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Research article

The Effects of a Duathlon Simulation on Ventilatory Threshold and Running Economy

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Abstract
Multisport events continue to grow in popularity among recreational, amateur, and professional athletes around the world. This study aimed to determine the compounding effects of the initial run and cycling legs of an International Triathlon Union (ITU) Duathlon simulation on maximal oxygen uptake (VO_{2max}), ventilatory threshold (VT) and running economy (RE) within a thermoneutral, laboratory controlled setting. Seven highly trained multisport athletes completed three trials; Trial-1 consisted of a speed only VO_{2max} treadmill protocol ($SOVO_{2max}$) to determine VO_{2max}, VT, and RE during a single-bout run; Trial-2 consisted of a 10 km run at 98% of VT followed by an incremental VO_{2max} test on the cycle ergometer; Trial-3 consisted of a 10 km run and 30 km cycling bout at 98% of VT followed by a speed only treadmill test to determine the compounding effects of the initial legs of a duathlon on VO_{2max}, VT, and RE. A repeated measures ANOVA was performed to determine differences between variables across trials. No difference in VO_{2max}, VT ($\%VO_{2max}$), maximal HR, or maximal RPE was observed across trials. Oxygen consumption at VT was significantly lower during Trial-3 compared to Trial-1 ($p = 0.01$). This decrease was coupled with a significant reduction in running speed at VT ($p = 0.015$). A significant interaction between trial and running speed indicate that RE was significantly altered during Trial-3 compared to Trial-1 ($p < 0.001$). The first two legs of a laboratory based duathlon simulation negatively impact VT and RE. Our findings may provide a useful method to evaluate multisport athletes since a single-bout incremental treadmill test fails to reveal important alterations in physiological thresholds.

Key words: Multisport, sport performance, endurance, exercise prescription.

Introduction

The International Triathlon Union (ITU) serves as the governing body for all internationally sanctioned multisport events. These multisport competitions place a unique demand on athletes due to their need to perform a variety of sport modalities in a single event. Similarly, the coaches of these athletes have to manage acute and chronic training loads from a variety of modalities that further complicates the training model. Whether utilizing a traditional periodization model or an alternative periodization model (Issurin, 2010), key physiological measures such as maximal oxygen uptake (VO_2max), ventilatory threshold (VT), heart rate (HR), and blood lactate (BL) are often used to monitor, prescribe, and measure training related performance gains for endurance athletes (Bunc et al., 1995). While each of these periodization models have limitations (Issurin, 2010) they all aim to build fitness and ultimately increase athletic performance.

Scientific research, and the presentation of this research to the public, plays an important role in progressing sport and the periodization methods in sport. Investigating the compounding effects of multisport events on athletic performance requires complex experimental designs with transitions from one modality to another. The compounding effects of the first two exercise bouts on the final run performance have become an increasingly popular topic of research as the winner of a multisport event is often decided during the last leg of the competition (Landers et al., 2000; Vleck et al., 2006). De Vito et al. (1995) previously reported a decline in maximal oxygen uptake (VO_{2max}) and VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) at VT during the final running leg of an ITU Triathlon simulation. De Vito et al. (1995) concluded that these declines could potentially influence performance during the last leg of a triathlon race and recommended that coaches and athletes consider this information when developing racing strategies. While triathlon and duathlon events have some similar characteristics, the physiological consequences associated with the transition phases may invoke different physiological responses. Few studies have investigated the effects of cycling on a subsequent running bout (Bernard et al., 2003; Gottschall and Palmer, 2000; Hue et al., 2000; Suriano et al., 2007) or running on subsequent cycling performance (Chapman et al., 2008; Gottschall and Palmer, 2000; Suriano et al., 2007; Vercruyssen et al., 2002). The compounding effects of a duathlon event on running performance have been minimally investigated (Moncada-Jiménez et al., 2009; Sparks et al., 2005; 2013; Vallier et al., 2003). Both Moncada-Jiménez et al. (2009) and Sparks et al. (2013) investigated the effects of dietary modifications on duathlon performance. While both of these studies reported significant differences in carbohydrate and fat metabolism between dietary modifications, neither found significant differences in overall time. Conversely, Sparks et al. (2005) reported that carbohydrate and fat oxidation did not differ significantly between duathlon simulations performed at 10°C and 30°C. However, they did report that overall performance was faster in the 10°C environment compared to 30°C. Vallier et al. (2003) investigated the energy cost of running during an outdoor duathlon simulation, reporting that the energy cost of running was not significantly different between the initial, and final, running bouts. Each of these studies provides unique and insightful information on duathlon performance. The external validity of Vallier et al. (2003)

