Article Type: Original report

Title: Day-to-day heart rate variability (HRV) recordings in world champion rowers: appreciating unique athlete characteristics

Author: Daniel J. Plews[1, 2, 3], Paul B. Laursen[1, 2] and Martin Buchheit

Affiliations:

1. High Performance Sport New Zealand, Auckland, New Zealand
2. Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand
3. University of Waikato, Hamilton, New Zealand
4. Performance Department, Paris Saint Germain Football, Saint-Germain-En-Laye, France

---

Contact Information:
Daniel Plews
High Performance Sport New Zealand
Millennium Institute of Sport & Health,
17 Antares Place,
Mairangi Bay, 0632, New Zealand
Ph: +64 21 250 9591
Fax: +64 9 479 1486
Corresponding Author: Daniel Plews: daniel.plews@hpsnz.org.nz

Abstract: 248
Main text: 2790
Figures and tables: 3 Figures, 2 Tables

Abstract

Keywords: cardiac parasympathetic function, monitoring, elites

Abstract

Purpose: Heart rate variability (HRV) is a popular tool for monitoring autonomic nervous system status and training adaptation in athletes. It is believed that increases in HRV indicate effective training adaptation, but these are not always apparent in elite athletes. **Methods:** Resting HRV was recorded in 4 elite rowers (Rower A, B, C and D) over the 7-week period prior to 2015 World Rowing Championship success. The natural logarithm of the square root of the mean sum of the squared differences between R–R intervals (Ln rMSSD), Ln rMSSD:R-R ratio trends, and the Ln rMSSD to R-R interval relationship were assessed for each champion-winning rower. **Results:** The time course of change in Ln rMSSD was athlete-dependant, with stagnation and decreases apparent. However, there were consistent substantial reductions in the Ln rMSSD:R-R ratio, Rower A: baseline towards week 5 (-2.35 ±1.94); Rower B baseline to week's 4 and 5 (-0.41 ±0.48; -0.64 ±0.65 respectively); Rower C baseline to week 4 (-0.58 ±0.66); Rower D baseline to week's 4, 5 and 6 (-1.15 ±0.91; -0.81 ±0.74; -1.43 ±0.69 respectively). **Conclusion:** Reductions in Ln rMSSD concurrent with reductions in the Ln rMSSD:R-R ratio are indicative of parasympathetic saturation. As such, 3 of 4 rowers displayed substantial increases in parasympathetic activity despite having decreases in Ln rMSSD. These results confirm that a combination of indices should be used accordingly to monitor cardiac autonomic activity.

Introduction

The routine measurement of heart rate variability (HRV) to monitor wellness and athletic "readiness to perform" has grown in popularity over the last decade.[1,2] Companies including Omegawave™ and various smartphone applications (e.g., ithlete, BioForce HRV, HRV4training, Elite HRV, Sweetbeat) have popularised HRV, permitting accessibility of HRV measurement to not only athletes, but all individuals interested in monitoring cardiac autonomic nervous system status. The need to effectively monitor both maladaptive and positive adaptations to training is of upmost importance to the elite athlete, who always push the boundary between functional (adapting positively) and non-functional overreaching. [3]

With respect to the elite athlete however, HRV interpretation must be more carefully considered.[4] As we have shown, interpretation of changes in HRV must consider the parasympathetic saturation effect and the Ln rMSSD to R-R interval relationship.[4] Indeed, parasympathetic saturation is a frequent occurrence in elite athletes, who typically display low resting heart rates (RHR, ~<50 bpm) due to high vagal tone.[5] Without appreciation of the saturation phenomenon however, HRV interpretation is misleading and often false.[6]

It can be assumed that athletes winning on the world stage do so with ideal preparation.[7] However, real-life longitudinal data in elite athletes, particularly those at the peak of their physical condition leading into pinnacle events, including world championships and Olympic Games, are particularly rare. Such examples may allow benchmarks for practitioners and coaches to help guide effective practice towards pinnacle performances.

In this study, daily morning resting HRV was monitored in 4 elite rowers during the 7-week training period prior to the 2015 Rowing World Championships; all athletes became world champions, winning their respective events in three separate boat classes. The aim of this observational study was to showcase the HRV trends occurring during the critical training lead-in period in these athletes. As with our previously reported work,[4] we confirm that athletes undergoing heavy training loads in the period leading into major event competition may experience increases or decreases in Ln rMSSD, but that the interpretation of its meaning (functional vs. non-functional) depends upon its relationship with the R-R interval and the associated saturation response.

Methods

Participants

Four lightweight rowers, 3 female (body weight: 59.0 ±0.9 kg; height: 166.7 ± 2.1 cm; VO_{2max}: 61.7 ±1.7 ml.kg.min^{-1}) and 1 male (body weight: 72 kg; height: 185 cm; VO_{2max}: 72.3 ml.kg.min^{-1}) across three boat classes were monitored for a 7-week period prior to the 2015 World Rowing Championships in Aiguebelette, France. All athletes agreed to take part in the day-to-day monitoring activities that are routinely performed as members of the National New Zealand Rowing Team. The publication of these data were approved by the human research ethics committee of AUT University.

