

Physiological Predictors of a Super-Sprint Triathlon Performance in Junior and U23 Triathletes

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Abstract

The mixed-team super-sprint triathlon relay (~300m swimming, ~6.6km cycling and ~1.5km running) performed in teams of four athletes, is the newest Olympic triathlon discipline. Until today, no scientific data is available on the specific physiological attributes. Our study aims to predict a super-sprint triathlon performance from physiological exercise testing. Fourteen national level triathletes performed physiological tests in swimming and running and competed in a super-sprint triathlon. The physiological profile in swimming and running was calculated and applied to predict triathlon performance. The speed at $\dot{V}O_{2\max_swim}$ corresponded well to the swimming speed during the triathlon ($0.013 \text{ m}\cdot\text{s}^{-1}$, n.s.), whereas the running speed was similar to the running speed at metabolic steady state ($MMSS_{run}$) ($0.05 \text{ m}\cdot\text{s}^{-1}$, n.s.). Stepwise multiple regression analysis selected $MMSS_{run}$ as the primary predictor of triathlon performance ($r^2 = 0.66$, $p < 0.05$). The swimming speed at metabolic steady state ($MMSS_{swim}$) ($r^2 = 0.84$, $p < 0.05$) and the amount of work that can be performed above $MMSS_{run}$ (W'_{run}) were also included in the prediction model ($r^2 = 0.91$, $p < 0.05$). Our data indicate that $MMSS_{run}$, $MMSS_{swim}$, and W'_{run} allow for a precise prediction of a super-sprint triathlon performance. This information can be used to optimize training and pacing strategies.

Keywords

Triathlon Performance; Super-Sprint Triathlon; Metabolic Profile, $\dot{V}O_{2\max}$, vL_{amax}



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1 Introduction

Triathlon combines swimming, cycling and running in a single event. Competition duration varies from ~20 min for the super-sprint distance to ~8h for the long distance in elite athletes. The sport made its Olympic debut at the 2000 Games in Sydney featuring the standard (Olympic) distance format comprising a 1,500m swim, 40km bike and a 10km run. During the Olympic Games in Tokyo 2020, the mixed-team relay (MTR) was added for the first time to the Olympic program (World Triathlon, 2023b). This triathlon discipline is performed in teams of 4 athletes, 2 women and 2 men. All four athletes on a team must complete a super-sprint triathlon - ~300m swim, ~6.6km bike and ~1.5km run - before tagging off to a teammate (World Triathlon, 2023a).

Due to the novelty of this event, scientific data concerning the MTR is extremely scarce. Quagliarotti and colleagues published one of the first scientific studies investigating the MTR performances in 6 World championship races in Hamburg (2014-2019) (Quagliarotti et al., 2022). They investigated the impact of each leg and discipline of the MTR on the result at the finish line, thereby providing preliminary insights into the characteristics required for optimal performance. They concluded that optimal performance is achieved by positioning triathletes that are stronger while racing in a group and capable of taking advantage of drafting in legs 1 and 2. Conversely, the last two team members should be strong in non-draft legal conditions as, at this stage of the race, the field has split up into smaller groups. Most determining for overall race performance appeared to be the swimming and cycling performances. Ledanois and colleagues used a similar approach to calculate the probabilities of reaching a victory, a podium, or a top 8 rank in

a MTR, according to the position of any of the four athletes during each of the four segments of the race (Ledanois et al., 2023). They showed that the differences between the winner, medalist, finalist, or finisher teams are apparent throughout the race. These differences continually increase until the end of the race. Legs 2 and 3 are preponderant on the outcome of the race, the position obtained by each triathlete, especially in swimming and cycling, greatly influences the final performance of the team. Leg 1 allows you to maintain contact with the head of the race, while leg 4 determines the position obtained by the rest of the team. At World Championship level, the running disciplines and performance of female team members, especially in the third leg, were ascertained to be the most significant determinants for the overall Mixed Team Relay result (Martínez Sobrino et al., 2023). Recently, a regulatory change has been made to the male and female relay order for the Paris 2024 Olympics. Results across five MTR World Triathlon Series and two MTR European Championships revealed that the new World Triathlon regulations meaningfully modify race dynamics in MTR. Participants were divided into several packs from the first race leg and, therefore, they spent a greater race contribution in the form of solo efforts. Consequently, a greater importance of the individual performance during cycling and swimming segments was detected compared to the previous regulations, although the running performance remained the most decisive discipline, with medalists recording the best running splits (Espejo et al., 2024). The super-sprint triathlon is not only performed in the MTR, but also as a stand-alone event. This distance is popular in the youth and junior categories. An analysis of the race results of World Triathlon continental cups and championships revealed that medalists consistently maintained a position within the

top eight throughout the race, with gap times not exceeding 12 seconds for both men and women (Espejo et al., 2024). In addition, medalists have faster running speeds than the non-successful triathletes with no differences in the remaining race segments (Espejo et al., 2024). These results provide coaches valuable tactical information, however, the physiological requirements to deliver these performances remain underexplored.

