



Application of near-infrared spectroscopy (NIRS) in the physiological assessment of sprint triathlon

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ABSTRACT: The purposes of the present investigation were: 1) to explore the utility of Near Infrared Spectroscopy (NIRS) as a measurement tool within triathlon; 2) create a profile of the physiological responses to triathlon.

A laboratory based study explored the utility of multi-site NIRS as a measurement tool within triathlon using recreational male triathletes (n=11). Participants completed maximal incremental exercise tests on a treadmill, cycle ergometer and swim ergometer, before completing a simulated sprint distance triathlon. A comprehensive profile of global and peripheral responses throughout the sprint triathlon was created, including pulmonary oxygen consumption, heart rate, blood lactate concentration, RPE and multi-site NIRS (vastus lateralis and latissimus dorsi). Repeated measures ANOVA was used to analyse the differences between relative intensity of TSI (%), HR and $\dot{V}O_2$ responses across triathlon stages.

NIRS devices were able to inform upon muscle oxygenation status across the simulated triathlon. NIRS identified different oxygenation responses between upper and lower limbs throughout; $p=0.016$ and identified a greater peripheral measurement variability between participants compared to global physiological measures.

As a measurement tool NIRS has the potential to increase the specificity of physiological information available to athletes and coaches. NIRS observed different peripheral muscle desaturation profiles in individuals, indicating variability in efficiency between athletes. This finding will have implications when creating strategies to be applied in sprint triathlon training and competition.

KEY WORDS Sprint triathlon, NIRS, Physiological Profile, Laboratory, Performance

INTRODUCTION

The demands of sprint triathlon are different to those experienced when performing swimming, cycling and running in isolation. Despite knowledge of the residual effects of each discipline on overall performance, few studies have simulated the event in its entirety (1). Without appropriate understanding of the demands of the sport it is not

possible to create informed training or competition strategies to optimise performance. Typically triathlon research has utilised tools that observe the global physiological responses (pulmonary oxygen consumption, heart rate, blood lactate concentration) that occur during participation (2), although a lone study has applied Near Infrared Spectroscopy (NIRS) technology to triathletes (3). Observation of a significantly



reduced muscle oxygen saturation profile, trivially elevated heart rate, and differences in run performance were seen when comparing running preceded by intense cycling vs. running alone. The authors suggested NIRS may provide an alternative tool for monitoring exercise intensity in some instances. NIRS is a light-based technology that offers insight into the relationship between oxygen delivery and consumption, or changes in tissue blood volume in muscle (4). Sprint distance triathlon is an aerobic event, therefore oxygen delivery and utilisation should be key indicators of performance. NIRS has successfully been applied to each component of a triathlon highlighting; triathletes predominantly use their upper body musculature (Latissimus Dorsi (LD)) for propulsion when swimming (5); a gradual decline in muscle oxygenation of the vastus medialis muscle across a 20 km cycling time trial (6), and; NIRS desaturation profiles reflected changes in exercise intensity as a result of undulating course terrain in long distance running (7). Understanding muscular contributions to exercise is important in multi-sport events, where the primary muscles being used for propulsion change across components of the race. NIRS has identified specific, individual differences in the ability to utilise oxygen within the muscle in biathletes, influenced by underlying variation in technique and muscle contributions to exercise (8).

No research has used NIRS to examine physiological responses across a sprint triathlon. The utilisation of portable, non-invasive technology that can inform upon changes in hemodynamic function at the site of the active muscle may provide athletes and coaches with new physiological information. The purposes of the present investigation were: 1) to explore the utility of NIRS as a measurement tool within triathlon; 2) create a profile of the physiological responses to triathlon.

