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To link to this article: https://doi.org/10.1080/17461391.2018.1458907

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Published online: 10 Apr 2018.

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Investigating the use of pre-training measures of autonomic regulation for assessing functional overreaching in endurance athletes

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Abstract
The use of heart rate variability (HRV) to inform daily training prescription is becoming common in endurance sport. Few studies, however, have investigated the use of pre-training HRV to predict decreased performance or altered exercising autonomic response, typical of functional overreaching (FOR). Further, a new cardiac vagal tone (ProCVT) technology purports to eliminate some of the noise associated with daily HRV, and therefore may be better at predicting same-day performance. The purpose of this investigation was to examine if changes to resting HRV and ProCVT were associated with alterations in performance, maximal heart rate (HRmax), or heart rate recovery (HRrec) in FOR athletes. Twenty-eight recreational cyclists and triathletes were assigned to experimental/control conditions and underwent: 1 week of reduced training, 3 weeks of overload (OL) or regular training (CON), and 1 week of recovery. Testing occurred following the reduced training week (T1), post-3 weeks of training (T2), and following the recovery week (T3). Measures of resting HRV/ProCVT were collected each testing session, followed by maximal incremental exercise tests with HRrec taken 60 s post-exercise. Performance decreased from T1 to T2 in the OL group vs. CON (Δ−9 ± 12 vs. Δ9 ± 11 W, P < .001), as did HRmax (Δ−8 ± 4 vs. Δ−2 ± 4 bpm, P < .001). HRrec increased from T1 to T2 in the OL group vs. CON (Δ10 ± 9 vs. Δ2 ± 5 beats/min, P < .01). HRV and ProCVT did not change in either group. Same-day resting autonomic measures are insufficient in predicting alterations to performance or exercising HR measures following overload training.

Keywords: Overtraining, heart rate variability, heart rate recovery, cardiac vagal tone, endurance athletes

Highlights
- Recreational endurance athletes who underwent three weeks of overload training demonstrated reductions in cycling performance, mood states, maximal heart rate, and an increase in heart rate recovery.
- Same-day resting heart rate measures, including heart rate variability and a novel cardiac vagal tone measure, were insufficient in predicting the subsequent alterations to performance or exercising heart rate in the overreached athletes.
- Coaches and athletes should not rely on resting measures to inform same-day exercise prescription or to predict performance.

Introduction
Endurance sport is often characterized by periods of intensified training, which lead to subsequent reductions in performance (Aubry, Hausswirth, Louis, Coutts, & Le Meur, 2014; Flatt, Hornikel, & Esco, 2017; Le Meur, Pichon, et al., 2013; Meeusen et al., 2013). This transient response to training overload may be considered functional overreaching (FOR), which is defined as a decrease in performance lasting days to weeks followed by a net increase in performance following recovery (termed supercompensation), or non-functional overreaching (NFOR) which results from inadequate recovery and leads to a stagnation or decreases in performance lasting weeks to months (Aubry et al., 2015; Le Meur, Hausswirth, et al., 2013; Meeusen et al., 2013). Whilst periods of intensified training are an inevitable aspect of performance sport, it is currently contested whether any form of overreaching is, in fact, beneficial for performance. Aubry et al. recently demonstrated that athletes who underwent a 3-week overload without decreased performance upon completion,
had a greater super-compensation and lower incidence of illness following recovery compared to their FOR teammates (Aubry et al., 2014). With this and with the equivocal nature of FOR in mind, it is imperative that athletes are monitored throughout particularly challenging training and racing periods (Aubry et al., 2014; Dupuy et al., 2014; Flatt et al., 2017; Le Meur, Pichon, et al., 2013).