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provides highly meaningful information about multisport performance to coaches and athletes alike, however, insight into the compounding effect of the first two legs of the duathlon event on performance during the final running bout may have been limited by pacing strategy. While the physiological consequences of either a triathlon or duathlon event may be different due to the different transitional demands of each event, the alterations in final running performance observed during triathlon (De Vito et al., 1995) and duathlon (Vallier et al., 2003) simulations warrant further investigation.

Thus, the purpose of this study was to further expand on previous findings of duathlon performance by having athletes complete a duathlon simulation at the highest attainable intensity within a controlled laboratory setting. Specifically, our objective was to compare performance between a single-bout treadmill run and the final run of a duathlon simulation. Measures of maximal oxygen uptake (VO_{2max}), ventilatory threshold (VT), and running economy (RE) were used to assess differences between trials. We hypothesized that 1) VO_{2peak} would remain the same between Trial-1 and Trial-3 2) that VT would decrease, and 3) that RE would decrease during the final running bout of the duathlon simulation.

Methods

Subjects

Seven highly-trained multisport male athletes (age: 34 ± 9 years; height: 1.78 ± 0.04 m; weight: 73.9 ± 2.7 kg) were recruited to participate in this study. Participants included professional and elite age-group athletes who had been training a minimum of fifteen hours per week for a minimum of six months prior to beginning the study. Prior to participating in the study, each subject was fully informed of the methodological procedures. This study was approved by the Biomedical Institutional Review Board of the University of North Carolina at Chapel Hill. Participants provided written consent before completing a physical examination, medical history questionnaire, and a Par-Q (physical activity readiness questionnaire). Once participants were deemed healthy and low-risk (American College of Sports Medicine, 2010), they were scheduled for their first session.

Overview

Each athlete completed three testing sessions separated by a minimum of 72 hours and completed within a span of three weeks (Figure 1). Participants were asked to abstain from intense training 24 hours prior to each testing session. Trial-1 consisted of a single incremental treadmill test to determine VO_2max. Trial-2 consisted of a 10 km run at VT proceeded by an incremental test on the cycle ergometer to determine VO_2max. During Trial-3, participants performed a 10 km run and 30 km cycling bout at threshold before transitioning back to the treadmill to perform an incremental treadmill test to volitional exhaustion.

Ergometers

Incremental tests, as well as running and cycling bouts, were performed using the T2100 GE treadmill system (General Electric Company, USA) and Lode Corival electromagnetic breaking cycle ergometer (Lode B.V., Groningen, Netherlands). Athletes provided their saddle height (center of the bottom bracket to the top of the saddle) upon arrival at the lab for Trial-2 and all settings were recorded and replicated in Trial-3. All athletes provided their own clipless pedals; enabling them to wear their cycling shoes.

Pre-trial measures and questionnaires

Height and weight were recorded using a stadiometer (Perspective MO, USA) and Detecto 2381 balance beam scale (Detecto, Webb City, MO, USA) respectively. Prior to the start of each trial, urine specific gravity was assessed using a refractometer (TS Meter, American Optical Corp, Keene, NH, USA), to determine hydration status. In addition, adherence to pre-trial guidelines and preparedness was assessed using a questionnaire developed explicitly for this study. Specifically, the questionnaire asked about 24-hour exercise history and used 5-point Likert scales to assess fatigue and sleep quality. Individuals reporting high levels of fatigue, poor or limited sleep quality or individuals with poor hydration status (Casa et al., 2000) were rescheduled for a later date.

