Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

Brattebø, Jan-Magnus

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Master's thesis in Physical Activity and Health - Exercise Physiology
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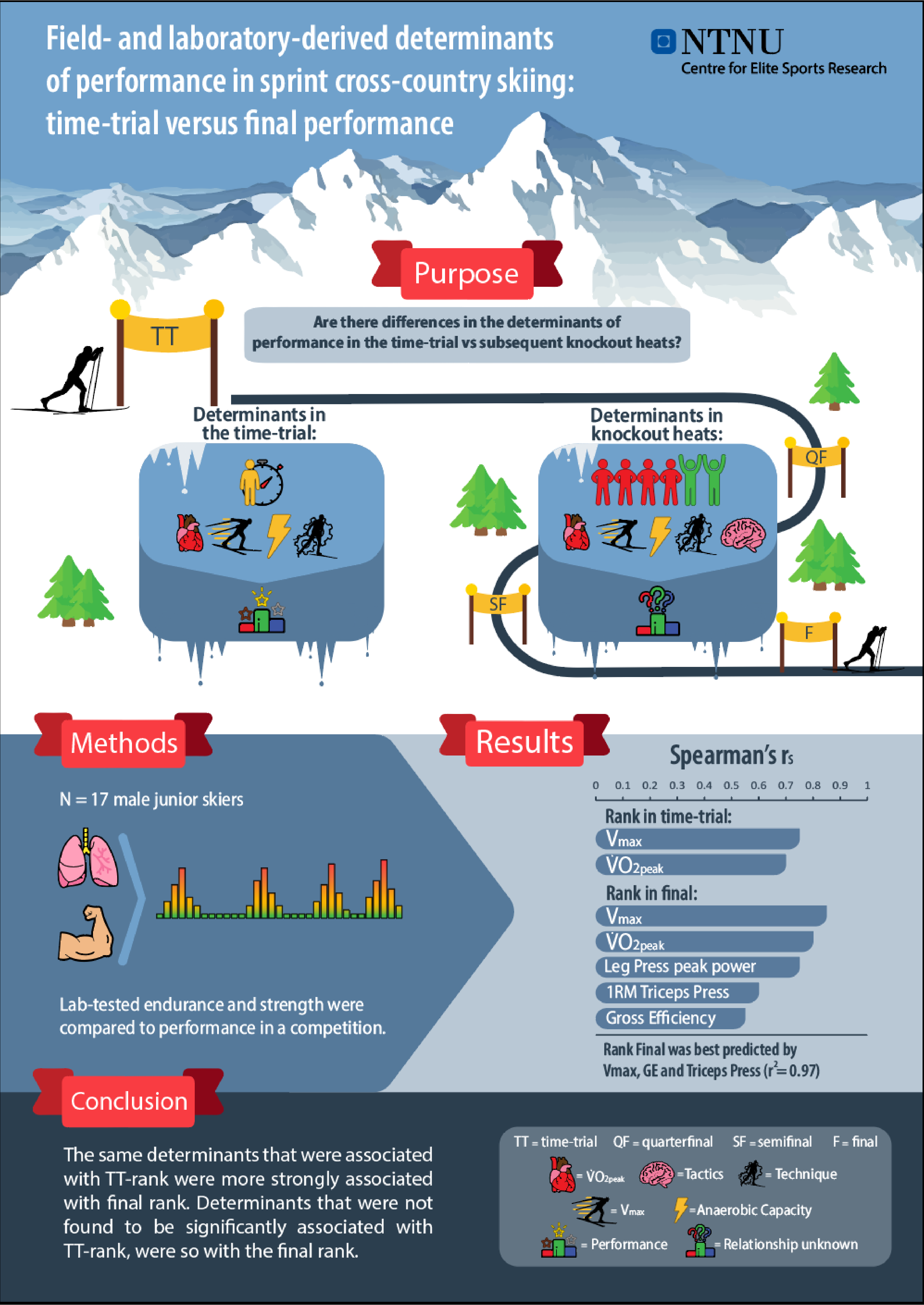

Field- and laboratory-derived determinants of performance in sprint cross-country skiing: time-trial versus final performance
NTNU
Centre for Elite Sports Research
Purpose
Are there differences in the determinants of performance in the time-trial vs subsequent knockout heats?
TT
Determinants in the time-trial:
Determinants in knockout heats:
QF
SF
F
Methods
N = 17 male junior skiers
Lab-tested endurance and strength were compared to performance in a competition.
Results
Spearman's r_s
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rank in time-trial:
V_{max}
$\dot{V}O_{2peak}$
Rank in final:
V_{max}
$\dot{V}O_{2peak}$
Leg Press peak power
1RM Triceps Press
Gross Efficiency
Rank Final was best predicted by V_{max}, GE and Triceps Press ($r^2 = 0.97$)
Conclusion
The same determinants that were associated with TT-rank were more strongly associated with final rank. Determinants that were not found to be significantly associated with TT-rank, were so with the final rank.
TT = time-trial
QF = quarterfinal
SF = semifinal
F = final
= $\dot{V}O_{2peak}$
= Tactics
= Technique
= V_{max}
= Anaerobic Capacity
= Performance
= Relationship unknown

ABSTRACT:

Purpose: To investigate field- and laboratory-derived determinants of performance in a sprint cross-country skiing (XCS) competition. Since the time-trial (TT) in sprint XCS has previously been well researched and there is limited knowledge of the knockout heats, a secondary aim was to compare the magnitude of the associations between determinants and performance in the time-trial and overall competition. **Methods:** Seventeen male junior athletes (age: 18.5 ± 0.8) competing on a national level performed a simulated sprint XCS competition, including a TT and four knockout heats, followed by the tests; (1) 5-min submaximal stages and an incremental test to exhaustion while treadmill G3 skating to determine peak oxygen uptake ($\dot{V}O_{2peak}$) and gross efficiency (GE); (2) maximal strength (1RM) in pulldown and triceps press, 1RM and peak power (PP) in leg press, and a 30-s Wingate double poling test; and (3) maximal velocity (V_{max}) tests in flat and uphill terrain on snow. Spearman's rank-order correlation (r_S) and multiple regression analysis explored the relationship between TT-rank and final rank in the XCS competition versus laboratory-, and field-based test-results. **Results:** Strong correlations were found between V_{max} flat and $\dot{V}O_{2peak}$ (L·min^{-1}) and both TT-rank (r_S= 0.75 and 0.70; both p< 0.01) and final rank (r_S= 0.86 and 0.80; both p< 0.01). Leg press PP, 1RM triceps press and GE also showed strong and moderate correlations to the final rank (r_S= 0.76, 0.60 and 0.54; all p< 0.05). Comparing the magnitude of associations between determinants and rank in the TT and final, found V_{max} flat and 1RM triceps press to be Δr_S > 1.5 SD (p= 0.07 and 0.06), with moderate effect size (*q*= 0.32 and 0.28). Together, V_{max} flat, GE and 1RM triceps press explained ~97% of variance in final rank. **Conclusion:** V_{max} and $\dot{V}O_{2peak}$ (L·min^{-1}) are the two greatest determinants of performance in junior sprint XCS. The same determinants that were associated with TT-rank were more strongly associated with final rank. Furthermore, determinants that were not found to be significantly associated with TT-rank, were so with the final rank, in which the effect of the changes ranged from moderate to small. The influence of known determinants of performance appears to be different in a single time-trial vs a competition event and aerobic and anaerobic power seem to be essential in achieving a high rank in a sprint XCS competition

SAMMENDRAG:

Formål: Å undersøke felt- og laboratorie-baserte faktorer som påvirker utøvernes prestasjon i en sprintkonkurranse i langrenn. Siden prologen er godt undersøkt og det er mindre kunnskap om betydningen av prestasjonsbestemmende faktorer i knockout løpene, er et sekundært formål å sammenligne størrelsen på sammenhengen mellom de ulike faktorene og prestasjon i prologen og konkurransen helhetlig. **Metode:** Sytten mannlige junior utøvere (alder: 18.5 ± 0.8) som konkurrerer på nasjonalt nivå, gjennomførte en simulert sprintkonkurranse bestående av en prolog og fire knockout løp, i tillegg til andre tester; (1) 5-min submaksimale stadier og en gradvis økende test til utmattelse på mølle i G3-skøyting, for å fastslå høyeste målte oksygenopptak ($\dot{V}O_{2peak}$) og effektivitet (GE); (2) maksimal styrke (1RM) i nedtrekk og tricepspress, 1RM og maksimal effekt (PP) i benpress, og en 30-s Wingate test i staking; og (3) maksimal hastighet (V_{max}) tester på snø i flatt terreng og oppoverbakke. Spearmans korrelasjon (r_S) og multippel regresjonsanalyse ble benyttet for å bestemme forholdet mellom laboratorie- og felt-baserte prestasjonsbestemmende faktorer til prestasjon i prologen og finalen, målt gjennom plassering. **Resultat:** Det ble observert sterk korrelasjon for V_{max} flat og $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) med plassering både i prologen (r_S= 0.75 og 0.70; begge p< 0.01) og i finalen (r_S= 0.86 og 0.80; begge p< 0.01). Benpress PP, 1RM tricepspress and GE hadde også sterk og moderat korrelasjon med plassering i finalen (r_S= 0.76, 0.60 og 0.54; alle p< 0.05). En sammenligning av størrelsen på korrelasjonene mellom faktorer og plassering i prolog og finale, viste at V_{max} flat og 1RM tricepspress hadde en endring tilsvarende Δr_S > 1.5 SD (p= 0.07 and 0.06) hvorav effekten av endringen var moderat (*q*= 0.32 and 0.28). En kombinasjon av V_{max} flat, GE og 1RM i tricepspress forklarte ~97% av all variasjon i plassering i finalen. **Konklusjon:** V_{max} og $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) er de to viktigste prestasjonsbestemmende faktorene i junior sprint langrenn. De samme faktorene som var assosiert med prestasjon i prologen, hadde en enda større betydning i finalen. Noen faktorer som ikke påvirket plassering i prologen, gjorde dette i finalen, hvorav effekten på endringen varierte fra moderat til liten. Betydningen av prestasjonsbestemmende faktorer ser ut til å være ulik i prologen vs konkurransen samlet sett, mens aerob og anaerob effekt ser ut til å være essensiell for å oppnå en høy plassering i en sprintkonkurranse i langrenn.