Heart rate variability (HRV) is a common monitoring tool for assessing cardiac autonomic regulation and fatigue among endurance athletes (Pichot et al., 2000, 2002; Plews, Laursen, Stanley, Kilding, & Buchheit, 2013), and is becoming increasingly accessible with emerging technologies (Weippert et al., 2010). The use of daily HRV to dictate same-day training prescription is gaining traction in endurance sport, such that when HRV is altered unfavourably, training on the day is reduced (Kiviniemi, Hautala, Kinnunen, & Tulppo, 2007; Plews et al., 2013; Vesterinen et al., 2016). Further, the use of HRV in the assessment of FOR may be valuable, however, to date there is no established autonomic profile of overreaching using HRV. Research groups have demonstrated increased (Hedelin, Wiklund, Bjerle, & Henriksson-Larsén, 2000; Le Meur, Hausswirth, et al., 2013), and decreased parasympathetic modulations (Bosquet, Merkari, Arvisais, & Aubert, 2008; Flatt et al., 2017; Pichot et al., 2002), and no changes to HRV (Dupuy et al., 2014; Hedelin, Kenttä, Wiklund, Bjerle, & Henriksson-Larsén, 2000), with FOR. This may be due to differences in overtraining protocols and hence fatigue levels (Schmitt et al., 2015), HRV methodology (Plews et al., 2013), or the inherent difficulties of HRV assessment due to day-to-day variability, breathing rates, and environmental factors (Plews et al., 2013). Of interest, alterations in HRV are rarely compared directly to same-day performance outcomes, or other chronotropic markers of overreaching such as reduced maximal heart rate (HRmax) (Bosquet et al., 2008; Hedelin, Kenttä, et al., 2000; Le Meur, Pichon, et al., 2013; Meeusen et al., 2013) or increased heart rate recovery (HRrec) (Aubry et al., 2015; Dupuy, Bherer, Audiffren, & Bosquet, 2013; Le Meur, Buchheit, Aubry, Coutts, & Hausswirth, 2017). As such, the strength of HRV as a monitoring tool for same-day fatigue and performance (FOR) is currently unclear.

Despite the issues with daily monitoring and HRV, novel technologies are emerging that aim to reduce the noise around HRV measures, and provide a more reliable measure of vagal activity (Julu, 1992; Paine, Kishor, Worthen, Gregory, & Aziz, 2009). The novel cardiac vagal tone (ProCVT) technology evaluates baroreflex-driven fluctuations in R–R intervals rather than extracting fluctuations due to respiratory sinus arrhythmia, thereby removing sympathetic contributions (Little, Julu, Hansen, & Reid, 1999), as the low-frequency contributions to HRV have repeatedly been shown unreliable for assessing sympathetic activity (Polanczyk et al., 1998; Reyes del Paso, Langewitz, Mulder, van Roon, & Duscek, 2013). Importantly, ProCVT technology evaluates vagal tone independent of breathing frequency and HR (Little et al., 1999), and uses a linear scale to better assess inter and intra-individual differences (Julu, 1992; Little et al., 1999). While ProCVT technology may be more accurate than HRV (Little et al., 1999), and could have value for assessing fatigue, this has not been reported with regards to endurance training.

While alterations to resting ProCVT and HRV have potential to inform appropriate daily training prescription based on pre-training fatigue-states, a clear association between fatigue related decreases in performance and an alteration in resting vagal modulation has not yet been established. Further, previous overtraining research tends to presume that an alteration in resting cardiac autonomic balance will be consistent across both rest and exercise, despite an obvious lack of empirical physiological support (Buchheit, Papelier, Laursen, & Ahmadi, 2007; Esco et al., 2010; Javorka, Zila, Balářek, & Javorka, 2002). Therefore, the dual purpose of this investigation was to determine (1) if alterations in resting HRV and ProCVT would be associated with decreases in performance consistent with FOR, and (2) whether alterations in HRV and ProCVT are associated with alterations in exercise-related cardiac regulation in FOR, including decreased HRmax and increased HRrec. It is hypothesized that despite high levels of fatigue, decreased exercise performance and altered chronotropic response to exercise, resting measures will not be predictive of exercising measures due to the lack of congruency between resting autonomic modulation, and exercising autonomic control.

Methods

A block-randomized experimental design was employed to ensure sex and age matched-controls. The study, as a part of a large study on cardiovascular and autonomic responses to overload training (Coates et al., 2017), was approved by the Research Ethics Board for human research at the University of Guelph, and all participants provided written informed consent.