Triathlon race times vary from ~20 min for the super sprint distance to +8h for the long distance. Not surprisingly, elite triathletes are characterized by high aerobic power in the range of 70-90 ml·kg⁻¹·min⁻¹ for male (Cejuela & Selles-Perez, 2023; Cuba-Dorado et al., 2022; Hue et al., 2000) and 55-75 ml·kg⁻¹·min⁻¹ for female triathletes (Cuba-Dorado et al., 2022). Maximal fat oxidation rate, $\dot{V}O_{2\max}$ and percentage of body fat mass have been identified as strong predictors of long-distance triathlons (Frandsen et al., 2017; Vest et al., 2018). In short course events, different from long course triathlons, drafting behind another athlete is allowed. Since drafting reduces frontal resistance and consequently energy expenditure (Blocken et al., 2013; Hausswirth et al., 1999, 2001; Mancha-Triguero et al., 2022), this might impact the race tactics, pacing strategy (Bentley et al., 2002) and the performance determinants in these events. Maximal aerobic velocity in running, years of triathlon experience and percentage of lean body mass has been identified as the strongest predictors of standard distance triathlon in recreational athletes (Puccinelli et al., 2020). In a cohort of elite triathletes, the maximal aerobic running speed and the lactate concentration at

a cycling power of 4 W·kg⁻¹, appeared to be the strongest predictors of standard distance triathlon, explaining 81% of the variance in race performance (Schabert et al., 2000). Van Schuylenbergh et al observed submaximal aerobic parameters as the strongest predictors of sprint triathlon performance (Van Schuylenbergh et al., 2004). These studies have been conducted in adult athletes. Similar information in a younger cohort is currently lacking, and the physiological determinants in super-sprint triathlons have not yet been investigated. Therefore, this study aims to predict a super-sprint triathlon performance in well-trained U23 triathletes based on physiological performance determinants. This information is valuable for athletes and coaches to design specific training regimens and evaluation procedures for the MTR in U23 triathletes.

2 Material and Methods

2.1 Participants

Fourteen subjects (10 males and 4 females) volunteered for this study after being informed about the nature and risks involved in participating in the experiments (table 1). All subjects were experienced triathletes (junior or U23), involved in regular triathlon training (minimal 12h per week) and racing for more than 3 years at national level. The subjects were tested in April, approximately 1 month before the start of triathlon season in Belgium, whereas the international season had already started. The study was approved by the Ethics Committee Research UZ/KU Leuven (Registration S65305).

Table 1. Subjects' anthropometric, physiological and performance characteristics. Mean $\pm$ SD.

Number	Women n = 4	Men n = 10	Total group n = 14
Age (yrs)	17.3 $\pm$ 1.3	17.9 $\pm$ 2.0	17.7 $\pm$ 1.8
Height (cm)	168 $\pm$ 4	179 $\pm$ 7	176 $\pm$ 8
Body mass (kg)	57.9 $\pm$ 6.5	66.5 $\pm$ 6.2	64 $\pm$ 7.2
Body fat (%)	21.5 $\pm$ 1.0	9.4 $\pm$ 0.8	12.9 $\pm$ 5.7
$\dot{V}O_{2\max_swim}$ (ml·kg ⁻¹ ·min ⁻¹)	51.0 $\pm$ 7.3	60.7 $\pm$ 7.5	57.9 $\pm$ 8.5
$v\dot{V}O_{2\max_swim}$ (m·s ⁻¹)	1.33 $\pm$ 0.09	1.43 $\pm$ 0.08	1.40 $\pm$ 0.1
$vLa_{\max_swim}$ (mmol·l ⁻¹ ·s ⁻¹)	0.23 $\pm$ 0.13	0.31 $\pm$ 0.09	0.29 $\pm$ 0.11
W'_{swim} (kJ)	4.35 $\pm$ 1.81	6.11 $\pm$ 1.37	5.61 $\pm$ 1.65
BLC _{acc_swim}	199.6 $\pm$ 39.1	98.6 $\pm$ 37.6	127.5 $\pm$ 59.8
MMSS _{swim} (m·s ⁻¹)	1.3 $\pm$ 0.07	1.38 $\pm$ 0.08	1.35 $\pm$ 0.08
MLSS _{swim} (m·s ⁻¹)	1.26 $\pm$ 0.07	1.34 $\pm$ 0.08	1.32 $\pm$ 0.08
V200 _{swim} (m·s ⁻¹)	1.39 $\pm$ 0.08	1.49 $\pm$ 0.07	1.46 $\pm$ 0.08
$\dot{V}O_{2\max_run}$ (ml·kg ⁻¹ ·min ⁻¹)	57.8 $\pm$ 3.1	71.3 $\pm$ 3.1	67.5 $\pm$ 7
$v\dot{V}O_{2\max_run}$ (m·s ⁻¹)	4.71 $\pm$ 0.2	5.56 $\pm$ 0.18	5.32 $\pm$ 0.44
$vLa_{\max_run}$ (mmol·L ⁻¹ ·s ⁻¹)	0.34 $\pm$ 0.10	0.35 $\pm$ 0.07	0.35 $\pm$ 0.07
W'_{run} (kJ)	8.1 $\pm$ 3.7	10.1 $\pm$ 3.5	9.5 $\pm$ 3.6
BLC _{acc_run}	165.7 $\pm$ 32	98.4 $\pm$ 15.8	117.6 $\pm$ 37.5
MMSS _{run} (m·s ⁻¹)	4.39 $\pm$ 0.25	5.2 $\pm$ 0.2	4.96 $\pm$ 0.43
MLSS _{run} (m·s ⁻¹)	4.19 $\pm$ 0.27	5 $\pm$ 0.22	4.77 $\pm$ 0.44
V800 _{run} (m·s ⁻¹)	5.19 $\pm$ 0.17	6.06 $\pm$ 0.3	5.81 $\pm$ 0.48
Triathlon speed (m·s ⁻¹)	5.35 $\pm$ 0.14	6.13 $\pm$ 0.23	5.91 $\pm$ 0.42
Triathlon swimming speed (m·s ⁻¹)	1.27 $\pm$ 0.07	1.44 $\pm$ 0.05	1.39 $\pm$ 0.1
Triathlon swimming (% $\dot{V}O_{2\max}$)	91.3 $\pm$ 5.4	100.9 $\pm$ 8.1	98.2 $\pm$ 8.5
Triathlon swimming (%aerobic)	91.9 $\pm$ 1.7	86.2 $\pm$ 3.3	87.8 $\pm$ 3.9
Triathlon swimming (%anaerobic)	8.1 $\pm$ 1.7	13.8 $\pm$ 3.3	12.2 $\pm$ 3.9
Triathlon cycling speed (m·s ⁻¹)	9.19 $\pm$ 0.27	10.64 $\pm$ 0.53	10.23 $\pm$ 0.82
Triathlon running speed (m·s ⁻¹)	4.44 $\pm$ 0.11	5.25 $\pm$ 1.17	5.02 $\pm$ 0.41
Triathlon running (% $\dot{V}O_{2\max}$)	93.2 $\pm$ 5.0	92.7 $\pm$ 4.7	92.8 $\pm$ 4.6
Triathlon running (%aerobic)	89.8 $\pm$ 1.9	89.9 $\pm$ 1.6	89.9 $\pm$ 1.6
Triathlon running (%anaerobic)	10.2 $\pm$ 1.9	10.1 $\pm$ 1.6	10.1 $\pm$ 1.6