ACKNOWLEDGEMENTS

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Thank you,
Jan-Magnus Brattebø

TABLE OF CONTENT:

ABBREVIATIONS

XCS = cross-country skiing

FIS = International Ski Federation

TT = time-trial

QF = quarterfinal

SF = semifinal

F = final

$\dot{V}O_{2max}$ = rate of maximal oxygen uptake

$\dot{V}O_{2peak}$ = highest measured rate of oxygen uptake

GE = gross efficiency

V_{max} = maximal velocity

BLa = blood lactate concentration

HR_{max} = maximal heart rate

μ = coefficient of friction

GNSS = global navigation satellite system

IMU = inertial measurement unit

1RM = 1 repetition maximum resistance

PP = peak power

PP% = point of peak power

$\overline{PO}_i$ - arithmetic mean of power output in segment *i*

PPO = peak power output

AnFI = anaerobic fatigue index

AnCap = anaerobic capacity

r_S = Spearman rank-order correlation

Δr_S = difference in r_S

SD = standard deviation

SEE = standard error of the estimate

W - watt

WG - Wingate

INTRODUCTION

Cross-country skiing (XCS) is a demanding endurance sport that includes whole-body exercise typically performed on hilly terrain with approximately one-third uphill, one-third undulating (1-9 m difference in elevation), and one-third downhill terrain. The Olympic competition distances vary between 1-50 km (FIS, 2020), with two main sub-specializations; sprint and distance skiing. In all disciplines, the undulating and hilly race profile distinguishes the technical and physiological demands from most other endurance sports by continuous variations in sub-technique utilization and energetic demands on the aerobic and anaerobic system.

The sprint sub-specialization of XCS was first introduced in 1996 (Hébert-Losier et al., 2017) and includes individual and team sprint events. The individual sprint event consists of up to 4 repeated sprints on a 1 - 1.8 km track with a duration of ~3-min (FIS, 2020). Each stage of the competition occurs with multiple parallel heats, with 6 competitors in each. Initially, there is an individual time-trial (TT) qualification in which the 30 fastest skiers are qualified for the finals. In the subsequent five quarterfinal (QF) heats, the two top ranked in each heat advance to the two semifinals (SF). Two lucky losers from the QFs, the fastest non-qualifying competitors, advance to fill the 6th spot in the two SFs. In a similar fashion, the two top ranked from the SFs, along with two lucky losers, compete in the finals (F) for the upper 6 ranks and the podium. Due to the number of heats and required resting time, sprint competition events typically last 3-4 hours and include all intensities from rest to supramaximal work rates (Hébert-Losier et al., 2017; Stöggl et al., 2007).

Due to its large energy demands when performing repeated 3-min heats in hilly terrain, sprint XCS requires concurrent utilization of all energy-producing pathways. In a 3-min timed trial, ~26% of the total energy release was estimated to come from anaerobic pathways (Losnegard et al., 2012) and in uphill segments, the work rate has been calculated to reach 140-160% of the skiers' maximal oxygen uptake ($\dot{V}O_{2max}$). Furthermore, skiers even operate at work rates close to 120% in the flat segments (Karlsson et al., 2018; Sandbakk et al., 2017). These findings show the importance of anaerobic capacity as complementary determinants to the aerobic capacity. Changes in terrain continually alter the energy demand and also require changes in sub-techniques, with different upper- and lower body contributions to maintain optimal efficiency and propulsion. Due to the natural delay in aerobic pathways, anaerobic turnover rate immediately increases to compensate for the fluctuating demands (Holmberg, 2015). The frequent undulation of the terrain is what creates, but also enables, the unique utilization of the anaerobic capacity, which clearly, but not exclusively, manifests itself in supramaximal work rates. Skiers intentionally go beyond their aerobic capacity in uphill and flat terrain, and recover in the subsequent downhill segments. In sprint skiing, 50% of the competition time is spent in various uphill segments, and therefore, the segment-specific performance of uphill terrain serves as a crucial determinant for overall performance. In addition to the frequent use of anaerobic energy production, elite skiers tend to employ a positive pacing strategy, where they start at an unsustainably high intensity and aim, to the best of their ability, to maintain it throughout the race (Andersson et al., 2010; Andersson et al., 2016; Stöggl et al., 2018).

To solve the complex demands of a sprint competition, where different capacities are challenged to the extreme, it is essential to understand the role of the various determinants and their relationship to performance. By performing laboratory-, and field-based testing, we can measure these capacities and their association with sprint XCS performance. Historically, the sport has produced multiple individuals with record values in $\dot{V}O_{2max}$ (Sandbakk et al., 2014). $\dot{V}O_{2max}$ is a valid measurement of aerobic power and the skier's capacity for intensity during prolonged work. Since $\dot{V}O_2$ depends on the involvement of active muscle mass, it varies between different activities and sport specific sub-techniques (Holmberg, 2015). $\dot{V}O_{2peak}$ is therefore often defined as the highest oxygen uptake produced in specific techniques. Stöggl et al. (2007) found that skiers reach and operate at ~95% of their $\dot{V}O_{2max}$ during a 3-min race. While $\dot{V}O_2$ reflect the inner mechanisms of oxygen consumption and its transference to metabolic energy, Gross efficiency (GE) is the percentage ratio of external work performed by the entire body, divided by the aerobic metabolic rate (Sandbakk et al., 2010). GE provides information about the efficiency of the skier's conversion of the energy produced by the current $\dot{V}O_2$ into kinetic force and propulsion against the external environment. In other terms, GE tells us something about the utilization of the available energy and may also reflect how much energy is wasted through e.g., an inefficient skiing-technique. A higher GE means skiers can either operate at a lower metabolic rate at submaximal work rates, or reach higher work rates at their maximal metabolic rate. This may just be the differentiating factor for success across both a single sprint or an overall competition. In the context of a competition event, with up to 4 repeated sprints, the development of these aerobic determinants and the aerobic capacity overall, are crucial for performance in repeated sprints. However, at the elite level, findings suggest that aerobic factors serve more as a prerequisite than what distinguishes performance (Stöggl et al., 2007; Tønnesen et al., 2015; Andersson et al., 2016).

Maximal velocity (V_{max}) is a result of physiological, neuromuscular, kinematic and coordinative properties, and has been found to be strongly correlated to sprint performance in elite skiers (Stöggl et al., 2007; Mikkola et al., 2010). Meanwhile, maximal strength and power capabilities are found to influence skiing performance (Mikkola et al., 2010; Stöggl et al., 2011) and this is suggested to be through maximal power generation and velocity, as well as reducing the energy cost of skiing through improved work economy (Losnegard et al., 2011). Furthermore, Stöggl et al. (2009) found cycle rate and relative poling time to be negatively correlated to maximal velocity across all techniques, while cycle length and relative swing time was positively correlated. This suggests that power capabilities are essential to generate the propulsive forces required in the short poling time that is available at higher velocities. However, it is not clear how or to what degree isolated strength and power translate to the more complex and dynamic sport-specific performance in skiing.

While there has been extensive research on sprint skiing, the majority is done on roller skis and through individual treadmill skiing, resembling a time-trial like sprint. The determinants for race-time performance for such a single sprint is well documented (Andersson et al., 2010; Sandbakk et al., 2011a; Losnegard et al., 2012). However, there has been less research on the subsequent mass start knockout style heats, and it is unclear whether determinants contribute differently to the performance in these, which ultimately is reduced to the placement rank. In the competition format, with the use of knockout heats, one can speculate on the importance of tactical decisions to secure a promoting rank in the current and following heats. These also create additional influential factors for overall performance or final rank. Zory et al. (2006) found that three repeated knockout sprints, separated by 12-min of recovery, resulted in a reduction of effort in maximal work, without affecting overall race-time. Meanwhile McGawley et al. (2022) found that, while longer recovery time is better, ~22-min between races sufficiently ensures that residual fatigue does not impact performance in subsequent heats. The finite limitation of the anaerobic capacity, despite its recovery in downhill terrain and between races, depletes throughout each sprint and the competition overall. This creates tactical dilemmas regarding the use of anaerobic capacity which primarily falls in two distinctions: 1) using a greater part of the capacity to secure a promoting rank, while risking overexertion and larger anaerobic depletion in the following heats, and 2) while in a promoting position, conserving the capacity for the homestretch sprint or the following heats and risk being overtaken before the finishing line. Due to the importance of supramaximal phases and their repetitions to secure a promoting rank in each race, V_{max} capabilities and the overall magnitude of the anaerobic capacity must also be considered tactical capacities for on-demand use, as each skier prefers in regard to their current physiological and tactical situation. While the influence of this can be considered relatively low between the TT and QF, it may increase with the lower recovery time toward the final. Skiers with a larger anaerobic capacity may therefore have an advantage in this situation due to a lower risk of overexertion and thereby greater tactical flexibility in their use of this capacity.

There are still many uncertain aspects to the challenges skiers face in a sprint competition and its heats. The purpose of this study is to investigate field- and laboratory-derived determinants of performance in a sprint XCS competition. Since the time-trial in sprint XCS has previously been well researched and there is limited knowledge of the knockout heats, a secondary aim was to compare the magnitude of the associations between determinants and performance in the time-trial and overall competition.

METHODS

Overall design of the study

The study consisted of three separate parts, which all occurred on separate days: 1) endurance tests, 2) sprint competition, and 3) maximal strength and power tests, all of which occurred in Granåsen Elite Sports Center, Norway. The simulated competition took place mid-December 2021 and was arranged as a freestyle sprint competition event, consisting of an individual TT followed by three heats simulating the QF, SF and F. The endurance tests were conducted ± 3 weeks within the simulated competition, while strength and power testing occurred in the 5th week following the sprint competition.

Participants

Twenty junior male XC skiers at national competition level were recruited from a regional high school. 3 of the participants were excluded due to lack of participation in the endurance tests, and the remaining 17 participants were used as subjects in this study, out of which 12 participated in strength and power testing. All participants gave their informed written consent to participate in the study, which was approved by the Norwegian Center for Research Data. The participants' anthropometric and physiological characteristics are shown in Table 1. Their previous accustomization to treadmill skiing varied from moderately experienced to no previous experience.

