Performance-determining variables in long-distance events: should they be determined from a rested state or after prolonged submaximal exercise?

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Abstract

Performance-determining variables are usually measured from a rested state and not after prolonged exercise, specific to when athletes compete for the win in long-distance events. **Purpose** 1) To compare cross-country (XC) skiing double poling (DP) performance and associated physiological and biomechanical performance-determining variables between a rested state and after prolonged exercise, and 2) to investigate whether the relationship between the main performance-determining variables and DP performance is different after prolonged submaximal DP compared to when tested from a rested state. **Methods** Male XC skiers (n=26) performed a blood lactate profile test and an incremental test to exhaustion (TTE) from a rested state on day 1 (D1; all using DP) and after 90-min submaximal DP on day 2 (D2). **Results** DP performance decreased following prolonged submaximal DP (D1: V_{peak} 15.33-20.75 $km \cdot h^{-1}$, *Mdn*=18.1 $km \cdot h^{-1}$; D2: V_{peak} 13.68-19.77 $km \cdot h^{-1}$, *Mdn*=17.8 $km \cdot h^{-1}$, *z*=-3.96, *p*<0.001, effect size *r*=-0.77), which coincided with a reduced submaximal gross efficiency (GE) and submaximal and peak cycle length, with no significant change in $\dot{V}O_{2peak}$ (*p*=0.26, *r*=0.23). The correlation coefficient between D1 cycle length at 12 $km \cdot h^{-1}$ and D2 performance is significantly smaller than the correlation coefficient between D2 cycle length at 12 $km \cdot h^{-1}$ and D2 performance (*p*=0.033), with the same result being found for peak cycle length (*p*<0.001). **Conclusions** The reduced DP performance after prolonged submaximal DP coincided with a reduced submaximal GE, and shorter peak cycle length. Our results indicate that performance-determining variables could be determined after prolonged exercise to gain more valid insight into long-distance DP performance.

Keywords: cross-country skiing, gross efficiency, maximal oxygen uptake, cycle length, fatigue

Introduction

Cross-country (XC) skiing is a demanding endurance sport, involving competitions from 3-min sprints to long-distance competitions performed over 2 to 4 hours in the classical and skating styles. In endurance sports, such as XC skiing, the model introduced by Joyner and Coyle,[1] suggests that performance is explained by the performance oxygen uptake ($\dot{V}O_2$, determined by the maximal oxygen uptake ($\dot{V}O_{2max}$) and $\dot{V}O_2$ at the lactate threshold), performance O_2 deficit, and gross efficiency (GE). These factors are regarded important for elite XC skiing performance, with XC skiers being among the athletes with the highest reported $\dot{V}O_{2max}$ values, able to also utilize a high fraction of $\dot{V}O_{2max}$ in competitive situations.[2,3] The role of $\dot{V}O_{2max}$ or peak oxygen uptake ($\dot{V}O_{2peak}$, as $\dot{V}O_{2max}$ is reached during the diagonal sub-technique and with the uphill skating sub-techniques (G2 and G3), but not when using other sub-techniques[4]) and GE has been highlighted, with several studies reporting a higher $\dot{V}O_{2peak}$ and GE, determined while treadmill roller skiing, in world-class XC skiers compared to national-level counterparts.[2,5] In addition, $\dot{V}O_{2peak}$ and GE, were closely correlated to on-snow sprint skiing performance.[6,7] These studies clearly show that the variables mentioned in the Joyner and Coyle model[1] are of importance to XC skiing performance, with the anaerobic energy contribution becoming less important with increasing distance.[8] However, in contrast to the massive examination of the Olympic XC skiing events, the long-distance competitions in XC skiing, like Worldloppet and Euroloppet, are almost unexplored. To date, only one study has examined the physiological characteristics of athletes competing in these long-distance races, indicating that GE may play a particular important role when using the double poling (DP) sub-technique during prolonged exercise.[9]

The long-distance races are organized as mass-starts and performed on relatively flat terrain, where the DP technique is used almost exclusively during classical style races.[8,9] These popular long-distance events are often performed as prolonged submaximal exercise, with the race result decided by the ability to perform well in the final phase of the race. However, the associated performance-determining variables, such as $\dot{V}O_{2peak}$ and GE, are normally determined from a rested state (after a warm up), which might differ from the corresponding values determined after prolonged exercise, like during the final part of the race, when athletes compete for the win in long-distance events. In addition, the relationship between these variables and performance, when measured after prolonged exercise, may differ from the relationship assessed in a rested state.

In cycling, prolonged submaximal exercise resulted in a decrease in GE,[10] which was significantly related to the coinciding decrease in performance after 60 min of submaximal exercise.[10] No significant change in $\dot{V}O_{2peak}$ was found due to the prolonged submaximal exercise bout.[10] In addition, Clark et al.[11] showed that 2 h of endurance exercise (at the gas exchange threshold (GET) + 25% of the difference between the work rate at GET and end-test power (EP) of a 3 min all-out cycle test) resulted in respectively a 11% and 20% decline in critical power/EP and W'/work done above EP. As critical power/EP and W/work above EP are related to performance,[12] Clark et al.[11] concluded that their findings might have important consequences for the prediction of performance. The only study examining the effect of prolonged XC skiing, showed that 48 km of DP reduced cycle length.[13] Although cycle length is often related to GE and performance,[6] the effect of prolonged DP on performance and performance-determining variables was not studied. Therefore, the main purposes of the current study were 1) to compare DP performance and the associated physiological and biomechanical performance-determining variables between a rested state and after prolonged exercise, and 2) to investigate whether the relationship between the main physiological and biomechanical performance-determining variables and DP performance is different after prolonged submaximal DP compared to when tested from a rested state.

Methods

Participants

Twenty-six (sub-)elite male XC skiers (age 24 ± 5 y; body mass 77.5 ± 7.6 kg; training volume 15.2 ± 11.1 h/week and 585 ± 169 h/year) participated in the current study, which was approved by the Local Ethics Committee at Lillehammer University College. Prior to the start of the study the skiers received written information on the purpose of the study and potential risks associated to it, after which they provided written informed consent. Participants were asked to refrain from strenuous exercise (>80% of their maximal heart rate) the day preceding the tests, and not to consume meals or caffeinated beverages during the last 3 hours before the tests.

Experimental protocol

Participants completed a blood lactate profile test and an incremental test to exhaustion (TTE); the two tests mainly used in cross-country skiing sports practice. These tests are normally performed on the same day, a protocol which was replicated on two test days 24-48 h apart in the current study, while executing the DP sub-technique. On test day 2, tests were preceded by a 90-min submaximal DP exercise bout (Figure 1). At both days, tests were carried out under thermoneutral conditions (room temperature between 17 and 19°C) and around the same time of the day (± 1-2 hours). The experimental protocol has been described before in Øfsteng et al.,[14] although to investigate a different research question.