2.2 Study Design

The present observational study involved two experimental sessions, one in swimming and one in running, as well as the participation in a super-sprint triathlon event. The subjects completed the swim and run tests in random order in ~1 week time. The triathlon race was performed within ~1 week of the experimental trials. The subjects were instructed to refrain from any strenuous physical activity for at least 48h prior to each experimental session and the triathlon race. Subjects followed their usual diet throughout the study, except for the final

meal consumed three hours before each experimental session and the triathlon, which was standardized (2.700 kJ, 71% carbohydrates, 15% fats, 14% protein). The subjects were asked to adopt an identical training and food regimen throughout the 2 days for all experimental sessions to avoid fluctuations in the muscle glycogen content and hydration status which may in turn impact on blood lactate concentration (Green et al., 2018; Pohl et al., 2024; Van Schuylenbergh et al., 2005).

At the first visit to the exercise laboratory, height, body mass (Seca, Hamburg, Germany) and body fat percentage was measured using dual-energy X-ray absorptiometry (DEXA, GE Healthcare, Madison, WI, USA). After these measurements were taken, subjects performed either the swimming or the running tests.

2.3 Methodology

2.3.1 Swimming Tests

The swimming tests were conducted in an indoor 25-m swimming pool (27°C). Subjects performed an 800-m warm-up and four exercise bouts of 200-400m length (figure 1). The exercise bouts were calibrated according to the perceived exertion (RPE) (0-10 Borg CR10 Scale) (Borg, 1998) to ensure exercise intensities in the high and severe exercise domain (Foster et al., 2017). Subjects were asked to complete the four exercise bouts at the following RPEs: 6-7 (bout 1), 8-9 (bout 2 and 3), and 10 (bout 4) (figure 1). After each exercise bout, subjects rested sitting on a chair during which post-exercise blood

lactate concentration (BLC) was measured at 1-min intervals (Lactate Pro 2, Akray, Japan). Once the peak BLC was detected, subjects performed a 200-500 m recovery swim to allow $BLC < 2.5 \text{ mmol}\cdot\text{L}^{-1}$.

2.3.2 Running Tests

The running test was performed on a 400m outdoor synthetic track (no rain, 10°C). Subjects performed a 2,000-m warm-up and four exercise bouts of 800-1,600m (figure 2). The exercise bouts were calibrated according to the perceived exertion (RPE) (0-10 Borg CR10 Scale) (Borg, 1998) to ensure exercise intensities in the high and severe exercise domain (Foster et al., 2017). Subjects were asked to complete the four exercise bouts at the following RPEs: 6-7 (bout 1), 8-9 (bout 2 and 3), and 10 (bout 4). After each exercise bout, subjects rested sitting on a chair during which post-exercise BLC was measured at 1-min intervals (Lactate Pro 2). Once the peak BLC was detected, subjects performed a 400-1200 m recovery run to allow $BLC < 2.5 \text{ mmol}\cdot\text{L}^{-1}$.

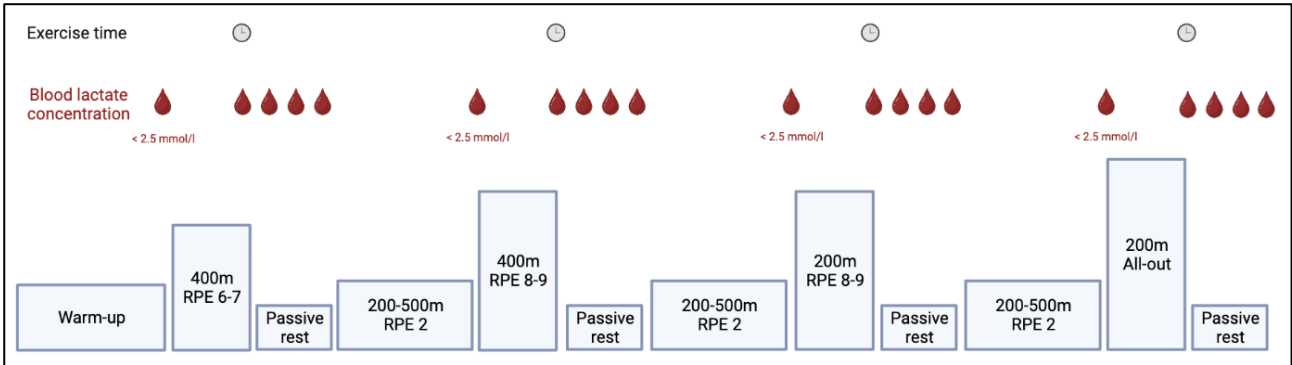


Figure 1. Test protocol swimming tests. Subjects performed 4 exercise bouts of 200-400m at RPE 6-10. BLC before and after each exercise bout and exercise time was measured.

