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Heart Rate Acquisition and Threshold-based Ranges for Triathletes

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Heart Rate Acquisition and Threshold-based Ranges for Triathletes

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in Physiological Sciences

by

Ethan Nguyen Ogden

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ABSTRACT OF THE THESIS

Heart Rate Acquisition and Threshold-based

Ranges for Triathletes

by

Ethan Nguyen Ogden

Master of Science in Physiological Sciences

University of California, Los Angeles, 2017

Professor Christopher B. Cooper, Chair

Introduction: Exercise intensity is a critical component of the exercise prescription model. Previous research suggests that the method of exercise intensity prescription may underpin the inter-individual variation in cardiorespiratory response (VO_2) to exercise training. Past studies that employed several non-specific exercise intensity protocols have reported wide variability in participants' VO_2 measured after training. This suggests a present lack of consensus regarding the optimal heart rate training zones that will result in maximal athletic performance. **Methods**: Thirteen (males=4) UCLA club-level triathletes were recruited for 8 weeks of remote heart rate monitoring during all running and cycling sessions. Participants donned a forearm-worn optical heart rate sensor device (Scosche Rhythm+ ™) paired to a smartphone that remotely collected, stored and transferred heart rates. **Results**: Subjects were categorized into Low (94.2 ± 3.0% in

Zone 1) and High (64.2 ± 9.4% in Zone 1) groups. The Low group spent significantly more time in Zone 1 (p=0.026). Significant increases were observed in absolute VO_{2max} (P = 0.030, g = 0.29), relative VO_{2max} (P = 0.007, g = 0.48), $VO_2\theta$ (P = 0.018, g = 0.35), and $V_E\theta$ (P = 0.030, g = 0.29) from baseline after eight weeks for both groups. Large and significantly greater changes in $VO_2\theta$ were observed in the High group (0.37 ± 0.15 L/min) compared to the Low group (0.17 ± 0.14 L/min). **Conclusion**: Data show that no significant differences were observed in individuals who spent significantly more time training above MT. However, spending more time training above MT led to greater delays in $VO_2\theta$, which has proven to be a key measure in predicting aerobic performance. All subjects favored the polarized method of training compared to the threshold-based model.

The thesis of Ethan Nguyen Ogden is approved.

James G. Tidball

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University of California, Los Angeles

2017

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Introduction

The goal of any individualized exercise prescription, whether for a competitive athlete or a general fitness enthusiast, is to maximize training efficacy and limit unresponsiveness. In terms of exercise prescription, there are four key components known as the F.I.T.T. principle: frequency, intensity, time, and type of exercise[36]. Of these four principles, exercise intensity seems to be the most vital to driving improvements. Exercise intensity prescription may underpin the inter-individual variation in cardiorespiratory (VO_2) response to exercise training. Individuals training below optimal exercise intensity levels see minimal results from their training while those who train above optimal intensity levels are prone to overtraining[36].

Cardiorespiratory fitness is best measured by testing an individual's maximal oxygen consumption (VO_{2max}). These tests are typically performed on a cycle ergometer or a treadmill, although the latter has been shown to produce more accurate results[30]. A recent study at the University of Southern Maine by Scott et al. revealed that an individual's rate of perceived exhaustion (RPE) was similar during both tests, but oxygen uptake was significantly higher during treadmill testing[30]. VO_{2max} testing is not only an important measure for athletic performance; it is also a key indicator of cardiovascular health. Increases in an individual's VO_{2max} provide strong correlations with a decreased risk of cardiovascular disease[4, 35, 36]. According to the Centers for Disease Control and Prevention, heart disease is the leading cause of death in the United States, accounting for 1 in every 4 deaths[6]. The value of VO_{2max} testing is evident and a prescription of exercise intensity to increase individuals' cardiorespiratory output thus warrants further investigation.