[Insert Figure 1 about here]

Test day 1

Participants started with a 10-min low-intensity exercise bout at an 3% incline and a speed of 12 $km \cdot h^{-1}$. Afterwards, participants started the blood lactate profile test (see Figure 1), at an inclination of 6% and a speed of 10 $km \cdot h^{-1}$, which was increased by 2 $km \cdot h^{-1}$ every 5 min. The first two treadmill speeds, 10 $km \cdot h^{-1}$ and 12 $km \cdot h^{-1}$, were equivalent to 76.1 ± 8.2% and 82.4 ± 7.5% of maximal heart rate. During the final 3 min of each bout, respiratory data were recorded, to determine the average $\dot{V}O_2$ and respiratory exchange ratio (RER). At the end of each 5-min bout participants were asked to indicate their rating of perceived exertion (RPE) according to the Borg's 6-20 scale[15] and blood samples were taken from the fingertip to analyze blood lactate concentration ($[La^-]$). The test finished when a $[La^-]$ of ≥ 4 $mmol \cdot L^{-1}$ was reached. Cycle length and cycle rate were determined using video recording, average values were calculated from ten consecutive DP cycles during the final minute of each submaximal exercise bout.

After 10-min low-intensity exercise at a 3% incline and a speed of 12 $km \cdot h^{-1}$, participants performed an incremental TTE (see Figure 1), to determine peak oxygen uptake ($\dot{V}O_{2peak}$) and performance, measured as peak speed (V_{peak}; mean speed attained during the last minute of the test). The test started at an 6% inclination and a speed of 10 $km \cdot h^{-1}$, which was increased each min by 1 $km \cdot h^{-1}$ until exhaustion. The test was ended when a marker placed 100 cm behind the front of the treadmill was passed with the front wheels. Immediately after termination, RPE and $[La^-]$ were determined. Respiratory data were continuously collected and $\dot{V}O_{2peak}$ was determined as the mean two highest 30-s consecutive measurements. Cycle length and cycle rate were determined using video recordings, average values were calculated from ten consecutive DP cycles during the last 30 s of each stage of the incremental TTE.

Test day 2

Participants performed the same 10-min low-intensity exercise bout as on day 1 (D1), before starting the 90 min prolonged submaximal DP bout (see Figure 1), which was performed at an incline of 6% and a workload (speed) equal to 65% of $\dot{V}O_{2peak}$. The workload was determined individually by using the data collected during the blood lactate profile test on D1; calculating the individual workload utilizing the relationship between workload and $\dot{V}O_2$. To ensure participants remained in fluid balance and to imitate race conditions skiers drank water *ad libitum*.

Immediately after the 90-min submaximal exercise bout participants performed the blood lactate profile test, as on D1, preceded by a 10-min low-intensity exercise bout. Finally, the incremental TTE test as on D1 was performed (see Figure 1).

[Insert Figure 1 about here]

Instruments

Participants performed DP on a roller-ski treadmill (Rodby RL2500E, Rodby Innovation AB, Vänge, Sweden) with the same pair of roller skis (Swenor-fiberglas, 2150 g each pair, Sport Import AS, Sarpsborg, Norway), using wheel type 2. The wheels were pre-warmed during the 10-min low-intensity exercise bout before testing. Participants used their own ski poles conforming to their body height, with individualized carbide tips. A safety harness was worn for security reasons.

Respiratory data were collected using a computerized metabolic system with a mixing chamber (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany), which has been shown to be accurate.[16] The metabolic system was calibrated prior to each test, according to the manufacturer's instructions. [La$^-$] was determined using a Biosen C-line lactate analyzer (EKF Diagnostic BmbH, Barleben, Germany), which was calibrated according to manufacturer's instructions before the testing period.

High resolution video recordings (1080p resolution, 30 frames per second, GoPro Hero+ , San Mateo, CA, USA) and Kinovea motion analysis software (version 0.8.15, available for download at: http://www.kinovea.org) were used to determine cycle length and cycle rate.

Data analysis

GE was determined during the last 3 min of each exercise bout during the blood lactate profile test from mean $\dot{V}O_2$ and RER data using equation 1, as long as RER ≤ 1.00.

$$GE\ [\%] = \frac{work\ rate\ [W]}{metabolic\ rate\ [W]}\ x\ 100 \qquad \text{Equation 1}$$

Work rate was calculated as the sum of power against gravity (P_g)and power against rolling friction (P_f). P_g is the product of mass (body mass + mass of the equipment), gravitational acceleration , sin(α; the angle of the treadmill incline) and velocity. P_f is calculated as the product of the friction coefficient, mass (body mass + mass of the equipment), gravitational acceleration , cos(α) and treadmill velocity. The friction coefficient of the rolling skis on the treadmill corresponded to the value of 0.018.[17] Aerobic metabolic rate is based on the mean $\dot{V}O_2$ and the oxygen equivalent, which is determined from mean RER and the standard conversion table of Lusk[18] and by taking into account the conversion between calories and joules (international calorie 4.186).

Cycle length was calculated by multiplying cycle time and speed. Cycle time was determined as the time between every second pole plant and averaged over 10 cycles. Cycle rate is the reciprocal of cycle time.

Statistics

Data are presented as means (SDs). The assumption of normality was checked by testing the differences between D1 and D2 using the Shapiro-Wilk test. In case data were normally distributed, multiple paired samples t-tests were conducted and p-values were adapted using a Bonferroni correction (0.05/5 = 0.01). Effect sizes were determined using $r = \sqrt{\frac{t^2}{t^2+df}}$. A Wilcoxon signed-rank test was performed when data were not normally distributed (performance, RER_{peak}, RPE_{peak}, and cycle rate at a speed of 16 $\text{km}\cdot\text{h}^{-1}$). Effect sizes were determined using $r = \frac{Z}{\sqrt{N}}$, in which N is the total number of observations. Pearson product-moment correlation coefficients were determined to assess the relationship between $\dot{V}O_{2\text{peak}}$, GE, [La^-], cycle length, and cycle rate and performance on D1 and D2, as data were normally distributed. Spearman's rank-order correlation coefficients were determined to assess the relationship between the difference in $\dot{V}O_{2\text{peak}}$, GE, and cycle length between D1 and D2 and the difference in performance. Pearson product-moment correlation coefficients were determined to assess the relationship between the difference in performance-determining variables and D2 performance (apart from the relationship between ΔPeak cycle length and D2 performance, for which the Spearman's rank-order correlation coefficient was determined). The corresponding confidence interval was determined by converting *r* into a Fisher Z-score and the resultant standard error, from which the lower and upper boundary of the confidence interval can be calculated and converted back to correlation coefficients.[19] Magnitudes of effect sizes and correlation coefficients were interpreted using the following scale: 0.0-0.1 trivial, 0.1-0.3 small, 0.3-0.5 moderate, 0.5-0.7 large, 0.7-0.9 very large, 0.9-1.0 nearly perfect.[20] Bivariate correlation coefficients were compared using Steiger's Z-test for correlated correlations.[21] Statistical analyses were performed using SPSS (IBM SPSS Statistics 25, Chicago, Illinois, USA).

