

## Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters

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Accepted for publication 28 April 2009

Determining the optimal balance between training load and recovery contributes to peak performance in well-trained athletes. The measurement of heart rate recovery (HRR) to monitor this balance has become popular. However, it is not known whether the impairment in performance, which is associated with training-induced fatigue, is accompanied by a change in HRR. Therefore, the aim of this study was to retrospectively analyze the relationship between changes in HRR and cycling performance in a group of well-trained cyclists ( $n = 14$ ) who participated in a 4-week high-intensity training (HIT) program. Subjects were assigned to either a group that continuous had a increase in

HRR ( $G_{\text{Incr}}$ ) or a group that showed a decrease in HRR ( $G_{\text{Decr}}$ ) during the HIT period. Both groups,  $G_{\text{Incr}}$  and  $G_{\text{Decr}}$ , showed improvements in the relative peak power output ( $P = 0.001$  and  $0.016$ , respectively) and endurance performance parameters ( $P = 0.001$  and  $<0.048$ , respectively). The average power during the 40-km time trial (40-km TT), however, improved more in  $G_{\text{Incr}}$  ( $P = 0.010$ ), resulting in a tendency for a faster 40-km TT time ( $P = 0.059$ ). These findings suggest that HRR has the potential to monitor changes in endurance performance and contribute to a more accurate prescription of training load in well-trained and elite cyclists.

Well-trained and elite cyclists need to be exposed to maximal effective training loads, followed by a minimal, but sufficient recovery period between each training session to achieve peak performances. Such a training program should prevent undertraining and overtraining (Meeusen et al., 2006), and result in a predictable progression of training adaptations and the ability to reach peak performance at the appropriate time.

To facilitate the development of such a training program, a variety of monitoring tools have been developed to track changes in training status (Lambert & Borresen, 2006). Most of these monitoring tools aim to measure the overall well-being of the athlete in response to the applied training load. Examples of these measurement tools are the Profile of Mood Status (POMS) questionnaire (McNair et al., 1971), the Daily Analysis of Life Demands for Athletes (DALDA) questionnaire (Rushall, 1990) and Kenttä's passive and/or active recovery scale (Kenttä & Hassmen, 1998). Another more direct method is to assess the responsiveness of the athlete's autonomic nervous system following a training stimulus. The autonomic nervous system consists of parasympathetic and sympathetic components and is

interlinked with many other physiological systems (Kiviniemi et al., 2007; Borresen & Lambert, 2008). The responsiveness of the autonomic nervous system may therefore provide useful information about the functional adaptations of the human body. The techniques used to measure the responsiveness of the autonomic nervous system include the measurement of heart rate variability (HRV) (Buchheit et al., 2007b, 2008; Kaikkonen et al., 2008) and heart rate recovery (HRR) (Lamberts et al., 2004, 2009a; Buchheit et al., 2007b). Interestingly, Buchheit et al. (2007b, 2008) recently concluded that indices of HRR seem to be a more sensitive marker of recently applied training loads compared with indices of HRV, which reflect a long-term modulation of the autonomic nervous system with changes in training status.

This is supported by a recent study that showed that HRR decreased less following a controlled bout of submaximal exercise in a group of trained runners who suddenly increased their training load by 55% (Borresen & Lambert, 2007). This response was interpreted as representing a negative training response to the sudden increase in training load. Unfortunately, performance parameters were not

measured in this study to verify whether the negative training effect was associated with an impairment in performance. This is an important question as a better understanding of any association between a negative training effect and impaired performance has potential practical implications.

Accordingly, the aim of this study was to monitor the relationship between HRR after exercise and cycling performance in a group of well-trained cyclists who participated in a 4-week high intensity training (HIT) program. Because of the nature of study, we chose to measure HRR directly after the HIT session, as described earlier by Buchheit et al. (2007a), and expected that symptoms of fatigue and an associated impaired performance would manifest in some of the participating cyclists. We hypothesized that HRR after exercise would improve in those cyclists who were able to tolerate the training load, whereas cyclists who showed signs of being unable to tolerate the training load would show a decrease in HRR associated with a blunted improvement in performance parameters.

## Methods

### Recruitment

The data of 14 well-trained male cyclists who successfully completed a 4-week HIT period were part of a larger study, of which a part has already been published (Lamberts et al., 2009a). However, whereas that study focused on changes in HRR after the 40-km time trial (40-km TT) ( $HRR_{40\text{km}}$ ) before and after the HIT training period, the current study focuses on changes in HRR after each HIT session ( $HRR_{\text{HIT}}$ ) during the HIT training period.

The characteristics of the subjects are presented in Table 1. All subjects had a minimal training load of 6 h/week with at least 3 years of cycling experience and were classified as well trained (Jeukendrup, 2002). Before the start of the study, subjects completed a Physical Activity Readiness Questionnaire (PAR-Q) (American College of Sports Medicine, 2007), were personally interviewed about their training history and signed an informed consent after they were informed about the risks and stresses associated with the research protocol. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town. The principles outlined by the Declaration of Helsinki for the Use of Humans were adopted in this study (2002).