Training

All athletes received their training plan from the same rowing coach. As such, training content was similar for each rower. Training consisted of 11 on-water rowing sessions and 1 indoor ergometer (Concept II) rowing session each week. The training microcycles during this period can be seen in Figure 1 and were comprised of 1 light week of training, 4 weeks of overload training, followed by a 2-week taper. One rower (Rower A, Figure 1) also competed at the U23 World Rowing Championships and joined the training group 1 week later. As such, this rower carried out 1 light training week, 3 overload training weeks and a 2-week taper.

All training sessions were monitored using the Garmin 910xt system (Garmin Ltd, Southampton, United Kingdom) which records heart rate (via ANT+ heart rate chest strap), rowing distance and rowing speed (via global positions systems) onto a wrist watch. Training volume, training distance and training intensity distribution was monitored using Trainingpeaks.com (TrainingPeaks.com, Boulder, Colorado). The demarcation of individual heart rate training zones (in order to describe training intensity distribution) was achieved using a 7 x 4-min step-test which was carried out during week 1 of a four week meso-cycle after a recovery week. Time in training zones were categorised as the time accumulated below the first lactate threshold ($<LT_1$), time accrued between the first and second lactate thresholds (LT_1-LT_2) and time training above the second lactate threshold ($>LT_2$), as described previously.[8]

Heart rate recordings

Heart rate was measured upon waking using the Polar Bluetooth H7 heart rate sensor and HRV was determined via the R-R series recorded. Rowers were instructed to leave the HR monitor electrode strap by their bedside each evening to ensure minimum disturbances when applying the apparatus. After a 30 second stabilization period, HR was captured for 1 min[9] in a supine position via an in-house built iPhone app (Igtimi HRV). Respiration rate was not controlled. R-R intervals were recorded at a rate of 250 Hz and the log-transformed square root of the mean sum of the squared differences between R-R intervals (Ln rMSSD) was calculated. Data was automatically sent from the smartphone device to the sport scientist for analysis once the recording was completed. HRV analysis was limited to rMSSD since it reflects vagal activity[10] and has greater reliability as an index of HRV than other spectral indicators[11] particularly during 'free-running' ambulatory conditions.[12] The R-R-to-Ln rMSSD ratio[4] and average resting heart rate (RHR) was also calculated. Ln rMSSD was averaged over a 1-week period, as this has been shown to provide a superior representation of training status.[13-16] If athletes achieved less than 3 HRV recordings in a week, the data point was removed from the overall analysis.[17] The individual Ln rMSSD interval to R-R relationship was also considered for each rower.[18] This was carried out by plotting the daily 1-min average of the R-R intervals against Ln rMSSD.

Heart rate variability data processing and filtering

For practicality and efficiency, HRV data was filtered for errors and ectopic beats via the smartphone application. This was performed by first extracting R-R values that differed by more than 75% from the previous value, after which the median R-R interval was then calculated. From this median, the minimum and maximum beat duration were then set at 0.6 and 1.4, respectively. The longest consecutive run of R-R intervals that were within this minimum and maximum duration were then found, and Ln rMSSD was then calculated. The result was only considered valid if the run lasted $\geq$ 30 seconds. This process avoids over-correcting, a problem of the widely employed removal of consecutive RR intervals differing by more than 25%[19] for individuals with very high beat-to-beat variability. In house testing revealed near perfect (r = 0.99) correlations between these methods and electrocardiograph. These differences are also similar to what has been reported by other applications that assess HRV via Smartphone applications.[20]

Statistical analysis

Individual weekly data are presented as means (Monday to Sunday) and 90% confidence limits (CL) unless otherwise stated. Individual baseline HRV was established during the first light week of training (Figure 1). Within-rower baseline-to-week differences in HR-based variables were expressed as standardised mean differences, or effect sizes (ES), and assessed using a magnitude of change approach.[21] The following threshold values for ES statistics utilized were ≤0.2 (trivial), >0.2 (small), >0.6 (moderate), >1.2 (large), and >2.0 (very large). The smallest worthwhile change (SWC) [22] in Ln rMSSD and RHR from baseline was deemed as 0.5 of the individual baseline coefficient variation (CV)[4,14] and 2%, respectively.[2] Quantitative chances of either higher or lower Ln rMSSD and RHR values versus baseline were also evaluated qualitatively as follows: 25-75% possibly, 75-95% likely, 95-99% very likely, >99% almost certain. If the chance of higher or lower differences was >5%, then the true difference was assessed as unclear. To analyse the day-to-day variation of within-rower HRV values, the weekly CV (%) was calculated.[14]

Results

All 4 athletes completed their prescribed training plans without disturbance from either illness or injury. All athletes recorded at least 3 HRV recordings per week (average number of weekly HRV recordings = 6.04 ± 0.23) or more during the monitoring period,[17] so no data points were removed from the analysis. All the athletes became world champions winning their respective boat classes.

