Reliability of Resting and Postexercise Heart Rate Measures

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Reliability of Resting and Postexercise Heart Rate Measures

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Key words
- heart rate variability
- heart rate recovery
- typical error
- repeatability
- autonomic nervous system
- vagal-related indices

Abstract

In this study, we compared the reliability of short-term resting heart rate (HR) variability (HRV) and postexercise parasympathetic reactivation (i.e., HR recovery (HRR) and HRV) indices following either submaximal or supramaximal exercise. On 4 different occasions, beat-to-beat HR was recorded in 15 healthy males (21.5 ± 1.4 yr) during 5 min of seated rest, followed by submaximal (Sub) and supramaximal (Supra) exercise bouts; both exercise bouts were followed by 5 min of seated recovery. Reliability of all HR-derived indices was assessed by the typical error of measurement expressed as a coefficient of variation (CV, %). CV for HRV indices ranged from 4 to 17 %, 7 to 27 % and 41 to 82 % for time domain, spectral and ratio indices, respectively. The CV for HRR ranged from 15 to 32 %. Spectral CVs for HRV were lower at rest compared with Supra (e.g., natural logarithm of the high frequency range (LnHF); 12.6 vs. 26.2 %; $p = 0.02$). HRR reliability was not different between Sub and Supra (25 vs. 14 %; $p = 0.10$). The present study found discrepancy in the CVs of vagal-related heart rate indices; a finding that should be appreciated when assessing changes in these variables. Further, Supra exercise was shown to worsen the reliability of HRV-spectral indices.

Introduction

Non-invasive assessment of cardiac autonomic function via heart rate (HR) variability (HRV) and HR recovery (HRR) is widely used to assess autonomic nervous system activity [11,21,35]. Evaluation of autonomic function in clinical populations are of great interest to practitioners, as low parasympathetic activity or a delayed parasympathetic reactivation following exercise has a well known association with the risk of sudden cardiac death [2,35]. For example, a lowered postexercise HRR [21], indicative of a reduced parasympathetic activity, is frequently reported in chronic heart diseases. Similarly, a decrease in postexercise vagal-related HRV indices, which provide insight into the level of 'parasympathetic reactivation' [11,13], has been observed in patients with coronary artery disease [12]. Additionally, such measurements have more recently been shown to be predictive of changes in aerobic endurance capacity [7,23]. Indeed, endurance training guided daily by HRV measurements has been shown to result in superior improvements in cardiorespiratory function (i.e., greater peak oxygen uptake) [23]. Moreover, resting and postexercise HRV measurements have been shown to be predictive of aerobic performance [7]. Despite the increased popularity of these techniques, few studies have assessed their reliability [5,10,25].

At rest or during (stationary) recovery periods, variations in heartbeats are generally examined via time domain (e.g., the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (rMSSD)) or spectral analysis (e.g., high frequency range (> 0.15–0.40; HF)). Parasympathetic function may also be assessed using postexercise HRR indices (e.g., number of heart beats recovered in the first minute after exercise cessation ($HRR_{60\,s}$)) [11]. Recently, time-varying analysis of HRV during recovery from exercise in humans on consecutive 30-s windows (i.e., $rMSSD_{30\,s}$) has also been used to assess the time course of parasympathetic reactivation [13]. While all the pre-cited indices can give insight into cardiac autonomic function, they are thought to provide independent information [11]. Correlations between these indices are not always strong [11] and their association with cardiorespiratory fitness and habitual physical activity varies [8]. Finally, these indices have also shown a variable response to training [7].

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Reliability of any physiological measurement (i.e., degree of change in a particular measure when repeated on different occasions in similar conditions, as evidenced by the coefficient of variation (CV) of a measurement) is of great importance for practitioners and coaches to avoid bias interpretation when assessing changes in a marker. Half of a CV, for example, is thought to represent a minimal threshold needed to assess a meaningful difference (between-group comparisons) or change (training studies), or the so called "smallest worthwhile difference/change" [18]. Many studies in healthy populations have reported moderate reliability of HRV indices at rest [27, 29, 32–34]. There is, however, less data on postexercise HRR indices [5, 10, 25], and the respective influence of exercise intensity on the reliability of this index is unclear. While Lamberts et al. [25] reported a decreased CV for HRR with increasing exercise intensity, Bosquet et al. [5] showed a lower CV following low-intensity exercise. Moreover, whether exercise intensity influences the reliability of post-exercise HRV indices is still unknown. Finally, data on the reliability of time-varying vagal-related indices (i.e., $rMSSD_{30\,s}$) are also lacking. Direct comparison between resting and postexercise indices in a single group of subjects has also yet to be examined. Such a comparison is important to establish so that assessment of the most convenient and accurate recording condition for the evaluation of cardiac autonomic function, along with the condition associated with the highest level of reliability, can be determined.