Subjects

Endurance athletes, aged 23–50 years, were recruited from local triathlon and cycling clubs. Inclusion
criteria stipulated that subjects be healthy and free from injuries, familiar with cycle pacing, and currently following an endurance training programme that was not in a competition phase. Subjects completed the Physical Activity Readiness Questionnaire— for Everyone (PAR-Q+) to ensure readiness for physical activity (Warburton, Jammik, Bredin, & Gledhill, 2011). An optimized sample size of 15 subjects per group was chosen, due to previous studies which demonstrated physiological disturbances with 10–13 FOR athletes compared to controls (Aubry et al., 2014; Le Meur, Pichon, et al., 2013). Following recruitment, 17 subjects were assigned to the overload (OL) condition, with 16 controls (CON).

**Experimental design**

The protocol consisted of a 3-week overload period, which is illustrated in the supplementary material online. Subjects were assigned HR monitors, and associated online accounts (Polar A300, Kempele, Finland) to track workout duration and intensity for the duration of the 5-week study. At onset, all athletes undertook a reduced training week whereby training volume was decreased by ∼50%. Athletes then completed either 3 weeks of OL training or maintained their regular training programme (CON). The OL training consisted of three supplementary cycle training sessions per week in addition to the athletes’ normal training. Session 1 was a high-intensity interval workout consisting of 4 × 30 s Wingate anaerobic tests on an electromagnetically braked cycle ergometer (Racermate Velotron, Seattle, WA, USA), at a load of 7.5% body weight, with 4 min of recovery. Session 2 was a 15 km virtual time-trial performed on the same ergometer over a standardized course with undulating terrain. Session 3 comprised a 2 h ride that athletes completed outdoors, and was tracked using the described HR monitoring. The ride was prescribed as four blocks of 30 min comprising: 10 min at an HR matching 50–60% VO$_2$max, and 20 min HR 66–75% VO$_2$max. Heart rate zones were calculated from the initial VO$_2$max testing. CON athletes were asked to maintain their regular training programme as prescribed by their coach or pre-planned programme. Testing took place following the first week of recovery (T1), following the 3 weeks of either OL or CON training (T2), and following the final recovery week (T3). The Profile of Mood States Second Edition (POMS-2, Multi-Health Systems Inc., NY, USA) Questionnaire was given to the athletes to complete after each testing session. The POMS-2 questionnaire consists of 65 items that assess the level of mood disturbance from categories of Tension, Depression, Anger, Fatigue, Vigour, and Confusion. Statements encompassing Vigour were subtracted from the final score, and a constant of 100 was added to the total mood disturbance score to account for possible negative scores (Morgan, Brown, Raglin, O’Connor, & Ellickson, 1987).

**Resting measures**

On testing days, athletes were instructed to abstain from alcohol, smoking, exercise, and drugs for 24 h prior to testing, and to keep their nutrition consistent on T1, T2, and T3. A food recall for the previous night’s and same-day meals/beverages prior to testing was given to each subject following the first visit. Athletes were told to maintain the same macronutrient content, and to mimic the timing of meals and beverages on T1 for future testing dates (T2 and T3).

All testing was performed in a quiet laboratory, maintained at 21 ± 1°C, in which only the participant and primary investigator were present. Baseline anthropometrics (height at T1, and weight for T1–T3) were taken at the beginning of each session. After ≥5 min of rest in the supine position, a 5 min HRV recording was taken using a SphygmoCor CPVH single lead ECG (AtCor Medical Ltd, NSW, Australia), during which participants were allowed to breathe spontaneously (Larsen, Tzeng, Sin, & Galletly, 2010). The SphygmoCor CPVH technology assesses normal R–R intervals and excludes ectopic beats, and is in accordance with European Society of Cardiology and the North American Society of Pacing and Electrophysiology guidelines (AtCor Medical). Mean resting HR, the square root of the mean of successive differences (RMSSD), and the standard deviation of normal-to-normal intervals (SDNN) were chosen for time-domain measures, with SDNN providing an overall estimate of variability (Task Force, 1996), and RMSSD providing an applicable measure of parasympathetic activity over a short time frame (Plewes et al., 2013). To remove the contributions of mean resting HR to HRV, RMSSD/HR was also calculated for the time period (Billman, Huikuri, Sacha, & Trimmel, 2015). For frequency domain analysis, absolute high frequency (HFa) power in ms$^2$ (0.15–0.4 Hz) was chosen to measure the contribution of parasympathetic modulation, and low frequency to high frequency ratio (LF/HF) was used as an indicator of sympathetic-parasympathetic balance in normalized units (Task Force, 1996).