Table 1. General characteristics of the group  $G_{\text{Incr}}$  and group  $G_{\text{Decr}}$ , expressed as  $X \pm s$

Variable	$G_{\text{Incr}}$ ( $n = 8$ )	$G_{\text{Decr}}$ ( $n = 6$ )
Age (years)	34 $\pm$ 4 <sup>a</sup>	25 $\pm$ 5 <sup>a</sup>
Stature (cm)	182 $\pm$ 3	176 $\pm$ 9
Body mass (kg)	76.9 $\pm$ 7.7 <sup>b</sup>	68.5 $\pm$ 6.0 <sup>b</sup>
Fat (%)	16.0 $\pm$ 3.5 <sup>c</sup>	11.7 $\pm$ 2.0 <sup>c</sup>
Sum of skinfolds (mm)	63.8 $\pm$ 23.0	49.8 $\pm$ 6.1
Years of competitive cycling (years)	13 $\pm$ 7	8 $\pm$ 5
Training hours/week (h)	10 $\pm$ 5	13 $\pm$ 2

<sup>a</sup> $P = 0.003$ , <sup>b</sup> $P = 0.049$ , <sup>c</sup> $P = 0.021$ .

During all performance tests and training sessions, heart rate was recorded continuously at a capturing rate of 34 Hz by the Computrainer™ software. HRR after the HIT sessions ( $HRR_{\text{HIT}}$ ) was also recorded with the Computrainer™ software. HRR was calculated as described previously (Lamberts et al., 2004) and defined as the reduction in heart rate within the first 60 s after the cessation of the eighth interval of an HIT session ( $HRR_{\text{HIT}}$ ) (Lamberts et al., 2009a). In an attempt to control the factors that could influence heart rate and HRR, subjects were asked to sit passively and straight up on their cycles (Gnehm et al., 1997), to remain still and not talk during the recovery period.

After the training program, the HRR were analyzed and subjects were assigned either to a continuous increasing HRR group ( $G_{\text{Incr}}$ ) or to a group that showed a decrease in HRR ( $G_{\text{Decr}}$ ) after exercise during the training period. The minimal sample size for this study was determined using the 40-km TT data from Palmer et al. (1996). Assuming that the smallest meaningful difference in performance is 1.0%, with a standard deviation of 0.5%, the sample size required for this study, to achieve a statistical power of 80% and a significance level of 5%, was therefore  $n = 5$  for each group (Altman, 1991).

### Identifying $G_{\text{Incr}}$ and $G_{\text{Decr}}$

After the completion of the study, which included all training sessions and performance testing (pre and post), each individual  $HRR_{\text{HIT}}$  pattern was analyzed retrospectively. Based on this pattern, cyclists were either assigned to a group that showed a continuous increase in  $HRR_{\text{HIT}}$  ( $G_{\text{Incr}}$ ) (faster) or to a group that showed a decrease in  $HRR_{\text{HIT}}$  ( $G_{\text{Decr}}$ ) (slower) during the HIT period. An *a priori* determined inclusion criterion for  $G_{\text{Decr}}$  was defined as at least two consecutive decreases in  $HRR_{\text{HIT}}$  during the HIT period. In contrast, all cyclists in  $G_{\text{Incr}}$  had to show a continuous increase in  $HRR_{\text{HIT}}$ . A once-off decrease or unchanged  $HRR_{\text{HIT}}$  in  $G_{\text{Incr}}$  was considered as an effect of an “off day” and therefore found to be acceptable for inclusion in  $G_{\text{Incr}}$ .

### Study design

A week before the testing and training period the subjects performed a 40-km familiarization time trial on an electronically braked cycle ergometer (Computrainer™ Pro 3D, RacerMate, Seattle, Washington, USA) over a flat course, as described previously (Lamberts et al., 2009a).

Three days before the start of the training period, all subjects performed a peak power output (PPO) test, which included respiratory gas analysis for measurement of maximal oxygen consumption ( $VO_{2\text{max}}$ ), followed by a 40-km TT 1 day before the start of the training period. After completing the initial tests, subjects started their 4-week training protocol, which consisted of two HIT sessions: two 90-min recovery rides below the lactate threshold (Solberg et al., 2005) and three rest days each week. During all testing and training sessions, subjects were blinded to any feedback of time, power output, heart rate and speed to prevent them from adopting a pacing strategy and possibly biasing the performance outcomes. The only exception to this was the display of completed distance during the 40-km TT. Additionally, subjects were asked to avoid participating in any racing or prolonged or high-intensity exercise during the study. Each subject was asked to maintain a detailed training diary and to record all heart rate data during all training sessions performed outside of the laboratory for the duration of the study. Subjects were questioned and training logbooks were inspected before the

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second testing phase to ensure that they had adhered to the training protocol (Lamberts et al., 2009a).

### Warm-up and calibration

Before all testing and training sessions, subjects performed a self-paced 15-min warm-up ride on a simulated 40-km flat TT course. Testing and training was performed on the subject's own bicycle, which was mounted on the Computrainer™ ergometer system (Computrainer™ Pro 3D, RacerMate, Seattle, Washington, USA). The system was calibrated as described previously by Lamberts et al. (2009a).