In light of the limited reliability data available on non-invasive cardiac function measurements, and since measurements of cardiac autonomic function is an important aspect of patient and athlete monitoring [7, 23], we aimed to investigate the short-term reliability of HRV and HRR indices in 2 widely used field conditions (i.e., at rest (HRV only) and following exercise (e.g., submaximal and supramaximal)). We have also aimed to verify whether or not exercise intensity could influence the level of postexercise HRV and HRR reliability. Defining the most reliable condition available for assessing cardiac autonomic function will assist practitioners in determining the most useful index to monitor changes in response to training.

Materials and Methods

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Participants

15 healthy moderately-trained males (21.5 ± 1.4 yr; 1.80 ± 0.06 m; 76.1 ± 11.2 kg, training 2–5 h per week) volunteered for the study after providing written informed consent. All participants were involved in various intermittent activities (i.e., basketball, handball, soccer and tennis) and supramaximal training. Participants were all familiar with exercise testing and supramaximal exercise (i.e., Wingate). Additionally, participants were not taking prescribed medications or any special dietary supplement and presented no contraindications for exercise. The study was approved by the local institution's human research ethics committee and conformed to ethical guidelines outlined in the Declaration of Helsinki and was performed in accordance with the ethical standards of the IJSM [15].

Study Overview

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1 week prior to reliability testing, participants performed a maximal graded exercise test (30-15 Intermittent Fitness test, $30\text{-}15_{IFT}$ [6]) to assess a reference velocity (V_{IFT}; speed reached at the end of the $30\text{-}15_{IFT}$) for the subsequent submaximal exercise bout. Participants then completed, on 4 different occasions, each separated by 7 days, a sequence composed of a resting period, a submaximal exercise bout (Sub), and supramaximal exercise bout (Supra). Participants were asked to refrain from intense physical activity in the 48 h preceding each testing session. Before the start of each testing session, participants were verbally questioned regarding the quantity and quality of physical activity and sleep that occurred in the preceding period prior to the 4 trials. These variables did not differ between the 4 testing days and were therefore not likely to affect the variability of HRV and HRR measures. HR was continuously recorded (s810 HR monitor, Polar Electro, Kemple, Finland) [29] during the sequence and subsequent recovery phases. In order to minimize circadian effects, all tests were conducted at same hour of the day (± 20 min). All participants were asked to consume their last light meal at least 3 h before each test session, and to refrain from consuming drinks containing caffeine for at least 12 h preceding the effort. Smokers were not included in the present study. All tests were performed on an indoor synthetic track where ambient temperature ranged from between 20–23 °C. Participants were instructed to breath regularly during all tests (i.e., avoid deep breathing and/or any changes in both respiratory frequency and amplitude, which was explained and emphasized during the familiarization sessions). Although respiratory rate is often controlled in HRV studies, we chose not to control respiratory rate in our participants to increase the applicability of present results in the field [7, 23]. Nevertheless, following exercise, respiratory rate was always in the HF range (> 0.15 Hz) and did not differ between the 4 trials. Moreover, vagal-related HRV indices during spontaneous and metronome-guided breathing differ little [4] and do not influence the reliability of HRV indices [24], although the latter point is still debated [33].

Exercise Testing

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Maximal graded exercise test

Participants performed the $30\text{-}15_{IFT}$ [6], consisting of 30 s of running interspersed with 15 s of passive recovery. The test started at $8\,km.h^{-1}$ and velocity increased linearly by $0.5\,km.h^{-1}$ every stage (45 s) until exhaustion. Running velocity was guided through a pre-recorded beep. The last fully completed stage was defined as the participants' V_{IFT}.

Testing sequence

Participants were first seated and asked to remain quiet and to avoid any body movement for 5 min, which was followed by 5 min of seated HR-recording. This period was immediately followed by 5 min of submaximal running at 45 % of V_{IFT} (Sub). This intensity (i.e., 45 % V_{IFT}) corresponds to approximately 60 % of the minimal velocity that elicits VO_{2max}, as assessed from a continuous maximal graded exercise test [6]. Furthermore, this intensity is widely used in studies assessing postexercise HRR and HRV [9]. Running pace was governed by a prerecorded beep that sounded at appropriate intervals in order to allow participants to adjust their running speed as they passed through specific zones of the field. Immediately at the end of Sub, participants were asked to recover passively for 5 min in the seated position. Following the 5-min recovery period, participants completed the Supra phase, which consisted of a Wingate test performed on a Monark cycle ergometer (Monark 884E). Seat height was adjusted to accommodate the subject's stature (e.g., to observe a slight bend in the knee). Participants performed a 2-min warm-up pedalling at a cadence of 80 rpm at a constant power output set at 50 W. At the end of the warm-up, 2 brief (2–3 s) sprinting bouts were conducted. Immediately after the warm-up period, subjects performed the 30-s all-out trial. Standard resistance applied corresponded to 7.5 % of the participant's body mass [22]. Participants were verbally encouraged to perform maximally throughout the 30-s test. Immediately after completing Supra, participants dismounted the cycle ergometer and, within less than 5 s, recovered passively in a seated position on a chair adjacent to the ergometer. The seated position was chosen because it was the most comfortable posture for the participants. Additionally, studies investigating cardiac autonomic function in the field, have generally used this posture to assess postexercise HRR [26] and HRV [30] indices. While we acknowledge that exercise mode might influence absolute postexercise HRR values [28], there is no evidence to suggest a different level of reliability between running and cycling exercise. The exercise modes used in the present study were selected based on previous studies that had employed either submaximal running [7] or supramaximal cycling [14] exercises, respectively.