Results

Differences between D1 and D2

Prolonged submaximal DP exercise resulted in a decline in performance on D2, with V_{peak} ranging from 13.68 to 19.77 $\text{km}\cdot\text{h}^{-1}$ (*Mdn* = 17.8 $\text{km}\cdot\text{h}^{-1}$) compared to D1, when V_{peak} ranged from 15.33 to 20.75 $\text{km}\cdot\text{h}^{-1}$ (*Mdn* = 18.1 $\text{km}\cdot\text{h}^{-1}$, $z = -3.96$, $p < 0.001$, effect size $r = -0.77$). The effect of prolonged submaximal DP exercise on physiological and biomechanical performance-determining variables is summarized in Table 1 and Figure 2. The effect sizes for D2-D1 changes in $\dot{V}O_2$, RER, GE, and [La^-] at 10 and 12 $\text{km}\cdot\text{h}^{-1}$ were considered very large or even nearly perfect. Large effect sizes for D2-D1 changes in RPE and moderate effect sizes for cycle length and cycle rate were found at submaximal speeds. The effect sizes for D2-D1 changes of peak values were much more variable (cycle rate trivial; $\dot{V}O_{2\text{peak}}$ small; RPE_{peak} moderate; cycle length large; RER_{peak}, $[\text{La}^-]_{\text{peak}}$ very large).

[Insert Table 1 about here]
[Insert Figure 2 about here]

Relationship between performance-determining variables and performance

The correlations between physiological and biomechanical performance-determining variables, assessed at different speeds, and performance are summarized in Table 2. D1 $\dot{V}O_{2peak}$, cycle length at 12 km·h^{-1}, peak cycle length, and cycle rate at 12 km·h^{-1} were significantly correlated to D2 performance. After prolonged submaximal exercise (D2), $\dot{V}O_{2peak}$, cycle length at 10 km·h^{-1}, 12 km·h^{-1}, peak cycle length, cycle rate at 10 km·h^{-1} and 12 km·h^{-1} were significantly correlated to D2 performance. Table 3 provides information on the differences between these correlation coefficients.

Determining the correlation coefficients between the difference in the performance-determining variables between D1 and D2 (D2-D1) and the difference in performance, resulted in trivial correlation coefficients for **Δ**cycle length at 10 km·h^{-1} and **Δ**cycle rate at 10 km·h^{-1}, small correlation coefficients for **Δ**cycle rate at 12 km·h^{-1} and **Δ**peak cycle rate, moderate correlation coefficients for $\mathbf{\Delta}\dot{V}O_{2peak}$, **Δ**GE$_{10}$, Δ[La$^-$]$_{max}$, and **Δ**cycle length at 12 km·h^{-1}, and large correlation coefficients for **Δ**GE$_{12}$, and **Δ**peak cycle length (see Table 2). In addition, small correlation coefficients were found between $\mathbf{\Delta}\dot{V}O_{2peak}$ $(r = -0.19, p = 0.18)$, Δ[La$^-$]$_{max}$ (r = 0.21, p = 0.15), **Δ**cycle length at 10 (r = 0.16, p = 0.23) and 12 km·h^{-1} (r = 0.29, p = 0.084), and **Δ**cycle rate at 10 km·h^{-1} (r = -0.17, p = 0.22), moderate correlation coefficients were found between **Δ**GE$_{10}$ (r = 0.48, p = 0.007), **Δ**peak cycle length (r_s = 0.45, p = 0.013), **Δ**cycle rate at 12 km·h^{-1} (r = -0.32, p = 0.064), and **Δ**peak cycle rate (r = -0.31, p = 0.065), and a large correlation coefficient was found between **Δ**GE$_{12}$ and D2 performance (r = 0.63, p < 0.001).

[Insert Table 2 and 3 about here]

Discussion

The current study compared DP performance and corresponding performance-determining physiological and biomechanical variables when tested from a rested state and after 90 min of prolonged submaximal exercise. The main findings are that: I) DP performance (i.e. V$_{peak}$) decreased after prolonged submaximal DP (D1 *Mdn* = 18.1 km·h-1, D2 *Mdn* = 17.8 km·h^{-1}), which coincided with reductions in submaximal GE and cycle length; II) Although $\dot{V}O_{2peak}$, cycle length (at 12 km·h^{-1} and peak cycle length), and cycle rate (at 12 km·h^{-1}) assessed from a rested state (D1) were significantly correlated to performance after prolonged submaximal exercise (D2), cycle length and cycle rate were closer related to D2 performance, when they were also assessed after prolonged submaximal exercise; III) $\Delta\dot{V}O_{2peak}$ (D2-D1), ΔGE$_{12}$, and Δcycle length (at 12 km·h^{-1} and peak cycle length) were significantly correlated to Δperformance.

In the current study, we demonstrated for the first time how prolonged submaximal exercise decreases DP performance, when compared to the same performance test executed from a rested state. There was only a small non-significant difference in $\dot{V}O_{2peak}$ between the two days, indicating that the ability to produce aerobic energy remains similar even after prolonged exercise, when there are indications of reduced glycogen stores (i.e. reduced maximal RER and [La$^-$] values).[22,23]

As was shown in cycling,[10] the decline in performance was accompanied by a decrease in GE. In a previous study on XC-skiing using the skating technique, high-intensity exercise resulted in a reduced GE and cycle length compared to the rested state.[24] However, the effect on a subsequent performance test was not investigated in that study. Zoppirolli et al.[13] found that prolonged exercise (a 48 km DP race) resulted in a decline in cycle length, which is in agreement with the current study. In another DP study, power output during a 3-min test decreased by 14% after 25-min trunkfatiguing exercise, which was accompanied by a 9% reduction in work per cycle, i.e. a variable corresponding to cycle length.[25] In summary, the current study provides novel evidence on the effect of prolonged submaximal exercise on DP performance and performance-determining variables.

As expected from the model of Joyner and Coyle,[1] and previous research on sprint XC-skiing,[6,26,27] $\dot{V}O_{2peak}$ is one of the main physiological performance-determining variables, while cycle length is one of the main biomechanical performance-determining variables. The relationship between $\dot{V}O_{2peak}$ determined from a rested state (D1) and performance after prolonged submaximal exercise (D2) was similar to when both were determined after prolonged submaximal exercise (D2). However, the correlation coefficients between D1 cycle length and cycle rate at 12 $km \cdot h^{-1}$ and peak cycle length and D2 performance were substantially smaller than the correlation coefficients between D2 cycle length and cycle rate and D2 performance. Therefore, our results indicate that the evaluation of performance-determining variables should be determined in a sport-specific situation, i.e. from a rested state when it concerns shorter duration performance and after prolonged exercise when it concerns long-distance events (> 90 min). Additional studies are needed to determine from which duration on the relationship between rested-state performance-determining variables and performance after prolonged-submaximal exercise diminishes. In contrast, testing after prolonged exercise seems less important for $\dot{V}O_{2peak}$.