Training

Average weekly training hours over the 7-week period was 13 hr, 7 min ± 32 min, including 121 ± 7 km of on-water rowing. The training intensity distribution for each rower is shown in Table 1.

Heart rate based variables

The individual weekly % differences in Ln rMSSD and RHR values from baseline are shown in Table 2 and Figure 1.

Within-rower % differences and 90% CL for both Ln rMSSD, Ln rMSSD:R-R ratio and RHR from baseline are shown in Figure 2, and Table 2. For Ln rMSSD, Rower A revealed a large reduction from baseline to week 2 and Rower D showed moderate reductions from baseline to weeks 4 and 6. All other values for Rowers B and C were deemed unclear. For the Ln rMSSD:R-R ratio, all rowers displayed a substantial decrease at some point during the 7-week period. Rower A expressed large decreases from baseline towards week 5 and Rower B had small and moderate decreases from baseline to weeks 4 and 5. Rower C displayed a small decrease from baseline to week 4. Rower D revealed large, moderate and large decreases from baseline to weeks 4, 5 and 6 (Figure 2).

The Ln rMSSD-to-R-R interval relationship collected over the entire period is also shown in Figure 3. Here, Rowers A and B display a "linear" Ln rMSSD-to-R-R interval pattern, while Rowers C and D show a "low-correlated" relationship [18].

Discussion

The aim of this observational study was to showcase HRV trends, and therefore the unique HRV characteristics of elite rowers prior to peak performance. By using practical examples of HR-derived indices leading towards elite athlete success, we hoped to highlight critical considerations for HRV assessment for sports scientists and coaches adjusting training using HRV.

It is becoming increasingly clear that heightened cardiac parasympathetic activity during overload periods of training are associated with functional overreaching during an overload period of training in both the laboratory[13,16] and the field.[4,23] Further, subsequent decreases in HRV appear associated with readiness to perform and ideal competitive performance after a period of reduced training (i.e. taper). For example, Le Meur et al. [13] showed that increases in HRV during an overload training period were associated with increased fatigue and decreased performance. In this study however, all athletes then improved after a taper period, coinciding with the HRV returning towards baseline values. The authors suggested that this trend may have been a sign of functional training adaptation and part of the super-compensation cycle. Indeed, a recent meta-analysis by Bellenger et al. [24] concludes that increases in vagal-related indices of resting HRV are evident when functional overreaching has occurred, and may contribute to enhanced performance when the training load is reduced.

In the current study, it is apparent that for two of these world champion rowers (C and D), the exact converse may be true when referencing Ln rMSSD alone. Figure 2 shows how for both Rower's C and D, their Ln rMSSD values fell below the individual SWC threshold on 3 and 2 occasions, respectively, during the heavy training period prior to winning the 2015 Rowing World Championships. Whilst recognising that Rower C had "unclear" changes in the HRV, with specific reference to HRV guided training, confidence limits/intervals are not generally used in the field to inform day-to day training decisions. [25,26] As such, practitioners in the field may alter training based on these changes.

The fact that these athletes still produced optimal performances with low Ln rMSSD through the loading period to win the World Championships is contradictory to what has been reported previously.[4,13,16] Indeed, such reductions in rMSSD have previously been associated with negative training adaptation in the case of NFOR and underperformance.[14] The reason for these differences may be due to the individual relationships between cardiac parasympathetic activity and R-R interval length (Figure 3). For example, Rowers A and B display "linear" Ln rMSSD to R-R interval correlations, while Rowers C and D display "low-correlated" behaviour.[18] The lack of correlation between the R-R interval and Ln rMSSD indicate that these athletes (C and D) are more likely to undergo parasympathetic saturation,[4] and explains the low Ln rMSSD values despite likely high parasympathetic tone (as inferred from low RHR).[28] In the case of rower D (Figure 2), it is apparent during weeks 4 and 6 that likely decreases in Ln rMSSD are associated with concomitant likely decreases in RHR and the Ln rMSSD: R-R ratio, which is indicative of parasympathetic saturation.[4] In the case of athlete C, although all changes in Ln rMSSD were deemed unclear, there was a likely decrease in RHR and Ln rMSDD: R-R interval during weeks 2 and 3 respectively. Indeed an 11% decrease in Ln rMSSD (Table 2, week 2 and 3) would likely be cause for concern for most practitioners. However, this rower's RHR was also the lowest amongst the group (RHR = 38 ± 3). As such, when vagal tone is high, parasympathetic modulation (HRV) is reduced.[5] Accordingly in such circumstances, reductions in HRV are not indicative of increases in sympathetic activity, but in fact reveal the opposite (increases in parasympathetic tone).[29]

We have shown previously how changes in parasympathetic saturation can be tracked using either the Ln rMSSD:R-R interval ratio or RHR alongside Ln rMSSD prior to sub-optimal performance (i.e. negative training adaptation).[4] However, for the first time in this study, we demonstrate how these variables can also change during positive adaptation to training. In this context, parasympathetic tone is likely maintained and/or increased**.** As such, the expected increases in Ln rMSSD[4,13,16] (a measure of vagal modulation) were blunted by the high levels of vagal tone and parasympathetic saturation in the case of athlete's C and D. This was not the case in athletes A and B who display more linear relationships.