Determination of maximal oxygen uptake (VO_{2max}) and ventilatory threshold (VT)

VO_{2max} and VT were determined from incremental protocols. To determine VO_{2max} during Trial-1 and Trial-3, the treadmill speed began at 8 $km \cdot h^{-1}$ and the speed was increased 1.6 km/h each minute until a speed of 17.6 km/h. Beyond this point, incremental increases in speed were 0.8 $km \cdot h^{-1}$ each minute until volitional exhaustion (Vanhoy, 2012). During Trial-2, participants completed an incremental test on a cycle ergometer. All participants started at 150 Watts and intensity increased 50 watts every two minutes until a workload of 250 watts was reached. After this, resistance increased by 30 watts every 2 minutes until volitional fatigue. Oxygen uptake, minute ventilation, and the respiratory exchange ratio were collected continuously with a Parvo Medics TrueMax® 2300 Metabolic system (Parvo Medics, Salt Lake City, UT, modified V-slope method (Sue et al., 1988) and by determining the point corresponding to an increase in the

Trial-1: Incremental Treadmill Test
Trial-2: 10 km run at VT → Incremental test on Cycle Ergometer
Trial-3: 10 km run at VT → 30 km cycling bout → Incremental Treadmill Test

Figure 1. Overview of study design.

Table 1. Comparisons of maximal and submaximal values obtained during the three trials. Data are means (±SD).

	T1	T2	T3
VO_2max (ml·kg^{-1}·min^{-1})	66.8 (6.1)	65.1 (5.0)	63.7 (7.0)
BLmax	12.6 (2.5)	11.0 (2.0)	8.2 (2.1)*
HRmax (bpm)	182 (10)	184 (11)	179 (10)
RPEmax	19.1 (.7)	18.7 (1.0)	18.6 (.6)
Max Running Speed (km·h^{-1})	20.6 (1.4)	-	18.7 (1.2)*
VT (ml·kg^{-1}·min^{-1})	50.6 (4.1)	50.8 (3.8)	47.0 (5.8)*
VT (% VO_2max)	75.7 (3.5)	77.3 (6.9)	73.7 (5.6)
RER (at VT)	.90 (.03)	.92 (.10)	.84 (.04)* #
RPE (at VT)	13.9 (1.1)	13.9 (1.3)	12.8 (1.6)
Running Speed at VT (km·h^{-1})	14.9 (1.3)	-	13.5 (1.6)*
HRavg (10 km run)	-	163 (13)	159 (9)
RPEavg (10 km run)	-	13.5 (1.0)	13.0 (1.0)
HRavg (30 km cycling)	-	-	153 (8)
RPEavg (30 km cycling)	-	-	13.9 (1.3)
Watts (30 km cycling)	-	-	223.0 (11.9)
RE (slope)	.232 (.013)	-	.213 (.027)

* Denotes statistical significance between T1 and T3 ($p < 0.05$). # Denotes difference between T1 and T2 ($p < 0.01$).

ventilatory equivalent for oxygen (VE/VO_2) without an accompanying increase in the ventilatory equivalent for carbon dioxide (VE/VCO_2) (Davis et al., 1980). Three minutes post exercise, a finger-prick was used to determine blood lactate levels using the Lactate Plus lactate analyzer (Sports Resource Group, Hawthorne, NY). Heart rate was measured continuously throughout the trial and Borg's Ratings of Perceived Exertion (RPE) was used to subjectively measure exertion (Borg, 1998) at the end of each stage.

