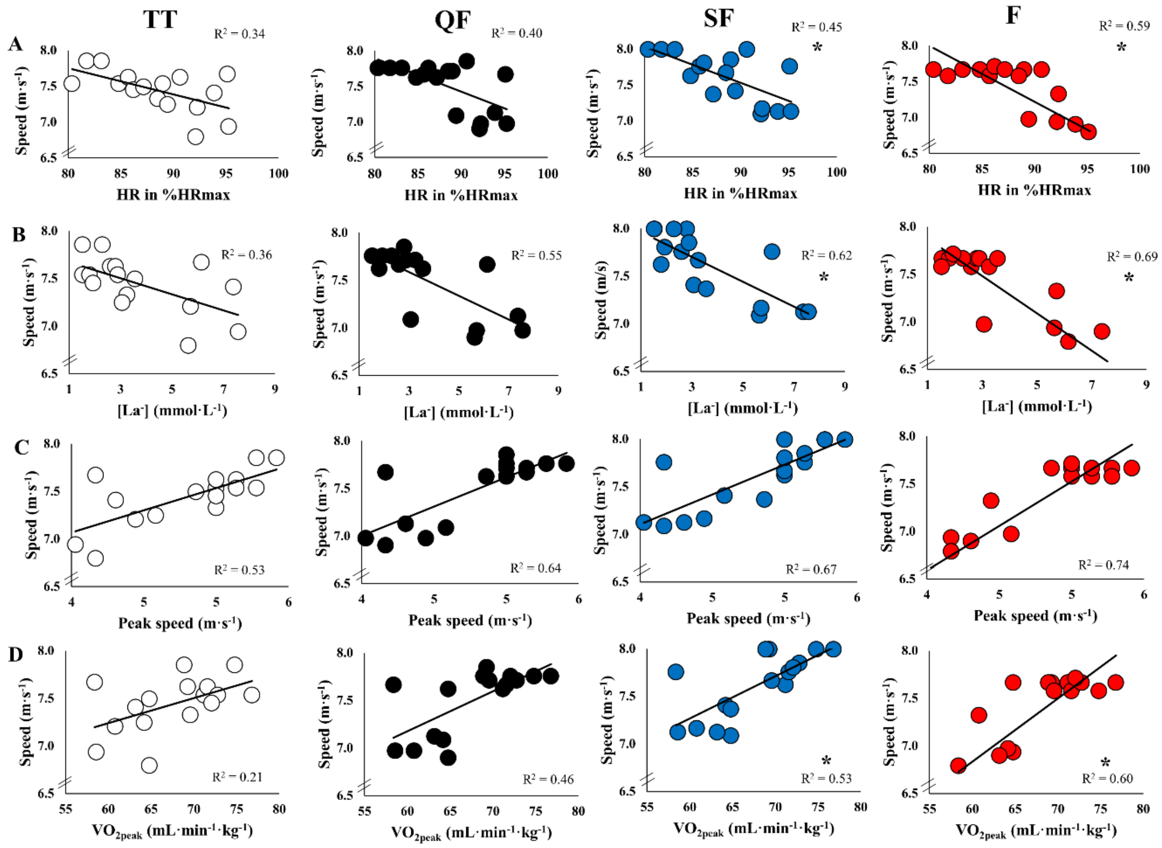