Data from the present study allow us to appreciate how a more holistic approach to HRV interpretation is needed when monitoring athletes; one that is inclusive of a variety of HR-derived indices. Monitoring methods involving HRV indices that include the Ln rMSSD, Ln rMSSD:R-R interval ratio and RHR, may together allow for accurate diagnosis of training status. Furthermore, other metrics such as wellness questionnaires and counter movement jumps (neuromuscular status) may also be beneficial to monitor athletes as effectively as possible.[2,16] It should also be noted that increases in vagal activity are not always indicative of improved competitive performance, but rather positive adaptation to the training stimulus. In most cases, HR-derived indices either returned to baseline values, or displayed reduced cardiac parasympathetic activity during competition week. For example, Rowers C and D had likely and very likely increases in RHR in week 7 from baseline (Table 2). This again is in agreement with what has been reported previously,[4,13,16,23] where HRV tends to decline during taper periods. Such decreases in parasympathetic activity may allow for superior cardio-acceleration (and potentially heightened sympathetic nervous system arousal) during exercise, thereby contributing to enhanced oxygen delivery and exercise performance.[30]

With respect to Rower's A and B, Rower A shows a substantially decreased Ln rMSSD during week 2, but then remained stable throughout the training period from that point on. However, this athlete competed in the Under 23 world rowing championships and then travelled to the training location. Given the incoming HRV data, training was subsequently altered (a reduction in high intensity) during week 2 to allow HRV values to return to baseline. Conversely, Rower B's Ln rMSSD remained within the SWC for the entire training period. Interestingly, Rower B had acquired the longest training history (the only rower of the 4 who also competed at the London Olympics). We can speculate that the reason for this stagnation in Ln rMSSD change may be due to attainment of a plateau in the cardiovascular training stimulus, whereby training may have been insufficient to induce the same vagal-activity adaptation as Rowers A, C and D.

The occurrence of parasympathetic saturation can indeed be an added complication when using HRV as a monitoring tool. It has been suggested that collecting HRV samples during upright sitting,[31] or standing[32] may eliminate this problem. However in some athletes, HRV data collected in the upright position does not always eliminate parasympathetic saturation,[26] and for the practitioner, daily compliance (in terms of HRV data collection) is important.[2] It has been observed that standing (and supine-to-standing) postures result in vastly reduced athlete compliance with critical daily data points often being missed (DJP personal observation).

It has been recently suggested that the use of spectral analysis and supine-to-standing procedures may offer a superior methodology for tracking adaptation to training[33] compared with the simpler method of rMSSD assessment alone from supine collection.[2,4] The suggested method by Schmitt et al[33] consists of a 30-min long procedure (15-min rest, 8-min supine and 7-min standing). However, it is unlikely that elite athletes or otherwise would commit to such a daily task despite the suggested greater sensitivity. Due to the relative 'noise' of all vagal-related indices of HRV,[11] regular daily recordings and compliance are fundamentally important. Such regular data points allow for more accurate analysis to be presented in the form of weekly and rolling averages. Importantly, the data collected for the present study was completed using just 1-minute samples, which again increases athlete compliance dramatically.[9] This occurrence reduces 'noise'[14,15] allowing for improved certainty around training decisions made by coaches or sport scientists.[2]

Practical Application

Increases in vagal-related activity during an overload period of training are believed to be associated with functional overreaching and subsequent peak performance[23] when the training load is reduced. However, when analysing such changes, practitioners must also consider the athlete's individual relationship between the Ln rMSSD and R-R interval and simultaneously track Ln rMSSD, the Ln rMSSD: R-R interval ratio and RHR. In some circumstances, such as vagal saturation, decreases in cardiac parasympathetic indices of HRV during this particular training phase can be related to positive performance outcomes and consequently reductions in HRV, so should not be viewed negatively. Importantly, practitioners should also consider the type of athlete (endurance vs. team sport),[34] their Ln rMSSD and R-R interval relationship[18] and the phase/type of training that is currently being performed (i.e. polarised endurance training or higher intensity repetition training).

Conclusion

These data add further support for the use of HRV as a monitoring tool to objectively track positive responses to training in athletes, with the caveat that the unique athlete characteristics are appropriately considered.

Conflicts of interest

The authors declare no conflict of interest with the publication of this study.