Because of the small non-significant difference in $\dot{V}O_{2peak}$ between the two days, a smaller correlation coefficient between $\Delta\dot{V}O_{2peak}$ and Δperformance than between D1 or D2 $\dot{V}O_{2peak}$ and performance, was expected. In contrast, the differences in GE and DP performance (D2-D1) were considered very large, which resulted in in a large correlation coefficient between ΔGE and ΔDP performance, with the decline in GE explaining 31% of the variance in the decline in performance due to prolonged submaximal exercise. Although the trivial (D1) and small (D2) correlations between GE and performance (Table 2) are in contrast with the very large correlation coefficient found between GE and XC-skiing sprint time-trial performance in previous research,[6] the large correlation coefficient between ΔGE and ΔDP performance (Table 2), strengthened by the large correlation coefficient between ΔGE_{12} and D2 performance, highlights the importance of GE for long-distance events. This is in agreement with the recent finding of Sagelv et al.,[9] showing that submaximal DP efficiency discriminates between national level XC skiers and long-distance skiers.

Limitations

To reduce the number of testing days for our elite participants, $\dot{V}O_{2peak}$ and performance were assessed in the same test and it is, therefore, unknown whether testing on different days influences the relationship between performance-determining variables and performance. In sports practice, the lactate-profile test and incremental TTE are the most common tests used to assess performance and performance-determining variables, which is why we chose the same tests and completed them on the same day. While this makes our study findings relevant for sports practice, we are aware of this limitation when interpreting our findings. In addition, although the 90 min prolonged DP bout at 65% $\dot{V}O_{2peak}$ seems suitable for long-distance cross-country skiing, it remains difficult to recommend a standard fatigue test for other events. Furthermore, performance during an incremental TTE test in the laboratory might differ from “real-world” performance, even though previous studies indicate that such treadmill tests are highly relevant for skiing performance.[6,9,28,29] Finally, the current study did not include measures of central fatigue (i.e. the decline in the capacity of the central nervous system to stimulate muscles)[30] and peripheral fatigue (i.e. reduced muscle function)[30], which would be interesting to include in future studies, as this might help to understand the cause of the decline in performance and performance-determining variables.

Practical applications

Cycle length and cycle rate at 12 km·h^{-1} and peak cycle length were substantially less related to D2 performance, when they were assessed from a rested state, compared to when they were also assessed after prolonged submaximal exercise. Therefore, sport scientists working with long-distance XC skiers should consider determining performance-determining variables after prolonged exercise, to gain more valid insight into long-distance DP performance, at least when it concerns events > 90 min. ΔGE_{12}, and Δcycle length (at 12 km·h^{-1} and peak cycle length) were most strongly related to Δperformance. Although correlation coefficients do not indicate causality, our data support the view that training aimed at obtaining and maintaining a high GE and cycle length during prolonged exercise is important for performance in long-distance events.

Conclusions

The current study showed that DP performance was reduced after prolonged submaximal DP, which is partly explained by a reduced submaximal GE, and shorter peak cycle length. In contrast, $\dot{V}O_{2peak}$ was not substantially different between when tested from a rested state and after prolonged submaximal DP. Although $\dot{V}O_{2peak}$, cycle length, and cycle rate determined from a rested state were significantly correlated to D2 performance, cycle length and cycle rate were substantially stronger related to D2 performance when they were determined after prolonged submaximal exercise.

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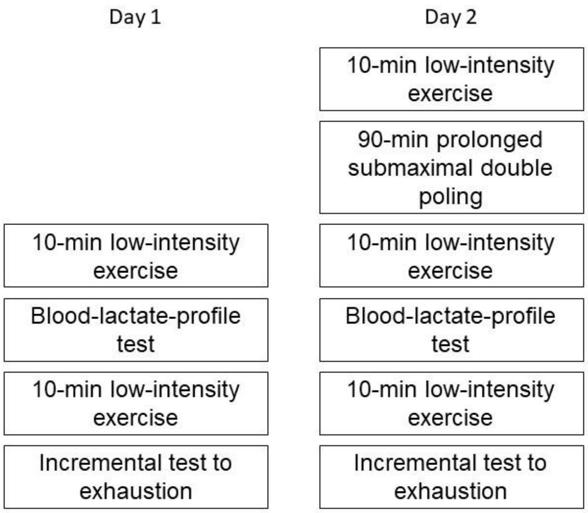


Figure 1. Overview of the study design.

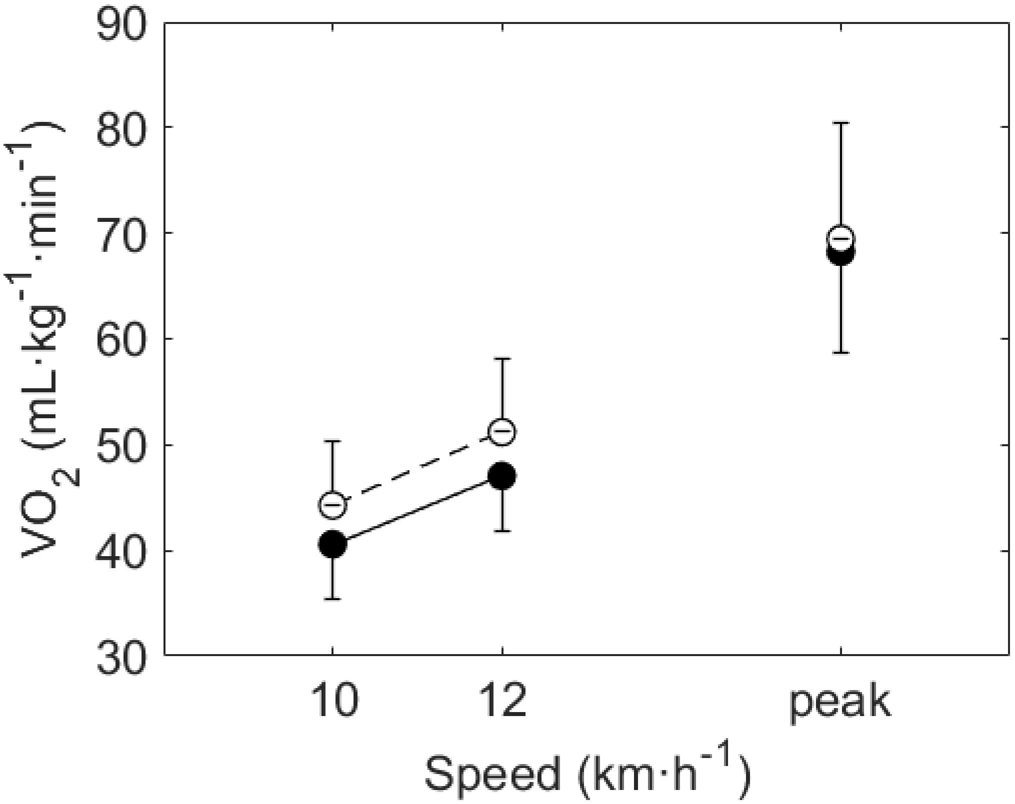
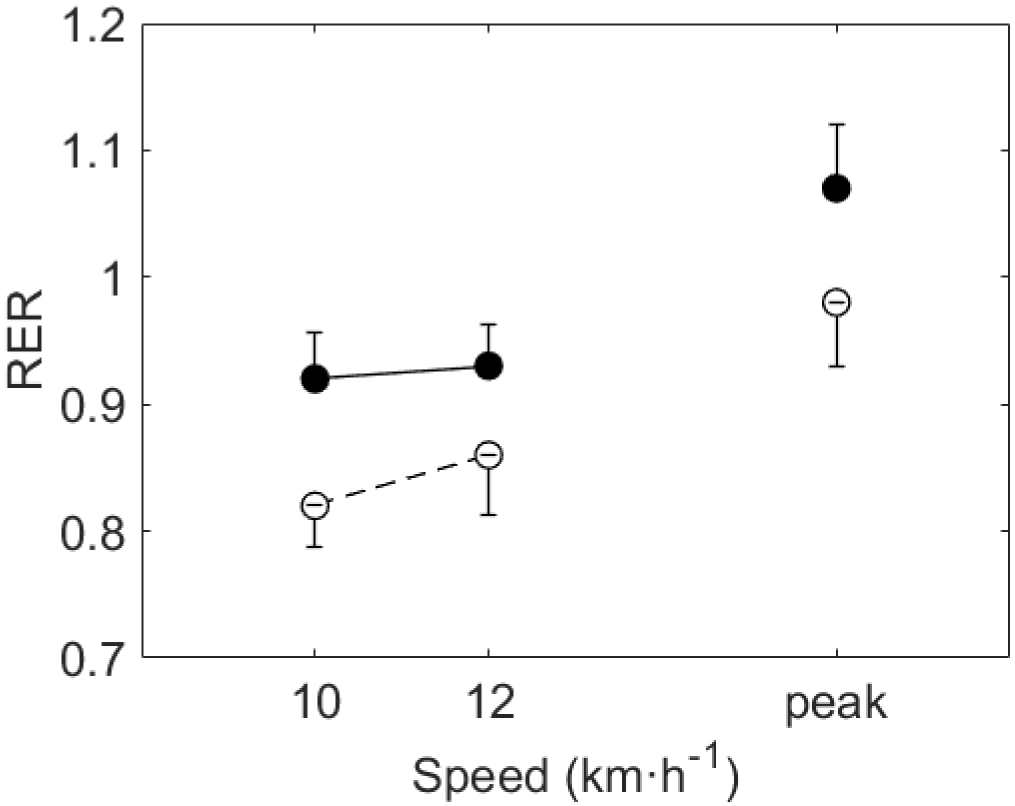