Prescribing and monitoring intensity during the 10 km run and 30 km cycling bout

Based on individual ventilatory threshold values, initial exercise intensity (running speed and wattage, respectively) for the 10 km run and 30 km cycling bout was set at 98% of VT for each subject. By definition, VT represents a workload that subjects can maintain for long durations. If a subject struggled to complete either of the steady state bouts during Trial-2 or Trial-3 at an intensity equal to 98% of VT, the intensity was decreased by 5%. To assure that individuals were not working above the desired intensity, oxygen uptake was monitored at regular intervals throughout the 10 km run [km 0-2, 5-7, and 9-10] and 30 km cycling [km 0-3, 10-13, and 25-28] bout. Subjects provided ratings of perceived exertion (RPE) every 5 minutes, while heart rate was monitored continuously throughout each of the three trials. Each subject was required to have an organized dietary and hydration plan, designed to mimic individual race-day nutritional preferences.

Calculation of running economy

Various methods are available for the calculation of running economy (RE). For the purposes of this study, RE was calculated as the oxygen uptake per given running speed (Conley and Krahenbuhl, 1980; Costill and Fox, 1969; Morgan and Craib, 1992). The slopes of the linear regressions obtained from submaximal VO_2 during Trial-1 and Trial-3 were subsequently compared (Costill and Fox, 1969; Saunders et al, 2004). Running economy was calculated for all sub-threshold running speeds and one running speed above the mean calculated threshold.

Statistical analyses

All data shown are mean ± standard deviation. All statistical procedures were performed using R statistical programming language. Normality was determined prior to analysis. Univariate repeated-measures analysis of variance (ANOVA) was used to determine differences between measures of VO_{2max}, HR_{max}, BL_{max}, RPE_{max}, VT (ml·kg^{-1}·min^{-1}), VT (% VO_{2max}), HR at VT, and RPE at VT across the three trials. Similarly, a repeated measures ANOVA assessed differences in oxygen uptake at each running speed between Trial-1 and Trial-3. Greenhouse-Geisser corrections addressed any sphericity violations and Bonferroni post-hoc tests compared differences whenever a main effect was present. Paired t-tests determined significant differences between maximal running speed, running speed at VT, and the regression slopes of VO_2 per running speed between Trial-1 and Trial-3. Significance was set at $\alpha = 0.05$ for all statistical procedures.

Results

Mean resting heart rate was 55(±8) bpm and was similar for all 3 trials. In addition, no significant differences in any of the potential confounding variables [hydration status, reported sleep, fatigue, and muscles soreness] were observed among the three trials (data not shown).

Maximal and submaximal values attained during the three trials appear in Table 1. There were no significant differences in VO_{2max} values attained during the three trials ($F_{(2,12)} = 3.02$, $p = 0.087$, $\eta^2 = 0.335$). Differences in maximal HR trended toward significance ($F_{(2,12)} = 3.73$, $p = 0.055$, $\eta^2 = 0.656$), and visual inspection suggests lower HR_{max} in Trial-3 compared to Trial-1 and Trial-2. A main effect for trial was observed for BL_{max} ($F_{(2,12)} = 28.9$, $p < 0.001$, $\eta^2 = 0.828$). Bonferroni post-hoc tests indicate a significant difference between BL_{max} values obtained during Trial-1 and Trial-3 ($p = 0.006$). No differences were observed in RPE_{max} among the three trials ($F_{(2,12)} = 0.93$, $p = 0.42$, $\eta^2 = 0.135$). Differences in maximal running speeds between Trial-1 and Trial-3 approached significance (df = 6, t = 2.291, $p = 0.06$). No differences were observed in VT among the three trials; sphericity was violated ($p < 0.001$) and a Greenhouse-Geisser correction was applied ($\mathcal{E} = 0.503$, $p = 0.34$, $\eta^2 = 0.153$). No differences among the three trials were observed for HR at VT ($F_{(2,12)} = 1.71$, $p = 0.22$, $\eta^2 = 0.222$), or for RPE at VT ($F_{(2,12)} = 3.21$, $p = 0.08$, $\eta^2 = 0.348$). No differences were observed between running speeds at VT between Trial-1 and Trial-3 (df = 6, t = 1.333, p = 0.23).