References

1. Bellenger CRF, J. T. Thomson, R. L. Davidson, K. Robertson, E. Buckley, J. D. Monitoring athletic training status through autonomic heart rate regulation: a systematic review and meta-analysis. Sports Med 2016; Epub ahead of print.
2. Buchheit M. Monitoring training status with HR measures: do all roads lead to Rome? Front Physiol 2014;5:73.
3. Meeusen R, Duclos M, Foster C, et al. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. Med Sci Sports Exerc 2013;45:186-205.
4. Plews DJ, Laursen PB, Stanley J, Kilding AE, Buchheit M. Training adaptation and heart rate variability in elite endurance athletes: opening the door to effective monitoring. Sports Med 2013;43:773-81.
5. Sacknoff D, Gleim G, Stachenfeld N, Glace B, Coplan N. Suppression of high-frequency power spectrum of heart rate variability in well-trained endurance athletes`. Circulation 1992;86:I-658.
6. Iellamo F, Legramante JM, Pigozzi F, et al. Conversion from vagal to sympathetic predominance with strenuous training in high-performance world class athletes. Circulation 2002;105:2719-24.
7. Tonnessen E, Sylta O, Haugen TA, Hem E, Svendsen IS, Seiler S. The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. PLoS One 2014;9:e101796.
8. Plews DJ, Laursen PB, Kilding AE, Buchheit M. Heart-rate variability and training-intensity distribution in elite rowers. Int J Sports Physiol Perform 2014;9:1026-32.
9. Flatt AA, Esco MR. Heart rate variability stabilization in athletes: towards more convenient data acquisition. Clin Physiol Funct Imaging 2016; 36(5):331-6.
10. TaskForce. Heart Rate Variability. European Heart Journal 1996:354-81.
11. Al Haddad H, Laursen PB, Chollet D, Ahmaidi S, Buchheit M. Reliability of resting and postexercise heart rate measures. Int J Sports Med 2011;32:598-605.
12. Penttila J, Helminen A, Jartti T, et al. Time domain, geometrical and frequency domain analysis of cardiac vagal outflow: effects of various respiratory patterns. Clin Physiol 2001;21:365-76.
13. Le Meur Y, Pichon. A, Schaal K, et al. Evidence of Parasympathetic Hyperactivity in Functionally Overreached Athletes. Med Sci Sports Exerc 2013; 45(11):2061-71.

14. Plews DJ, Laursen PB, Kilding AE, Buchheit M. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. Eur J Appl Physiol 2012;112:3729-41.
15. Plews DJ, Laursen PB, Kilding AE, Buchheit M. Evaluating training adaptation with heart-rate measures: a methodological comparison. Int J Sports Physiol Perform 2013;8:688-91.
16. Bellenger CR, Karavirta L, Thomson RL, Robertson EY, Davison K, Buckley JD. Contextualising Parasympathetic Hyperactivity in Functionally Overreached Athletes With Perceptions of Training Tolerance. Int J Sports Physiol Perform 2015; 11(7):685-92
17. Plews DJ, Laursen PB, Le Meur Y, Hausswirth C, Kilding AE, Buchheit M. Monitoring training with heart rate-variability: how much compliance is needed for valid assessment? Int J Sports Physiol Perform 2014;9:783-90.
18. Kiviniemi AM, Hautala AJ, Seppanen T, Makikallio TH, Huikuri HV, Tulppo MP. Saturation of high-frequency oscillations of R-R intervals in healthy subjects and patients after acute myocardial infarction during ambulatory conditions. Am J Physiol Heart Circ Physiol 2004;287:H1921-7.
19. Lippman N, Stein KM, Lerman BB. Comparison of methods for removal of ectopy in measurement of heart rate variability. Am J Physiol 1994;267:H411-8.
20. Flatt AA, Esco MR. Validity of the ithlete Smart Phone Application for Determining Ultra-Short-Term Heart Rate Variability. Journal of human kinetics 2013;39:85-92.
21. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 2009;41:3-13.
22. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. Int J Sports Physiol Perform 2006;1:50-7.
23. Stanley J, D'Auria S, Buchheit M. Cardiac parasympathetic activity and race performance: an elite triathlete case study. Int J Sports Physiol Perform 2015;10:528-34.
25. Vesterinen V, Nummela A, Heikura I, et al. Individual Endurance Training Prescription with Heart Rate Variability. Med Sci Sports Exerc 2016; 48(7):1347-54
26. Kiviniemi AM, Hautala AJ, Kinnunen H, Tulppo MP. Endurance training guided individually by daily heart rate variability measurements. Eur J Appl Physiol 2007;101:743-51.
27. Pagani M, Lucini D. Can autonomic monitoring predict results in distance runners? American journal of physiology Heart and circulatory physiology 2009;296:H1721-2.
28. Buchheit M, Papelier Y, Laursen PB, Ahmaidi S. Noninvasive assessment of cardiac parasympathetic function: postexercise heart rate recovery or heart rate variability? Am J Physiol Heart Circ Physiol 2007;293:H8-10.
29. Hedman AE, Hartikainen JE, Tahvanainen KU, Hakumaki MO. The high frequency component of heart rate variability reflects cardiac parasympathetic modulation rather than parasympathetic 'tone'. Acta Physiol Scand 1995;155:267-73.
30. Parouty J, Al Haddad H, Quod M, Lepretre PM, Ahmaidi S, Buchheit M. Effect of cold water immersion on 100-m sprint