Figure 2. $\dot{V}O_2$ (A), respiratory exchange ratio (RER, B), gross efficiency (GE, C), blood lactate concentration ([La$^-$], D), rating of perceived exertion (RPE, E), cycle length (F), and cycle rate (G) presented as mean ± standard deviation in rested state (solid line; D1) and after prolonged submaximal DP exercise (dotted line; D2).

Physiological and biomechanical data at 10 km·h^{-1} to 16 km·h^{-1} were collected during the blood lactate profile test. Peak values were determined during the incremental time to exhaustion test. Peak cycle length and peak cycle rate were not necessarily attained at the highest velocity reached, as indicated on the x-axis. Peak cycle length was attained at 17.1 km·h^{-1} on D1 and on 16.2 km·h^{-1} on D2, while peak cycle rate was attained at 18.2 km·h^{-1} on D1 and 17.1 km·h^{-1} on D2.



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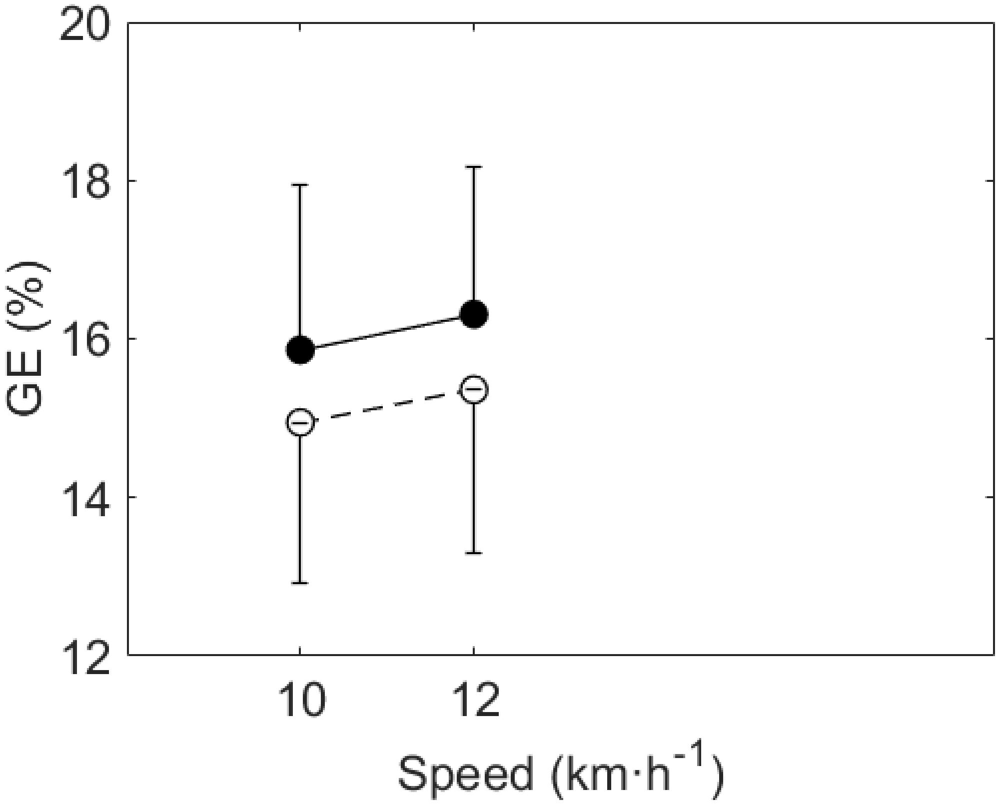

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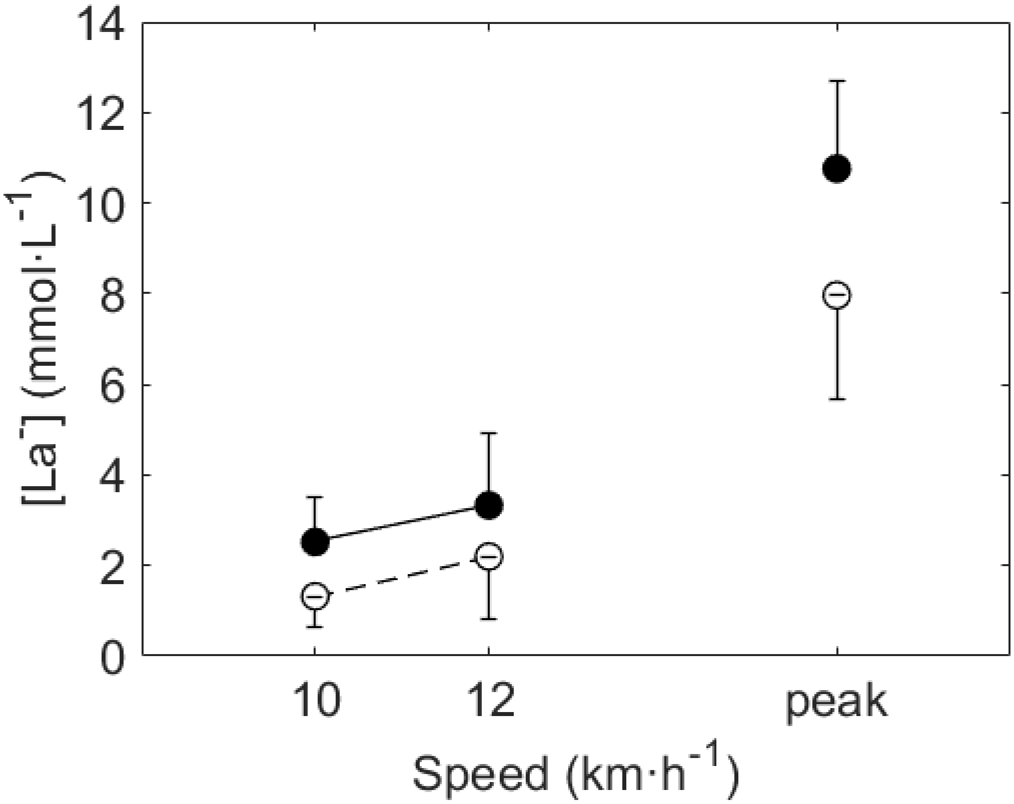