METHODS

Eleven recreationally active male participants (age: 38 ± 5 years, stature 1.8 ± 0.1 m; mass: 78.9 ± 8.2 kg; skin fold thickness Latissimus Dorsi (LD) 14.1 ± 3.2 mm; skin fold thickness Vastus Lateralis (VL) 7.4 ± 1.4 mm) volunteered to participate in the study. All participants were physically active, familiar with treadmill running and stationary cycling, and free from musculoskeletal injury. In the 24 hours prior to testing, participants were instructed to refrain from intense physical exercise and caffeine whilst also avoid eating a heavy meal 2 hours prior. Ethical approval was received from the university ethics sub-committee. Participants provided written informed consent in accordance with the Declaration of Helsinki.

Participants were required to attend on four occasions, separated by seven days. Each participant attended the laboratory (temperature: $19 \pm 1.0^\circ$ C) at the same time each visit to minimise variation in physiological parameters that might change with circadian rhythm (9). Three maximal incremental exercise tests were completed (swim, cycle, run) before

completing a simulated triathlon. A randomised, crossover design was implemented for the treadmill (Saturn, HP Cosmos, Germany) and cycle (Lode, Excalibur Sport, Netherlands) maximal incremental exercise tests (visit 1 and visit 2) to counterbalance any order effects. Following the treadmill and cycle maximal exercise tests, participants completed a 10-minute simulated swimming familiarisation to minimise the learning effect associated with the swim-ergometer (Vasa, SwimErg, USA). At visit 3, participants performed a maximal incremental simulated swim test. The simulated triathlon took place during Visit 4. Maximal Incremental Exercise Tests

Participants wore a chest heart rate strap (Polar RCX5, Polar Electro OY, Finland) which was synced to a portable gas analyser (Cosmed, Cosmed K5, Italy). NIRS devices were placed onto the VL and LD. During a five-minute seated baseline period, measures of heart rate and muscle oxygenation were recorded, then a blood lactate sample was taken. Following this, the portable gas analyser was attached, and a five-minute warm up was completed. Currently there is no guidance for maximal incremental exercise testing protocols conducted on a swim ergometer, therefore the test was created for this study in line with treadmill test guidance. The starting swim pace was calculated during familiarisation sessions, by determining the maximal pace that the participant could maintain for 2:30 minutes. This starting pace was then derived with an aim of completing six stages. The maximal incremental exercise test was discontinuous and consisted of 2:30 minutes stages that increased by $10 \text{ sec} \cdot 100\text{m}^{-1}$ each stage, followed by 30 second rest periods. The maximal incremental bike test was continuous and followed the protocol of Barton et al, starting at $1\text{W} \cdot \text{kg}^{-1}$ of bodyweight and increasing by $0.5\text{W} \cdot \text{kg}^{-1}$ of bodyweight every 2 minutes (10). During the maximal incremental run test the treadmill was set at 1% gradient at all times to mimic outdoor running (11), and followed the protocol described by Jones et al, with 3:00 minute stages starting at 9 kmh and increasing by 1.3 kmh, separated by a 30 second rest period between each stage(11). Tests were terminated at volitional exhaustion.

Respiratory gas data, muscle oxygenation and heart rate were recorded throughout, with blood lactate concentration and RPE recorded at the end of each stage. Blood lactate concentration and RPE data are not presented.

Simulated Sprint Distance Triathlon

An electromagnetically braked cycle ergometer (Racermate, Velotron Pro, USA) was used for the bike stage to allow for self-pacing, all other equipment remained the same. The same bike set up as the exercise test was used. Participants completed a 5-minute cycling warm up and targeted $1 \text{ W} \cdot \text{kg}^{-1}$, with a cadence between 70-90 rpm followed by a five-minute rest period, then the simulated triathlon began. Participants completed 750 m swimming, 20 km cycling and 5 km running. Transition areas were replicated using shuttle runs within the laboratory,

totalling a distance of 100 m for both swim-bike and bike-run transitions. Transitions were standardised as 120 seconds for T1 and 150 seconds for T2. This was slightly longer than during competition (13) to facilitate recording of BLC at the start and end of each stage, and attaching participants to the treadmill harness in T2. NIRS data were recorded throughout.