In terms of athletic performance, increases in VO_2 correlate to increased endurance during competition and the ability to perform at maximum capabilities. In triathletes and other elite endurance athletes, training at optimal exercise intensity is crucial for maximizing training efficacy. Traditionally, exercise intensity prescriptions followed the relative percent method determined by the American College of Sports Medicine (ACSM)[24, 36]. These methods use either percentages of maximum heart rate (%HR_{max}), heart rate reserve (%HRR), or oxygen uptake reserve (%VO_2R), prescribing training at an exercise intensity of 40-59% of these three measures[24]. This method of training is outdated and provides no individualization, yet it remains ubiquitous throughout prescriptions of intensity-based training. Wide variability exists in this method due to the assumption that stress levels during exercise are equivalent across individuals even though absolute exercise capabilities differ[22]. A more individualized training approach is needed to minimize variation in training adaptation.

One important measure omitted from the relative percent concept is an individual's blood lactate levels during exercise[17]. This key limitation contributes significantly to the lack of consistency in the efficacy of this training method. Analysis of blood lactate, whether by direct or indirect methods, is critical for the determination of an appropriate exercise intensity prescription. Studies using the relative percent method as the training methodology have demonstrated wide variation in blood lactate levels in elite endurance athletes[23, 34]. Recommending a fixed-intensity training method based solely on %HR_{max}, %HRR, and %VO_2R results in substantial variability because the metabolic threshold (MT)—defined in Dolezal et al.[9] as the threshold between the lower and intermediate domains of exercise intensity[33]—occurs at different percentages of these measurements across individuals. For example, increases in VO_{2max} are highly correlated to delays in reaching MT, so undertrained individuals will reach MT much sooner than elite endurance athletes. Therefore, prescriptions of exercise intensity must account for metabolic responses in order to maximize the individualization and efficacy of training.

The most prominent of these exercise prescription paradigms is the threshold-based method, which stands as the current recommendation by the American Council on Exercise (ACE)[5]. This method utilizes both the MT and ventilatory threshold (VT)[9] in programming an intensity-based exercise training protocol. With this approach, individuals spend the preponderance of time training at or near their MT[18, 20, 31]. Based on the results of a recent study at Western State Colorado University comparing the threshold-based method to the relative percent method, the former produced significant increases in VO_{2max} in 100% of subjects whereas the relative percent method increased VO_{2max} in only 41.7% of subjects[36].

Other training methods using key metabolic responses have been examined. The polarized training method employs a combination of the threshold-based method and the relative percent method, leading to the majority of training time spent significantly above or below MT[31, 32]. Evidence suggests that this method is preferred for elite-level endurance athletes while the threshold-based model remains more efficacious in untrained individuals[3, 14, 20, 31]. However, debate exists whether the polarized training model is indeed an effective intensity-based training prescription. Further research ought to establish an optimized intensity-based training program for elite endurance athletes based on key metabolic responses in order to maximize effectiveness of training and improve performance.

The purpose of this study was to (*i*) remotely acquire heart rates (HRs) of collegiate triathletes during 8 weeks of training in preparation for a national competition, and (*ii)* determine the identity and efficacy of the training method used by characterizing the percentage of time spent in HR zones derived from baseline VO_{2max}, MT, and VT. It was hypothesized that participants who spent more time training in the HR zones above MT would experience greater improvements in VO_{2max} compared to those who spent a greater percentage of training time below MT.

Methods

Thirteen triathletes, both male and female (male = 6), were recruited from the club level triathlete team and the University of California, Los Angeles. All subjects were between the ages of 18 and 25 and were recruited by their coach, who was an elite-level triathlete. Subjects agreed to 8 weeks of HR monitoring during their training and were instructed not to change their diet throughout and to maintain training as usual throughout the 8 weeks in preparation for their national competition. These subjects were enrolled in 8 weeks of training leading up to their team competition for the national championship. At the national championship meet, the girl's team finished first and the guy's team finished third, combining for an overall second place finish.