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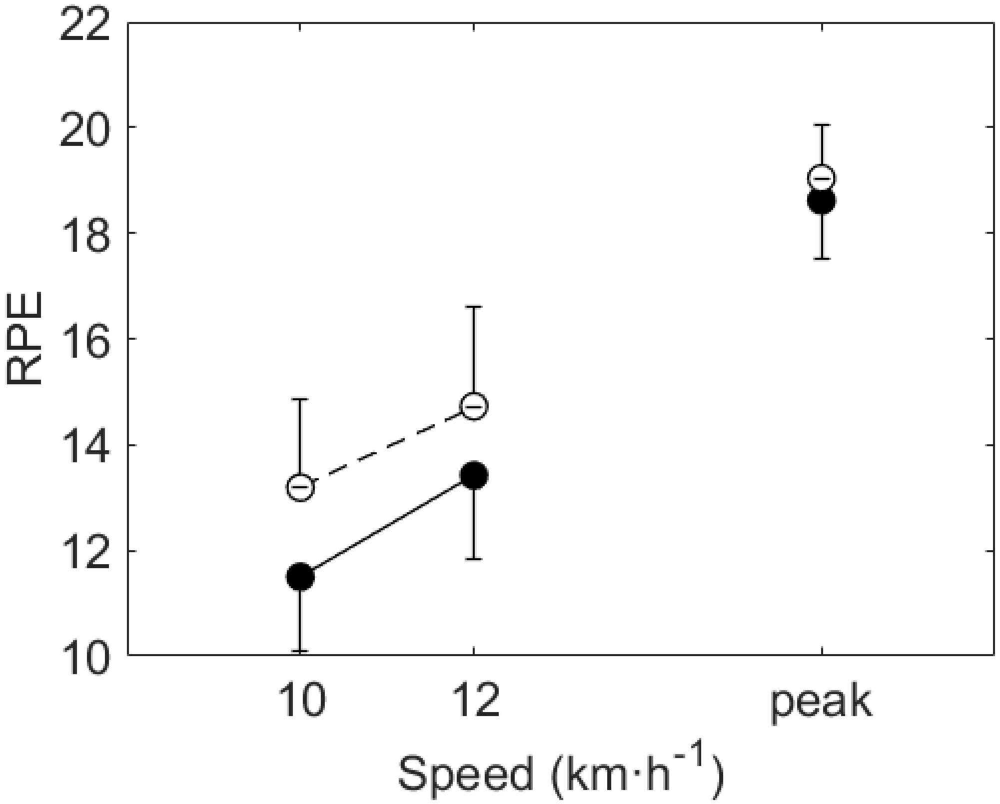

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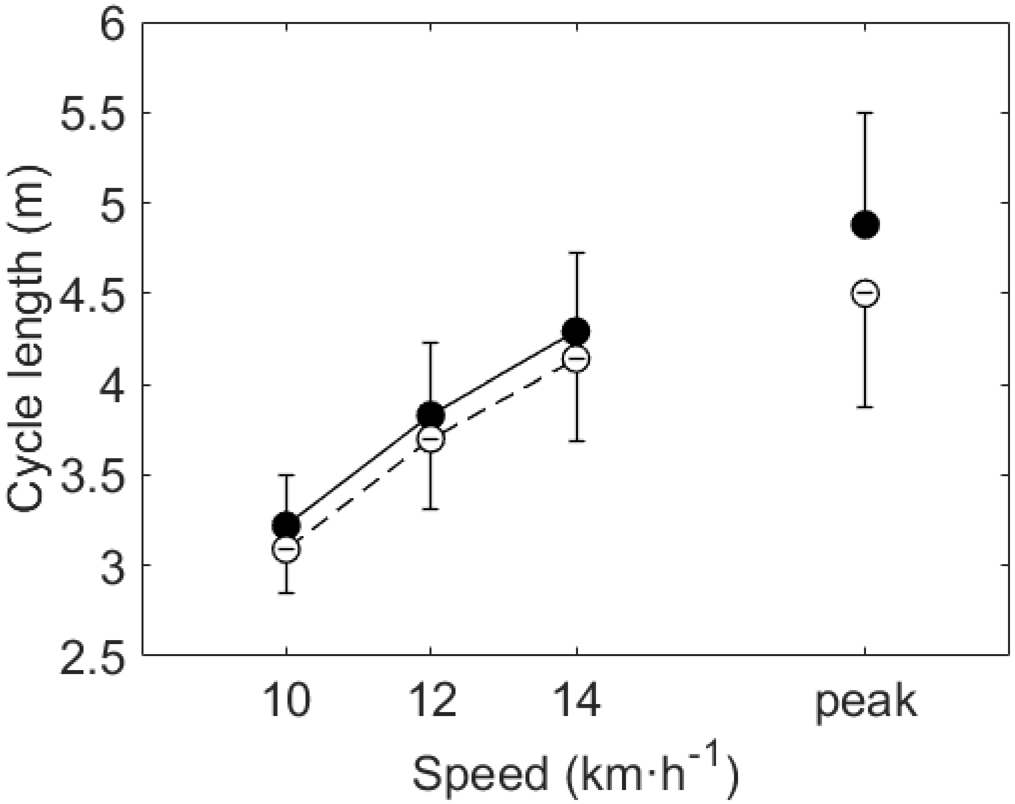