Near-Infrared Spectroscopy

PortaMon (Artinis Inc, The Netherlands) devices were placed on the belly of the VL muscle midway between the greater trochanter of the femur and the lateral femoral epicondyle; and the LD muscle at the midpoint between the mid-axilla and the spinal column. The devices were secured to the skin with adhesive tape (Hypafix, BSN medical, Hamburg Deutschland). A further black neoprene strapping was wrapped around the device to block out external light, with the cup shaping ensuring no extra pressure was placed on the device, to ensure measurement accuracy (14). Data was recorded at 10 Hz, with one second averages used for analysis.

NIRS data analysis

In order to observe a complete haemodynamic profile, all NIRS measurements have been presented; Tissue Saturation Index (%), oxyhaemoglobin (O_2Hb), deoxyhaemoglobin (HHb) and total haemoglobin (tHb). However, TSI (%) is considered the most robust of the NIRS signals, least affected by surface interference and skin blood flow (14). TSI (%) provides information about muscle oxygen utilisation, and because oxidative metabolism is the primary source of energy during sprint triathlon events, it is the major signal of interest. NIRS data are displayed as one second averages of absolute values from a representative subject. TSI data from all participants are available within Supplement 1 (S1). Average and delta (Δ) TSI, O_2Hb , HHb and tHb are provided within Supplement 2 (S2). Δ was calculated as maximum minus the minimum value during each stage of the triathlon, approximately 60 s into the beginning of each stage.

Data analysis

Descriptive statistics are presented as mean \pm SD unless otherwise stated. Relative intensity was calculated for each discipline as:

$$\text{Relative Intensity} = \frac{\text{Averaged values across stage during simulated triathlon after plateau}}{\text{Maximal values achieved during maximal incremental exercise test}} \times 100 (\%)$$

Equation 1. Relative Intensity (%) calculation.

A two-way repeated measures ANOVA was used to analyse the differences between relative intensity of TSI (%), HR and $\dot{V}O_2$ responses across swim, cycle and run stages. Where interaction effects resulted in statistical significance, simple main effects were used to identify the

specific measure (TSI %, HR and $\dot{V}O_2$), or stage of the race (swim, cycle and run). Additional, pairwise comparisons were used to highlight differences within measures or race stage. A Bonferroni adjustment of alpha was applied to correct for the multiple comparisons in this analysis. Where data violated the assumption of sphericity, degrees of freedom were adjusted using the Greenhouse-Geisser estimate (16). All analyses were performed using GraphPad Prism 8 (GraphPad Software, San Diego, CA, USA).

STATISTICAL RESULTS

Maximal Incremental Tests

Table 1. shows the group physiological responses to maximal incremental exercise tests and mean responses achieved during simulated triathlon for comparison.

Figure 1 displays the absolute TSI (%), O_2Hb , HHb, tHb, $\dot{V}O_2$ and HR responses during Laboratory Simulated Sprint Distance Triathlon for a representative subject.