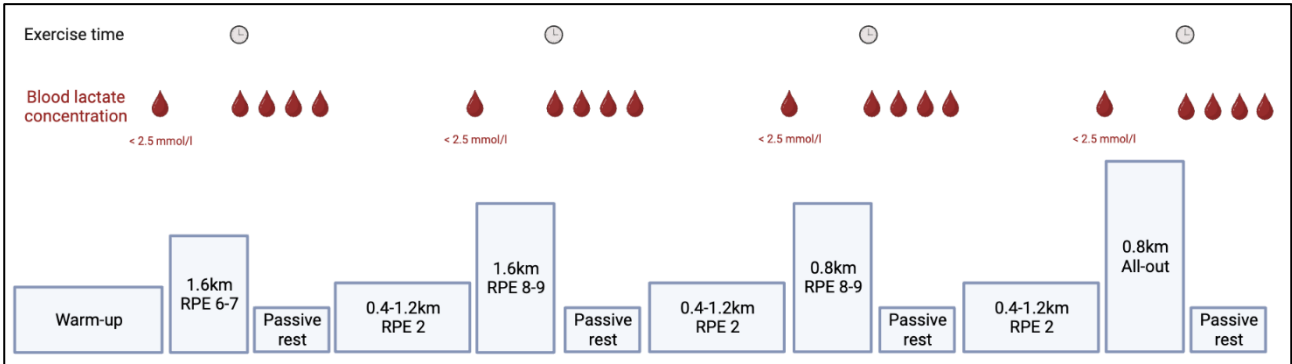


Figure 2 Test protocol running tests. Subjects performed 4 exercise bouts of 800-1600m at RPE 6-10. BLC before and after each exercise bout and exercise time was measured.

Both the swimming and running tests were conducted in accordance with the recommendations of the manufacturer of the software that has been used to analyse the lactate data (INSCYD GmbH, Salenstein, Switzerland).

2.3.3 Triathlon Race

Within 1 week after the laboratory tests all subjects competed in a super-sprint triathlon. This triathlon was a qualification race to be selected for the Belgian triathlon team. Weather conditions were mild (no rain, air 24°C, water 18°C). The race consisted of a 338-m swim, a 4.6-km bike race and a 1.5-km run, replicating the race distance during a MTR. The swim distance was measured with an optical device (Nikon LRF Laser 30 Rangefinder, Tokyo, Japan). The swim course was marked with buoys. The bike and run distances were measured with GPS (Garmin, Phenix 6, Olathe, USA). The subjects used neoprene triathlon wetsuits. Both bike and run segments were performed on a flat, out-and-back course to minimize the effect of wind.

Subjects started one-by-one with a 1-min time difference. Drafting was not allowed. This procedure was implemented to measure the individual race performance as drafting can impact the energy cost and subsequent running performance (Hausswirth et al., 1999; Mancha-Triguero et al., 2022).

Triathlon race time was recorded to the nearest second using an electronic timing system (MyLaps, Harlem, Netherlands). The times of the swim-bike and bike-run transitions were recorded but not included in the dataset for this study, as transition times are dependent on the specific design and distance of the transition areas. The times to complete the swim-, bike- and run-course were converted into speed ($\text{m}\cdot\text{s}^{-1}$) for further analysis.

2.4 Data Analysis

The subjects' metabolic profiles in swimming and running, including the maximal oxygen uptake ($\dot{V}\text{O}_{2\text{max}}$), the speed corresponding the $\dot{V}\text{O}_{2\text{max}}$ ($v\dot{V}\text{O}_{2\text{max}}$), the maximal lactate accumulation rate ($v\text{La}_{\text{max}}$), the maximal lactate steady state (MLSS), the maximal metabolic steady state (MMSS), anaerobic work capacity (W') and the blood lactate accumulation rate (BLC_{acc}), were calculated using a specific analytic software (INSCYD GmbH, Salenstein, Switzerland) (Podlogar et al., 2022; Poffé et al., 2024). Individual data used to run these calculations were: sex, body mass, body fat %, the recorded exercise times (to the nearest tenth of a second) and the pre- and postexercise BLC for each exercise bout. All other settings in the software such as detailed body composition and gross efficiency were kept at default values as preset in the software. The software's algorithms normalize the $v\text{La}_{\text{max}}$ to the body mass and body composition using a two-compartment model. It then calculates the energy contribution from aerobic and glycolytic energy sources under steady state conditions. From this analysis, a causational MLSS is calculated as the highest power output or speed at which an equilibrium of aerobic lactate combustion and glycolytic lactate production is achieved, hence resulting in a zero net lactate accumulation. The model also calculates the maximal metabolic steady state (MMSS), as the highest power output or speed in absence of a slow component in the oxygen consumption. The BLC_{acc} quantifies the rate of lactate accumulation at workloads above MLSS based on the steepness (slope) of the lactate accumulation curve.

2.5 Statistical Analysis

A Shapiro Wilk test was applied to verify normal distribution of the data. All data are expressed as $\text{mean}\pm\text{SD}$.