Table 1: Main characteristics of participants, N=17

Characteristics	Mean ± SD
Age (years)	18.5 ± 0.8
Height (cm)	181.5 ± 5.4
Body Mass (kg)	75.8 ± 7.9
$\dot{V}O_{2peak}$ ($L\cdot min^{-1}$)	5.1 ± 0.7
$\dot{V}O_{2peak}$ ($ml\cdot kg^{-1}\cdot min^{-1}$)	67.2 ± 5.7
BLa_{peak} ($mmol\cdot L^{-1}$)	11.5 ± 1.7
HR_{max} ($beats\cdot min^{-1}$)	194.3 ± 8.4
V_{max} flat ($km\cdot h^{-1}$)	30.5 ± 1.2

SD - standard deviation, $\dot{V}O_{2peak}$ - Peak Oxygen Consumption, BLa_{peak} - Blood Lactate Peak, HR_{max} - Maximal Heart Rate, V_{max} flat - Maximal Velocity Flat Terrain.

Endurance tests

The endurance testing consisted of submaximal stages paired with an incremental test to exhaustion. Six of the participants had recently performed near identical testing in conjunction with another project. For practical reasons, the data from these previous tests were used. The ventilatory data from these participants were extracted from the software and put through the same method for calculating the variables as the rest of the study sample, while simple values for BLa and Heart Rate (HR) were copied. A visualization of the overall test protocol can be seen in Figure 1.

Instruments and measurements

Roller skiing was performed on a 3x5 m motor-driven treadmill (Forcelink S-mill, Motekforce Link, Amsterdam, The Netherlands). The treadmill belt was covered with a non-slip rubber, allowing the skiers to use their own poles with special-fitted carbide tips. All skiers used the same pair of roller skis (IDT Sports, Lena, Norway) with standard wheels. Rolling friction was determined to be 0.018 μ, using methods described in Sandbakk et al. (2010) and was included in the later calculation of work rate. Ventilatory variables were measured using open-circuit indirect calorimetry (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany), while blood samples were analyzed for lactate concentrations using the Biosen C-line Clinic (EKF Diagnostics, Cardiff, UK). Heart rate was measured using the participants' own sports watches with an electrode chest belt (equivalent to: Garmin Forerunner 920XT/935, Garmin Ltd., Olathe, United States).

Protocols

Submaximal tests

The participants performed a 5-min warm up at 8 $km \cdot h^{-1}$ before commencing the 4-stage submaximal testing. The test was structured as 5-min work phases, separated by 2-min breaks. The incline of all stages was locked to 5 %, while the velocity was 8, 10, 12 and 14 $km \cdot h^{-1}$, respectively. The 6 forementioned participants had only performed 3 stages, of which the respective velocities were 10, 12 and 14 $km \cdot h^{-1}$ (N= 5) and 12, 14 and 16 $km \cdot h^{-1}$ (N= 1). $\dot{V}O_2$ along with other ventilatory variables were registered using the average of the last 2-min in each stage, while HR was registered as the average of the last 30 seconds. A blood lactate sample was taken within 30 sec after each stage.

Incremental test to exhaustion

After the Submaximal test and a 10-min break, the participants performed a continually incremental test. They were secured using a safety harness and the incline was locked at 7 % and initial velocity set to 12 $km \cdot h^{-1}$, increasing with +1 $km \cdot h^{-1}$ each minute. The test was concluded at: 1) the participant's own wish or 2) if the participant failed to keep up with the treadmill.

Calculations

Work rate and Gross Efficiency (GE) were calculated in accordance with Sandbakk et al. (2010) as respectively, 1) the sum of power against gravity and friction, and 2) as the external work rate performed by the entire body divided by the aerobic metabolic rate, presented as percentage. In subsequent analyses, GE from 12 $km \cdot h^{-1}$ was used as this was the lowest intensity performed by all participants. $\dot{V}O_{2peak}$ was calculated as the highest average over 1-min, while the highest observed HR and BLa, in either the incremental test or during the sprint competition, was registered as HR_{max} and BLa_{peak}.

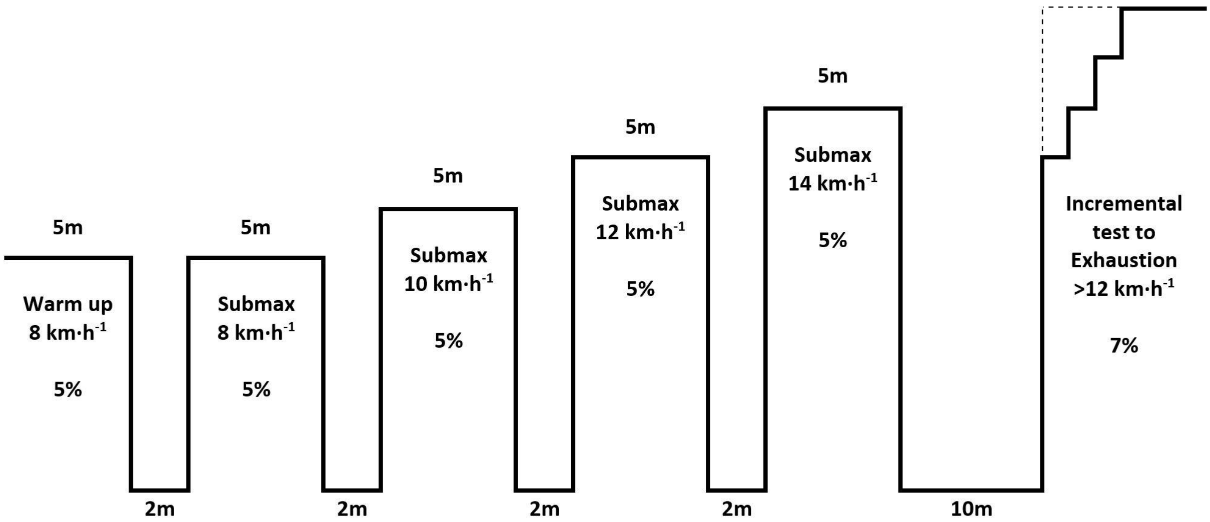


Figure 1: Visualization of the treadmill endurance testing protocol, consisting of submaximal testing and an incremental test to exhaustion, all in G3 skating. Incline for the warm-up and submaximal stages was 5 %, while the incremental test was set at 7 %.

Simulated competition

Tracks and conditions

The track was an adaptation from a FIS-approved track previously used in the elite national sprint championship earlier the same year. It was adjusted to a length of 1311 m and was, for analytical purposes, separated into 5 sections as per Table 2. An illustration of the track profile is visualized in Figure 2. Weather conditions were stable throughout the day, with some clouds but no precipitation. The air temperature ranged between -2.6 and -1.4 ℃ while the average snow temperature was measured to be, on average, -3.5 ℃ (range -5.3, -1.1 ℃). The tracks were prepared the same morning by a trail machine. Throughout the entire day, the participants had access to an indoor resting area and a supply of energy drinks with small snacks. Additionally, they were in full control of their own warm-up, resting-time activity and food consumption.

Table 2: The division of the racetrack per its five segments with length and terrain type.

Segment	Length (m)	Cumulative Length (m)	Terrain Type
S1	301	301	uphill
S2	370	671	downhill
S3	280	951	uphill
S4	280	1231	downhill
S5	80	1311	flat

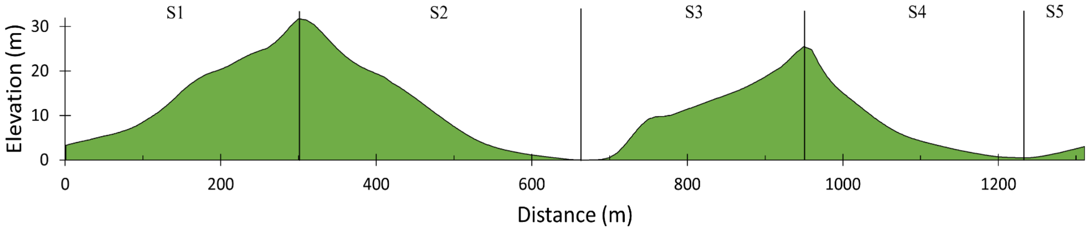


Figure 2: Visualization of the 1311 m racetrack elevation profile with segmental division. S1-5 - Segment 1 to 5

<u>Instruments and measurements</u>

GPS and movement data were measured during all sprints using a *Catapult* sensor with integrated Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU) (Optimeye S5, Catapult Innovations, Melbourne, Australia). GNSS and IMU data were sampled at 10-Hz and 100-Hz, respectively. The sensor was carried in a small bib pocket under the starting bib during each sprint. HR was monitored throughout the entire day using a Garmin Forerunner 920XT/935 sports watch with an electrode chest belt. The participants brought their own skiing equipment and were encouraged to use what they would in a competition. Furthermore, they were instructed to prepare their skis with CH6 glide wax (Swix, Lillehammer, Norway) to standardize glide. For each race, a blood sample was taken from the fingertip, approximately 2-min before and after each heat using the Lactate Pro 2 measurement kit (Arkray Europe B.V, Amstelveen, the Netherlands) for a total of 8 samples per participant.

<u>Protocol</u>

The participants arrived between 08:00-08:10 in the morning for registration and fitting of the equipment and were free to start warm-up as they saw fit. The individual TT started at 09:15 with 1-min delay between each participant. Based on their time, they were distributed into one of 3 ranked groups: A, B and C, of which A had the fastest, B the intermediate, and C slowest skiers. For the QF and SF, a rank-up/down system was employed in place of the normal knockout system, where the top/bottom 2 skiers would move up or down a group for the next sprint. This would maintain the sample size throughout the entire competition event while ensuring a similar competitive setting across all groups, including those who would realistically be “knocked out”. Figure 3 presents the competition format as well as the time schedule. Due to differences in TT starting time and the rank-up/down system, the actual time and range between the sprints were on average (range): 71 (58-78), 47 (38-54) and 32 (25-40) minutes. Descriptive and physiological data from the four sprints in the competition event can be found in Appendix 1.