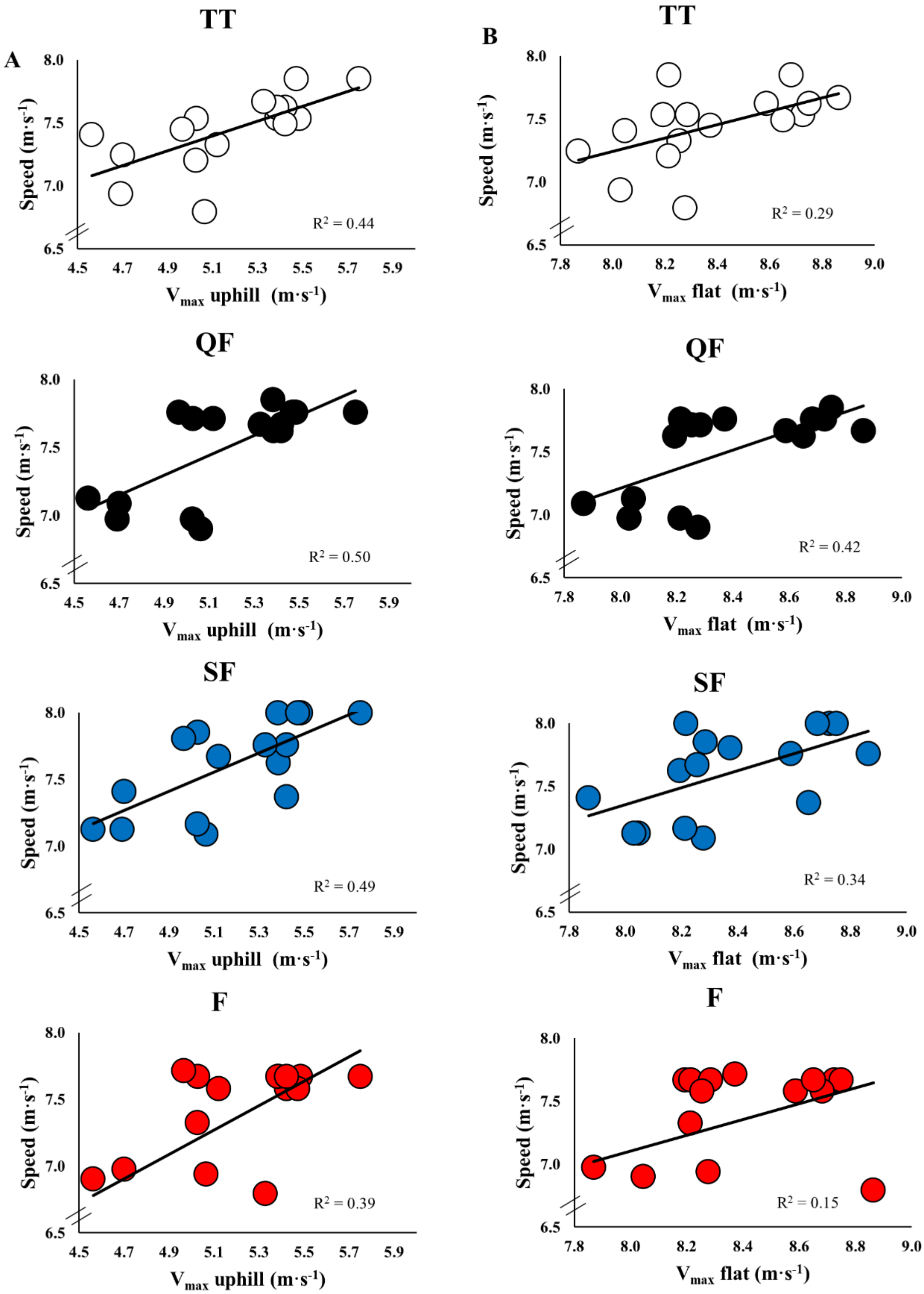