NIRS Profile during Laboratory Simulated Sprint Distance Triathlon

During the initial seconds of the swim, a significant decrease in TSI (%) of the LD was evident caused by a fall in O_2Hb and an increase in TSI (%) of the VL. There was an immediate rise in TSI (%) of the LD after this initial response back to baseline levels by 250 m, where all NIRS signals (O_2Hb , HHb, tHb) remained fairly stable throughout the entirety of the swim. Individual responses were similar during the swim, although notably, participant b showed continual desaturation of the LD muscle while participants h and k (Figure 2) showed more pronounced desaturation in the VL muscle across the swim. All signals display significant disruption during T1 and T2 with large increases (restoration) in TSI (%) of the VL and LD, together with increases in O_2Hb in both muscles. This significantly decreased when the bike commenced and then remained stable (plateau). There was a noticeable increase in tHb of the VL during the bike, as a result of a large increase in HHb with a slight decrease in O_2Hb . Differences in TSI (%) of the VL and LD were most evident during the bike in all participants. The extreme desaturation seen in TSI (%) of the VL is evident in participant d (Figure 2). Participants' e, f and j showed an increase (resaturation) in TSI (%) of the VL in the final moments of the cycle stage, indicating a decrease in intensity (S1). Outside of transition areas, no significant changes occurred in O_2Hb , HHb or tHb in the LD muscle during the laboratory simulated triathlon. Both TSI (%) signals showed an increase during T1, with a greater increase in TSI (%) of the LD. From this point TSI (%) of the LD decreased to a plateau ~6 km into the bike, where it remained stable for the rest of the bike. The reduction in TSI (%) of the VL occurred at a significantly faster rate where a plateau was reached at ~2 km. During T2, both TSI (%) traces displayed an 'M' shape,

characterised by rapid increases in TSI (%) upon the completion of the bike stage, then a drop in TSI (%), before a second spike as participants moved onto the run. During the run, both TSI (%) of the VL and LD decreased steadily until a plateau was reached, before a significant decrease in TSI (%) towards the end. $\dot{V}O_2$, HHb and tHb of the VL remained stable during the run. The greatest individual differences in TSI (%) response were seen during the run, with participants showing increases, decreases or stability in TSI (%) of the VL and LD. TSI (%) response across the full simulated triathlon from a representative subject is displayed in Figure 2, panel a.

Oxygen Consumption and Heart Rate Profile during Laboratory Simulated Sprint Distance Triathlon

HR increased rapidly as participant's commenced swimming, with the increase continuing 500 m, after which the rate of increase decreased. $\dot{V}O_2$ had small fluctuations throughout the swim but did not largely deviate from the pre-exercise baseline value. From T1 onwards, $\dot{V}O_2$ and HR followed a similar pattern. During T1, both variables rapidly returned levels similar to the first seconds of exercise, before rising equally as quickly as the bike commenced. After ~6 km of cycling there was a slight decline in $\dot{V}O_2$ and HR, before a plateau was reached which was maintained until the end of the bike. During T2, both $\dot{V}O_2$ and HR portrayed a 'W' shaped trace, characterised by a significant drop, a brief spike, and then a return to levels of that seen at the end of the bike. A slight consistent rise in $\dot{V}O_2$ and HR was seen during the run. This increased further from ~3 km, with an accelerated rise in the final stages which was most evident in the $\dot{V}O_2$ trace. $\dot{V}O_2$ and HR response across the full simulated triathlon from a representative subject is displayed in Figure 1 panel b.

Relative intensity

Relative intensity for $\dot{V}O_2$, HR and TSI (%) is provided in Figure 3. There was no significant effect of discipline (swim, bike, run) on relative intensity throughout the simulated triathlon ($F(2,18) = 3.487$, $p=0.052$, $\eta^2 = 0.023$). There was a significant effect of measure ($\dot{V}O_2$, HR, TSI (%)) on relative intensity throughout the simulated triathlon ($F(3,27) = 31.560$, $p<0.001$, $\eta^2 = 0.460$). There was a significant interaction effect between discipline and measure on relative intensity throughout the simulated triathlon ($F(6,54) = 11.277$, $p<0.001$, $\eta^2 = 0.182$).