Comparison of RE expressed as relative oxygen uptake at each running speed indicated a significant interaction ($F_{(6, 36)} = 4.88$, $p = 0.001$, $\eta^2 = 0.449$) between time (Trial-1 and Trial-3) and running speed (Figure 2), however, the simple comparisons only approached significance (9.6 km·h^{-1}, p = 0.09; 11.2 km·h^{-1}, p = 0.06; 12.8 km·h^{-1}, p = 0.08). The slope of the regression lines for Trial-1 and Trial-3 were not statistically different (Table 1), and were very similar to those values previously reported (Conley and Krahenbuhl, 1980; Costill and Fox, 1969). No differences were observed between the regression slopes of submaximal VO_2 between Trial-1 and Trial-3 (df = 6, t = 1.658, p = 0.15).

Discussion

The purpose of this study was to investigate the effects of a laboratory based duathlon simulation, completed at the highest attainable intensity, on final run performance. Our goal was to effectively control for exercise intensity within a thermoneutral environment and examine the physiological responses of highly-trained multisport athletes. We hypothesized that; 1) VO_{2peak} would not differ between Trial-1 and Trial-3, 2) VT would decrease during the final running bout of the duathlon simulation, and 3) RE would decrease during Trial-3. We observed a significant decrease in relative oxygen uptake at VT during Trial-3 compared to Trial-1. Corresponding running speeds decreased; falling from 15.5 km·h^{-1} during Trial-1 to 13.9 km·h^{-1} during Trial-3. In our population, this decline in running speed equates to a 134 second increase in the time to complete a 5 km running bout, a substantial difference for any competitive athlete. Training practices that mitigate this decline in running speed would provide significant competitive advantages to high performance multi-sport athletes.

Contrary to the findings previously reported by Vallier et al. (2003), these results suggest a negative effect of the cycle-to-run transition during a duration event and more closely agree with findings previously reported in triathlon (De Vito et al., 1995). However, it is important to consider the external validity of Vallier et al. (2003). The complex nature of an ITU Duathlon often means that athletes are not always working at, or near, threshold. The draft legal nature of the ITU Duathlon means that race dynamics are drastically different from the highly controlled laboratory environment of the current study. Both tactical awareness and split second decision-making are vitally important in determining who crosses the line in first place. For instance, drafting during a cycling event has been shown to elicit a 39% reduction in energy cost (McCole et al., 1990). The nature of these events forces these athletes to periodically work above threshold in an effort to either strain, or detach, their opponents from the lead group, or maintain contact with others trying to form a split in the group. While an outdoor simulation may offer a more race-like experience by allowing individuals to employ pacing strategies similar to a competitive event, our design maintains a higher degree of control. This provides us the opportunity to determine the physiological consequences associated with having performed a duathlon event at the highest attainable intensity. While it is unlikely that an athlete would complete a competitive event at the intensities outlined in the current design, the controlled laboratory setting of this study provides a unique opportunity to determine the metabolic and mechanical consequences of a duathlon event if an individual could maintain such high intensities during competition. Most importantly, our findings stress the importance of employing various pacing strategies throughout a competitive event.

As a means of removing the effects of environmental conditions and race strategies, the intensities