All test and training sessions were performed under stable climate conditions ( $22.3 \pm 1.3$  °C,  $53.7 \pm 2.4\%$  relative humidity,  $101.9 \pm 0.8$  kPa) and at a similar time of the day (within 60 min). Before each testing or training session, body mass was measured. Stature and body fat [expressed as a percentage (Durnin & Womersley, 1974) and the sum of seven skinfolds (Ross & Marfell-Jones, 1991)] were measured before the start of the 40-km TT.

### Performance tests

Markers of cycling performance were determined by a peak performance test (PPO including  $\text{VO}_{2\text{max}}$ ) and an endurance cycle test (40-km TT) (Hawley & Noakes, 1992; Padilla et al., 2000; Mujika & Padilla, 2001; Lucia et al., 2002a, b). These tests were conducted before and after the 28-day training period and a 10-day low-intensity taper period. This tapering period allowed the cyclists to recover from their HIT before they were re-tested (Shepley et al., 1992; Jeukendrup, 2002).

All subjects were asked to perform a 90-min submaximal recovery ride, below the lactate threshold (Solberg et al., 2005), 24 h before the performance tests. As described previously (Lamberts et al., 2009a), the PPO test was performed at a starting work rate of 2.50 W/kg body mass, after which the load was increased incrementally by 20 W each min until the cyclist could not maintain a cadence  $> 70$  revolutions per minute (rpm) or was voluntarily exhausted. During this test ventilation, oxygen uptake ( $\text{VO}_2$ ) and  $\text{CO}_2$  production ( $\text{VCO}_2$ ) were measured over 15-s intervals using an on-line breath-by-breath gas analyzer (Oxycon, Viasis, Hoechberg, Germany). Subjects were verbally encouraged to perform to maximal exhaustion. Maximal PPO was determined as the mean power output during the final minute of the PPO test whereas,  $\text{VO}_{2\text{max}}$  (L/min) was defined as the highest recorded reading over a 30-s period. The 40-km TT was performed on a simulated 40-km flat TT course that was programmed into the Computrainer™. Subjects were allowed to drink water *ad libitum* throughout the test and were given clear instructions to complete the 40-km distance in the fastest possible time. All subjects refrained from consuming any food and caffeine for 2 and 3 h, respectively, before all performance testing and training sessions.

### Training sessions

All subjects followed the same structured training program, which included HIT sessions, rest days and recovery rides. Each HIT session consisted of eight intervals at approximately 80% of peak power output, determined for each subject during the initial PPO test. Each interval had a duration of 4 min and was followed by a 90-s self-paced recovery period (see also Fig. 1). All HIT sessions were closely supervised while speed (km/h), power output (W), cadence rpm and heart rate (beats/min) were captured at a rate of 34 Hz, as described previously by Lamberts et al. (2009a).

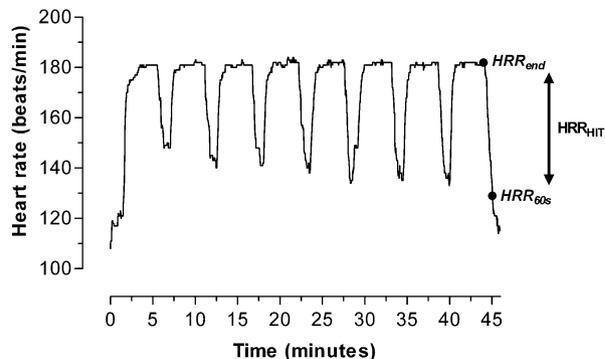


Fig. 1. The average heart rate response of an arbitrary subject undergoing eight high-intensity periods within a high-intensity training (HIT) session. heart rate recovery (HRR)<sub>end</sub> represents the start of the heart rate recovery measurement (HRR<sub>HIT</sub>). HRR<sub>60s</sub> represents the end of the heart rate recovery measurement (HRR<sub>HIT</sub>). HRR<sub>HIT</sub> was calculated as the difference between HRR<sub>end</sub> and HRR<sub>60s</sub>.

### Data analysis

Analysis of performance and training data was performed using CyclingPeaks™ analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, Colorado, USA) and the Computrainer™ coaching software (Version 1.5.308, RacerMate). Data were expressed as absolute values whereas changes in performance parameters were expressed in absolute and relative (percentages) values. Percentage change was calculated as:

Percentage change

$$= \frac{(\text{Post-training session value} - \text{pre-training session value})}{(\text{Pre-training session value})} \times 100$$

Heart rate data were analyzed using CyclingPeaks™ analysis software and Polar precision performance software (Version 4.03.049, Polar Electro, Kempele, Finland).