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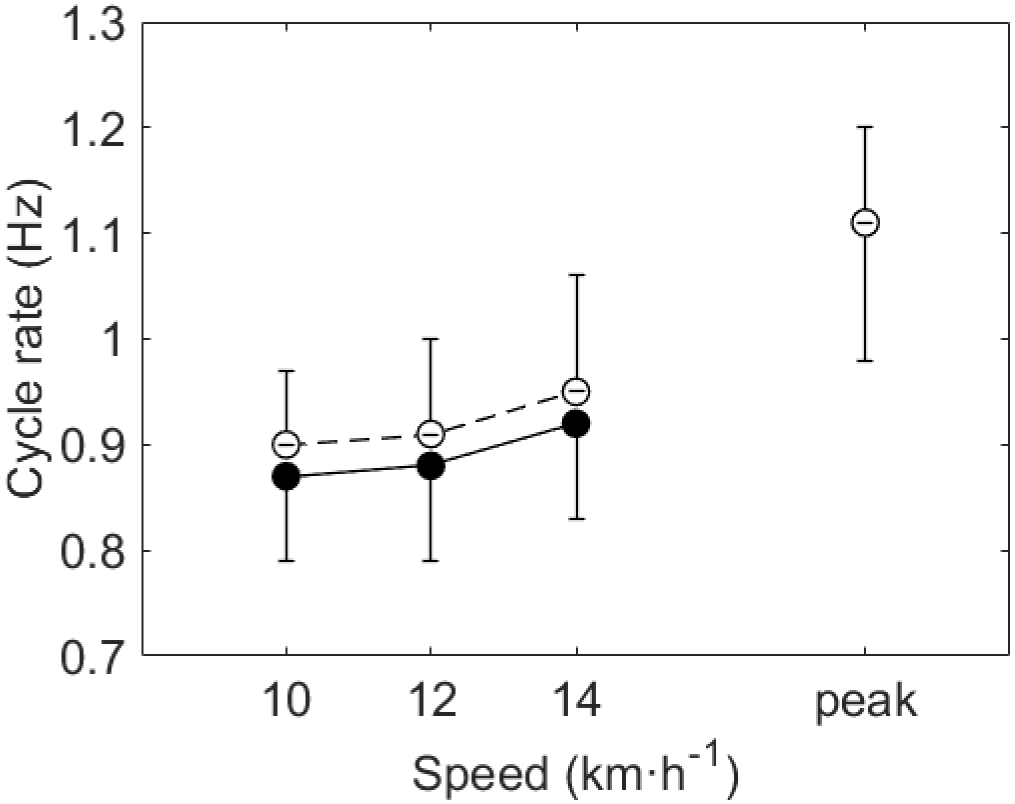

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Table 1. Effect of prolonged submaximal double-poling on physiological and biomechanical performance-determining variables (day 2 – day 1).

	N	Mean ± SD	95% CI	*t*	*p*	Effect size
$\dot{\mathbf{V}}\mathbf{O_2}$@10 km·h^{-1} (mL·kg^{-1}·min^{-1})	26	3.67 ± 2.89	[2.51, 4.84]	6.48	< 0.001	0.79
@12 km·h^{-1}	26	4.14 ± 3.35	[2.79, 5.49]	6.31	< 0.001	0.78
@14 km·h^{-1}	15	3.45 ± 3.31	[1.61, 5.28]	4.03	0.001	0.73
@16 km·h^{-1}	6	2.98 ± 4.04	[-1.26, 7.21]	1.81	0.13	0.63
$\dot{\mathbf{V}}\mathbf{O_{2peak}}$ (mL·kg^{-1}·min^{-1})	26	1.21 ± 5.30	[-0.94, 3.34]	1.16	0.26	0.23
RER@10 km·h^{-1}	26	-0.096 ± 0.040	[-0.11, 0.081]	-13.6	< 0.001	0.94
@12 km·h^{-1}	26	-0.075 ± 0.041	[-0.092, -0.059]	-9.35	< 0.001	0.88
@14 km·h^{-1}	15	-0.075 ± 0.038	[-0.095, -0.054]	-7.70	< 0.001	0.90
@16 km·h^{-1}	6	-0.052 ± 0.029	[-0.082, -0.021]	-4.32	0.008	0.89
RER$_{peak}$	26	*D1 Mdn* = 1.07 *D2 Mdn* = 1.00		*z* = -4.20 (based on positive ranks)	< 0.001	-0.82
GE@10 km·h^{-1} (%)	26	-0.92 ± 0.95	[-1.30, -0.53]	-4.92	< 0.001	0.70
@12 km·h^{-1}	26	-0.95 ± 0.97	[-1.34, -0.56]	-5.01	< 0.001	0.71
@14 km·h^{-1}	15	-0.75 ± 1.08	[-1.35, -0.15]	-2.69	0.018	0.58
@16 km·h^{-1}	6	-0.65 ± 1.29	[-2.01, 0.71]	-1.23	0.27	0.48
[La$^-$]@10 km·h^{-1} (mmol·L^{-1})	26	-1.20 ± 0.63	[-1.46, -0.95]	-9.69	< 0.001	0.89
@12 km·h^{-1}	26	-1.14 ± 0.90	[-1.50, -0.77]	-6.47	< 0.001	0.79
@14 km·h^{-1}	15	-1.31 ± 0.89	[-1.80, -0.81]	-5.66	< 0.001	0.83
@16 km·h^{-1}	6	-1.05 ± 1.09	[-2.19, -0.10]	-2.35	0.066	0.72
[La$^-$]$_{peak}$ (mmol·L^{-1})	26	-2.80 ± 2.40	[-3.77, -1.83]	-5.96	< 0.001	0.77
RPE@10 km·h^{-1}	26	1.69 ± 1.91	[0.92, 2.47]	4.51	< 0.001	0.67
@12 km·h^{-1}	26	1.31 ± 1.46	[0.72, 1.90]	4.56	< 0.001	0.67
@14 km·h^{-1}	15	0.73 ± 1.28	[0.025, 1.44]	2.22	0.044	0.36
@16 km·h^{-1}	6	0.50 ± 1.38	[-0.95, 1.95]	0.89	0.41	0.37
RPE$_{peak}$	26	*D1 Mdn* = 18.0 *D2 Mdn* = 19.0		*z* = -1.82 (based on negative ranks)	0.069	-0.36
CL@10 km·h^{-1} (m)	23	-0.12 ± 0.24	[-0.23, -0.019]	-2.45	0.023	0.46
@12 km·h^{-1}	24	-0.13 ± 0.36	[-0.28, 0.024]	-1.75	0.094	0.34
@14 km·h^{-1}	24	-0.15 ± 0.40	[-0.32, 0.023]	-1.79	0.087	0.35
@16 km·h^{-1}	18	-0.18 ± 0.38	[-0.37, 0.0091]	-2.01	0.061	0.44
CL$_{peak}$ (m)	25	-0.39 ± 0.46	[-0.57, -0.20]	-4.22	< 0.001	0.64
CR@10 km·h^{-1} (Hz)	23	0.033 ± 0.068	[0.0039, 0.062]	2.35	0.028	0.4
@12 km·h^{-1}	24	0.031 ± 0.087	[-0.0055, 0.068]	1.76	0.092	0.34
@14 km·h^{-1}	24	0.034 ± 0.093	[-0.0056, 0.073]	1.78	0.089	0.40
@16 km·h^{-1}	18	*D1 Mdn* = 0.96 *D2 Mdn* = 0.98		*z* = -1.54 (based on	0.12	-0.36

				negative ranks)		
CR$_{peak}$ (Hz)	25	0.00024 ± 0.10	[-0.043, 0.043]	0.012	0.99	0.0024

CI, confidence interval; *Mdn*, median; z, z-score of Wilcoxon signed-rank test; CL$_{peak}$, peak cycle length; CR$_{peak}$, peak cycle rate.