performance in well-trained swimmers. Eur J Appl Physiol 2010; 109(3):483-90.
31. Stanley J, Peake JM, Buchheit M. Cardiac parasympathetic reactivation following exercise: implication for training prescription. Sports Med 2013; 43(12):1259-77
32. Mourot L, Bouhaddi M, Perrey S, Rouillon JD, Regnard J. Quantitative Poincare plot analysis of heart rate variability: effect of endurance training. Eur J Appl Physiol 2004;91:79-87.
33. Schmitt L, Regnard J, Millet GP. Monitoring Fatigue Status with HRV Measures in Elite Athletes: An Avenue Beyond RMSSD? Front Physiol 2015;6:343.
34. Flatt AA, Esco MR, Nakamura FY, Plews DJ. Interpreting daily heart rate variability changes in collegiate female soccer players. J Sports Med Phys Fitness 2016. Epub ahead of print

Figure Legends

Figure 1. The basic training load of rower A (top panel) and rowers B, C and D (lower panel) during the 7 week training period. The white patterned bars represent a light week of training where the individual HRV baseline was established. The grey bars represent the heavy "overload" periods of training. The black bars represent the two weeks of taper prior to the World Rowing Championships. Data are presented as a % of the squad's standard training load.

Figure 2. Changes in the natural logarithm of the square root of the mean sum of the squared differences between R–R intervals (Ln rMSSD) with 90 % confidence intervals (CI) and the Ln rMSSD to R–R interval ratio for Rowers A, B, C and D during the 7-week training period prior to the 2015 World Rowing Championships. Black circular symbols indicate the weekly average values for Ln rMSSD and triangular symbols indicate the Ln rMSSD to R–R interval ratio. The grey shaded area indicates the individual smallest worthwhile change (SWC) in Ln rMSSD (see methods); if the 90 % CI overlap positive or negative SWC thresholds the change is deemed unclear. *="possible" and **="likely" ***= "very likely" changes in Ln rMSSD. # = small, ## = moderate, ### = large change in Ln rMSSD: R-R ratio.

Figure 3. The relationship between the R-R interval length and the natural logarithm of the square of the mean sum of the squared differences between R-R intervals (Ln rMSSD) in Rowers, A, B, C

and D. Rower A and B, with higher resting heart rates have correlated relationships (R = 0.66 and 0.80) between Ln rMSSD and R-R interval length. Comparatively Rowers C and D, with lower resting heart rates, have low-correlated relationships (R = 0.00 and 0.09).