### Statistical analysis

The data were analyzed using STATISTICA Version 7.0 (Stat-Soft Inc., Tulsa, Oklahoma, USA) for any statistical significance ( $P < 0.05$ ). All data are expressed as means  $\pm$  standard deviation ( $\bar{X} \pm s$ ). An independent *t*-test by groups was used to determine any differences in the general characteristics between  $G_{\text{Incr}}$  and  $G_{\text{Decr}}$  and relative changes (%) between groups. A two-way analysis of variance (ANOVA) with repeated measures was used to determine differences between the groups for changes in performance parameters [ $\text{VO}_{2\text{max}}$  (absolute and relative), PPO (absolute and relative), 40-km TT time, average power during the 40-km TT (absolute and relative)] and HRR<sub>HIT</sub> over the eight HIT sessions. Where a significant difference was found for either main effect (Group or Time), or the interaction between Time  $\times$  Group, a Tukey *post hoc* analysis was performed. A significant interaction (Group  $\times$  Time) was interpreted as meaning that the groups responded differently over time during the training period for that variable. Effect sizes were calculated as the difference between the means divided by the mean standard deviation to characterize the practical (clinical) significance rather than the statistical significance. The following criteria for effect sizes were used:  $< 0.1$  = trivial,  $0.1$ – $0.3$  = trivial/small,  $0.3$ – $0.5$  = small,  $0.5$ – $0.7$  = small/moderate,  $0.7$ – $1.1$  = moderate,  $1.1$ – $1.3$  = moderate/large,  $1.3$ – $1.9$  = large,  $1.9$ – $2.1$  = large/very large and  $> 2.1$  = very large, which were adapted from Hopkins criteria

in Sportscience 6 (available at: <http://www.sportsci.org/jour/0201/wghprob.htm>). Differences in percentage change in performance parameters were determined using an independent *t*-test. Relationships between changes in performance parameters and changes in  $HRR_{HIT}$  were established using a Pearson's product-moment correlation (GraphPad Prism Version 3.00 for Windows, GraphPad Software, San Diego, California, USA). Confidence intervals (95% CI) for the correlations were calculated using a spreadsheet designed for this purpose and downloaded from <http://www.sportsci.org>.

## Results

The 14 cyclists who completed the HIT program were retrospectively allocated to either  $G_{Incr}$  ( $n = 8$ ) or  $G_{Decr}$  ( $n = 6$ ). The general characteristics of  $G_{Incr}$  and  $G_{Decr}$  are shown in Table 1. Subjects in  $G_{Incr}$  were significantly older, heavier and had a higher percentage of body fat than  $G_{Decr}$ . The absolute PPO, 40-km TT performance and  $VO_{2max}$  values were similar between groups. However, when these were expressed relative to body mass  $VO_{2max}$  ( $P = 0.047$ ), PPO ( $P = 0.016$ ) and average power during the 40-km TT ( $P = 0.039$ ) were higher in  $G_{Decr}$ . (Table 2). Analysis of the mean heart rate and power during the HIT sessions revealed that both groups trained at the same intensity ( $G_{Incr}$   $78 \pm 2\%$  of PPO and  $89 \pm 2\%$  of  $HR_{max}$ ;  $G_{Decr}$   $79 \pm 1\%$  of PPO and  $89 \pm 2\%$   $HR_{max}$ ).

### $HRR_{HIT}$ patterns of $G_{Incr}$ and $G_{Decr}$

The exercise intensity (expressed as  $\%HR_{max}$ ) at the end of each HIT session remained constant in both groups throughout the study ( $G_{Incr}$   $94 \pm 2\%$  vs  $G_{Decr}$   $93 \pm 2\%$ ). As  $HRR_{HIT}$  may be influenced by exercise intensity, this indicates that any change in  $HRR_{HIT}$  could not be attributed to this methodological point. The changes in  $HRR_{HIT}$  for  $G_{Incr}$  and  $G_{Decr}$  after the eight HIT sessions are shown in Fig. 2.  $HRR_{HIT}$  in  $G_{Incr}$  improved throughout the HIT sessions and, by the fourth HIT session, was significantly higher than  $HRR_{HIT}$  after the initial HIT session ( $34 \pm 9$  vs  $40 \pm 9$  beats;  $P = 0.006$ ). The largest improvement

of  $11 \pm 1$  beats ( $P = 0.001$ ) for  $G_{Incr}$  was found after the eighth HIT session (Table 3). Throughout the HIT period, all participant within  $G_{Incr}$  showed 1 day during which  $HRR$  was similar to or slightly lower than during the previous session.

$HRR_{HIT}$  in  $G_{Decr}$  also improved, being significantly higher after the sixth HIT session ( $9 \pm 4$  beats) when compared with the initial HIT session ( $39 \pm 6$  vs  $47 \pm 5$  beats;  $P = 0.001$ ). However, this significant change disappeared during the seventh and eighth HIT interval.

### Changes in performance parameters

Changes in performance parameters after HIT were calculated and analyzed as absolute changes and relative changes expressed as a percentage of the initial value.

Absolute changes in performance parameters in both groups ( $G_{Incr}$  and  $G_{Decr}$ ) are shown in Table 2. Although no significant changes were found for  $VO_{2max}$ , the relative PPO (W/kg) improved in both groups after the training period while absolute PPO (W) only improved in  $G_{Incr}$ . All endurance performance parameters that were measured during the 40-km TT also improved after the training period in both groups (see also Table 2). A significant interaction effect of Time  $\times$  Group was found for average power during the 40-km TT ( $P = 0.010$ ). This indicates that the average power during the 40-km TT improved significantly more in  $G_{Incr}$  than in  $G_{Decr}$ . A similar tendency was found for the 40-km TT time; however, this interaction effect was not statistically significant ( $P = 0.059$ ).