A 3 min measurement of ProCVT was performed simultaneous to HRV recordings, using a ProCVT (ProBiometrics, London, UK) single lead ECG with bluetooth telemetry. The ProCVT unit has not previously been studied in a training/overtraining context, however, application of the underlying...
algorithms has been researched in clinical settings under the name Neuroscope (Medifit, London, UK) (Paine et al., 2009). ProCVT algorithms are not provided, however, the system relies on the consistent 240 ms latency and 0.1 Hz resonancy of the arterial baroreflex to predict the phase shifts in heart periods due to vagal innervation, independent of breathing rate or heart rate (Little et al., 1999). The ProCVT unit converts pulse intervals into a linear CVT index given in arbitrary units (a.u.), which has been validated against progressive atropine infusions, whereby zero represents no vagal activity (Julu, 1992).

Exercise test

Following resting measures, subjects performed a maximal incremental cycling test (Velotron) with oxygen consumption measured via mixing chamber using a Moxus metabolic cart (Moxus, PA, USA). Men followed a protocol beginning at 100 W and increasing 1 W every 2 s, with women similarly starting at 100 W, but increasing 1 W every 3 s. The test was terminated and peak watts were recorded when athletes could no longer maintain a cadence above 40 rpm seated or standing. Athletes were not asked to stop upon reaching a plateau in VO2; however, a plateau in VO2 (increase in Borg rate of perceived exertion (RPE) ≥ 1.15 and a respiratory exchange ratio (RER) ≥ 1.15 and a Borg rate of perceived exertion (RPE) ≥ 18, with the inability to continue pushing the pedals above 40 rpm, was required for an adequate test. HR was monitored using a Polar heart rate strap (A300) and was recorded at the moment of exercise termination, and following 60 s of seated rest on the bike. HRrec was determined by subtracting the HR at 60 s from HR at exercise termination. Lactate sampling was initiated at 60 s, using standard finger stick sampling, with samples every 30 s until values declined (Lactate Plus, Nova Biomedical, Waltham, MA, USA), and maximal blood lactate concentration was recorded as highest observed value.

Determination of FOR

The criteria for FOR diagnosis in elite and well-trained athletes is a decrement in performance (Meeusen et al., 2013), and more recently, concomitant decreases in mood states or increased perceived fatigue (Aubry et al., 2015; Dupuy et al., 2014), HRmax (Le Meur, Pichon, et al., 2013), and lactate (Le Meur, Hausswirth, et al., 2013). As the athletes in the present study were sub-elite athletes, we determined that FOR may not be accurately quantified due to the large increases in fitness which may mask the subsequent performance decrements. We created a formula to individually diagnose athletes with suspected FOR as: power (W) at [T1 − T2] + (T3 − T2)]. This formula combines the decrease in power output expected from T1 to T2 from overload training, with the super-compensation expected at T3. In this fashion, should decrements to performance be masked at T2 due to increases in fitness over the 3 weeks, this would become apparent following a week of recovery and present as a substantially larger super-compensation than that of the CON group. Should performance not change from T1 to T3, or improve steadily from T1 to T3, this would be indicative of a CON athlete. A change in power output greater than the upper limit of the 95% confidence interval of this equation for the CON group was required for individual diagnosis of high levels of fatigue and suspected FOR, along with increased total mood disturbance scores and decreased HRmax. A possible limitation of the formula would be if the OL athlete developed NFOR, as in this population this could present as no change in power outputs across the 5 weeks. That said, we suspect should an athlete develop NFOR, they would have a decrease in power output from T1 to T2 due to augmented fatigue, which would be detectable by the formula.