Pre-Testing Guidelines

All participants were asked to report to the UCLA Exercise Physiology Research Laboratory well hydrated and to refrain from consuming alcohol and caffeine for at least 24 hours, as well as refrain from engaging in strenuous exercise at least 12 hours prior to testing. Prior to testing, participants gave written informed consent. Inclusion criteria included absence of musculoskeletal conditions or cardiovascular, pulmonary, metabolic or other disorders that would preclude high-intensity exercise testing. The pre- and post-tests included body mass (BM) and body fat percentage (%BF) measures and a continuous, incremental maximal treadmill test (VO_{2max}).

Anthropometric Measures

Using a recently validated, octopolar, multi-frequency bioelectrical impedance analysis scale (InBody R20 scale, Biospace, Inc, Seoul Korea), participants stood upright with the ball and heel of each foot on two metallic footpads with both hands gripping a bar with metallic electrodes. The instrument measured both weight and body fat percentage (%BF) within 30 seconds. Height was also measure prior to testing using a stadiometer.

VO_{2max} Assessment

Aerobic capacity, (VO_{2max}), and the lactate and ventilatory thresholds determined by gas exchange were measured during an incremental, symptom-limited maximal treadmill exercise test using standard procedures with an incremental walking-running treadmill protocol. Oxygen uptake (VO_2), carbon dioxide output (VCO_2), and pulmonary minute ventilation (VE) were measured breath-by-breath with a metabolic measurement system (Oxycon Pro; CareFusion, Yorba Linda, CA, USA). These data were continuously monitored and recorded during 3 minutes of warm-up and throughout the exercise test. Similarly, heart rate was continuously monitored with a 12-lead EKG interfaced to the metabolic measurement system for display and storage. Testing started immediately following the 3-minute walking warm-up, with the treadmill set to 4 mph with a grade of 1%. Speed on the treadmill increased 0.5 mph every minute and grade increased 1% every 2 minutes. Trained and experienced investigators conducted all testing in accordance with established guidelines for cardiopulmonary exercise testing. Maximal oxygen uptake was determined from the highest 15-second average and accepted as maximal in the presence of a plateau in VO_2 with increasing work rate. Gas exchange indices of VO_2 at thresholds were ascertained graphically from plots of VCO_2 versus VO_2 and/or the ventilatory equivalents for oxygen (V_E/VO_2) and carbon dioxide (V_E/VCO_2). Two investigators independently selected VO_2 at MT and VT. If both selected VO_2 values at these thresholds agreed within 150 ml/min, the average was used. If the difference was > 150 ml/min, a consensus value was achieved by discussion. Rating of perceived exertion (RPE) was taken periodically during and immediately following the test using the Borg 6-20 scale.

Heart Rate Zone Threshold Determination

Three HR zones were determined after each subject performed the baseline maximal endurance exercise test. Metabolic Threshold and Ventilatory Threshold were used to denote thresholds and both were determined using a Cooper 4-plot (Figure 1). The top left plot in the Cooper 4-plot is a plot of VO_2 (red) and VCO_2 (blue) over time. Absolute VO_{2max} can be determined using this plot. An estimation of MT can also be determined from this plot by the crossing over of VO_2 and VCO_2. A more accurate determination of MT was obtained from the top right plot of VCO_2 versus VO_2. Typically, 2 breaks in linearity are observed in this graph. The first break in linearity represents MT and should be closely related to the crossover point in the top left plot. The second break in linearity represents VT, and this threshold can be confirmed in the bottom left plot. This plot shows the relationship between ventilation during the test and VCO_2. One break in linearity is typically observed in this plot, representing VT. The bottom right plot is a plot of HR versus VO_2, typically showing a linear relationship in healthy individuals. This plot was used to determine the three HR zones. Since the x-axis of this plot mirrors the x-axis of the plot directly above it, HR at MT and VT was determined by drawing a straight line down from the MT and VT determined in the above plot. HR zone 1 was characterized by heart rates below MT, HR zone 2 was characterized by heart rates between MT and VT, and HR zone 3 was characterized by heart rates above VT.