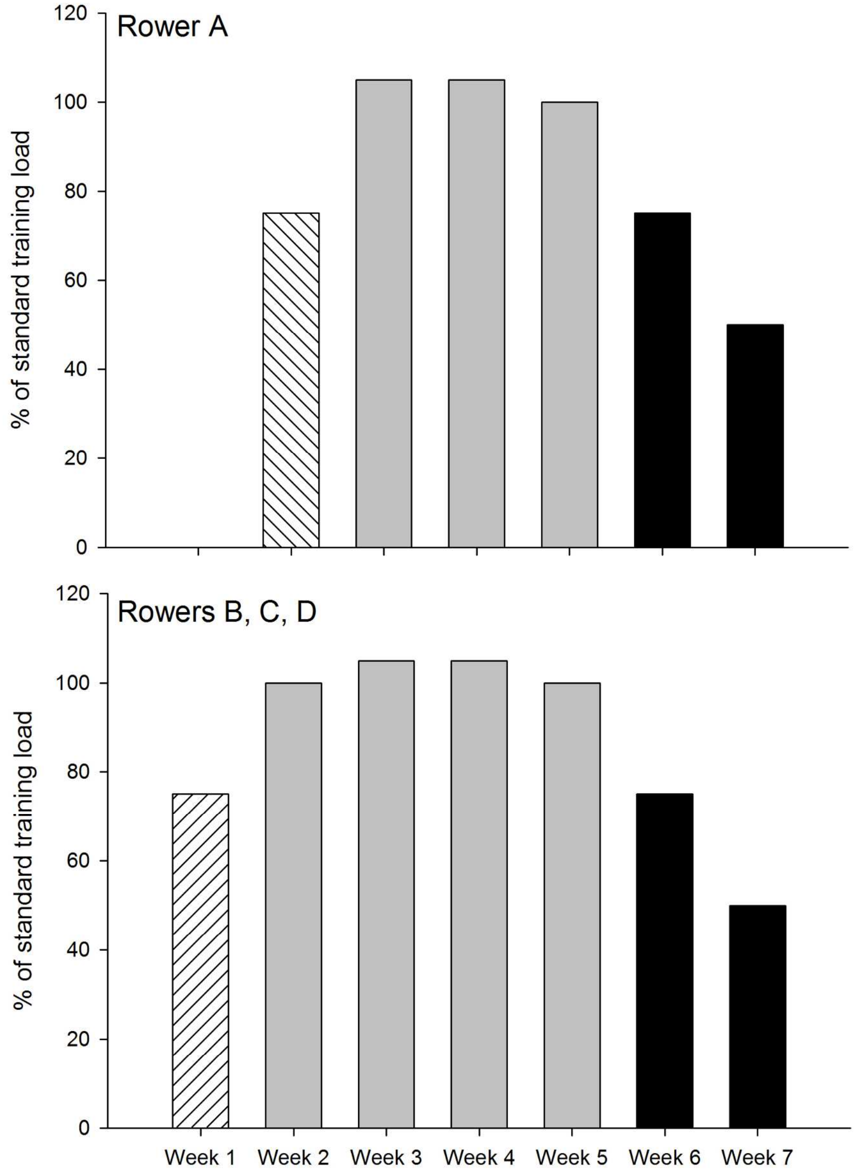

Figure 1. The basic training load of rower A (top panel) and rowers B, C and D (lower panel) during the 7 week training period. The white patterned bars represent a light week of training where the individual HRV baseline was established. The grey bars represent the heavy "overload" periods of training. The black bars represent the two weeks of taper prior to the World Rowing Championships. Data are presented as a % of the squad's standard training load.
149x201mm (300 x 300 DPI)

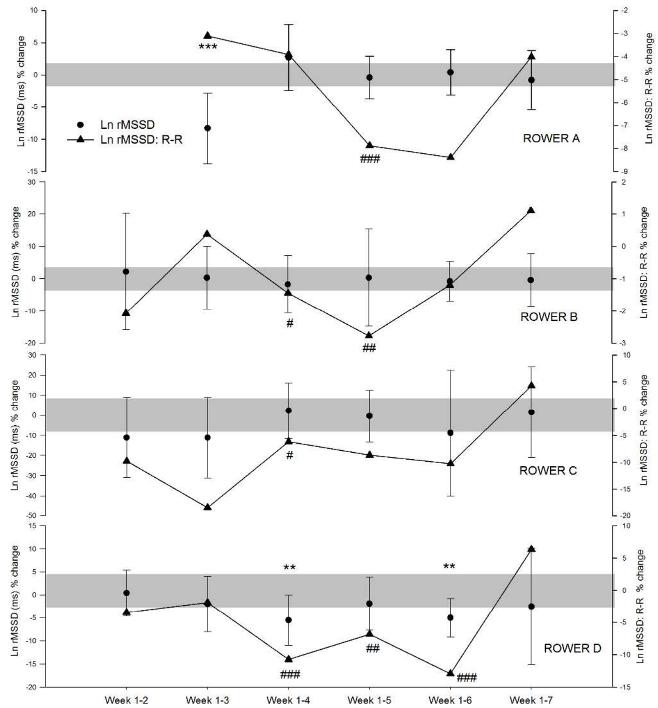

Figure 2. Changes in the natural logarithm of the square root of the mean sum of the squared differences between R–R intervals (Ln rMSSD) with 90 % confidence intervals (CI) and the Ln rMSSD to R–R interval ratio for Rowers A, B, C and D during the 7-week training period prior to the 2015 World Rowing Championships. Black circular symbols indicate the weekly average values for Ln rMSSD and triangular symbols indicate the Ln rMSSD to R–R interval ratio. The grey shaded area indicates the individual smallest worthwhile change (SWC) in Ln rMSSD (see methods); if the 90 % CI overlap positive or negative SWC thresholds the change is deemed unclear. *="possible" and **="likely" ***= "very likely" changes in Ln rMSSD. # = small, ## = moderate, ### = large change in Ln rMSSD: R-R ratio.
296x209mm (300 x 300 DPI)