Statistical analysis

Two-way ANOVA [group (OL, CON) × time (T1, T2, T3)] with repeated measures was used to examine changes in training duration, training intensity, peak power, lactate, mood state, VO2max, HRrec, HRmax, HRrest, HRV, and ProCVT variables. Data were assessed for normality using the Shapiro–Wilk test, and non-normal data were natural-log transformed; therefore, all resting measures other than HR were analysed using natural-log transformed data. When Mauchly’s test of sphericity was violated, Greenhouse–Geisser corrections were used. Bonferroni’s test was used for post-hoc analysis. To account for baseline differences and provide specific time point analysis, change scores were calculated for peak power, VO2max, HRmax, HRrec, POMS-2, HRV, and ProCVT by subtracting T1 from T2, and T2 from T3. The differences between mean deltas were assessed between groups using un-paired student t-tests. Pearson’s correlation was performed to examine relationships between deltas in HRrec, HRmax, and performance (peak power) with resting HR, HRV, and ProCVT. Normally distributed data are reported as mean ± standard deviations with significance set a priori at P < .05. Non-normally distributed data are presented
as median with interquartile ranges. All statistical analysis was executed using Statistical Package for the Social Science (SPSS, version 24; IBM, Chicago, IL, USA).

**Results**

**Overreaching diagnosis**

In the OL group, one athlete became ill and was unable to complete the protocol, and a further subject was deemed insufficiently overreached as per the novel formula. In the CON group, two athletes became ill, and one athlete was injured independent of the study, resulting in 13 CON subjects. Subject characteristics are presented in Table I. Ninety-five per cent of the incremental exercise tests resulted in a plateau or decline in VO2max upon failure, and the four tests which did not achieve a plateau in oxygen consumption achieved RER levels $\geq 1.15$ and RPE $\geq 18$.

Using the derived formula and concomitant decreases in HRmax and mood states, 15 OL subjects were individually diagnosed with very high levels of fatigue and suspected FOR. The mean net change in power using the formula was $30 \pm 16$ W for the OL group, and $-4.5 \pm 13$ W for the CON group ($P < .001$), with the upper limit of the 95% confidence interval of the CON group being 7 W. Only three OL athletes diagnosed using our formula had moderately increased peak power at T2; therefore, we individually assessed their changes in HRmax and negative mood states from T1 to T2. The mean $\Delta$HRmax for the 3 athletes was $-9 \pm 4$ beats/min, which is a greater decrease than the mean $\Delta$HRmax ($-8 \pm 4$ beats/min) for the remaining 12 OL athletes. The mean POMS-2 scores of the 3 athletes increased by 42 $\pm 17$ units, much greater than the 26 $\pm 25$ unit change of the remaining 12 athletes.

Training durations and proportion of time spent at different exercise intensities are presented in the supplementary material online. There was an increase in duration in both groups from T1 to T2 as expected, however, the OL group had a larger change in duration than the CON group (interaction $F(2,52) = 8.7, P < .001$).