Remote Heart Rate Monitoring

After baseline VO_{2max} testing, each subject was given a Scosche Rhythm+ ™ forearm band heart rate monitor. They were instructed to capture HR data during every running and cycling training session without deviating from their typical pre-competition training. The Scosche Rhythm+ ™ collected HR data every second and paired with any Bluetooth compatible device. Subjects used their phones to pair the HR monitor to an iRunner smartphone application. This application allowed subjects to see their HR during training and easily send the data straight from their phone. Each subject was instructed to send the HR data after each training session. The data consisted of HRs captured every second during training, as well the method of training (running or cycling) and a self-reported intensity of exercise.

Statistical Analysis

HRs were sent via the iRunner smartphone application following every workout. The R and Python programming languages were used as the primary methods of HR data analysis. Some of the packages used include "pandas", "NumPy", and "Matplotlib". Jupyter Notebook, an interactive environment within an open-source application, was used for the code execution. The raw HR data points were first cleaned and organized via basic parsing and reformatting. Percentage of HR data below, within, and above ranges delineated by the MT and VT were then programmatically calculated. The data points were incorporated workout-by-workout to coordinate each dependent y-value to an independent x-value established from a normalized time axis. After plots for each subject were generated, mean percentages for time spent in each HR zone during training were calculated for all subjects. Participants were then divided into two groups based on the percentage of time (%time) spent in Zone 2: Low (< 20%) and High (≥ 20%).

Because no previous data exist for these parameters in this population, this investigation was treated as a pilot study and thus sample size was not formally determined. Analysis was performed in Excel (Microsoft Corporation, Redmond, Washington) and R (version 3.4.0; R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics are presented as mean ± standard deviation (SD). Statistical significance was determined based on $\alpha = 0.05$ and all tests were two-tailed. Continuous variables were first assessed for normality via Shapiro-Wilk tests. Comparisons at baseline and after eight weeks of training were made by paired t-tests using a Holm-Bonferroni correction to control the familywise error rate. Hedges' g measured effect sizes and a Pearson's product-moment correlation matrix examined linear relationships. Due to the small sample sizes, the changes in variables between the Low and High groups were analyzed using nonparametric bootstrapping with 10,000 replicates to yield a bias-corrected and accelerated 95% confidence interval.

Results

Data at baseline and after eight weeks of training were collected for nine subjects who completed all testing and monitoring. Four of the 13 participants did not complete the study due to incomplete remote HR monitoring (n = 1), failure to complete final testing (n = 2), or injury (n = 1). The breakdown of %time spent in each of the three HR zones is displayed in Table 1. Six triathletes constituted the Low group, and three comprised the High group. All subjects trained primarily in Zone 1 (84.2 ± 15.9%); however, triathletes in the Low group spent significantly more time in Zone 1 (94.2 ± 3.0%) than those in the High group (64.2 ± 9.4%; P = 0.026). In contrast, the Low group trained significantly less in Zone 2 (5.1 ± 2.3%) than the High group (28.5 ± 4.9%; P = 0.008). Figure 2 shows a plot of individual HR data for each workout with demarcation lines at MT and VT. %Time spent in Zone 2 is also shown on these graphs. These plots were generated for all subjects.

From initial testing, all participants were measured to be in the 90th percentile or above for VO_{2max} based on the American College of Sports Medicine's age- and gender-matched cardiorespiratory rankings[16]. As demonstrated in Table 2, significant increases were observed in absolute VO_{2max} (P = 0.030, g = 0.29), relative VO_{2max} (P = 0.007, g = 0.48), $VO_2\theta$ (P = 0.018, g = 0.35), and $V_E\theta$ (P = 0.030, g = 0.29) from baseline after eight weeks. No significant differences were measured in body mass, %BF, or $VO_2\theta/VO_{2max}$. Moderate linear correlations were identified between the %time in Zone 2 and the change in $VO_2\theta$ (r = 0.48) as well as the %time in Zone 2 and the change in $VO_2\theta/VO_{2max}$ (r = 0.44); however, neither were statistically significant (P = 0.194 and P = 0.237, respectively). The change in outcome variables between the Low and High groups after eight weeks is depicted in Table 3. A 95% confidence interval that did not include zero (-0.38, -0.03; g = 1.26) revealed a large and significantly greater change in $VO_2\theta$ in the High group (0.37 ± 0.15 L/min) versus the Low group (0.17 ± 0.14 L/min). Although not significant, a large effect size (95% CI: -7.27, 0.22; g = 0.95) was observed between the change in $VO_2\theta/VO_{2max}$ (High: 3.6 ± 3.3%; Low: 0.3 ± 3.0%). Changes in all other measures lacked significance and exhibited small effect sizes.