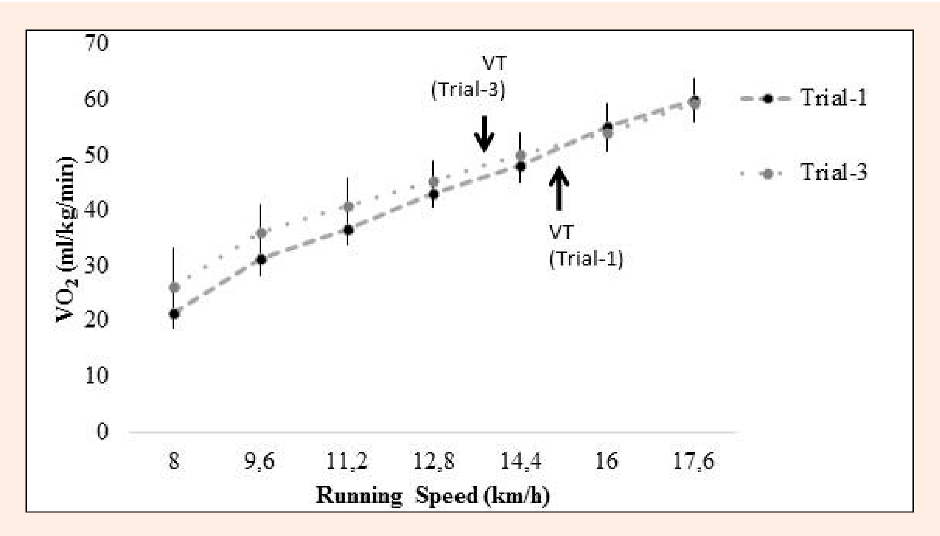

Figure 2. Running economy, expressed as a comparison of VO_2 at each submaximal running speed during the incremental treadmill tests performed during Trial-1 and Trial-3. Arrows indicate the calculated ventilatory threshold for Trial-1 and Trial-3 respectively.

throughout the 10 km run and 30 km cycling time trial were intensely monitored and controlled (Table 1); forcing each participant to work at the highest attainable intensity. Although subjects were not able to vary their power output throughout the cycling bout, participants did vary their cadence. While freely chosen cadence has been shown to contribute to an increased energy cost and the appearance of the VO_2 slow component during subsequent running bouts (Vercruyssen et al., 2002), individuals were permitted to choose their own cadence as a means of increasing the application of our findings into a training environment. The potential limitation of different cadences on energy cost was certainly attenuated by using an electronically braked cycle ergometer, allowing subjects to pedal at their chosen cadence, and interval checks on oxygen uptake.

Our analysis of RE, expressed as oxygen uptake at each running speed, indicate that oxygen uptake was altered at different intensities. Our results show that at intensities below ventilatory threshold, individuals were working at a higher percentage of maximal oxygen uptake per given running speed during Trial-3 compared to Trial-1 (Figure 2). While the slopes of the regression lines between Trial-1 and Trial-3 were not statistically different, visual interpretation of this data indicated a leftward shift in the regression lines. This observation supports the findings from our ANOVA, suggesting a decrease in RE during the final running bout of a duathlon simulation. The lack of statistical significance is likely due to the small sample size of the current study. The increase in the RER and decrease in peak blood lactate observed during Trial-3 suggests a higher contribution of energy coming from gluconeogenic processes. These findings suggest that individuals were more reliant on anaerobic energy production at lower running speeds and may have been one of the key factors responsible for reduced peak blood lactate values observed in Trial-3. These findings are supported by the RPE data collected at VT which suggests that the athletes perceived to be working at the same intensity.

Tactical decisions made by the athletes throughout a race influence the strategies that are required to finish the race and ultimately determine final race time and placement. While an individual working at an increasingly inefficient intensity during the final running leg of a duathlon competition would likely have fewer glycogen stores available at the very end of the race, this issue becomes completely irrelevant if an un-bridgeable gap between this individual and the other competitors is already present. Analogously, if an athlete has worked at the intensity that we have discussed but they are not part of the lead group and can't bridge the gap late in the race despite significantly increasing their pace, it does not matter whether the necessary energy stores are present. In either case, the race outcome is similar despite the reason(s) and the delicate balance between energy availability and race strategy/tactical decisions is indisputable.

We recognize that our findings have limitations inherent to this type of study design. A relatively small sample size limits the statistical power and a larger sample would be necessary for confident interpretation of the results. Although individuals were encouraged to adjust the cycle ergometer to mimic their own time-trial bikes as closely as possible, they were often unable to reproduce the exact racing position. A slight alteration in position may have affected performance during the incremental test in Trial-2 and the cycling bout completed during Trial-3. The main objective of the current study was to examine the physiological effects of a duathlon simulation on running performance during the last 5 km of a duathlon event in absence of tactical and/or pacing strategies normally used in these types of events. While we recognize that our design severely limits the application of the results into both an outdoor situation and a competitive race situation, assessing physiological effects on performance outcomes during actual competition often result in complicated or muddied results confounded by environmental influences and the context surrounding competition. However, both types of studies are necessary to provide a rigorous scientific basis for training multi-sport athletes. Our findings provide additional, complementary information for athletes and coaches that when combined with the findings from studies that more closely mimic competition, such as Vallier et al. (2003), allow athletes to prepare more judiciously for multi-sport events. Specifically, these findings suggest that coaches and athletes should monitor VT throughout the training schedule as well as changes in running speed during and across training sessions in order to evaluate the effect of training on an individual's resistance to fatigue.