One-way analyses of variance (Anova) were used to compare $\dot{V}O_{2\max}$, MLSS, MMSS and racing speed in swimming and in running. Tukey post-hoc tests were applied when appropriate. In addition, 95% confidence intervals (CI) of the differences were calculated.

Pearson product correlations (r) quantified the correlation between the measured physiological and the performance characteristics in swimming and in running ($\dot{V}O_{2\max}$, $vL_{\max}$, MLSS, MMSS, W' , BLA_{acc}, V200swim, V800run) versus the racing speed. The following criteria were adopted to interpret the magnitude of correlations between the measured variables: <0.50, poor; 0.50 to 0.69, moderate; 0.70 to 0.89 good; and > 0.90, excellent (Koo & Li, 2016). Stepwise multiple regression analyses were performed with the anthropometric (height, body mass, body fat percentage) and physiological characteristics ($\dot{V}O_{2\max}$, $v\dot{V}O_{2\max}$, $vL_{\max}$, MLSS, MMSS, W' , and BLC_{acc}) in swimming and running as independent variables and average racing speed in swimming, running and in the triathlon race as dependent variables. The forward stepwise regression model was used to observe the individual contributions of variables one by one based on the r^2 value. The Root Mean Square Error (RMSE) was used to assess the model fit. In addition, 95% confidence intervals (CI) were calculated. Significance level was set at $p < 0.05$. Statistical analyses were performed using JASP 0.18 (<https://jasp-stats.org/> Amsterdam, Netherlands) and PRISM Graphpad software (version 10).

3 Results

The racing speed during the swim leg of the triathlon race was similar to the $v\dot{V}O_{2\max_swim}$ ($\Delta 0.013 \text{ m}\cdot\text{s}^{-1}$, 95% CI: -0.032 - 0.058, n.s.) and significantly faster than $MLSS_{swim}$ ($\Delta 0.073 \text{ m}\cdot\text{s}^{-1}$, 95% CI: -0.121 - -0.025) (figure 3). The racing

speed during the run leg was similar to $MMSS_{run}$ ($\Delta 0.05 \text{ m}\cdot\text{s}^{-1}$, 95% CI: -0.19 - 0.87, n.s.). $MLSS_{run}$ underestimated ($\Delta 0.25 \text{ m}\cdot\text{s}^{-1}$, 95% CI: -0.4 - -0.11) and $v\dot{V}O_{2\max_run}$ overestimated ($\Delta 0.3 \text{ m}\cdot\text{s}^{-1}$, 95% CI: 0.13 - 0.47) the running speed during the triathlon race significantly (figure 3).

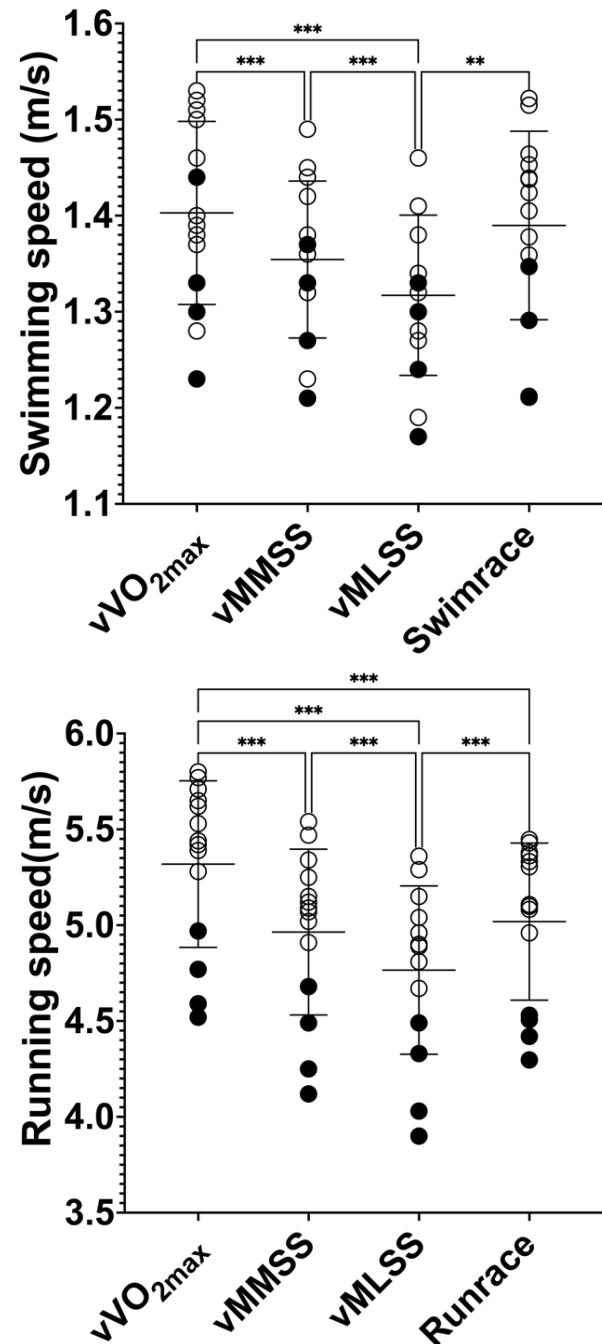


Figure 3. Swimming (Left panel) and running (Right panel) speed at $\dot{V}O_{2\max}$, MLSS, MMSS and during the triathlon race. Individual and mean $\pm$ SD data. Open circles represent the data of the male subjects, closed circles represent the data of the female subjects. Anova. **** $p < 0.0001$, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns $p > 0.05$

Pearson correlations with the race performances are shown in table 2 and 3. The 200-swim performance and 800-run performance showed the highest correlations with the race performance in the swimming ($r=0.87$, $p<0.001$) and running leg ($r=0.93$, $p<0.001$) respectively. The physiological characteristics of aerobic metabolism (e.g., $\dot{V}O_{2max}$, MMSS, MLSS) significantly correlated with triathlon race performance ($0.67 < r < 0.81$, all $p<0.05$). The vLa_{max} , as a marker of anaerobic power, was not correlated with triathlon performance. W'_{swim} ($r=0.67$, $p<0.05$) but not W'_{run} was significantly correlated with the overall race performance ($r=0.49$, $p=0.08$). The BLC_{acc} negatively correlated with triathlon performance ($0.63 < r < 0.72$, all $p<0.05$), meaning that subjects with faster BLC

accumulation kinetics at workloads above MLSS have a slower race performance.