Discussion

The primary conclusion of this study is an indication that these triathletes trained in an effective manner for eliciting significant improvements in absolute and relative VO_{2max}. However, no significant differences were observed in individuals who spent significantly more time training above MT, so the hypothesis that spending more time training above MT correlates to greater improvements in VO_{2max} cannot be accepted. Overall, these triathletes spent 84.2% of their training time below MT, eliciting significant improvements in VO_{2max}. Further testing needs to be done to determine specific percentages in each HR zone to maximize training efficacy. Although the results from the group that spent significantly more time training above MT did not show significance, the method of training employed by both groups correlates with the polarized model of training. The data from this study suggests this method to be superior to the threshold-based model for training in elite endurance athletes.

These techniques could be applied to triathlon training prescriptions. Olympic distance triathlon training is typically a 12-18 week program broken into 3 phases: base, build, and taper. The base phase is comprised of the first few weeks of training, characterized by limited increases in pace. Pace increases in the build phase, but this phase focuses more heavily on volume. Finally, the taper phase begins 2 weeks prior to competition characterized by a reduction in volume[2, 8, 12, 13, 19, 29].

Although these training programs mention intensity, they stress volume. Better results would be seen if a greater emphasis were placed on intensity. In addition, better methods for measuring intensity could be used. Almost all triathlon training plans prescribe intensity by specifying pace. Although pace can be a marker for intensity, it is a non-specific measure and a more individualized intensity measurement should be applied. Even when intensity is factored into training, it follows the relative percent method, which is proven to be inferior in comparison to intensity-based prescriptions using key physiological markers. Moreover, when intensity is mentioned in these programs, it is purely subjective. A recent study done at Newman University concluded that subjective measures of intensity (RPE scale) show moderate to large differences to objective measures (HR)[26]. Altogether, more objective measures using individualized physiological markers for intensity-based training programs should be used to optimize the training response in these athletes.

Previous research has derived two different intensity-based training methods: the threshold-based method and the polarized training method. From the results of this present study, the polarized training method seems to be the preferred method of training for this group of elite endurance athletes. Collectively, these subjects spent 87.1% of their total training time well above and below MT (84.2% below and 2.9% above). Although this finding is clear for these well trained endurance athletes, the threshold-based model could still be effective for lesser-trained individuals. Increasing endurance is typically accompanied by a delay in reaching MT. In world-class athletes, MT does not occur until 70-80% of VO_{2ma}[11], whereas an untrained individual would reach MT between 50-60% of VO_{2max}[7]. Highly trained endurance athletes can even delay MT up to 90% of VO_{2max}[15]. Because MT is so delayed in these triathletes, spending a large portion of training time at MT is much more challenging. Threshold-based training programs could be highly efficacious for lesser-trained individuals due to the earlier onset of MT in this population.

Increasing VO_{2max} is highly predictive of performance in endurance athletes, but equally as important is the delay of MT. Looking at the onset of MT as a percentage of VO_{2max} should be a primary outcome measure when examining the efficacy of different training programs, especially for well-trained endurance athletes. In this present study, the method of training of these triathletes produced different results in $VO_2\theta$. The high group that spent more time training above MT saw significant improvements in $VO_2\theta$ compared to the low group. $VO_2\theta/VO_{2max}$ did not show significance between the two groups, but a large effect size was observed. This speaks to the effectiveness of spending more time training above MT. This intensity of training leads to greater delays in reaching MT, which has proven to be a key measure in predicting aerobic performance. Further research should be done to examine this large effect size between the two groups. This research could lead to a training protocol that shows improvements in VO_{2max}, with corresponding improvements in $VO_2\theta/VO_{2max}$.