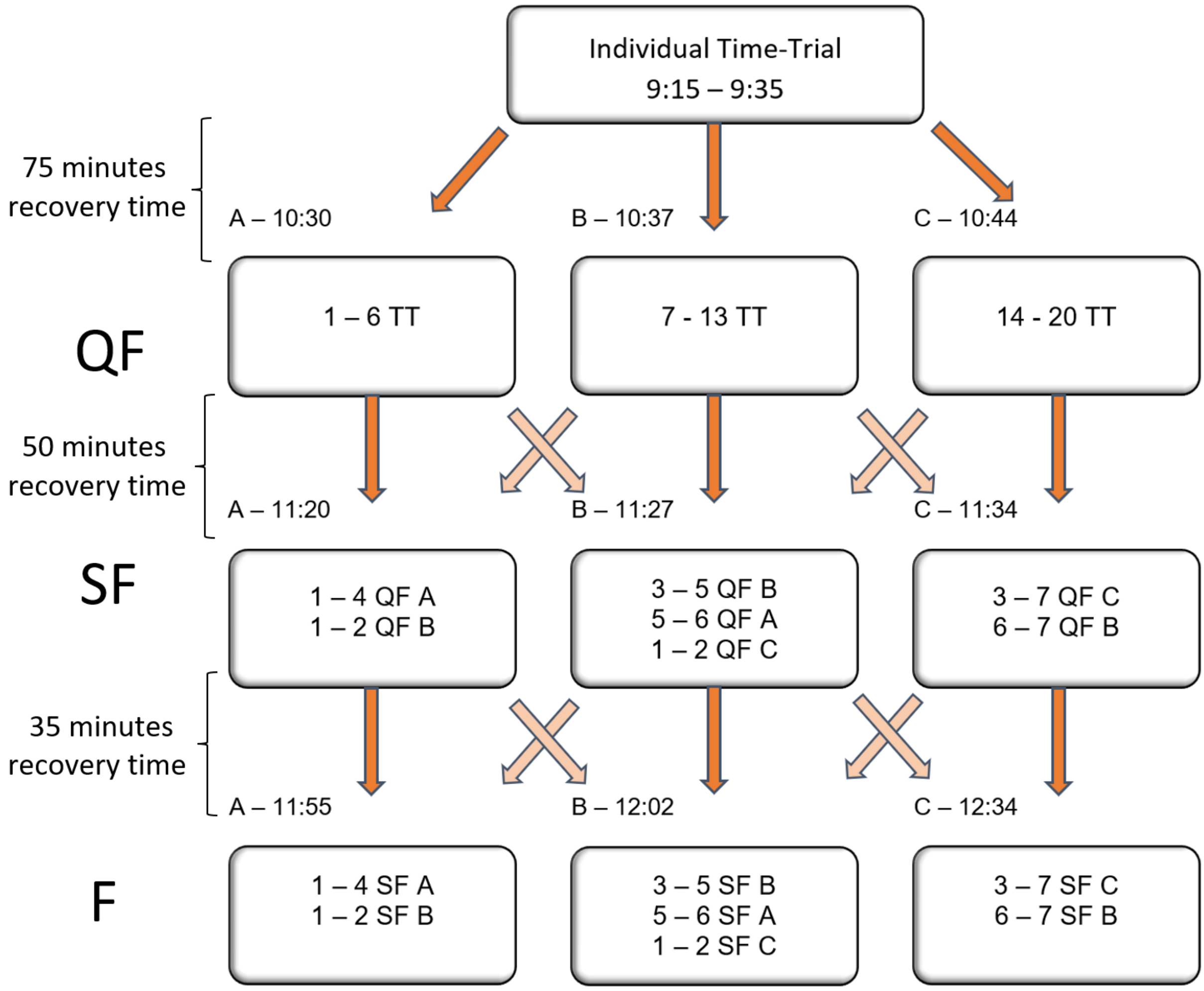


Figure 3: Overview of the competition event by time and format. TT - time-trial, QF - quarterfinal, SF - semifinal, F - final. A, B and C - heats A, B and C. Modified from Berdal (2022).

Maximal velocity

After the finals had concluded, the participants were given approximately 20 minutes recovery time while equipment was set up. Maximal velocity was measured in a similar fashion to Haugnes et al. (2019). Two sets of photocells with 1000-Hz sampling rate (TCi Timing System, Brower Timing Systems, Draper, UT) were placed at the start and finish of a 20 m distance. Two locations, which were part of the sprint track, were used. An uphill segment was placed at the initial climb in segment 3, at 9.7° incline, finishing on its peak, while the flat segment used the last 20 m of the track, at 2.5° incline (see Figure 2). The participants were given a run-up distance to build velocity before entering the measuring segments, corresponding to the start of segment 3 and 5. All participants performed two successful attempts in the uphill segment, separated by 3-5 minutes active recovery, before repeating the protocol in the flat segment. The fastest attempt in each section was used to calculate V_{max} in uphill and flat terrain. V_{max} was calculated as the distance divided by time, then converted to $km \cdot h^{-1}$.

Maximal strength and power

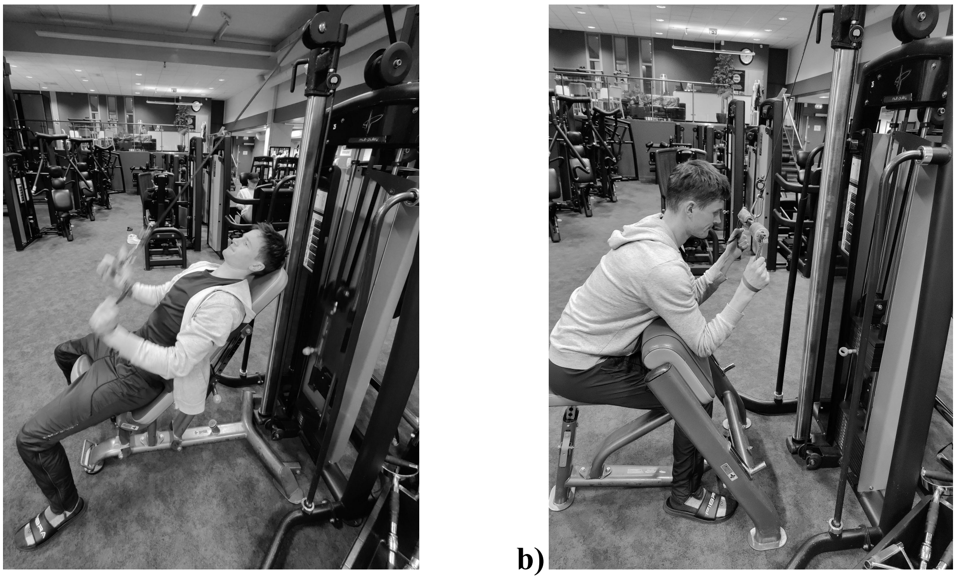
Instruments and measurements

The participants were tested in 4 exercises in the same serial order: Pulldown, Triceps Press, Leg Press and a 30s maximum effort double poling test (Wingate test). The two first exercises were performed in a cable pulley apparatus (Multi Pulley, Pulse Fitness, Cheshire, UK) using a custom fitted handle to simulate a double poling motion. Leg press was performed on a Keiser machine (A300 leg press with A420 computer display, Keiser, Fresno, CA, USA) locked to bilateral movement, while the Wingate test was performed on a ski ergometer (SkiErg, Concept2, Morrisville, VT, USA) with the damper positioned at the highest drag setting. The *ErgData* app was used for detailed data extraction.

Protocols

The protocol for strength and power testing was inspired by Losnegard et al. (2011). Participants performed a general warm-up for 10-min, jogging on a treadmill (intensity zone-1, 55-77% HR_{max}), followed by three submaximal series (6-3-2 reps) with increasing load (40%, 70% and 80% of estimated 1RM) in pulldown. For triceps press, the participants performed one warm-up set with 3 repetitions at 70% estimated 1RM. The 1RM attempts started at ~90% of the expected 1RM with 2-min breaks between attempts. Each successful attempt was followed by an increasing load of 2 - 5 kg until two consecutive failed attempts were reached. The participants reached their 1RM between 2 and 8 attempts.

The pulldown exercise (see Figure 4a) utilized a regular gym bench locked at 45° incline, facing away from the pulley and with its back pushed against the apparatus to prevent movement. The pivot of the pulley was set to the 7th heigh configuration, ensuring the cable was parallel to the bench. The starting position was with the handle pulled to the height of the forehead, in parallel to the bench, while the end position was reached when the arms or handle touched the legs or hip. The triceps press exercise (see Figure 4b) utilized a biceps curl bench, facing toward the pulley**,** providing the participants with upper body support. The bench was positioned so that its front legs were directly below the pivot of the pulley. The starting position was with the upper arms and elbows in contact with the supporting bench, resulting in a ~70° angle in the elbow joint, while the end position was at a full extension of the elbow joint. In both exercises, for the attempts to be considered successful, the arms had to remain parallel and the movement continuous. Additionally for triceps press, there could be no displacement of the upper body, upper arms and elbow.



a) b)

Figure 4: Strength exercises (a) pulldown and (b) triceps press

On the Kaiser apparatus, participants performed a built-in incremental power profile test with 10 lifts. The program started at very low resistance, increasing load with ~25kg after each lift until a preset load (~20kg below expected 1RM) was reached. The resting time ranged between 10-90s, increasing with load. Once the preset load was reached, the test continued through manual increments of 10-20kg with each successful lift, until two consecutive failed attempts were reached. The participants reached their 1RM between -1 and 3 additional lifts (-1 = means that participants failed the final lift of the 10-lift protocol). The maximal successful load was registered, while peak power, and the point of peak power (PP%), was extracted from the Keiser Software. Prior to the Wingate test, the participants performed a 1-min warm-up and accustomization at low intensity, followed by a 1-min break. They were then instructed to complete a 32s all out double poling sprint "as they would" in a final sprint without any further specifications or limitations.

<u>Calculations</u>

For the Wingate test results, the first 2s of the data were excluded to remove low values during the "ramp up" of the initial pulls, while the remaining 30 sec were separated into 6 segments (i) of 5 seconds each, for which the arithmetic mean value was calculated for power output ($\overline{PO}_i$) across the given number of strokes in the segment. Using the mean power output values of the 6 segments, absolute peak power output (PPO) was extracted, see Eq. 1. Relative peak power output (PPO_{rel}) was calculated by Eq. 2, adjusting for the participants' body mass (m). Anaerobic Fatigue Index (AnFI), or power decrease, and Anaerobic Capacity (AnCap) were calculated across the segments, using Eq. 3 and Eq. 4:

$$PPO = max\,\overline{PO}_i\,;\ [w] \qquad \text{(Eq. 1)}$$

$$PPO_{rel} = \frac{PPO}{m}\,;\ [w \cdot kg^{-1}] \qquad \text{(Eq. 2)}$$

$$AnFI = \frac{max\,\overline{PO}_i - min\ \overline{PO}_i}{max\,\overline{PO}_i} \cdot 100\,;\ [\%] \qquad \text{(Eq. 3)}$$

$$AnCap = \Sigma_{i=1}^{6}\overline{PO}_i\,;\ [W] \qquad \text{(Eq. 4)}$$

Loss of data

One participant did not perform the final heat or V_{max} testing. Instead, his time in the QF and SF was used to project a race-time in the final. This race-time was then used to determine a rank within the heat in which he would have raced. A second participant had loss of power data from the leg press exercise.