Stepwise multiple regression analysis revealed that $v\dot{V}O_{2max_swim}$ explained ~68% of the variance in swimming race performance. The BLC_{acc} added another ~12% to the regression analysis, and the vLa_{max} added an additional ~10% (table 4). $MMSS_{run}$ explained 85% of the variance in running performance. W'_{run} added an extra 7.8% to the prediction model (table 5). $MMSS_{run}$ was selected as the primary predictor of overall triathlon performance ($r^2 = 0.66$). $MMSS_{swim}$ was included in the prediction model as the second ($r^2 = 0.84$) and W'_{run} as the third predictor ($r^2 = 0.91$) (table 6).

Table 2. Pearson correlation coefficients between the measured physiological and performance characteristics in swimming and running ($\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, VL_{max} , MLSS, MMSS, W' , BLC_{acc} , $V200_{swim}$, $V800_{run}$) versus the racing performances.

	Swim ($m \cdot s^{-1}$)	Bike ($m \cdot s^{-1}$)	Run ($m \cdot s^{-1}$)	Triathlon ($m \cdot s^{-1}$)
$\dot{V}O_{2max_swim}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.82 ***	0.76 **	0.55 *	0.72 **
$v\dot{V}O_{2max_swim}$ ($m \cdot s^{-1}$)	0.83 ***	0.75 **	0.54 *	0.71 **
vLa_{max_swim} ($mmol \cdot L^{-1} \cdot s^{-1}$)	0.50 ns	0.48 ns	0.33 ns	0.42 ns
W'_{swim} (kJ)	0.61 *	0.68 **	0.56 *	0.67 **
BLC_{acc_swim}	-0.77 **	-0.72 **	-0.68 **	-0.72 **
$MMSS_{swim}$ ($m \cdot s^{-1}$)	0.81 ***	0.72 **	0.49 ns	0.69 **
$MLSS_{swim}$ ($m \cdot s^{-1}$)	0.79 ***	0.71 **	0.48 ns	0.67 **
$V200_{swim}$ ($m \cdot s^{-1}$)	0.87 ***	0.80 ***	0.58 *	0.78 ***

* $p<0.05$, ** $p<0.01$, *** $p<0.001$, ns $p>0.05$.

Table 3. Pearson correlation coefficients between the measured physiological and performance characteristics in running ($\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, VL_{max} , MLSS, MMSS, W' , BLC_{acc} , $V800_{run}$) versus the racing performances.

	Swim ($m \cdot s^{-1}$)	Bike ($m \cdot s^{-1}$)	Run ($m \cdot s^{-1}$)	Triathlon ($m \cdot s^{-1}$)
$\dot{V}O_{2max_run}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.67 **	0.75 **	0.89 ***	0.77 ***
$v\dot{V}O_{2max_run}$ ($m \cdot s^{-1}$)	0.68 **	0.75 **	0.89 ***	0.78 ***
vLa_{max_run} ($mmol \cdot L^{-1} \cdot s^{-1}$)	0.06 ns	-0.12 ns	-0.09 ns	-0.12 ns
W'_{run} (kJ)	0.44 ns	0.51 ns	0.42 ns	0.49 ns
BLC_{acc_run}	-0.64 *	-0.60 *	-0.68 **	-0.63 *
$MMSS_{run}$ ($m \cdot s^{-1}$)	0.68 **	0.78 ***	0.92 ***	0.81 ***
$MLSS_{run}$ ($m \cdot s^{-1}$)	0.67 **	0.78 **	0.92 ***	0.81 ***
$V800_{run}$ ($m \cdot s^{-1}$)	0.73 **	0.84 ***	0.93 ***	0.86 ***

* $p<0.05$, ** $p<0.01$, *** $p<0.001$, ns $p>0.05$.

Table 4. Stepwise multiple regression analysis with triathlon-swimming speed as dependent variable and the anthropometric (height, body mass, body fat percentage) and physiological characteristics in swimming ($\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, vLa_{max} , MLSS, MMSS, W' , BLC_{acc}) as independent variables.

Step	Regression analysis	R ²	RMSE	CI
1	Swimming speed (m·s ⁻¹) = 0.199 + 0.849* $v\dot{V}O_{2max_swim}$ (m·s ⁻¹)	0.68	0.058	1.36-1.421
2	Swimming speed (m·s ⁻¹) = 0.658 + 0.584* $v\dot{V}O_{2max_swim}$ (m·s ⁻¹) – 0.0007* BLC_{acc}	0.793	0.049	1.363-1.415
3	Swimming speed (m·s ⁻¹) = 0.444 + 0.865* $v\dot{V}O_{2max_swim}$ (m·s ⁻¹) - 0.001* BLC_{acc} – 0.485* vLa_{max_swim} (mmol·L ⁻¹ ·s ⁻¹)	0.898	0.036	1.371-1.408

RMSE: Root Mean Square Error; CI: 95% confidence interval

Table 5. Stepwise multiple regression analysis with triathlon-running speed as dependent variable and the anthropometric (height, body mass, body fat percentage) and physiological characteristics in running ($\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, vLa_{max} , MLSS, MMSS, W' , BLC_{acc}) as independent variables.