The results of this present study did not come without limitations. A sample size of 9 is adequate to produce significant results, but a greater sample size could lead to generation of specific percentages for an optimal polarized training program for endurance athletes. Additionally, HR during training for these triathletes was only monitored for cycling and running sessions. The Scosche Rhythm+ ™ heart rate monitor was tested in a pool prior to the study to see whether HR could be captured during swimming training sessions, but connection to the pairing device was lost during testing. A heart rate monitor capable of capturing HR data during swimming training sessions would have been valuable for more robust HR data collection, incorporating all three training modalities.

The results of this study could be used for future studies to determine an optimized training program for triathletes. Since significant improvements in absolute and mass-specific $VO_{2\ max}$ were observed in these subjects, designing a training program with more subjects based on these percentages is the next step. Further research could develop a training program instructing triathletes, and other endurance athletes, to spend 80-85% of their training time below MT and 15-20% of their training between MT and VT. These studies could also generate a more specific breakdown of an optimal percentage of time training at or near MT, with the goal of delaying the occurrence of MT. If significant improvements are observed, it can be concluded that this intensity of training maximizes adaptation and efficacy. Furthermore, this training protocol could look deeper into the large effect size observed in the high group. Using their breakdown of percentages in each zone with more subjects could produce significant results in $VO_2\theta/VO_{2max}$. Recent studies have proposed a 6-week volitional respiratory muscle training program for increasing VO_{2max}. These exercises are meant for athletes to learn how to control breathing in order to maximize breathing economy[25]. Incorporating volitional respiratory muscle training, in combination with the conclusions of this study, could be critical in the continual pursuit of determining an individualized, intensity-based training regimen to optimize training efficacy and limit unresponsiveness.