As per traditional criteria of FOR, group differences occurred over time for peak power ($F(2,52) = 10.1, P < .001$), wherein performance decreased from baseline (T1) to overload (T2) in the OL group ($\Delta -9 \pm 12$ W, $P = .02$), but increased in CON ($\Delta 9 \pm 11$ W, $P = .03$). Both groups increased their VO2max over time ($F(2,52) = 4.4, P = .02$), with the OL group demonstrating an increase in VO2max following the recovery week, whereas the CON group stayed the same from T2 to T3 (OL $0.16 \pm 0.18$ vs. CON $0.002 \pm 0.14$ L/min, $P = .02$). HRmax decreased $8 \pm 4$ beats/min from T1 to T2 with OL ($F(2,52) = 20.7, P < .001$) and recovered by T3, but did not change in CON. Lactate did not change significantly between groups, however, analysis of change scores revealed a difference between groups from T1 to T2 (OL $-2.7 \pm 4.1$ vs. CON $-0.1 \pm 2.1$ mmol/L, $P = .05$). Total mood disturbance scores were much greater at T2 following OL training than following CON training ($F(2,50) = 4.1, P = .02$), increasing by $29 \pm 24$ vs. $9 \pm 15$ units. Lastly, HRrec increased in OL and in CON from T1 to T2, and did not recover by T3 (time effect, $F(2,52) = 8.3, P < .001$) (Figure 1). Examination of the change scores for HRrec (delta between tests) shows the change in HRrec from T1 to T2 was $10 \pm 9$ beats/min in OL, vs. $2 \pm 5$ beats/min in CON ($P = .01$). Alterations to peak power, VO2max, POMS-2, HRmax, max lactate, and HRrec are presented in Figure 1. Individual changes in peak power can be seen in supplemental figure 2.

**Resting measures**

From T1 to T2 both groups had a decrease in resting HR (OL $-2 \pm 5$ bpm, CON $-4 \pm 7$ bpm, time effect $F(2,52) = 4.3, P = .02$). There were no changes across time or between groups for any of the other resting measures including: all HRV measures, RMSSD normalized to resting HR, or ProCVT (Table II). Complete data from the ProCVT was restricted to 8 athletes in the OL group, and 10 in the CON group due to technical difficulties with the Bluetooth telemetry. Between T1 and T2, data from the ProCVT was complete for 11 OL athletes and 11 CON athletes.

**Correlations between exercising and resting measures**

Alterations to peak power, HRrec and HRmax from the increased training load were unrelated to changes in resting cardiac measures (all HRV measures, HRrest or ProCVT) when groups were pooled. Representation of delta ProCVT and delta RMSSD/HR to changes in peak power, HRmax, and HRrec from T1 to T2 can be seen in Figure 2. The only chronotropic variable predictive of changes in performance from T1 to T2 when groups were pooled was alterations to HRmax ($r = 0.52, P = .005$, 95% CI [0.5,2.5]), which also occurred from T2 to T3 ($r = 0.67, P < .001$, 95% CI [0.9,2.5]).

Changes to ProCVT were significantly related with changes in other resting variables including HRrest
Discussion

The main finding of this study was that objective decreases in performance, Lastly, decreased HRmax may be the best indicator to assess FOR in this population, as fitness gains may obscure decrements to performance in recreational endurance athletes.

Correlations between HRV/ProCVT and HRrec/HRmax

Previous literature suggests that there may be an alteration in overall parasympathetic tone with FOR, as evidenced by altered resting HRV, decreased HRmax, and increased HRrec (Aubry et al., 2015; Flatt et al., 2017; Le Meur, Pichon, et al., 2013). In the present investigation, changes to resting measures of parasympathetic regulation were not evident, despite clear alterations in the cardiac response following exercise. While cross-sectional data exists to support an association between resting HRV and HRrec (Danieli et al., 2014), this likely reflects the effects of fitness on vagal activity and reactivity (Daanen, Lamberts, Kallen, Jin, & Van Meeteren, 2012), and not acute alterations in sympathovagal balance. Unique to our study, we aimed to determine whether the magnitude of individual changes in HRmax and HRrec would be associated with changes in resting vagal measurements (e.g., HRV and ProCVT), and did not find this to be the case. In agreement with our findings, a lack of an association between resting vagal regulation and post-exercise measures of parasympathetic

Table I. Descriptive characteristics of recreational cyclists and triathletes participating in a function overreaching exercise protocol, to examine changes to autonomic control divided by group allocation and sex