Step	Regression analysis	R ²	RMSE	CI
1	Running speed (m·s ⁻¹) = 0.68 + 0.874*MMSS _{run} (m·s ⁻¹)	0.851	0.165	4.93-5.11
2	Running speed (m·s ⁻¹) = 0.547 + 0.834*MMSS _{run} (m·s ⁻¹) + 0.035* W'_{run} (kJ)	0.94	0.109	4.96-5.08

RMSE: Root Mean Square Error; CI: 95% confidence interval

Table 6. Stepwise multiple regression analysis with triathlon speed as dependent variable and the anthropometric (height, body mass, body fat percentage) and physiological characteristics in swimming and running ($\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, vLa_{max} , MLSS, MMSS, W' , BLC_{acc}) as independent variables.

Step	Regression analysis	R ²	RMSE	CI
1	Triathlon speed (m·s ⁻¹) = 2.031 + 0.781*MMSS _{run} (m·s ⁻¹)	0.655	0.255	5.77-6.04
2	Triathlon speed (m·s ⁻¹) = -0.334 + 0.623* MMSS _{run} (m·s ⁻¹) + 2.33* MMSS _{swim} (m·s ⁻¹)	0.835	0.184	5.81-6.01
3	Triathlon speed (m·s ⁻¹) = -0.0128 + 1.885* MMSS _{run} (m·s ⁻¹) + 0.6141* MMSS _{swim} (m·s ⁻¹) + 0.0338* W'_{run} (kJ)	0.91	0.143	5.84-5.99

RMSE: Root Mean Square Error; CI: 95% confidence interval

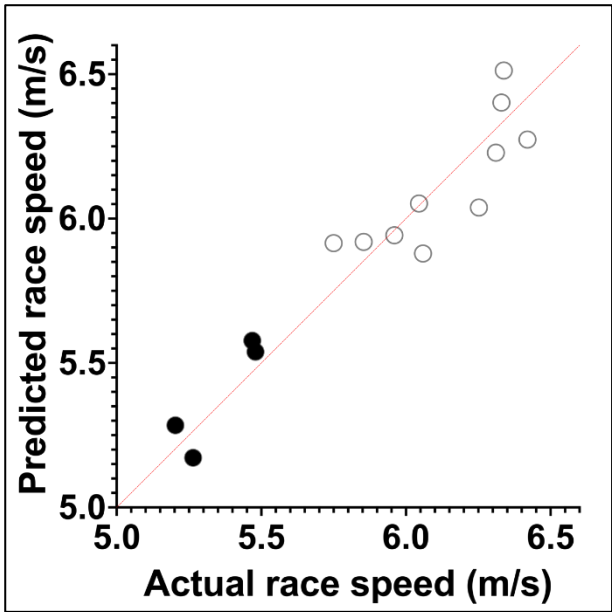


Figure 4. Actual triathlon racing speed (m·s⁻¹) versus predicted racing speed (m·s⁻¹). The red line indicates the line of identity. Open circles represent the data of the male subjects, closed circles represent the data of the female subjects

4 Discussion

The goal of the present study was to explore whether a super-sprint triathlon performance could be predicted from physiological characteristics in swimming and running. MMSS_{run} in conjunction with MMSS_{swim} and W'_{run} were the strongest predictors of triathlon performance explaining 91% of the variance in racing speed. In previous research, MLSS (Van Schuylenbergh et al., 2004) and the velocity at the ventilatory threshold (VT) (Sleivert & Wenger, 1993) were used as markers of maximal sustainable workload and showed high predictive power with short course triathlon performance. MLSS, VT and MMSS have conceptual similarities, aiming to represent a maximal sustainable steady state workload, but the concepts are not identical (Jones et al., 2019). In the present study, high

correlations were found between MLSS and MMSS ($r=0.99$, $p<0.001$). However, MLSS was 3 to 4% lower compared to MMSS (figure 3) which aligns with previous observations (Jones et al., 2019). MMSS is likely a more preferred marker of maximal metabolic steady state as continuous exercise performed at 10 W above MLSS resulted in a steady state $\dot{V}O_2$ equivalent to $\sim 90\%$ $\dot{V}O_{2max}$ (Mattioni Maturana et al., 2016). The maximal amount of work that can be performed above MMSS (W'_{run}) was the third predictor of overall race performance. Elite triathletes competing in short course triathlons adopt a relatively constant pace during the run with an acceleration at the end of the race (Le Meur et al., 2009; Vleck et al., 2008). This pacing strategy is used to optimize performance in short course triathlon. Although not investigated in these studies, likely an important contribution of anaerobic energy is required to allow this final acceleration. Our data showed that the $MMSS_{run}$ corresponds with the average running speed during the triathlon race (figure 3). The ability to increase the speed above the metabolic steady state requires additional anaerobic energy, and can differentiate subjects with similar speeds at MMSS (Foster et al., 2023; Skiba et al., 2012).