Conclusion

In summary, we suggest that our findings may provide a more appropriate, and reliable, method for evaluating duathlete preparedness for competition, since a single-bout treadmill run to exhaustion fails to reveal important information regarding the alteration of physiological thresholds. Future research should include a more robust method of determining acute and chronic training loads in these athletes prior to their enrollment into the study; it would be ideal to test each subject closer to the point at which they plan to peak for competition. Additional measures, such as long- and short-term analysis of resting heart rate variability, power output, heart rate, sleep patterns, and subjective questionnaires in the weeks preceding and during the laboratory tests would provide useful information in quantifying training load and readiness. A larger sample size would provide the means to predict running economy during the last leg of the duathlon. Nevertheless, the relatively homogeneous sample of highly trained multi-sport athletes, and the precision of the measurements used in the study, gives us a robust idea of the potential compounding effects of the initial run and cycling performance on the final run of a ITU duathlon simulated event in the laboratory.

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References

American College of Sports Medicine., Thompson, W.R., Gordon, N.F. and Pescatello, L.S. (2010) *ACSM's guidelines for exercise testing and prescription*. Philadelphia: Lippincott Williams & Wilkins.

Bernard, T., Vercruyssen, F., Grego, F., Housswirth, C., Lepers, R., Vallier, J.-M. and Brisswalter, J. (2003) Effect of cycling cadence on subsequent 3 km running performance in well trained triathletes. *British Journal of Sports Medicine* **37(2),** 154-158.

Borg, G. (1998) *Borg's Perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Bunc, V., Hofmann, P., Leitner, H. and Gaisl, G. (1995) Verification of the heart rate threshold. *European Journal of Applied Physiology and Occupational Physiology* **70(3),** 263-269.

Casa, D.J., Armstrong, L.E., Hillman, S.K. and Montain, S.J. (2000) National Athletic Trainers' Association position statement: Fluid replacement for athletes. *Journal of Athletic Training* **35(2),** 212-224.

Chapman, A.R., Vicenzino, B., Blanch, P., Dowlan, S. and Hodges, P.W. (2008) Does cycling effect motor coordination of the leg during running in elite triathletes? *Journal of Science and Medicine in Sport* **11(4),** 371-380.

Conley, D.L. and Krahenbuhl, G.S. (1980) Running economy and distance running performance of highly trained athletes. *Medicine and Science in Sports and Exercise* **12(5),** 357-360.

Costill, D.L. and Fox, E.L. (1969) Energetics of marathon running. *Medicine & Science in Sports & Exercise* **1(2),** 81-86.

Davis, J.A., Whipp, B.J. and Wasserman, K. (1980) The relation of ventilation to metabolic rate during moderate exercise in man. *European Journal of Applied Physiology and Occupational Physiology* **44(2),** 97-108.

De Vito, G., Bernardi, M., Sproviero, E. and Figura, F. (1995) Decrease of endurance performance during olympic triathlon. *International Journal of Sports Medicine* **16(1),** 24-28.

Gottschall, J.S. and Palmer, B.M. (2000) Acute effects of cycling on running step length and step frequency. *Journal of Strength and Conditioning Research* **14,** 97-101.

Hue, O., Le Gallais, D., Boussana, A., Chollet, D. and Prefaut, C. (2000) Performance level and cardiopulmonary responses during a cycle-run trial. *International Journal of Sports Medicine* **21(4),** 250-255.

Issurin, V.B. (2010) New horizons for the methodology and physiology of training periodization. *Sports Medicine* **40(3),** 189-206.