<table>
<thead>
<tr>
<th>Sex (n)</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Initial VO₂max (mL/kg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overload</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males (8)</td>
<td>40 ± 6</td>
<td>178 ± 5</td>
<td>80.2 ± 6.7</td>
<td>59.4 ± 4.1</td>
</tr>
<tr>
<td>Females (7)</td>
<td>35 ± 9</td>
<td>168 ± 7</td>
<td>61.7 ± 6.3</td>
<td>48.8 ± 5.1</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males (8)</td>
<td>37 ± 10</td>
<td>181 ± 6</td>
<td>78.5 ± 7.8</td>
<td>59.6 ± 7.6</td>
</tr>
<tr>
<td>Females (5)</td>
<td>34 ± 11</td>
<td>167 ± 4</td>
<td>62.9 ± 4.1</td>
<td>47.1 ± 3.5</td>
</tr>
</tbody>
</table>

Discussion

The main finding of this study was that objective decreases in performance, increases in HRRec and decreases in HRmax in athletes following overload training were not reflected in alterations to resting HRV or ProCVT measures. The important secondary finding was that while changes to ProCVT measures and select vagal HRV measures were highly correlated, and can be used interchangeably with traditional HRV measures of parasympathetic modulation, ProCVT measures are not necessarily a better predictor than HRV of decreased exercise performance. Lastly, decreased HRmax may be the best indicator to assess FOR in this population, as fitness gains may obscure decrements to performance in recreational endurance athletes.

Correlations between HRV/ProCVT and HRrec/HRmax

Previous literature suggests that there may be an alteration in overall parasympathetic tone with FOR, as evidenced by altered resting HRV, decreased HRmax, and increased HRrec (Aubry et al., 2015; Flatt et al., 2017; Le Meur, Pichon, et al., 2013). In the present investigation, changes to resting measures of parasympathetic regulation were not evident, despite clear alterations in the cardiac response following exercise. While cross-sectional data exists to support an association between resting HRV and HRrec (Danieli et al., 2014), this likely reflects the effects of fitness on vagal activity and reactivity (Daanen, Lamberts, Kallen, Jin, & Van Meeteren, 2012), and not acute alterations in sympathovagal balance. Unique to our study, we aimed to determine whether the magnitude of individual changes in HRmax and HRrec would be associated with changes in resting vagal measurements (e.g., HRV and ProCVT), and did not find this to be the case. In agreement with our findings, a lack of an association between resting vagal regulation and post-exercise measures of parasympathetic

Table II. Resting heart rate, HRV, and ProCVT measures in recreational triathletes and cyclists following a week of reduced training (T1), 3 weeks of regular (CON) or overload (OL) training (T2), and a final week of recovery (T3)

<table>
<thead>
<tr>
<th></th>
<th>HRrest (beats/min)</th>
<th>RMSSD (ms)</th>
<th>RMSSD/HR (a.u.)</th>
<th>SDNN (ms)</th>
<th>LF/HF (ms²)</th>
<th>HFa (ms²)</th>
<th>CVT (a.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>60 (55–65)</td>
<td>64 (29–90)</td>
<td>1.0 (0.4–1.7)</td>
<td>78 (48–98)</td>
<td>1.4 (0.9–2.7)</td>
<td>1030 (248–1450)</td>
<td>12.2 (5.6–14.8)</td>
</tr>
<tr>
<td>T2</td>
<td>58 (52–62)</td>
<td>57 (39–73)</td>
<td>1.0 (0.5–1.4)</td>
<td>63 (48–86)</td>
<td>1.7 (0.8–2.7)</td>
<td>737 (372–1613)</td>
<td>10.0 (8.7–13.1)</td>
</tr>
<tr>
<td>T3</td>
<td>57 (54–62)#</td>
<td>57 (38–74)</td>
<td>1.0 (0.4–1.5)</td>
<td>68 (48–93)</td>
<td>1.4 (0.6–3.2)</td>
<td>1034 (247–1504)</td>
<td>10.0 (7.7–12.8)</td>
</tr>
<tr>
<td>CON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>60 (56–63)</td>
<td>73 (37–87)</td>
<td>1.2 (0.6–1.7)</td>
<td>90 ± 51</td>
<td>1.6 ± 1.3</td>
<td>1038 (342–1710)</td>
<td>12.8 (7.2–14.9)</td>
</tr>
<tr>
<td>T2</td>
<td>56 (53–60)</td>
<td>65 (48–120)</td>
<td>1.1 (0.9–2.3)</td>
<td>93 ± 50</td>
<td>1.9 ± 1.4</td>
<td>1015 (399–2608)</td>
<td>12.2 (7.6–17.7)</td>
</tr>
<tr>
<td>T3</td>
<td>56 (52–60)#</td>
<td>93 (38–109)</td>
<td>1.7 (0.7–2.1)</td>
<td>100 ± 53</td>
<td>2.0 ± 1.8</td>
<td>1893 (210–2320)</td>
<td>14.0 (5.6–18.0)</td>
</tr>
</tbody>
</table>