Statistical Analysis

IBM SPSS Statistics 27 was used as the analytical software (SPSS Inc., Chicago, IL, United States). The normality of variables was reviewed based on skewness and kurtosis through a normal descriptive analysis and by a Shapiro-Wilk test, in which economy was the only variable that deviated from a normal distribution. However, TT-rank and final rank were ordinal variables and Spearman's rank-order correlation, r_S, was therefore used for all calculations of correlation. Statistical significance was accepted at $p< 0.05$, while any greater significance is indicated. A z-test of dependent samples was used to compare the r_S-values of the various determinants to TT-rank and final rank, providing a z-score, in which $z = 1.0$ indicates a difference of +1 standard deviation (SD). Additionally, for significant determinants with $\Delta r_S > 1$ SD, the r_S-values were transformed through Fisher's Z and subtracted to provide an interpretation of effect size by Cohen's q (Cohen, 1988).

Multiple regression analysis was used with TT-time, TT-rank and final rank as dependent variables. Independent determinants were grouped hierarchically by differences in N and a stepwise method was applied with a cutoff of $p< 0.05$. The same methods were also applied with V_{max} flat and -uphill, and average time in S1 and S3, as dependent variables. In these analyses, parametric correlations were used due to its integration of the linear regression analysis.

RESULTS

Table 3 presents mean values ± standard deviation for the determinants as well as their correlations to TT-time and the two rank parameters. V_{max} and $\dot{V}O_{2peak}$ were strongly correlated with the ranking parameters in both sprints. For TT-rank, these were the only significant correlations, while for final rank, absolute values for leg press peak power, 1RM in triceps press and GE also showed strong and moderate correlations. The correlation between the two rank parameters was $r_S = 0.88$ ($p < .001$), which was used to generate the z-score that compares the magnitude of the r_S-values for TT-rank and final rank.

1RM in triceps press and V_{max} flat showed the greatest change in correlation with $\Delta r_S > 1.5$ SD ($p = .06$ and $.07$) between TT-rank and final rank. Absolute $\dot{V}O_{2max}$, leg press PP and GE all showed a noteworthy $\Delta r_S > 1$ SD ($p \geq .10$). Effect size was calculated through Cohen's q and was found to be moderate for V_{max} flat (0.324) and small for 1RM triceps press (0.284), leg press PP (0.291), $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) (0.244) and GE (0.162).

Stepwise multiple regression found V_{max} flat to be the single most important determinant across multiple measurements of performance (TT-time, TT-rank and final rank) as shown in Eq. 5 to Eq. 7. V_{max}, GE and 1RM triceps press were the best predictors for final rank, explaining 97% of variation (Eq. 7). TT-rank was solely predicted by V_{max} at $r^2 = .72$ (Eq. 6), while TT-time was predicted by V_{max} and Wingate PPO_{rel} at $r^2 = .83$ (Eq. 5). A more complete breakdown of the regression models can be found in Appendix 2. Furthermore, examining V_{max} flat as the dependent variable identified absolute leg press PP as the only predictor at $r^2 = .41$ ($p < .05$). Similarly, V_{max} uphill was predicted by leg press PP at $r^2 = 0.55$ ($p < .05$)

$$TTtime = 290.518 - 2.834 \cdot (V_{max} flat) - 4.041 \cdot (WG\ PPO_{rel}) \qquad \text{(Eq. 5)}$$

$r^2 = 0.83$ ($p = 0.002$), SEE = 2.127

$$TTrank = 92.938 - 2.779 \cdot (V_{max} flat) \qquad \text{(Eq. 6)}$$

$r^2 = 0.72$ ($p = 0.002$), SEE = 2.393

$$Final\ rank = 141.926 - 2.406 \cdot (V_{max} flat) - 3.303 \cdot (GE) - 0.188 \cdot (Triceps\ Press) \qquad \text{(Eq. 7)}$$

$r^2 = 0.97$ ($p = 0.001$), SEE = 1.141

More detailed analyses of overall and segment specific time were conducted to investigate how determinants correlated to different parts of the heats. Uphill performance was confirmed to be most strongly associated with overall performance (see Appendix 3). Analysis of average time in segments 1 and 3 showed absolute V_{max} flat to be the only significant predictor for time in S1 ($r^2 = 66$, $p < .05$), while time in S3 was predicted by V_{max} flat, relative $\dot{V}O_{2peak}$ and Wingate PPO at $r^2 = .93$ ($p < .01$). Further details on the development of variables to overall race-time and time in S3 can be found in Appendix 4 and 5, respectively.

Table 3: Mean values and Spearman's correlation (r_S) of determinants to TT-time, TT-rank and final rank, followed by a z-score comparing the r_S of the two rank parameters. (TT-rank & final rank, r_S = .88)

Variable	N =	Mean value ± SD	Correlation to TT-time	Correlation to TT-rank	Correlation to final rank	z-score / p-value
Endurance						
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	17	5.1 ± .7	-.681**	-.699**	-.804**	1.283 / .10
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	17	67.2 ± 5.7	-.459	-.513*	-.565*	.478 / .32
Economy ($ml \cdot m^{-1}$)	17	17.0 ± 1.7	-.122	-.113	-.199	.666 / .25
G. Efficiency (%)	17	14.1 ± .5	-.373	-.412	-.537*	1.098 / .14
Strength and power						
Pulldown (kg)	12	86.4 ± 6.6	-.267	-.300	-.208	-.584 / .29
$Pulldown_{rel}$ ($kg \cdot kg^{-1}$)	12	1.11 ± .06	-.080	-.081	.133	-1.316 / .09
TricepsPress (kg)	12	74.6 ± 8.0	-.339	-.380	-.594*	1.532 / .06
$TricepsPress_{rel}$ ($kg \cdot kg^{-1}$)	12	.96 ± .10	-.261	-.266	-.424	1.039 / .15
Leg Press (kg)	11	299.6 ± 35.9	-.198	-.207	-.400	1.179 / .12
Leg Press PP (w)	11	968.0 ± 145.1	-.523	-.600	-.755*	1.270 / .10
Leg Press PP% (%)	11	.79 ± .13	-.575	-.579	-.560	-.135 / .45
WG PP (w)	12	606.1 ± 57.2	-.382	-.413	-.487	.512 / .30
WG PPO (w)	12	568.9 ± 56.5	-.346	-.378	-.399	.140 / .44
WG PPO_{rel} ($w \cdot kg^{-1}$)	12	7.31 ± .44	-.123	-.164	-.075	-.550 / .29
WG AnCap (w)	12	3089.7 ± 342.5	-.321	-.203	-.203	0 / .50
WG AnFI (%)	12	20.3 ± 6.8	-.155	-.189	-.105	-.521 / .30
Field						
BLa_{peak} ($mmol \cdot L^{-1}$)	17	11.5 ± 1.7	-.016	-.029	-.007	-.135 / .45
V_{max} Uphill ($km \cdot h^{-1}$)	16	19.0 ± 1.3	-.731**	-.760**	-.792**	.392 / .35
V_{max} Flat ($km \cdot h^{-1}$)	16	30.5 ± 1.2	-.765**	-.745**	-.858**	1.510 / .07

*- P< .05, **- P< 0.01, SD - standard deviation, $\dot{V}O_{2peak}$ - rate of peak oxygen consumption, G. Efficiency - Gross Efficiency, PP - Peak Power, PP% - Point of Peak Power, PPO - Peak Power Output, WG - wingate, AnCap - Anaerobic Capacity, AnFI - Anaerobic Fatigue Index, BLa_{peak} - peak blood lactate, V_{max} - maximal velocity

DISCUSSION

Main findings

The purpose of this study was to investigate field- and laboratory-derived determinants of performance in a sprint XCS competition, and to compare the magnitude of the associations between determinants and performance in the time-trial and overall competition. The main findings of this study were:

1. V_{max} flat and $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) were strongly correlated to TT-rank ($r_S = 0.75, 0.70$; $p < 0.01$) and very strongly correlated to final rank ($r_S = 0.86, 0.80$; $p < 0.01$).
2. Leg press PP, 1RM triceps press and GE also showed strong and moderate correlations to final rank ($r_S = 0.76, 0.60$ and 0.54; $p < 0.05$), but not to TT-rank.
3. Comparing the magnitude of associations between TT-rank and final rank, found V_{max} flat and 1RM triceps press to be $\Delta r_S > 1.5$ SD ($p = 0.07$ and 0.06), while the effect size was moderate and small ($q = 0.32$ and 0.28).
4. Leg press PP, $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) and GE were found to be $\Delta r_S > 1$ SD ($p \geq .10$), while the effect size was small ($q = 0.29$ to 0.16)
5. Together, V_{max} flat, GE and 1RM triceps press were found to explain ~97% of variations in the final rank of the competition. Meanwhile, for TT-rank, V_{max} flat alone explained 72% of the variations.

As a preliminary point of discussion, it is important to note that race-time and rank are not interchangeable, and a clear distinction must be established. All previous literature use race-time, or average velocity, as the measure of performance, mostly due to the studies investigating performance in a single race, similar to the TT, but the few studies investigating repeated sprints have also done this. While race-time and rank are ordinally similar in the TT and within each of the knockout heats, they are so through a monotonic function, not a linear one. As Table 3 shows, the correlation values to TT-time and TT-rank are comparable, but not identical. Furthermore, when the current study compares determinants to final rank, it does so across the three parallel final heats (A, B and C) which no longer has any guarantee of final rank being ordinally similar to race-time. This is shown to be the case in Appendix 6, where we can see that ranks 7-10 in Final B had a faster race-time than ranks 4-6 in Final A. This is important, as despite their faster race-time, their previous performance prevented them from qualifying for a better rank than 7. It is therefore important to be mindful of the difference in approach and how these different methods affect the results that are generated.