Table 2. Relationship between physiological and biomechanical performance-determining variables and performance (peak speed attained during the incremental time to exhaustion test) itself on day 1, day 2, the relationship between day 1 performance-determining variables and day 2 performance, and the relationship between the difference in performance-determining variables (D1-D2, Δ) and the difference in performance.

	D1 performance-determining variables and D1 performance (rested state)			**D2 performance-determining variables and D2 performance (after prolonged DP)**		
	N	***r* [90% CI]**	***p****	N	***r* [90% CI]**	***p****
$\mathbf{\dot{V}O_{2peak}}$ (mL·kg^{-1}·min^{-1})	26	0.60 [0.28, 0.80]	0.001	26	0.55 [0.21, 0.77]	0.002
GE$_{10}$ (%)	26	0.079 [-0.32, 0.45]	0.35	26	0.19 [-0.21, 0.54]	0.18
GE$_{12}$ (%)	26	0.062 [-0.33, 0.44]	0.38	26	0.23 [-0.17, 0.57]	0.13
[La^{-}]$_{max}$ (mmol·L^{-1})	26	-0.069 [-0.44, 0.33]	0.37	26	0.23 [-0.17, 0.57]	0.13
Cycle length at 10 km·h^{-1} (m)	26	0.35 [-0.043, 0.65]	0.038	23	0.56 [0.19, 0.79]	0.003
Cycle length at 12 km·h^{-1} (m)	25	0.63 [0.31, 0.82]	< 0.001	25	0.55 [0.20, 0.78]	0.002
Peak cycle length (m)	25	0.83 [0.65, 0.92]	< 0.001	25	0.86 [0.70, 0.94]	< 0.001
Cycle rate at 10 km·h^{-1} (Hz)	26	-0.38 [-0.67, 0.0086]	0.030	26	-0.57 [-0.78, -0.23]	0.002
Cycle rate at 12 km·h^{-1} (Hz)	25	-0.64 [-0.83, -0.33]	< 0.001	25	-0.55 [-0.78, -0.20]	0.002
Peak cycle rate (Hz)	26	-0.065 [-0.44, 0.33]	0.38	25	-0.26 [-0.59, 0.15]	0.11

	D1 performance-determining variables and D2 performance			**ΔPerformance-determining variables and Δperformance**		
Δ$\mathbf{\dot{V}O_{2peak}}$ (mL·kg^{-1}·min^{-1})	26	0.54 [0.19, 0.77]	0.002	26	r_s = 0.33 [-0.066, 0.64]	0.048
ΔGE$_{10}$ (%)	26	-0.035 [-0.42, 0.36]	0.43	26	r_s = 0.37 [-0.020, 0.66]	0.033
ΔGE$_{12}$ (%)	26	-0.080 [-0.45, 0.32]	0.35	26	r_s = 0.56 [0.22, 0.78]	0.002
Δ[La^{-}]$_{max}$ (mmol·L^{-1})	26	0.003 [-0.38, 0.39]	0.49	26	r_s = 0.32 [-0.077, 0.63]	0.055
ΔCycle length at 10 km·h^{-1} (m)	26	0.12 [-0.28, 0.48]	0.27	23	r_s = 0.040 [-0.38, 0.44]	0.43
ΔCycle length at 12 km·h^{-1} (m)	25	0.36 [-0.041, 0.66]	0.039	25	r_s = 0.40 [0.0058, 0.69]	0.025
ΔPeak cycle length (m)	26	0.56 [0.21, 0.78]	0.001	25	r_s = 0.70 [0.42, 0.86]	< 0.001
ΔCycle rate at 10 km·h^{-1} (Hz)	26	-0.16 [-0.52, 0.24]	0.22	23	r_s = -0.065 [-0.46, 0.36]	0.38
ΔCycle rate at 12 km·h^{-1} (Hz)	25	-0.39 [-0.68, 0.0061]	0.028	25	r_s = -0.29 [-0.61, 0.12]	0.084
ΔPeak cycle rate (Hz)	26	0.11 [-0.29, 0.48]	0.30	25	r_s = -0.20 [-0.55, 0.21]	0.17

*1-tailed; GE$_{10}$, GE at 10 km·h^{-1}; GE$_{12}$, GE at 12 km·h^{-1}; [La^{-}]$_{max}$, maximal blood lactate concentration, r_s, Spearman's rank-order correlation coefficient.

Table 3. The relationship between physiological and biomechanical performance-determining variables (D1 and D2) and D2 performance, the relationship between D1 performance-determining variables and D2 performance-determining variables, and the difference between the correlation coefficients, assessed using Steiger's Z.

	N	**D1 performance-determining variables and D2 performance ***	**D2 performance-determining variables and D2 performance***	**D1 performance-determining variables and D2 performance-determining variables***	**Steiger's Z for the difference between the correlations of column 1 and column 2**	**p***
$\dot{\mathbf{V}}\mathbf{O}_{\mathbf{2peak}}$ (mL·kg^{-1}·min^{-1})	26	0.54 ($p = 0.002$)	0.55 ($p = 0.002$)	0.88 ($p < 0.001$)	-0.19	0.43
GE_{10} (%)	26	-0.035 ($p = 0.43$)	0.19 ($p = 0.18$)	0.89 ($p < 0.001$)	-2.33	0.010
GE_{12} (%)	26	-0.080 ($p = 0.35$)	0.23 = ($p = 0.13$)	0.88 ($p < 0.001$)	-3.09	0.0010
$[La^-]_{max}$ (mmol·L^{-1})	26	0.0032 ($p = 0.49$)	0.23 ($p = 0.13$)	0.36 ($p = 0.034$)	-0.97	0.17
Cycle length at 10 km·h^{-1} (m)	23	0.35 ($p = 0.051$)	0.56 ($p = 0.003$)	0.59 ($p = 0.002$)	-1.21	0.11
Cycle length at 12 km·h^{-1} (m)	24	0.38 ($p = 0.033$)	0.67 ($p < 0.001$)	0.58 ($p = 0.002$)	-1.84	0.033
Peak cycle length (m)	25	0.58 ($p = 0.001$)	0.86 ($p < 0.001$)	0.73 ($p < 0.001$)	-3.12	< 0.001
Cycle rate at 10 km·h^{-1} (Hz)	23	-0.37 ($p = 0.042$)	-0.57 ($p = 0.002$)	0.57 ($p = 0.002$)	1.14	0.13
Cycle rate at 12 km·h^{-1} (Hz)	24	-0.40 ($p = 0.025$)	-0.68 ($p < 0.001$)	0.56 ($p = 0.002$)	1.75	0.040
Peak cycle rate (Hz)	25	0.075 ($p = 0.36$)	-0.26 ($p = 0.11$)	0.60 ($p = 0.001$)	1.80	0.036

*1-tailed; missing values were removed listwise to make sure the different correlation coefficients were based on the same N and could be compared; GE_{10}, GE at 10 km·h^{-1}; GE_{12}, GE at 12 km·h^{-1}; $[La^-]_{max}$, maximal blood lactate concentration.