Relative intensity of $\dot{V}O_2$ was comparable during swim, bike and run stages ($72 \pm 10\%$; $80 \pm 9\%$; and $82 \pm 6\%$ respectively) $p=0.144$. Relative intensity of HR remained consistent throughout swim, bike and run ($90 \pm 9\%$; $93 \pm 10\%$; $82 \pm 6\%$ respectively) $p=0.064$, with $\dot{V}O_2$ and HR portraying smaller standard deviations compared to TSI (%) values. TSI (%) of the VL was significantly different across disciplines, $p=0.016$. Pairwise comparisons highlighted differences between swim and bike disciplines ($14 \pm 32\%$ vs $91 \pm 54\%$; $p<0.001$), and bike and run disciplines ($91 \pm 54\%$ vs $41 \pm 36\%$, $p<0.001$) but comparable between swim and run disciplines ($14 \pm 32\%$ vs $41 \pm 36\%$; $p=0.571$) with large standard deviations across this measure. TSI (%) of the LD followed the same pattern with significant main effects across disciplines $p=0.016$. Significant differences were found between swim and bike ($43 \pm 32\%$ vs $8 \pm 16\%$; $p=0.047$), but comparable between swim and run ($43 \pm 32\%$ vs $19 \pm 18\%$; $p=1.000$), and bike and run ($8 \pm 16\%$ vs $19 \pm 18\%$; $p=1.000$), with swim having the greatest intensity followed by run and bike. When comparing between variables, TSI (%) of the VL was significantly lower than $\dot{V}O_2$ and HR across swim ($\dot{V}O_2$ $p<0.001$, HR $p<0.001$) and run disciplines ($\dot{V}O_2$ $p=0.047$, HR $p=0.041$), whilst TSI (%) of the LD differed to $\dot{V}O_2$ and HR in the bike ($\dot{V}O_2$ $p<0.001$, HR $p<0.001$) and run disciplines ($\dot{V}O_2$ $p<0.001$, HR $p<0.001$). When comparing upper and lower limb intensities, TSI (%) of the VL was higher than that of the LD during the bike ($p<0.001$) but comparable in both swim and run ($p=1.000$).

Table 1 - Maximal physiological responses to incremental exercise tests and mean responses during simulated triathlon (mean \pm SD).

		Swim	Bike	Run
$\dot{V}O_2$	Max Test	33 \pm 4	54 \pm 6	62 \pm 5
	Triathlon	24 \pm 6	43 \pm 7	51 \pm 6
HR	Max Test	142 \pm 18	168 \pm 14	180 \pm 14
	Triathlon	128 \pm 16	156 \pm 13	164 \pm 15
TSI VL	Max Test	-9 \pm 3	-16 \pm 5	-15 \pm 6
	Triathlon	-4 \pm 3	-1 \pm 3	-3 \pm 3
TSI LD	Max Test	-6 \pm 4	-14 \pm 3	-16 \pm 6
	Triathlon	-1 \pm 2	-13 \pm 8	-6 \pm 5

Note. TSI data is calculated as change from baseline.

$\dot{V}O_2$ = Oxygen Consumption ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), HR = Heart Rate (bpm), TSI = Tissue Saturation Index (%).