Relative changes in performance parameters (i.e. changes in performance parameters as a percentage from the initial measurement) are shown in Table 4. When the data were expressed as a percentage change, no significant changes in any of the peak performance parameters over time were found. In contrast, absolute and relative mean power during the 40-km TT (endurance parameters) improved significantly in both groups after the training period.

Table 2. Performance parameters before and after the high-intensity training period in both groups ( $G_{Incr}$  and  $G_{Decr}$ ), expressed as  $X \pm s$

Variable	$G_{Incr}$ ( $n = 8$ )		$G_{Decr}$ ( $n = 6$ )	
	Before	After	Before	After
$VO_{2max}$ (L/min)	$4.3 \pm 0.4$	$4.4 \pm 0.4$	$4.5 \pm 0.6$	$4.5 \pm 0.7$
$VO_{2max}$ (mL/kg/min)	$56.5 \pm 5.1$	$58.5 \pm 5.2$	$65.3 \pm 6.7$	$65.9 \pm 5.8$
Peak power output (W)	$375 \pm 30^a$	$391 \pm 34^a$	$377 \pm 39$	$388 \pm 39$
Relative peak power (W/kg)	$4.9 \pm 0.5^b$	$5.2 \pm 0.5^b$	$5.5 \pm 0.5^c$	$5.7 \pm 0.5^c$
40-km TT time (40-km TT) (min. s)**	$66.17 \pm 2.09^d$	$64.26 \pm 1.51^d$	$64.51 \pm 2.46^e$	$63.58 \pm 2.26^e$
Power during 40-km TT (W)*	$251 \pm 22^f$	$271 \pm 21^f$	$260 \pm 32^g$	$270 \pm 29^g$
Rel. power during 40-km TT (W/kg)	$3.3 \pm 0.4^h$	$3.6 \pm 0.4^h$	$3.8 \pm 0.3^i$	$3.9 \pm 0.3^i$

<sup>a</sup> $P = 0.008$ , <sup>b</sup> $P = 0.001$ , <sup>c</sup> $P = 0.016$ , <sup>d</sup> $P = 0.001$ , <sup>e</sup> $P = 0.028$ , <sup>f</sup> $P = 0.001$ , <sup>g</sup> $P = 0.013$ , <sup>h</sup> $P = 0.001$ , <sup>i</sup> $P = 0.048$ .

\*Group  $\times$  Time effect  $P = 0.010$ , \*\*Group  $\times$  Time effect  $P = 0.058$  (trend, not significant).

In contrast, there was a tendency for the 40-km TT time to improve in both groups but this was not significant ( $P = 0.058$ ).

#### Relationships between the change in $HRR_{HIT}$ and 40-km TT performance parameters

There were significant relationships between the change in  $HRR_{HIT}$  and changes in absolute and relative 40-km TT performance parameters (Fig. 3).

Changes in  $HRR_{HIT}$  had the strongest relationship with the change in the mean absolute power when expressed either as a absolute (W) or as a relative value (%) [ $r = 0.81$ ; 95% CI: 0.49–0.94 ( $P = 0.001$ ) and  $r = 0.80$ ; 95% CI: 0.47–0.93 ( $P = 0.001$ ), respectively]. A weaker relationship was found between changes in  $HRR_{HIT}$  and the change in relative mean power, both expressed as an absolute value (W/kg) ( $r = 0.67$ ; 95% CI: 0.22–0.89;  $P = 0.008$ ) or as a relative (%) value ( $r = 0.76$ ; 95% CI: 0.38–0.92;  $P = 0.002$ ). Relationships of  $r = 0.73$  (95% CI: 0.33–0.91;  $P = 0.003$ ) and  $r = 0.75$  (95% CI: 0.36–0.92;  $P = 0.002$ ) were found between  $HRR_{HIT}$  and abso-

lute and relative 40-km TT improvement, respectively.

#### Discussion

The main finding of this study was that endurance performance (40-km TT) improved more in the group of cyclists who showed a continuous increase in HRR during the 4 weeks of HIT compared with the group of cyclists who showed a decrease in HRR toward the end of the HIT period.

#### Changes in performance parameters

Improvements in performance parameters in both groups were in accordance with earlier reported improvements after HIT in already well-trained cyclists (Stepito et al., 1999; Laursen et al., 2002). However, when the improvements in the performance of the subjects were compared with a HIT study, which used a similar training protocol with cyclists of the same caliber ( $VO_{2max}$ : 65.7 mL/kg/min, relative PPO: 5.3 W/kg), the improvements in  $G_{Decr}$  seemed to be low (Lindsay et al., 1996). The improvement of  $HRR_{HIT}$  in  $G_{Incr}$  ( $11 \pm 1$  beats) over the entire training period was comparable to the findings of Buchheit et al. (2008). This study reported a non-significant change in HRR of about 16 beats over 60s (from  $60 \pm 12$  beats before training to  $76 \pm 14$  beats after training), which was higher than their pre assumed meaningful difference of 13 beats in already active adolescents after a HIT program. However, this was not discussed in the paper. Additionally, it is interesting to note that the variation in HRR and certain performance parameters increased after the HIT period, which could indicate that subjects responded differently to the HIT training.