V_{max} and $\dot{V}O_{2peak}$

The results of this study showed V_{max} flat and $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) to be the most strongly associated determinants to sprint performance, both in the qualifying TT and in the final rank. This is in line with previous literature and the suggestion that aerobic factors are required to compete at a high level of XCS, while anaerobic and neuromuscular factors at some point start to become the distinguishing determinants (Stöggl et al., 2007; Mikkola et al., 2010; Sandbakk et al., 2011a; Losnegard et al., 2012; Tønnesen, 2015; Holmberg, 2015; Andersson et al., 2016). The measured values of V_{max} were similar to Haugnes et al. (2019), from which the V_{max}-testing method was derived, but it is difficult to compare with other studies due to differences in technique, incline and surface. V_{max} reflects the sum of aerobic and anaerobic power, combined with technical or coordinative capabilities, and is an important capacity in skiing overall. However, its association increased between TT-rank and final rank. The role of the V_{max} capacity seems to be more important with the introduction of the tactical aspects of the knockout sprints. Additionally, skiers with a high V_{max}, or maximal skiing power probably also had a larger aerobic and anaerobic capacity (Mikkola et al., 2010) which may have sustained them through the repeated races. This assumption is further supported by the relationship and collinearity seen between V_{max} flat and multiple of the aerobic and anaerobic determinants in Appendix 7a and b. Considering V_{max} as a key determinant for the homestretch sprint of each heat and an essential capacity to secure a promoting spot, it makes sense that its correlation to rank would increase with each heat as the rank up/down system distributed the participants on their ability to stay with the lead through the heat, and be among the first two to cross the finish line. This becomes more apparent as we inspect Appendix 4 and see V_{max}'s association to race-time decrease through the competition. Through these results, we can therefore argue that V_{max} is essential for achieving a promoting rank and the continued participation in the competition.

Absolute $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) showed similar development between TT-rank and final rank, while its relative counterpart ($ml \cdot kg^{-1} \cdot min^{-1}$) did not. Absolute $\dot{V}O_2$'s stronger association with sprint performance is likely due to the higher requirements of anaerobic and strength capabilities found in sprint skiing, going as far as creating different anthropometric measures seen between the two specializations (Losnegard et al., 2014). Due to the age of the participants and their level of performance, $\dot{V}O_{2peak}$ was expected to be strongly correlated to performance as the aerobic capacity is often not yet fully developed in junior skiers, probably resulting in a higher heterogeneity in the group (Armstrong et al. 2011, Roaas et al., 2022). While it is difficult to judge whether this was the case or not in this sample, when comparing $\dot{V}O_{2peak}$ to other studies on senior skiers (Andersson et al., 2010; Sandbakk et al., 2011a; Sandbakk et al., 2011b; Losnegard et al., 2014) the values in this study are consistently lower and present with larger standard deviations, making the argument for age and heterogeneity relevant. While this effect would overestimate the correlation of $\dot{V}O_{2peak}$, it also shows how important aerobic capacity is to skiing performance. Despite lower associations to rank compared with V_{max}, it is no surprise to find that aerobic power is very strongly associated with final rank, both in the sense of the generation of sustainable high power through the heats, as well as the contribution of aerobic capacity to the recovery of anaerobic energy production such as the BLa removal rate (Sandbakk et al., 2011b).

Strength and power capabilities

Strength and power also seem to be more influential to performance in repeated sprints. 1RM in triceps press and leg press PP was not significantly correlated to rank in the TT but was in the final. Furthermore, the Δr_S for both were larger than + 1.25 SD, again indicating a notable change in the required determinants of performance. For the upper body, 1RM in triceps press became moderately associated, while pulldown, which more closely resembles the poling motion in ski skating, had low correlations to the two rank parameters as well as a negative development from TT-rank to final rank. Danielsen et al. (2018) found that, in the double poling technique, the shoulder generates the bulk of the power in the upper body, increasing with intensity, while the power generated in the elbow is reduced with intensity. While not directly comparable to the findings in this study, it raises questions as to why there was such a low correlation for the pulldown exercise.

Despite a similar motion, there was a major difference between the pulldown exercise and poling in skating. In pulldown, the angular direction of the forces applied by the pulley, which were parallel to the upper body, remained the same throughout the entire range of motion. However, in skiing, the direction of the force rotates around the mediolateral axis, alongside the orientation of the poles, starting in parallel with the upper body, but ending in a near horizontally oriented angle at the end stage of the poling phase. This results in a different utilization and activation-pattern of the muscles included. Furthermore, for the upper body, there might be differences as to how the joint specific forces are applied to generate propulsion in different techniques as well as possible differences between the use of an ergometer vs treadmill skiing vs skiing on snow, as reported by Zoppirolli et al. (2020). On a tangent, greater strength and cross-sectional area results in greater work economy and anaerobic endurance (Hoff et al., 1999), which is likely contributing to lower peripheral fatigue in later heats. It is possible that this effect is more prominent in the triceps press exercise, as it isolates a single muscle as opposed to the slightly more complex movement and muscle contribution found in pulldown. However, this remains speculative.

Stöggl et al. (2011) found that 1RM in the upper body as well as rate of force development and jump height in the squat jump, were related to V_{max} in G3 skating. In the current study, both V_{max} flat and uphill was predicted by leg press PP. While there are indicative findings of the relationship between these determinants, there might be less transferability between specific strength exercises and sport-specific performance (Stöggl et al., 2011; Losnegard et al., 2011). Furthermore, it is also suggested that general strength and power per se, may not be the major determinants for V_{max} and skiing performance, but rather the coordination and timing of these capacities (Stöggl et al., 2011). Another example of this may be how performance in uphill segments is primarily explained by greater utilization of the G3 over G2 technique (Anderson et al., 2010). In G3, the generation of propulsion is restricted to the poling phase, which is distinctive, while in G2 the bilateral poling motion is desynced resulting in a more even distribution of the generation of propulsion. The G3 technique therefore requires a greater rate of force development to maintain during the increasing work against gravity in uphill terrain.

Δr_S, significance and effect size

None of the z-scores reported in this study were below the typically accepted threshold of significance at p = 0.05, which relates to the chance that the observed difference/effect is the result of coincidence. However, for 1RM in triceps press and V_{max} flat, the specific p-values were 0.06 and 0.07. Considering the fact that the sample sizes for these two exercises were rather small, at 12 and 16, by the context in which the p-value is meant to be used (Mascha et al., 2018), one can speculate if these results would have been significant (i.e., below $p < 0.05$) under slightly different circumstances. Discarding these results may be a type II error, where we reject the null hypothesis when it is in fact true. Furthermore, examining the *z*- and *q*-value for V_{max} and 1RM triceps press tells us that the observed r_S for final rank was 1.5 standard deviations greater than in TT-rank, and that the effect size of this difference was moderate and weak, regardless of significance. The interpretation of these results is that the association of both V_{max} and 1RM in triceps press to performance was moderately stronger in the final race vs the time-trial by a magnitude of +1.5 SD. Furthermore, the possibility of this observed effect being the pure result of coincidence is 7 and 6 %, respectively, which ought to be considered acceptable in the current context. However, for the other variables, leg press PP, $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) and GE, it is less clear how to interpret the conjunction of the *z*, *q* and p-values. In the practical context, coaches and skiers are always looking to get an edge vs their competitors, and in this sense the change in magnitude and effect size ought to be considered as relevant. On the other hand, it would also be necessary to view this in the context of time required to develop these capacities and diminishing return vs the expected yield.

Predicting final rank

A combination of V_{max} flat, Gross Efficiency and 1RM in triceps press explained 97% of the variations in the final rank of the competition. These variables had a unique association with final rank that was sufficiently strong and significant to add to the model. As an example, despite being the second strongest correlation to final rank, $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) was not found to be uniquely significant, likely due to its collinearity with the more strongly associated predictor V_{max} flat (see Appendix 7a and b). What this means, is that GE and 1RM in triceps press had enough remaining association with the final rank, after being controlled against V_{max}, and that their independent relationship to final rank was greater than other relevant determinants of performance. Of course, this model is the result of specific occurrences and likely some coincidences in this data set and would likely be impossible to reproduce. However, it is interesting to find that determinants such as GE and 1RM in triceps press were sufficiently independent from V_{max} while remaining significantly correlated to final rank. While $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$) and leg press peak power had stronger associations with final rank, compared with GE and 1RM in triceps press, due to their lacking independence from V_{max} the associations of the latter two can be seen as more influential in the context of a sprint competition. Some studies have suggested that high aerobic capacity is associated with performance across multiple heats of sprint skiing, whereas high anaerobic capacity is associated with better performance in the first heats only. (Vesterinen et al., 2009; Andersson et al., 2010; Mikkola et al., 2010). Others have found stable associations for both V_{max} and $\dot{V}O_{2max}$ (Stöggl et al., 2007) across three heats. The regression models generated in the present study tells us that high aerobic, anaerobic power and efficiency is associated with overall performance in a sprint XCS competition. While anaerobic determinants may be less associated with race-time in the later heats, its association with final rank means its influence may be more important toward the final heats than previously thought.

Methodological strengths and limitations

It is a clear strength that the simulated competition was performed both on snow and under general conditions that very closely resembles a real competition. Additionally, the timing of the simulated competition was at the very beginning of the competitive season, which in part had been canceled due to Covid-19, meaning the participants were at, or close to, their peak performance. These factors generated a setting with highly motivated participants at an ideal time of testing.

The participants in this study were junior skiers and so their performance as well as physiological and technical capabilities are generally lower, and possibly more heterogeneous when compared with senior skiers (Armstrong et al., 2011; Roaas et al., 2022). This may affect comparison with previous literature studying repeated races, which mostly has been done on senior skiers. Furthermore, it may limit or affect the generalizability of this study's results to sprint XCS overall. However, one could rather look at it the other way. Since the results for the time-trial are generally in agreement with the existing literature in both junior and senior skiers, we can assume that the results for the final rank, and the differences found between the two, are generalizable to senior athletes as well.

The endurance tests of 6 of the participants occurred in a different study's data collection. Minor and unaccountable differences between how the given data were collected are therefore expected, which may have an impact on these variables. However, given that the raw data was extracted and processed in an identical manner, the chances of any potential differences being significantly impactful are reduced.

The simulated competition was part of a collaboration of two master projects, and due to conflicting interests, there had to be compromises on both sides. The main compromise for this study was that V_{max} testing had to occur after the competition event, as opposed to before. This means that V_{max} was tested in an unstandardized fatigued state. An unfortunate consequence of this is the possibility that the V_{max} variable to a greater degree reflects the participants' anaerobic endurance or ability to repeat sprints, as opposed to more truly reflecting the participants maximal aerobic and anaerobic power. Additionally, this may have created further bias for the V_{max} variables, as the participants' final rank were in great part selected on that capability to begin with, possibly creating a falsely strong correlation between this study's V_{max} variable and final rank. While it is almost certain that this had some effect on the measured velocities in the V_{max}-tests, the average values and variation were almost identical to those found in Haugnes et al. (2019), which were tested in a similar population and occurred after individual warm-up only. While this only in part addresses the distribution of the determinant, the similar measurements found argues that the effect of the unstandardized fatigued state was small.