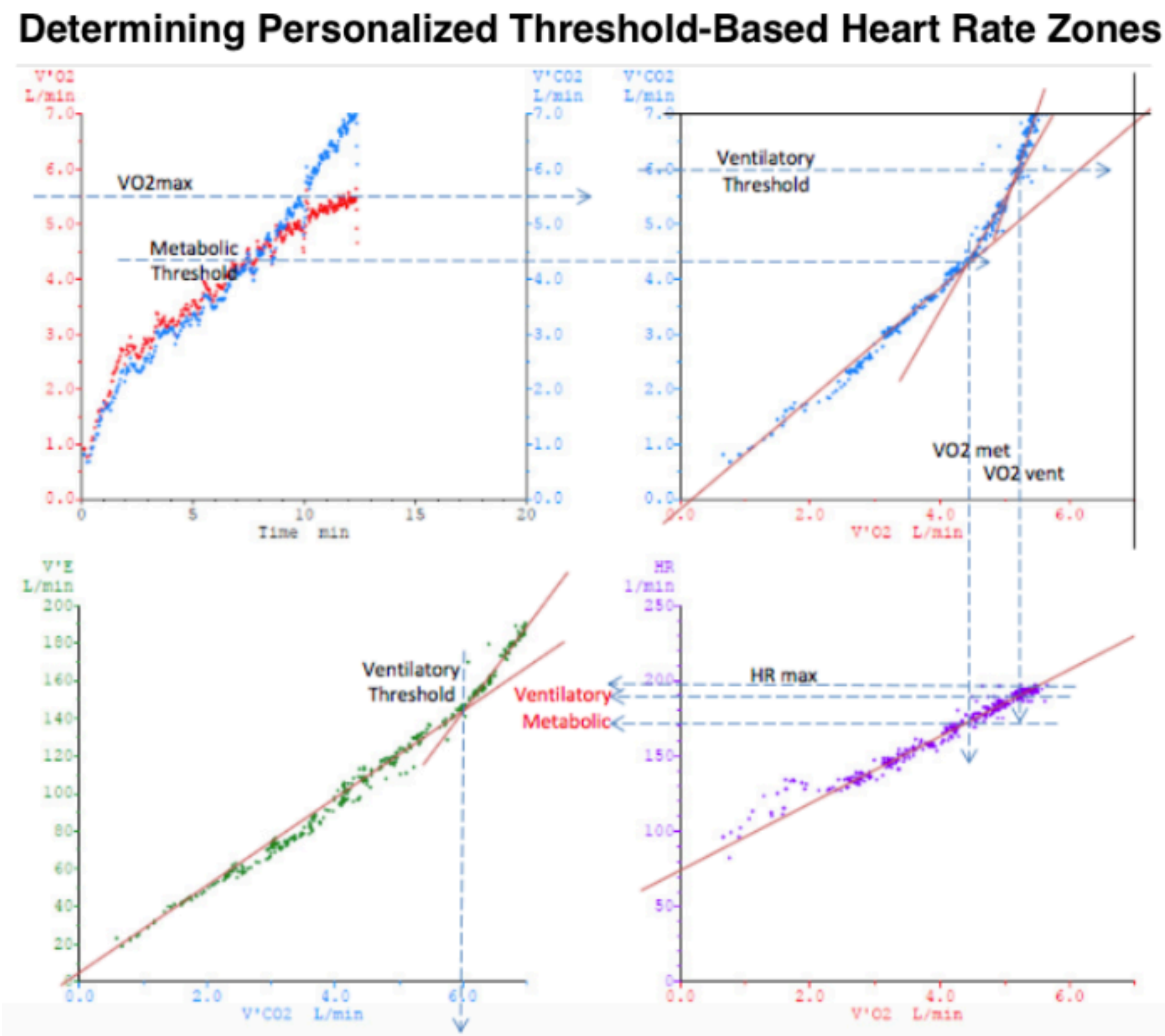
Determining Personalized Threshold-Based Heart Rate Zones
VO2max
Metabolic Threshold
Ventilatory Threshold
VO2 met
VO2 vent
Ventilatory Threshold
HR max
Ventilatory
Metabolic
Time min
V'O2 L/min
V'CO2 L/min
V'E L/min
HR 1/min

Figure 1

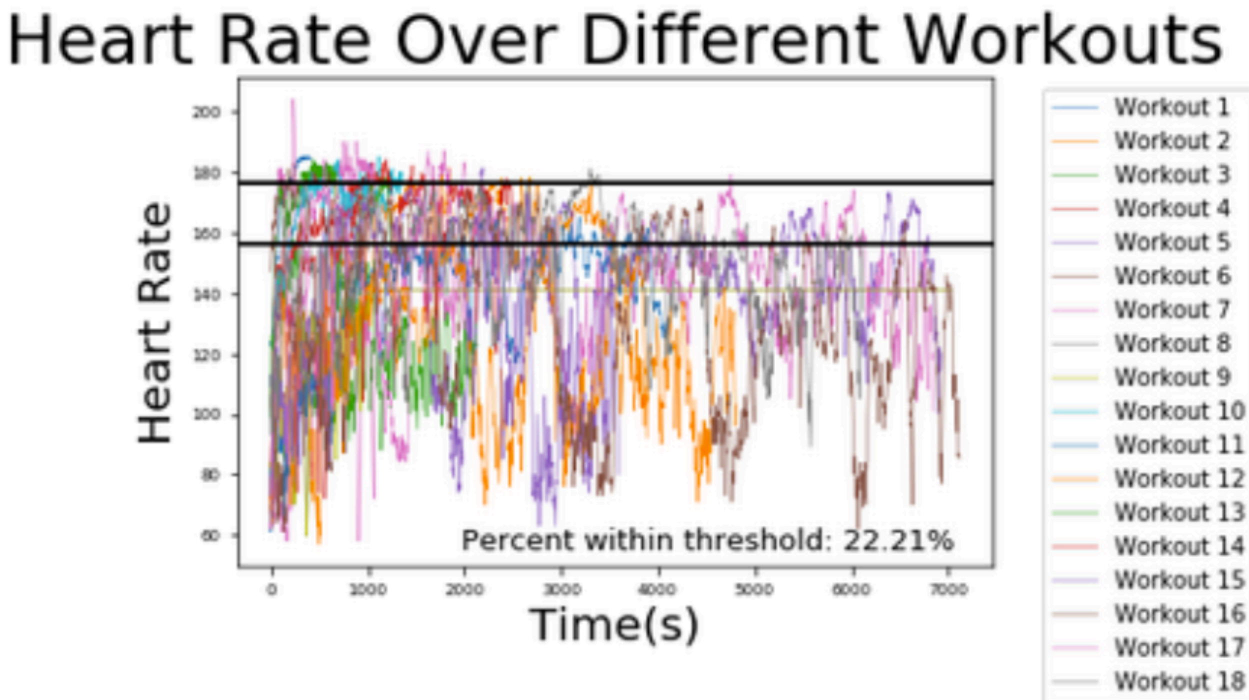
Heart Rate Over Different Workouts
Heart Rate
Time(s)
200
180
160
140
120
100
80
60
0
1000
2000
3000
4000
5000
6000
7000
Percent within threshold: 22.21%
Workout 1
Workout 2
Workout 3
Workout 4
Workout 5
Workout 6
Workout 7
Workout 8
Workout 9
Workout 10
Workout 11
Workout 12
Workout 13
Workout 14
Workout 15
Workout 16
Workout 17
Workout 18