Although significant changes in descriptive parameters were found between  $G_{Incr}$  and  $G_{Decr}$  for age, bodyweight and body fat percentage, these differences are not expected to impact the relative change in the performance parameters.

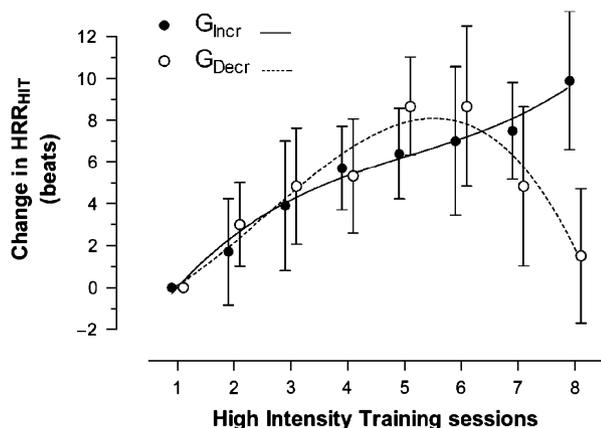


Fig. 2. Changes of Heart rate recovery ( $HRR$ ) $_{HIT}$  during the eight high-intensity training (HIT) sessions in  $G_{Incr}$  (●) and  $G_{Decr}$  (○), expressed as a relative change to the initial heart rate recovery during session 1 ( $X \pm s$ ). A third polynomial regression line ( $y = a + bx + cx^2 + dx^3$ ) for each group (●,  $r = 0.77$ ; ○,  $r = 0.72$ ) over time is drawn to indicate the  $HRR_{HIT}$  pattern.

Table 3. Mean heart rate recovery after each of the eighth high-intensity training sessions ( $HRR_{HIT}$ ) in  $G_{Incr}$  ( $n = 8$ ) and  $G_{Decr}$  ( $n = 6$ )

HIT session	1	2	3	4	5	6	7	8
$G_{Incr}$								
Absolute	$34 \pm 9$	$36 \pm 10$	$38 \pm 11$	$40 \pm 9^*$	$40 \pm 9^*$	$40 \pm 10^*$	$42 \pm 10^{**}$	$46 \pm 9^{**}$
Relative	$0 \pm 0$	$2 \pm 3$	$4 \pm 3$	$6 \pm 2$	$6 \pm 2$	$6 \pm 3$	$8 \pm 2$	$11 \pm 1$
$G_{Decr}$								
Absolute	$39 \pm 6$	$41 \pm 6$	$39 \pm 8$	$41 \pm 9$	$40 \pm 11$	$47 \pm 5^{**}$	$44 \pm 6$	$40 \pm 6$
Relative	$0 \pm 0$	$3 \pm 2$	$3 \pm 3$	$5 \pm 3$	$9 \pm 2$	$9 \pm 4$	$5 \pm 4$	$2 \pm 3$

Data are expressed  $X \pm s$  in absolute [heart rate at end of the test minus heart rate 60 s later (beats)] and relative values [ $HRR_{HIT} - HRR_{HIT}$  during the first HIT session (beats)].

\* $P < 0.01$ , \*\* $P < 0.001$  when compared with training session 1.

Table 4. Absolute and relative changes in performance parameters after the HIT training period, expressed as  $X \pm s$ 

Variable	$G_{\text{Incr}} (n = 8)$		$G_{\text{Decr}} (n = 6)$		Difference % change P-value	Chances that the differences between $G_{\text{Incr}}$ and $G_{\text{Decr}}$ are truly meaningful	
	Change (absolute)	Change (%)	Change (absolute)	Change (%)		Effect size	Descriptor
$\text{VO}_{2\text{max}}$ (L/min)	$0.1 \pm 0.2$	$2.5 \pm 4.6$	$0.0 \pm 0.3$	$0.8 \pm 6.1$	0.551	0.33	Small
$\text{VO}_{2\text{max}}$ (mL/kg/min)	$2.1 \pm 2.2$	$3.7 \pm 3.8$	$0.6 \pm 3.1$	$1.1 \pm 4.8$	0.270	0.57	Small/moderate
Peak power output (W)	$16 \pm 14$	$4.4 \pm 3.8$	$10 \pm 6$	$2.7 \pm 1.6$	0.347	0.60	Small/moderate
Relative peak power (W/kg)	$0.3 \pm 0.1$	$5.6 \pm 2.8$	$0.2 \pm 0.1$	$3.2 \pm 2.2$	0.113	1.00	Moderate
40-km TT time (min.s)	$-1.51 \pm 0.45$	$-2.8 \pm 1.1^{**}$	$-1.00 \pm 0.45$	$-1.5 \pm 1.1^{**}$	0.058**	1.13	Moderate/large
Mean power during 40-km TT (W)	$20 \pm 6$	$8.0 \pm 2.8^*$	$10 \pm 6$	$3.8 \pm 2.4^*$	0.013*	1.67	Large
Mean relative power during 40-km TT (W/kg)	$0.3 \pm 0.1$	$8.0 \pm 3.4^*$	$0.1 \pm 0.1$	$3.8 \pm 3.8^*$	0.049*	2.00	Very large