Data presented as median (interquartile range) due to non-Gaussian distributions. Repeated measures ANOVAs performed on natural-log transformed data. # = Main effect of time, P < .05.
Figure 1. Typical markers of FOR for recreational endurance athletes following a week of reduced training (T1), 3 weeks of either overload (OL) or regular (CON) training (T2), and following a week of recover (T3). Within group change across time. Data as mean ± SD. *P < .05, **P < .001.
regulation, is fairly well established (Bosquet et al., 2008; Esco et al., 2010; Javorka et al., 2002). While HRV assesses the level of (predominantly) vagal cardiac modulations, it does not provide a measure of vagal tone—which, presumably, is consistent at rest and following exercise (Task Force, 1996). Resting HRV also does not accurately assess central sympathetic drive (Polanczyk et al., 1998; Reyes del Paso et al., 2013), which may be increased following overload training (Coates et al., 2017). In addition, while HRRec is due to primarily parasympathetic reactivation (Imai et al., 1994), it may be more heavily influenced by sympathetic withdrawal following supra-maximal/anaerobic exercise (Buchheit, Laursen, & Almadi, 2007; Buchheit, Papelier, et al., 2007). Further, as FOR athletes have been demonstrated to have reduced catecholamine and metabolite production during exercise (Le Meur, Pichon, et al., 2013), this could explain the increases in HRRec with overreaching, independent of parasympathetic tone. In summary, the notion that an increase in parasympathetic tone causes increased HRRec with FOR is unclear at this point in time, and is not related to alterations in resting vagal indices.

Using HRV/ProCVT for athlete monitoring

In the present investigation, we did not observe any changes in HRV or ProCVT measures, despite periods of fatigue and/or increases in fitness. Le Meur et al. found that while daily supine and standing measures of HRV during overreaching were inconclusive, weekly averages demonstrated increased parasympathetic modulation with FOR (Le Meur, Pichon, et al., 2013). Plews et al. also advocate for the use of weekly averages for the detection of NFOR in elite athletes (Plews et al., 2013), and further suggest the use of an HRV (Ln RMSSD) to resting HR ratio in order to account for decreases in parasympathetic modulation due to vagal saturation (Plews et al., 2013).

While overload training was not accompanied with increased illness or reduced performance super-compensations in the present investigation, athlete monitoring is still important for the assessment of fatigue status, and prevention of NFOR (Meeusen et al., 2013). Recreational athletes may be difficult to diagnose as FOR, as traditional criteria (a decrease in performance) may be masked by fitness gains incurred over the preceding training block, therefore other physiological assessments are warranted and we present a novel formula for this purpose. HRV and ProCVT measures are easy to use, and are gaining popularity with coaches and athletes for assessing daily fatigue and prescribing daily training (Kiviniemi et al., 2007); however, this investigation indicates that any alterations to HRV/ProCVT are not predictive of reduced performance or altered cardiac response during same-day exercise. In contrast, decreased HRmax and increased HRRec may be a better indicator of suspected FOR in this population, with the awareness that sub–elite athletes will have increases in HRRec with fitness (Daanen et al., 2012).

Limitations and future directions

It is possible that our mixed-sex groups caused changes in parasympathetic modulation to be...
Investigating the use of pre-training measures of autonomic regulation

Funding

This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grant 03974; and the Canada Foundation for Innovation under Grant 460597.

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