Conclusion

Maximal velocity, $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$), leg press peak power, 1RM in triceps press and gross efficiency had very strong to moderate associations with the final rank in the competition. For TT-rank, only V_{max} and $\dot{V}O_{2peak}$ were associated. The change in the magnitude of the associations, from TT-rank to final rank, was moderate for V_{max} and 1RM in triceps press and small for the other determinants. The influence of known determinants of performance appears to be different in a single time-trial vs a competition event. The association of anaerobic determinants is higher in the final rank and may be more important across multiple heats than previously considered. Finally, aerobic and anaerobic power seem to be essential in achieving a high final rank in a sprint XCS competition.

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APPENDIX

Appendix 1: Descriptive data of the simulated sprint competition presented as mean values ± standard deviation.

Variables	TT	QF	SF	F
Race-time (s)	176.6 ± 6.9 ^{SF}	175.9 ± 8.6 ^{SF}	173.1 ± 7.8 $^{TT\ QF}$	175.8 ± 7.5
HR pre (beats·min^{-1})	138.1 ± 10.3 $^{QF\ SF\ F}$	132.2 ± 9.3 ^{TT}	131.1 ± 10.3 ^{TT}	132.7 ± 11.1 ^{TT}
BLa pre (mmol·L^{-1})	2.99 ± 1.32	2.64 ± 1.58 ^{F}	2.18 ± 0.51 ^{F}	4.51 ± 2.13 $^{QF\ SF}$
BLa post (mmol·L^{-1})	9.71 ± 1.61	9.07 ± 1.97 ^{F}	8.77 ± 1.79 ^{F}	10.91 ± 1.42 $^{QF\ SF}$
RED	7.9 ± 1.1 ^{F}	7.5 ± 1.2 ^{F}	7.3 ± 1.4	6.7 ± 1.3 $^{TT\ QF}$
RPE	17.8 ± 0.9 $^{QF\ SF}$	15.5 ± 1.7 ^{TT}	16.6 ± 1.2 ^{TT}	16.8 ± 1.9

^{TT}, ^{QF}, ^{SF}, ^{F} - significant difference to TT, QF, SF and F ($p < 0.05$)
TT - time trial, QF - quarterfinal, SF - semifinal, F - final, RED - readiness scale (1-10), RPE - rate of perceived exertion scale (6-20)

Readiness scale (Nurmvetki et al., 2001), RPE/borg scale (Borg, 1982)

Appendix 2: Breakdown of models created by multiple regression for race-time and rank as dependent variable in the time-trial and final race.

TT-time					
model r-value	Determinants	B	Std.Error	t-value	Sig.
.909	Constant	290.518	20.370	14.262	.000
p = .002	V_{max} Flat ($km \cdot h^{-1}$)	-2.834	.545	-5.204	.001
	Wingate PPO_{rel} ($w \cdot kg^{-1}$)	-4.041	1.592	-2.538	.039
TT-rank					
model r-value	Determinants	B	Std.Error	t-value	Sig.
.848	Constant	92.938	18.701	4.970	.001
p = .002	V_{max} Flat ($km \cdot h^{-1}$)	-2.779	.613	-4.535	.002
final rank					
model r-value	Determinants	B	Std.Error	t-value	Sig.
.983	Constant	141.926	13.910	10.203	.000
p = .001	V_{max} Flat ($km \cdot h^{-1}$)	-2.406	.373	-6.453	.001
	G. Efficiency (%)	-3.303	.837	-3.948	.008
	Triceps Press (kg)	-.188	.062	-3.046	.023

TT - Time-trial, - V_{max} - maximal velocity, PPO - peak power output, G. Efficiency - Gross Efficiency.

Appendix 3: Spearman's correlation r_S between time spent in specific segments and the total time in each respective race.

Segment	TT	QF	SF	F
S1	.801**	.728**	.834**	.648*
S2	.844**	.570*	.536*	-.413
S3	.900**	.842**	.921**	.653*
S4	.678**	.639**	.424	.499
S5	.413	.625**	.567*	.437

*- P< .05, **- P< 0.01, S1-5 - Segment 1 to 5, TT - time trial, QF - quarterfinal, SF - semifinal, F - final

Appendix 4: Development of Spearman's correlation (r_S) between determinants and total race-time throughout the competition. Trend indicator, simple indicator of trend across competition.

Determinants	TT	QF	SF	F	Trend indicator
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	-.681**	-.676**	-.685**	-.754**	→
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	-.459	-.691**	-.687**	-.588*	→
Economy ($ml \cdot m^{-1}$)	-.122	-.059	-.040	-.294	→
G. Efficiency (%)	-.373	-.435	-.511*	-.503	↗
Pulldown (kg)	-.267	-.039	-.135	-.269	→
$Pulldown_{rel}$ ($kg \cdot kg^{-1}$)	-.080	-.104	-.002	-.032	→
Triceps Press (kg)	-.339	-.622*	-.683*	-.607	↗
Tri.Press ($kg \cdot kg^{-1}$)	-.261	-.474	-.597*	-.467	↗
Legpress (kg)	-.198	-.372	-.365	-.676*	↗
Legpress PP($kg \cdot kg^{-1}$)	-.523	-.550	-.569	-.529	→
Legpress PP% (%)	-.575	-.593	-.349	-.566	→
WG PP (w)	-.382	-.249	-.394	-.537	→
WG PPO (w)	-.346	-.198	-.303	-.511	→
WG PPO_{rel} ($w \cdot kg^{-1}$)	-.123	-.025	-.173	-.248	→
WG AnCap (w)	-.155	-.060	-.102	-.369	→
WG AnFI (%)	-.321	-.198	-.240	-.071	↘
BLa_{peak} ($mmol \cdot L^{-1}$)	-.016	.179	.198	.219	↗
V_{max} uphill ($km \cdot h^{-1}$)	-.731**	-.510*	-.597*	-.480	↘
V_{max} flat ($km \cdot h^{-1}$)	-.765**	-.661**	-.690**	-.594*	↘

*- P< .05, **- P< 0.01, TT - time trial, QF - quarterfinal, SF - semifinal, F - final, $\dot{V}O_{2peak}$ - rate of peak oxygen consumption, G. Efficiency - Gross Efficiency, PP - Peak Power, PP% - Point of Peak Power, PPO - Peak Power Output, WG - wingate,AnCap - Anaerobic Capacity, AnFI - Anaerobic Fatigue Index, BLa_{peak} - peak blood lactate, V_{max} - maximal velocity

Finals ranks 6 and 17 "gave up" in the final race, as seen in Appendix 5. Their time-points were therefore removed in the analysis against race-time in the final.

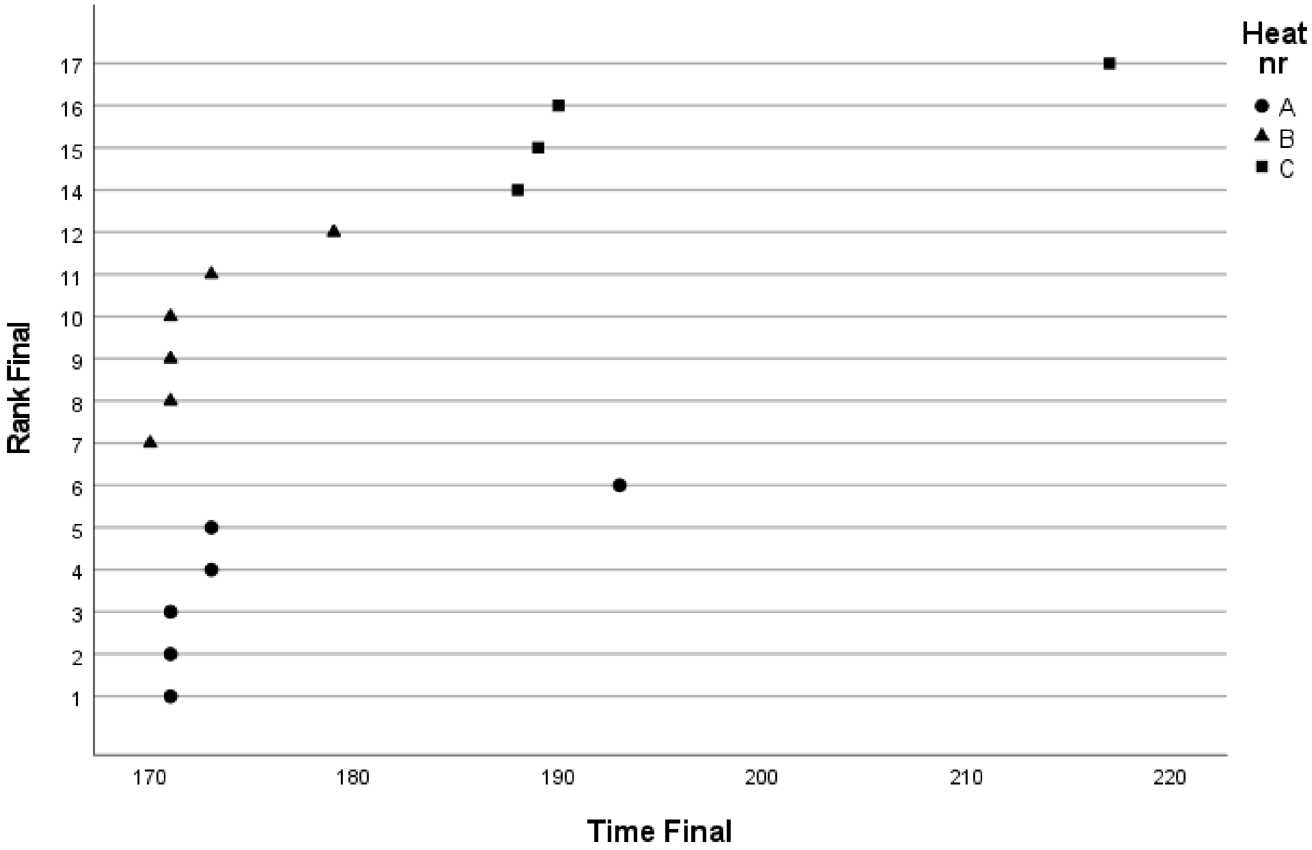
Appendix 5: Development of Spearman's correlation (r_S) between determinants and time spent in S3 throughout the competition.