Effect size calculated as: (absolute change  $G_{\text{Incr}}$  – absolute change  $G_{\text{Decr}})/(\text{mean standard deviation of } G_{\text{Incr}} \text{ and } G_{\text{Decr}})$ .

\* $P < 0.05$ .

\*\*Trend, not significant.

40-km TT, 40-km time trial; HIT, high-intensity training program.

### Relationships between $\text{HRR}_{\text{HIT}}$ and 40-km TT performance parameters

Relatively weak correlations ( $r = 0.67\text{--}0.81$ ) were found between the change in  $\text{HRR}_{\text{HIT}}$  and the change in the 40-km performance (Fig. 3). The relationship between  $\text{HRR}_{\text{HIT}}$  and the relative performance parameters was slightly better compared with the absolute performance values. We could only find one study that could be used as a source of comparison (Buchheit et al., 2008). This study showed a comparable relationship ( $r = 0.62$ ) between absolute change in a performance parameter (repeated sprint time) and a change in 60 s  $\text{HRR}$  indices.

### Change in performance parameters in $G_{\text{Incr}}$ and $G_{\text{Decr}}$

There were no differences in the performance parameters between  $G_{\text{Incr}}$  and  $G_{\text{Decr}}$  when the data were expressed in absolute units. However, when these data were expressed in relative values, the mean 40-km TT power (W) and relative 40-km TT power improved significantly more in  $G_{\text{Incr}}$  when compared with  $G_{\text{Decr}}$ . These improvements in 40-km TT time (s) only showed a strong tendency ( $P = 0.058$ ) to have improved more in  $G_{\text{Incr}}$  than in  $G_{\text{Decr}}$ . Effect size statistics of the 40-km TT time (1.13) showed a “moderate” to almost “large” chance that the difference found was clinically meaningful. This interpretation is supported by three other studies showing that performance changes of 0.7–1.0% in well-trained and elite cyclists should be regarded as meaningful (Paton & Hopkins, 2006; Currell & Jeukendrup, 2008; Lamberts et al., 2009b). The mean difference of the 40-km TT time between  $G_{\text{Incr}}$  and  $G_{\text{Decr}}$  was 1.3%.

A possible explanation for the blunted improvement in endurance performance in  $G_{\text{Decr}}$  could be that the training load after the sixth HIT session became intolerable and fatigue started to accumulate. This is supported by two independent studies. Halson et al. (2002) reported a significant decline in PPO and TT performance after a 2-week period of intensified training (eight HIT sessions), in conjunction with a 29% increase in global mood disturbances and the significantly higher DALDA score during the intensified training period. Urhausen et al. (1998), in contrast, reported no change in peak performance parameters (10 and 30 s sprint power and maximal peak power) but a 27% decrease in a time-to-exhaustion test (riding at 83% of  $\text{VO}_{2\text{max}}$ ) in a group of overtrained endurance athletes (cyclists and triathletes). These findings are in accordance with our study, which shows an initial impairment in endurance performance rather than in peak performance parameters.

A paradoxical finding, however, was that the young and better trained cyclists generally struggled to accommodate the training load, in contrast to the slightly less trained cyclists, who were able to cope. The explanation is not immediately clear. One possibility could be that the subjects in  $G_{\text{Decr}}$  performed more training than was prescribed. This, however, is speculative and will have to be verified in future studies.

Overall, our data suggest that a decrease in  $\text{HRR}_{\text{HIT}}$  is initially associated with a decrease in endurance cycling capacity rather than in peak power performance parameters and possibly reflects the accumulation of fatigue. This has interesting implications for monitoring cycling performance as it suggests that changes in endurance cycling performance