Landers, G.J., Blanksby, B.A., Ackland, T.R. and Smith, D. (2000) Morphology and performance of world championship triathletes. *Annals of Human Biology* **27(4),** 387-400.

McCole, S.D., Claney, K., Conte, J.C., Anderson, R. and Hagberg, J.M. (1990) Energy expenditure during bicycling. *Journal of Applied Physiology (Bethesda, Md. : 1985)* **68(2),** 748-753.

Moncada-Jiménez, J., Plaisance, E.P., Mestek, M.L., Ratcliff, L., Araya-Ramírez, F., Taylor, J.K., Grandjean P.W. and AragónVargas L.F. (2009) Duathlon performance unaltered by short-term changes in dietary fat and carbohydrates. *International Journal of Sport Nutrition* **19(1),** 47.

Morgan, D.W. and Craib, M. (1992) Physiological aspects of running economy. *Medicine and Science in Sports and Exercise* **24(4),** 456-461.

R Development Core Team. (2008) R: A language and environment for statistical computing (Version 3.2.2). Vienna, Austria: R Foundation for Statistical Computing. Available form URL: http://www.R-project.org.

Saunders, P.U., Pyne, D.B., Telford, R.D. and Hawley, J.A. (2004) Reliability and variability of running economy in elite distance runners. *Medicine and Science in Sports and Exercise* **36(11),** 1972-1976.

Sparks, S.A., Cable, N.T., Doran, D.A. and Maclaren, D.P.M. (2005) The influence of environmental temperature on duathlon performance. *Ergonomics* **48(11-14),** 1558-1567.

Sparks, S.A., MacLaren, D.P., Bridge, N.E., Cable, N.T. and Doran, D.A. (2013) Laboratory simulated duathlon performance: effects of pre-exercise meals. *International Journal of Sport Nutrition and Exercise Metabolism* **23(6),** 610-616.

Sue, D., Wasserman, K., Moricca, R. and Casaburi, R. (1988) Metabolic acidosis during exercise in patients with chronic obstructive pulmonary disease. Use of the V-slope method for anaerobic threshold determination. *Chest* **94(5),** 931-938.

Suriano, R., Vercruyssen, F., Bishop, D. and Brisswalter, J. (2007) Variable power output during cycling improves subsequent treadmill run time to exhaustion. *Journal of Science and Medicine in Sport* **10(4),** 244-251.

Vallier, J.-M., Mazure, C., Hausswirth, C., Bernard, T. and Brisswalter, J. (2003) Cout energetique de la course a pied lors de l'enchainement specifique d'un duathlon. *Canadian Journal of Applied Physiology* **28(5),** 673-684.

Vanhoy, R. (2012) *A Comparison of two different treadmill protocols in measuring maximal oxygen consumption in highly trained distance runners* (Thesis). The University of North Carolina at Chapel Hill, Chapel Hill, NC.

Vercruyssen, F., Brisswalter, J., Hausswirth, C., Bernard, T., Bernard, O. and Vallier, J.-M. (2002) Influence of cycling cadence on subsequent running performance in triathletes. *Medicine and Science in Sports and Exercise* **34(3),** 530-536.

Vleck, V. E., Bürgi, A. and Bentley, D.J. (2006) The consequences of swim, cycle, and run performance on overall result in elite olympic distance triathlon. *International Journal of Sports Medicine* **27(1),** 43-48.

Key points

- Decrease in relative oxygen uptake at VT ($ml\cdot kg^{-1}\cdot min^{-1}$) during the final leg of a duathlon simulation, compared to a single-bout maximal run.
- We observed a decrease in running speed at VT during the final leg of a duathlon simulation; resulting in an increase of more than 2 minutes to complete a 5 km run.
- During our study, highly trained athletes were unable to complete the final 5 km run at the same intensity that they completed the initial 10 km run (in a laboratory setting).
- A better understanding, and determination, of training loads during multisport training may help to better periodize training programs; additional research is required.

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