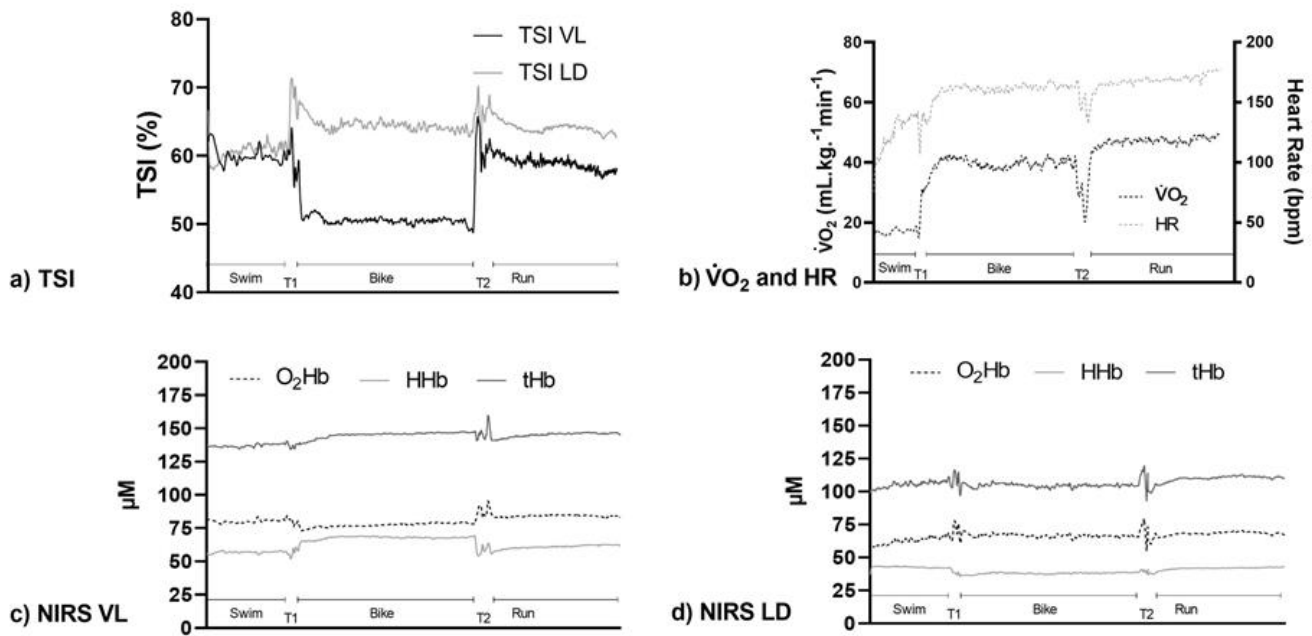


Figure 1. Panel A shows the TSI (%) VL (black line) and LD (grey line) response during swim, bike and run sections; Panel B shows the $\dot{V}O_2$ (dark line) and HR (light line); Panel C and D show the O_2Hb , HHb , tHb responses for the VL and LD respectively. T1 and T2 denote transition 1 and transition 2 respectively