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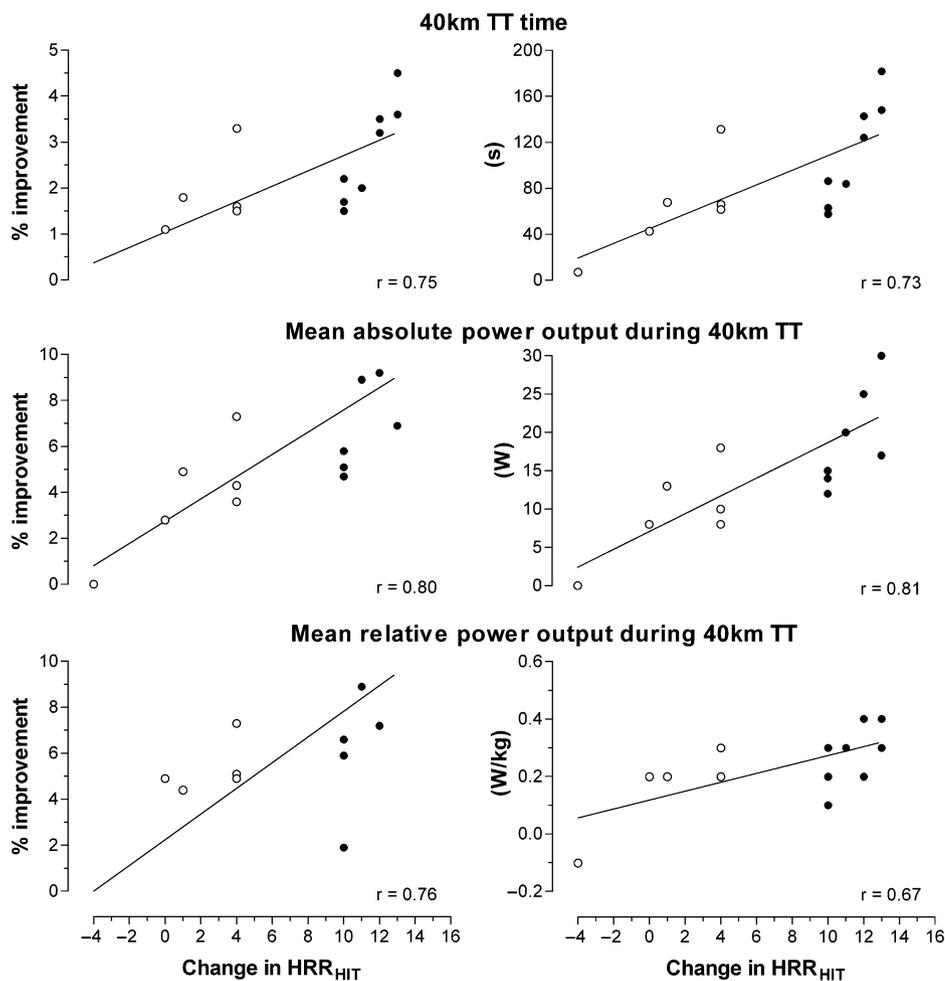


Fig. 3. Change in heart rate recovery ( $HRR_{HIT}$ ) [between the eighth and first high-intensity training (HIT) session] and change in absolute and relative 40-km time trial (40-km TT) performance parameters in  $G_{Incr}$  (●) and  $G_{Decr}$  (○).

can possibly be monitored by changes in HRR in contrast to peak power performance.

### Limiting factors of the study and future research

Although the predetermined sample size requirement was met, future studies should attempt to increase the sample size to strengthen the statistical power.

Based on the curvilinear relationship between training status and improving performance (Foster et al., 1996), it can be expected that better cyclists are able to improve less than less trained cyclists after a similar training program. It can therefore be argued that  $G_{Decr}$ , who had a relatively higher relative power, improved less than  $G_{Incr}$  based on a better training status. However, when the changes in performance parameters were calculated as relative values, which partly corrects for these differences, significant differences were maintained.

Future research should focus on comparing groups that are fully matched based on general characteristics and physiological parameters. In addition, subjective measurements of symptoms of fatigue, such as RPE (Borg, 1982), POMS (McNair et al., 1971) and the DALDA (Rushall, 1990) scores,

should be included in the study design to confirm the development of fatigue and its relationship with changes in HRR.

In conclusion, this study shows that a decrease in HRR during a HIT training period is possibly a consequence of an imbalance between training load and recovery and is associated with a blunted improvement in endurance performance, while peak performance is initially unaffected. Therefore, the measurement of HRR has the potential to be a useful tool for monitoring fatigue and prescribing training load in well-trained and elite cyclists.

### Perspectives

Improvements in training status are associated with changes in HRR and HRV indices after exercise (Sugawara et al., 2001; Yamamoto et al., 2001; Borresen & Lambert, 2007; Buchheit et al., 2008; Lamberts et al., 2009a). Although it is widely accepted that these changes are associated with lower health risks (Cole et al., 1999), it is not known whether they can also be used to monitor changes in the training status in well-trained athletes.

Buchheit et al. (2007b, 2008) recently reported that changes in HRR indices are mainly associated with recently applied training loads, while changes in HRV indices are mainly associated with a long-term modulation of the autonomic nervous system.

The outcomes of this study support this hypothesis as it shows that HRR indeed responds to a recently applied training load. In addition, we showed that a decrease in HRR is associated with a blunted improvement in endurance performance. This suggests that a decrease in HRR can possibly predict an inability to cope with the training load and the accumulation of fatigue. Therefore, the measurement of HRR after a standardized warm-up (Lamberts

et al., 2009b) has the potential to play an important role in monitoring cycling performance and optimizing training programs.

**Key words:** cycling, monitoring, overreaching, performance, adaptation, recovery, overtraining, autonomic nervous system.

### Acknowledgements

The authors would like to thank all the cyclists who participated in this study. This study was funded by the van Ewijk foundation and the Medical Research Council of South Africa.

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