Figure 2

	All (n = 9)	Low (n = 6)	High (n = 3)
Zone 1 (%)	84.2 ± 15.9	94.2 ± 3.0	64.2 ± 9.4
Zone 2 (%)	12.9 ± 12.1	5.1 ± 2.3	28.5 ± 4.9
Zone 3 (%)	3.0 ± 5.8	0.8 ± 0.9	7.3 ± 9.4

Table 1

	Baseline (n= 9)	8 Weeks (n = 9)	*P*-value†	Hedges' *g*
Body mass (kg)	66.4 ± 8.2	65.7 ± 8.1	0.747	0.08
Body Fat (%)	18.1 ± 8.1	18.4 ± 7.1	0.785	0.03
VO_2max (L/min)	3.47 ± 0.72	3.70 ± 0.81	0.030*	0.29
Relative VO_2max (ml/min/kg)	52.2 ± 7.8	56.1 ± 7.6	0.007**	0.48
$VO_2\theta$ (L/min)	2.91 ± 0.63	3.14 ± 0.63	0.018*	0.35
$VO_2\theta/VO_2$max (%)	84.0 ± 3.8	85.3 ± 3.0	0.747	0.38
$V_E\theta$ (L/min)	3.33 ± 0.70	3.56 ± 0.76	0.030*	0.29

Table 2

	Low (n = 6)	High (n = 3)	95% CI†	Hedges' *g*
ΔBody Mass (kg)	-1.0 ± 2.1	-0.1 ± 0.4	(-3.02, 0.27)	0.46
ΔBody Fat (%)	0.5 ± 3.4	-0.1 ± 0.8	(-1.62, 3.62)	0.18
ΔVO_2max (L/min)	0.20 ± 0.20	0.30 ± 0.17	(-0.33, 0.08)	0.46
ΔRelative VO_2max (ml/min/kg)	3.6 ± 2.4	4.5 ± 1.7	(-3.82, 1.10)	0.35
Δ$VO_2\theta$ (L/min)	0.17 ± 0.14	0.37 ± 0.15	(-0.38, -0.03)*	1.26
Δ($VO_2\theta/VO_2$max) (%)	0.3 ± 3.0	3.6 ± 3.3	(-7.27, 0.22)	0.95
Δ$V_E\theta$ (L/min)	0.20 ± 0.22	0.27 ± 0.06	(-0.25, 0.08)	0.32

Table 3

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