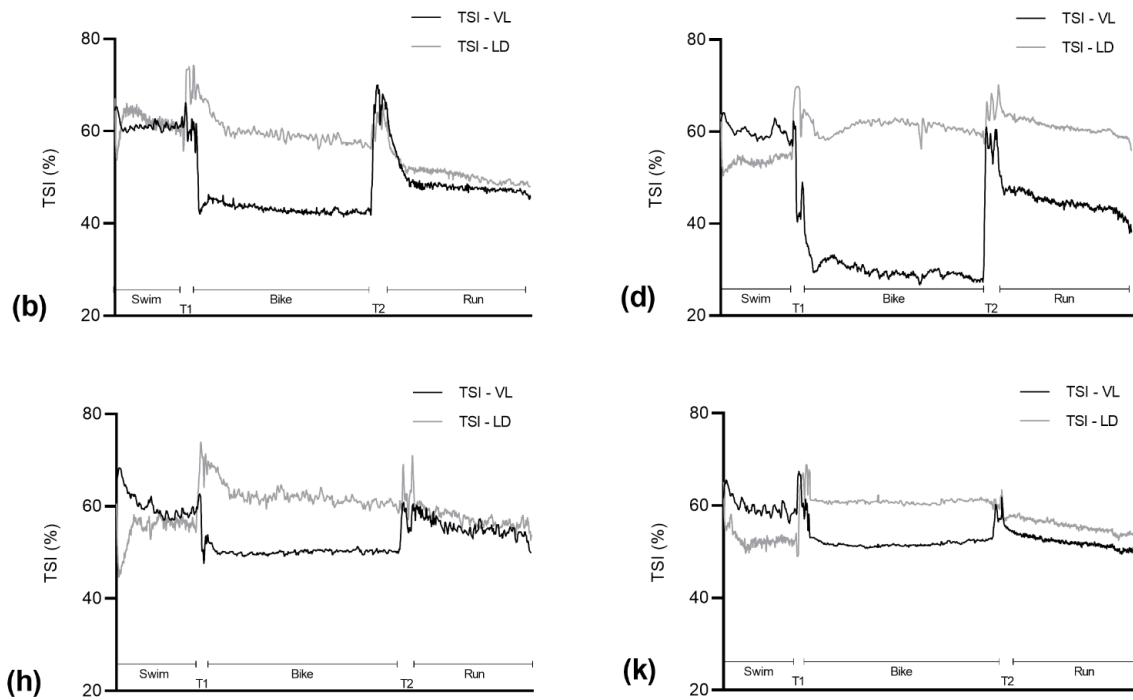


Figure 2. Panel B, D, H & K shows the TSI (%) VL (dark line) and LD (light line) response during swim, bike and run sections of simulated triathlon from selected participants. T1 and T2 denote transition 1 and transition 2 respectively.

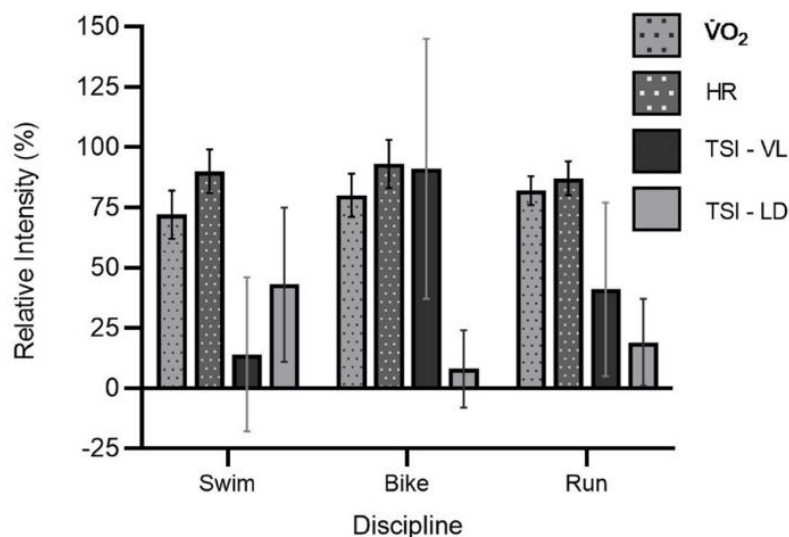


Figure 3. Relative Intensity of effort compared to maximal incremental tests for Tissue Saturation Index (TSI %); Vastus Lateralis (VL) and Latissimus Dorsi (LD), Heart Rate (HR) and Maximal Oxygen Uptake ($\dot{V}O_2$) during Laboratory Simulated Sprint Distance Triathlon for swim, bike and run disciplines.

DISCUSSION

Triathletes completed a simulated sprint triathlon at comparable exercise intensities to those seen within the literature; swim $72 \pm 10\%$, bike $80 \pm 9\%$, run $82 \pm 6\%$ for $\dot{V}O_2$ max (17, 18). Triathletes maintained $90 \pm 9\%$ of HRmax during the swim, higher than previously reported (85%) (19) with differences most likely due to differing maximal tests to calculate HRmax i.e., swim ergometry vs. treadmill test. Whilst not reported here, levels of blood lactate concentration and rating of perceived exertion were similar to those reported in competition, suggesting this was a valid simulation of a triathlon competition (19, 20).

Swim

The TSI (%) and $\dot{V}O_2$ measurements provide new insight into the swim discipline during triathlon. No study has previously reported the $\dot{V}O_2$ response during a swim stage of a triathlon. We saw that triathletes operated at a lower percentage $\dot{V}O_2$ max than any other time during the race. Unfortunately, there is no comparable $\dot{V}O_2$ or muscle oxygenation data for swim ergometry within the literature. The TSI (%) responses in the upper (LD) and lower limb (VL) have previously been reported in club level swimmers and triathletes (5). Triathlete swimmers demonstrated substantial desaturation in the upper but not lower limb which was different to the present study where most participants showed similar desaturation patterns in the upper and lower musculature, similar to that shown by club level swimmers (5). Interestingly, two participants (h and k (Figure 2)) had greater desaturation of the VL compared to the other participants. Differences were previously attributed to swim specialists using the lower body to a greater extent for propulsion in comparison to triathletes (5) but participants h and k did not display a