The regression analyses selected a different set of physiological characteristics to predict the swimming performance compared to the running performance (table 3, 4). Swimming performance was positively related with the $v\dot{V}O_{2max}$ and negatively with BLC_{acc} and the vL_{amax} . Running performance was predicted by the $MMSS_{run}$ and W'_{run} . The regression analyses should be interpreted in the context of a triathlon race, where performance in the later disciplines is evidently affected by the preceding disciplines. For instance, it has been shown that the swimming intensity has an impact on subsequent cycling and running (Peeling et al., 2005; Peeling & Landers, 2009). Swimming around 80-85% of the maximal

swimming speed over 750m, resulted in significant higher cycling power outputs and faster triathlon finishing times, compared to an all-out swimming strategy. It has been suggested that a more conservative pacing approach during the swim prevents excessive lactate accumulation and favours the subsequent bike and run performances (P. D. Peeling et al., 2005). The regression model in the present study is compatible with such process in that vL_{amax} was negatively correlated with swimming performance. Recently, vL_{amax} , as an estimate of the maximal glycolytic power, has received more attention in the scientific literature (Wackerhage et al., 2022). Yang and colleagues observed vL_{amax} values of 0.97 ± 0.18 $mmol\cdot L^{-1}\cdot s^{-1}$ in elite cycle track sprinters (Yang et al., 2023). In highly-trained swimmers specialized in 50m and 100m sprint events, vL_{amax} values amounted 0.75 ± 0.18 $mmol\cdot L^{-1}\cdot s^{-1}$ (Mavroudi et al., 2023). In endurance athletes, vL_{amax} values are typically in the range of 0.3 - 0.7 $mmol\cdot L^{-1}\cdot s^{-1}$ (Ji et al., 2021; Quittmann et al., 2021; Schünemann et al., 2023; Weber, 2003). To the best of our knowledge, reference data in neither triathletes nor junior athletes have been published yet. In our study, vL_{amax} values ranged between 0.14 and 0.43 $mmol\cdot L^{-1}\cdot s^{-1}$ in swimming and 0.20 and 0.45 $mmol\cdot L^{-1}\cdot s^{-1}$ in running. Relatively low vL_{amax} values might be favourable for optimal triathlon performance as it allows higher exercise intensities in metabolic steady state (Bleicher, 1999; Nolte et al., 2022; Poffé et al., 2024; Wackerhage et al., 2022). In the present study, such rationale is represented in the performance model for swimming, as the maximal aerobic speed positively, and the vL_{amax} negatively impact on swimming speed. This finding suggests that training regimens to increase vL_{amax} , such as repeated sprint training, might be counterproductive for the swimming performance in a super sprint

triathlon, and training should be focused on developing maximal aerobic power.

Some limitations of this study should be recognized. Due to the COVID pandemic at the time of the experiments; specific restrictions regarding laboratory testing and sport events were in place. For instance, no laboratory tests could be conducted to determine the physiological characteristics in cycling. As the bike segment takes about ~55% of the triathlon racing time, including physiological characteristics during cycling exercise might have improved the prediction model (Schabort et al., 2000). It should be noted that the subjects in this study were highly trained triathletes competing at a national level. Although somewhat speculative, these athletes are likely equally trained in the three sports which can explain the good correlations between the three sport activities. The question arises to what extent data from a cycling test could further enhance our prediction model.

Secondly, the super sprint triathlon in the current study was organized in a time-trial format, due to COVID restrictions at the time of this investigation, which is different from the typical draft-legal race situation. Drafting can reduce energy expenditure up to 40% during cycling (Blocken et al., 2013; Defraeye et al., 2014) and create a competitive advantage in the subsequent run. (Hauswirth et al., 1999, 2001). Drafting typically creates a more stochastic effort and might alter performance determinants and tactics (Bentley et al., 2002). This could attenuate the importance of optimal triathlon performance towards swimming and running.

Thirdly, the relatively small sample size of this study, especially in the female subgroup ($n=4$), implies that the results should be interpreted with caution and considered rather as exploratory. It is documented in the scientific literature that the performance

characteristics in female triathletes differ from those in male triathletes (Barbosa et al., 2023; Figueiredo et al., 2016; Lepers, 2019; Lepers et al., 2013). However, such information in super-sprint triathlons is currently lacking. As sex differences appear to be more pronounced as race distance decreases (Joyner, 2017), future research should include larger samples of female participants, to facilitate the development of sex-specific prediction models.

It should be noted that the $MMSS_{swim}$ was derived from swimming-pool data, whereas the swim leg in the triathlon was performed in open water, wearing neoprene wetsuits. Wetsuits used in swimming events can improve performance by enhancing buoyancy, reducing drag, and increasing stroke efficiency. Studies indicate that swimmers can achieve faster times, with some reporting improvements of up to 11% in performance due to decreased energy costs and better propulsion (Gay et al., 2022; Quagliarotti et al., 2023). This would imply that the participants in our study completed the swimming leg during the triathlon at approximately the $MLSS$ intensity.

5 Practical Applications

This study was the first to explore the physiological predictors of a super-sprint triathlon performance in junior and U23 triathletes. Our data demonstrate that $MMSS_{run}$ in conjunction with $MMSS_{swim}$ and W'_{run} computed from field test data, can accurately predict a super-sprint triathlon performance. Alternatively, these metrics can be obtained from conventional critical speed test procedures. The regression analysis for the swimming performance alone indicates that high lactate accumulation rates negatively impact race performance which is in line with observations from the literature. This information can be valuable for athletes and coaches developing strategies to improve

super-sprint triathlon performance and training strategies. Especially in leg 3 and 4 of the mixed team relay, when the field is split up into smaller groups and individuals and the race becomes more a solo-time-trial effort, racing at the highest metabolic steady state is likely the fastest strategy. Training for the super-sprint triathlon should emphasize both the development of aerobic power and anaerobic capacity.

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