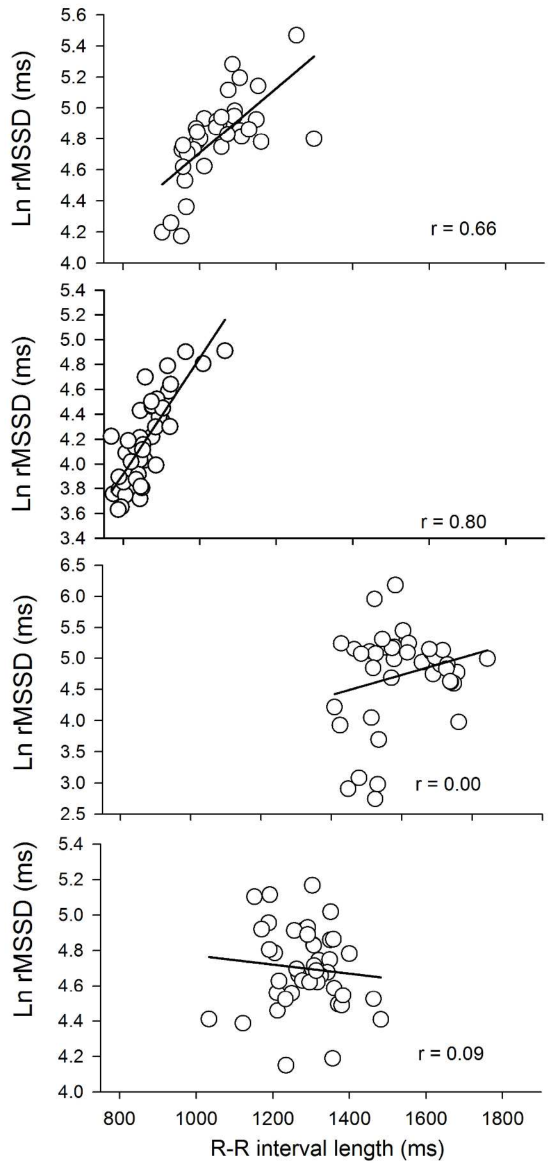

Figure 3. The relationship between the R-R interval length and the natural logarithm of the square of the mean sum of the squared differences between R-R intervals (Ln rMSSD) in Rowers, A, B, C and D. Rower A and B, with higher resting heart rates have correlated relationships (R = 0.66 and 0.80) between Ln rMSSD and R-R interval length. Comparatively Rowers C and D, with lower resting heart rates, have low-correlated relationships (R = 0.00 and 0.09).
143x304mm (300 x 300 DPI)

	% time spent <LT_1	% time spent LT_1-LT_2	% time spent >LT_2
Rower A	84	9	8
Rower B	84	13	3
Rower C	68	24	8
Rower D	68	27	5

Table 1. Training intensity distribution between for Rowers A, B, C and D during the 7-week training period. Percent of time training below the first lactate threshold ($<LT_1$), between the first and second lactate thresholds (LT_1-LT_2) and above the second lactate thresholds ($>LT_2$) are shown.

Rower	Weeks	% diff Ln rMSSD	90% CL	Inference	Outcome	% diff Ln RHR	90% CL	Inference	Outcome
	1-2	-8.3	5.5	1/2/96	V.likely decrease	5.6	5.1	91/7/2	Likely increase
	1-3	2.7	5.1	65/29/6	Unclear	-6.2	9.8	8/12/80	Unclear
A	1-4	-0.4	3.3	12/68/20	Unclear	-5.4	4.9	2/8/90	Likely decrease
	1-5	0.4	3.5	21/67/12	Unclear	-9.1	13.7	8/8/84	Unclear
	1-6	-0.8	4.6	14/52/84	Unclear	-4.2	6.6	6/18/75	Unclear
	1-2	2.2	18	42/32/26	Unclear	-4.2	12	17/18/65	Unclear
	1-3	0.3	9.7	24/55/21	Unclear	-0.4	3	8/76/16	Unclear
B	1-4	-1.7	8.9	13/54/33	Unclear	-0.4	7.6	27/39/34	Unclear
	1-5	0.3	15	32/38/29	Unclear	-3.6	14	23/18/59	Unclear
	1-6	-0.8	6.2	9/72/18	Unclear	-0.8	6	19/46/35	Unclear
	1-7	-0.4	8.1	17/62/21	Unclear	3.3	6.3	66/27/7	Unclear
	1-2	-11.1	19.9	7/30/63	Unclear	3.9	6.5	71/23/6	Unclear
	1-3	-11.1	20.1	7/30/63	Unclear	-6.4	7.2	4/10/86	Likely decrease
C	1-4	2.3	13.7	21/70/9	Unclear	-3.6	8.4	12/23/65	Unclear
	1-5	0.4	12.9	13/72/15	Unclear	-2.7	7.9	15/28/57	Unclear
	1-6	-8.8	31.2	16/31/53	Unclear	0.7	13.3	42/25/33	Unclear
	1-7	1.5	22.6	29/50/21	Unclear	8.2	5	97/2/1	Very likely increase
	1-2	0.4	5	21/64/15	Unclear	-3.1	5.9	8/28/64	Unclear
	1-3	-2	6	11/40/45	Unclear	2-5	9.3	50/29/21	Unclear
D	1-4	-5.5	5.5	2/14/84	Likely decrease	-5.2	5.5	2/12/85	Likely decrease
	1-5	-1.9	5.8	10/48/42	Unclear	-5.4	5.4	2/11/87	Likely decrease
	1-6	-5	4.2	1/14/85	Likely decrease	-8.3	3.4	0/1/99	Very likely decrease
	1-7	-2.5	12.7	21/28/50	Unclear	9.1	5	98/11/1	Likely increase

Table 2: Percentage changes and ±90% confidence limits (CL) with qualitative chances of substantial differences for the log-transformed square root of the mean sum of the squared differences between R-R intervals (Ln rMSSD) and resting heart rate (RHR) during the training period. Percentage changes are compared from baseline (week 1) to weeks 2, 3, 4, 5, 6 and 7.