kicking motion during the swim, although it may be possible they were engaging the VL muscle to aid balance on the ergometer. The substantial desaturation in the VL of these participants (h and k) are most likely a result of sustained contraction of the lower limb during swimming and could be interpreted by a coach as a poor or inefficient swim technique in a live race setting.

Bike

During the bike large differences in the upper and lower body TSI (%) were seen, primarily due to the lower limb being responsible for power generation. The relatively stable nature of the VL TSI (%) during the bike indicates that triathletes maintained a constant power effort. This was supported by power output data (not reported). The relative intensity of the VL TSI (%) matched the HR and $\dot{V}O_2$ intensity which was one of the few occasions where peripheral and global intensity were similar. However, large inter-individual variations in desaturation were most pronounced in VL TSI (%) during the bike (Figure 3). For example, participant d experienced considerable desaturation (35.5% vs 16.6% group mean) without displaying any noticeable differences in HR or $\dot{V}O_2$. Similarly, variation in TSI (%) of the LD were seen during the bike which is likely explained by some participants using their upper body to generate extra power (21, 22). Indeed, this was evident from the LD TSI (%) desaturation during maximal incremental testing, when participants started to consciously pull on the bars in order to create more power (potentially a result of local vasoconstriction rather than a redistribution of oxygenation). Importantly, the large disparity between participant d and the group was only detectable via TSI (%), indicating the potential of this measurement for athletes and coaches.

Run

Variation in TSI (%) responses across all participants was greatest during the run. Generally, the TSI (%) was characterised by a steady decrease in oxygen saturation throughout, with more dramatic reductions towards the end as participants made their final burst to the finish line. The triathlon run is the only component where VL oxygenation has previously been investigated (3). Muscle oxygenation pattern in this study was similar; ~60% muscle oxygen saturation at run onset, although desaturation during running was slightly greater in this study (minimum desaturation 52% vs <40%). This difference may be explained by the differing muscle oxygenation devices used or different run distances (5 km vs 3 km) and therefore intensities which affects desaturation. The LD TSI (%) response during running has not previously been reported and was similar to that of the VL. $\dot{V}O_2$ and HR responses were comparable to those reported for similar events (17-19).

Practical Applications

Here we show the ability of NIRS to identify large variation in desaturation profiles across a homogenous group of triathletes. Muscle oxygenation usage was different between individuals, potentially indicating variation in discipline specific technique. NIRS can therefore aid coaches in examining athletes' techniques in order to refine movement patterns, with the long term aim of improving exercise efficiency/economy. Previous observations of muscle oxygenation in biathlon (8) and short track speed skating (23) have indicated similar

technical applications. As economy is an important determinant of triathlon performance (24), and swimming economy in particular an area where triathletes can make sizeable improvements (25), NIRS could provide valuable insight.

We acknowledge this study has limitations in terms of ecological validity. Whilst the primary aim was to complete a laboratory-simulation of sprint triathlon, there is a need to replicate this work within an outdoor environment, whereby a multitude of factors including; pacing strategy, responding to competitors and environmental demands (26, 27) would affect the physiological demands. However, $\dot{V}O_2$ and HR responses match those previously reported (17-19).

Conclusions

NIRS technology can be successfully implemented into triathlon to provide information on multi-site muscle oxygenation, identify differences between muscles and highlight potential areas that might improve technique and economy. We do not currently understand how the variance in muscle oxygenation between individuals is related to overall triathlon performance. These findings do however have implications for training and competition strategies, as they highlight the differences in physiological demand between the upper and lower body and between individuals across each discipline.

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