Figure 2



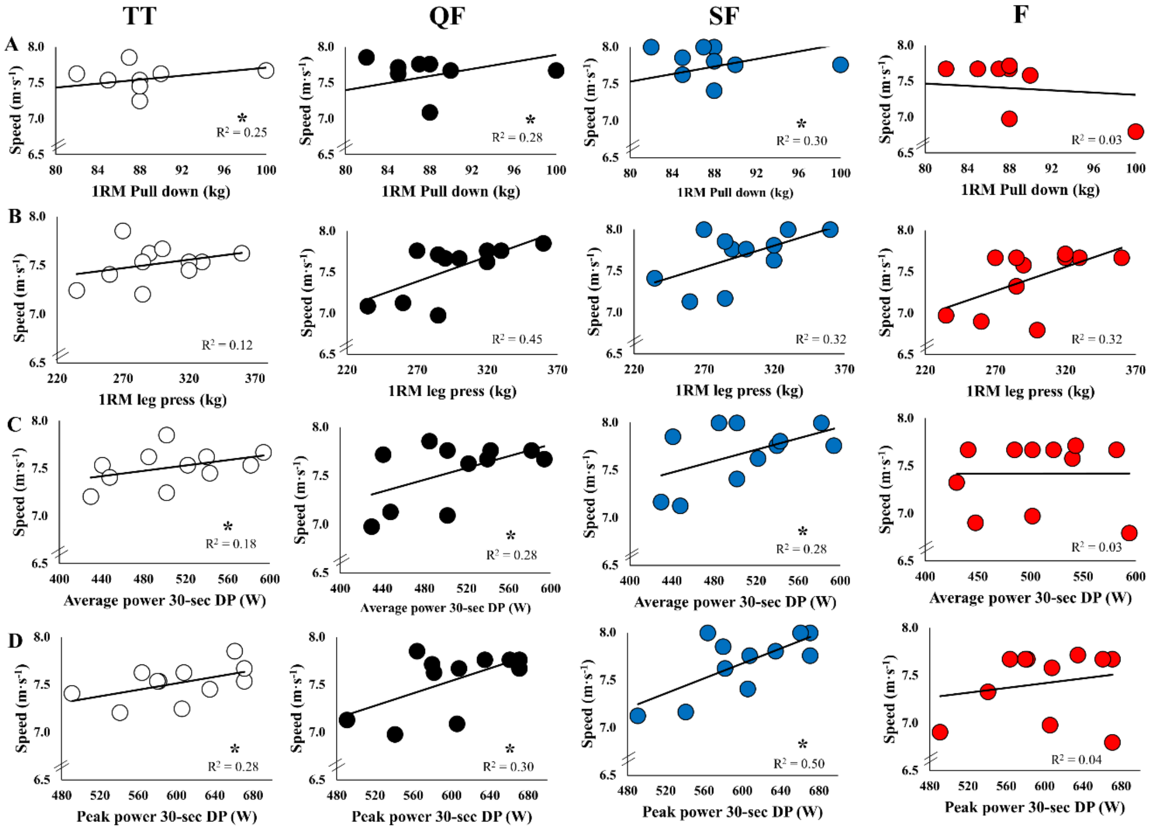
TT
QF
SF
F
A
B
C
D
R² = 0.34
R² = 0.40
R² = 0.45
R² = 0.59
R² = 0.36
R² = 0.55
R² = 0.62
R² = 0.69
R² = 0.53
R² = 0.64
R² = 0.67
R² = 0.74
R² = 0.21
R² = 0.46
R² = 0.53
R² = 0.60
*
Speed (m·s⁻¹)
Speed (m/s)
HR in %HRmax
[La⁻] (mmol·L⁻¹)
Peak speed (m·s⁻¹)
VO2peak (mL·min⁻¹·kg⁻¹)

Figure 3



A
B
TT
QF
SF
F
Speed (m·s-1)
Vmax uphill (m·s-1)
Vmax flat (m·s-1)
8.0
7.5
7.0
6.5
4.5
4.7
4.9
5.1
5.3
5.5
5.7
5.9
7.8
8.0
8.2
8.4
8.6
8.8
9.0
R2 = 0.44
R2 = 0.29
R2 = 0.50
R2 = 0.42
R2 = 0.49
R2 = 0.34
R2 = 0.39
R2 = 0.15

Figure 4



TT
QF
SF
F
A
B
C
D
Speed (m·s⁻¹)
1RM Pull down (kg)
1RM leg press (kg)
Average power 30-sec DP (W)
Peak power 30-sec DP (W)
*
R² = 0.25
R² = 0.28
R² = 0.30
R² = 0.03
R² = 0.12
R² = 0.45
R² = 0.32
R² = 0.32
R² = 0.18
R² = 0.28
R² = 0.28
R² = 0.03
R² = 0.28
R² = 0.30
R² = 0.50
R² = 0.04