Determinants	TT	QF	SF	F	Trend indicator
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	-.684**	-.781**	-.728**	-.789**	↗
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	-.511*	-.532*	-.674**	-.579*	→
Economy ($ml \cdot m^{-1}$)	-.136	-.260	-.080	-.266	→
G. Efficiency (%)	-.362	-.341	-.551*	-.582*	↗
Pulldown (kg)	-.060	-.409	-.136	-.505	⤳
$Pulldown_{rel}$ ($kg \cdot kg^{-1}$)	-.144	-.305	-.037	-.006	→
Triceps Press (kg)	-.394	-.566	-.710**	-.758*	↗
Tri.Press ($kg \cdot kg^{-1}$)	-.245	-.172	-.649*	-.596	↗
Legpress (kg)	-.228	-.312	-.431	-.518	↗
Legpress PP($kg \cdot kg^{-1}$)	-.673*	-.473	-.688*	-.717*	→
Legpress PP% (%)	-.647*	-.378	-.491	-.450	↘
WG PP (w)	-.280	-.613*	-.377	-.745*	⤳
WG PPO (w)	-.231	-.524	-.322	-.806*	⤳
WG PPO_{rel} ($w \cdot kg^{-1}$)	-.004	.079	-.204	-.401	↗
WG AnCap (w)	-.077	-.413	-.116	-.552	⤳
WG AnFI (%)	-.126	-.203	-.130	-.067	→
BLa_{peak} ($mmol \cdot L^{-1}$)	-.145	.115	.236	.077	↘
V_{max} uphill ($km \cdot h^{-1}$)	-.769**	-.451	-.757**	-.740**	→
V_{max} flat ($km \cdot h^{-1}$)	-.763**	-.625**	-.787**	-.836**	↗

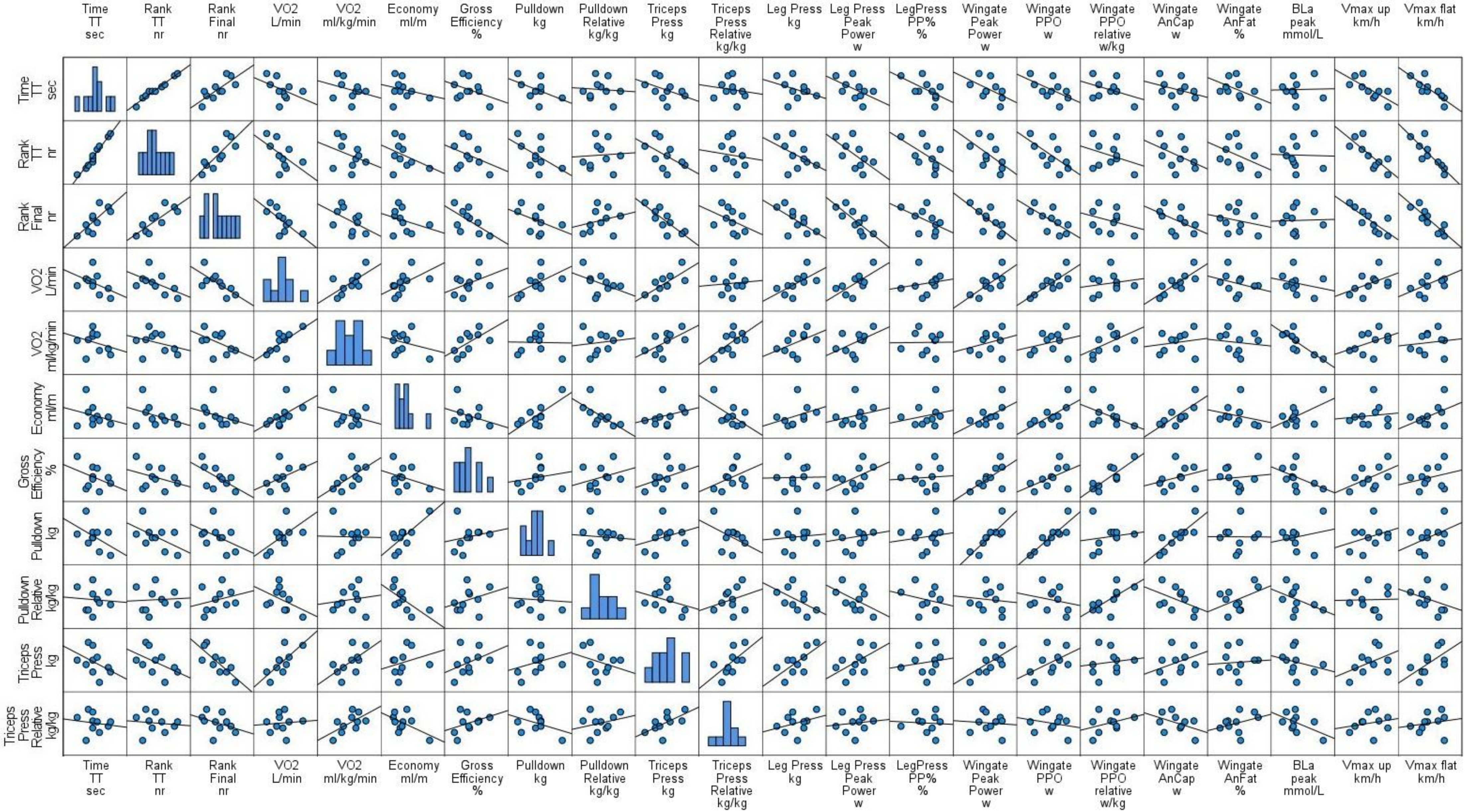
*- P< .05, **- P< 0.01, TT - time trial, QF - quarterfinal, SF - semifinal, F - final, $\dot{V}O_{2peak}$ - rate of peak oxygen consumption, G. Efficiency - Gross Efficiency, PP - Peak Power, PP% - Point of Peak Power, PPO - Peak Power Output, WG - wingate,AnCap - Anaerobic Capacity, AnFI - Anaerobic Fatigue Index, BLa_{peak} - peak blood lactate, V_{max} - maximal velocity

Finals ranks 6 and 17 "gave up" in the final race, as seen in Appendix 5. Their time-points were therefore removed in the analysis against time-S3 in the final.

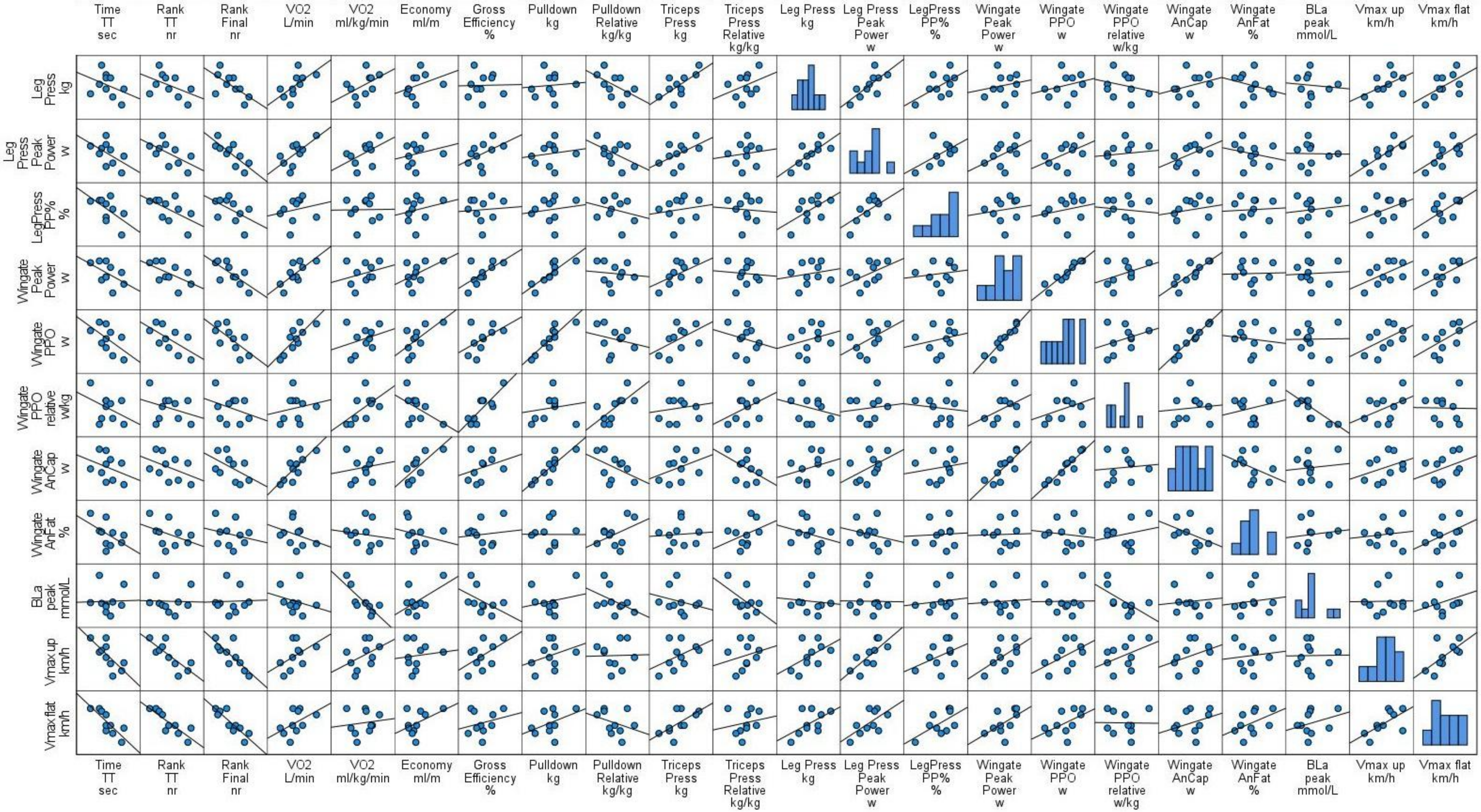
Appendix 6: Scatterplot of time and rank in the final, separated by heat. The correlation between the two were $r_S = .71$ ($p < 0.01$)



Appendix 7a: Scatterplot matrix of measures and determinants of performance



Appendix 7b: Continuation of scatterplot matrix of measures and determinants of performance



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