Data Measurement and Analyses

Heart rate

Recorded HR data were downloaded on a computer using compatible Polar software (Polar Precision Performance SW 5.20, Polar Electro, Kemple, Finland). All irregular heartbeats were automatically identified and replaced with interpolated adjacent R-R interval values using the Polar Software. The default setting of a minimum beat protection zone of 6 beats was used [29].

Short-term resting HRV analysis

HRV indices were calculated from the last 3 min of the 5-min resting periods (▶ **Fig. 1**) with the accompanying Polar software, which has been shown to provide accurate measurements for short-term HRV analysis [29]. Time domain indices included the mean R-R interval (mRR), the natural logarithm of the standard deviation of the R-R series (Ln SDNN; estimates overall HRV) and the natural logarithm of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (Ln rMSSD; estimates parasympathetic activity). Spectral analysis was conducted to obtain the power densities in the low frequencies (≥ 0.04–0.15; LF), mediated via both sympathetic and parasympathetic systems, and in the high frequencies (> 0.15–0.40; HF), mediated via the parasympathetic system under respiratory influence. Both spectral components were log-transformed (i.e., LnLF and LnHF). The sympathovagal balance (LF/HF), as well as the normalized HF ratio, were also calculated as HFnu = HF/(LF + HF). Ratio (i.e., LF/HF and HFnu) indices were calculated from the non-transformed LF and HF data. VLF was not analysed in this study since their interpretation during short recordings (< 5 min) remains unclear [35].

Postexercise HRR assessment

As previously described [11], HRR was assessed by 1) calculating the absolute difference between the final HR at exercise end and the HR recorded 60 s later (HRR_{60s}) (▶ **Fig. 1, 2**) fitting the 5-min postexercise R-R data into a first-order exponential decay curve. A HR time constant (HRR_τ) was then obtained by modelling the resultant first 5 min of HR data using an iterative technique (Sigmaplot 10; SPSS Science, Chicago, IL) by the following equation: $HR = HR_0 + HRamp\ e^{(-T/HRR_\tau)}$, where HR_0 is resting (final) HR, HRamp is maximal HR (HRmax) – HR_0, and T is time (s) (▶ **Fig. 1**).

Time-varying vagal-related HRV index

A time-varying vagal-related index based on the Ln rMSSD was calculated for each of the 30-s segments over the 5 min of recovery (Ln $rMSSD_{30s}$) [13]. The Ln $rMSSD_{30s}$ was conducted for recoveries from Sub and Supra exercises in the 4 testing days. Data were median-filtered in order to smooth out transient outliers in the HRV plots (HRV vs. time in recovery). The first and last values were not median filtered [13].

Statistical analyses

The distribution of each variable was examined with the Shapiro-Wilk normality test. Homogeneity of variance was verified by a Levene test. Data was transformed by taking the natural logarithm to allow parametric statistical comparisons that assume a normal distribution. To examine the reliability of the test over the 4 consecutive trials, a one-way ANOVA with repeated measures was first applied to determine any changes between the 4 tests (one factor *day*). We used a specifically designed spreadsheet [17], which provides reliability statistics for consecutive pairs of trials for each individual when there are at least 2 trials (statistics can be obtained even when subjects do not present the same number of trials). In this spreadsheet, all analyses are performed on log-transformed data, which substantially reduce non-uniform errors. Prior to reliability calculation, the absence of non-uniformity and outliers was confirmed by plotting the difference score (e.g., Trial 2 − Trial 1) against Trial 1. While several reliability indices have been used in the past, we chose to restrict our analysis to the typical error of measurement (TE) expressed as coefficient of variation (CV, %) for an easier comparison with the literature. TE represents the typical amount by which a repeated measurement deviates from the true value [16] and has received growing interest in past years. To examine the most reliable condition (i.e., Rest vs. following Sub or Supra), a one-way ANOVA for repeated measures (HRV) with Bonferroni's *post hoc* analyses and a paired *t*-test (HRR) were used to compare the CV of the latter HR-derived indices as a function of recordings phases. For all analyses, the level of significance was set at $p \leq 0.05$.

Results

As detailed in ▶ **Table 1**, 15 participants accomplished the first and second trials, while only 14 and 11 of them took part in the 3rd and 4th testing sessions, respectively. Therefore, values for HRV and HRR indices are presented for the 11 subjects with complete data sets only (▶ **Table 2**). Reliability data, however, have been calculated on the overall available set of data (▶ **Table 1**). ▶ **Fig. 1** illustrates the time course of HR in a single representative subject over the 4 different trials during rest and following both Sub and Supra exercises.

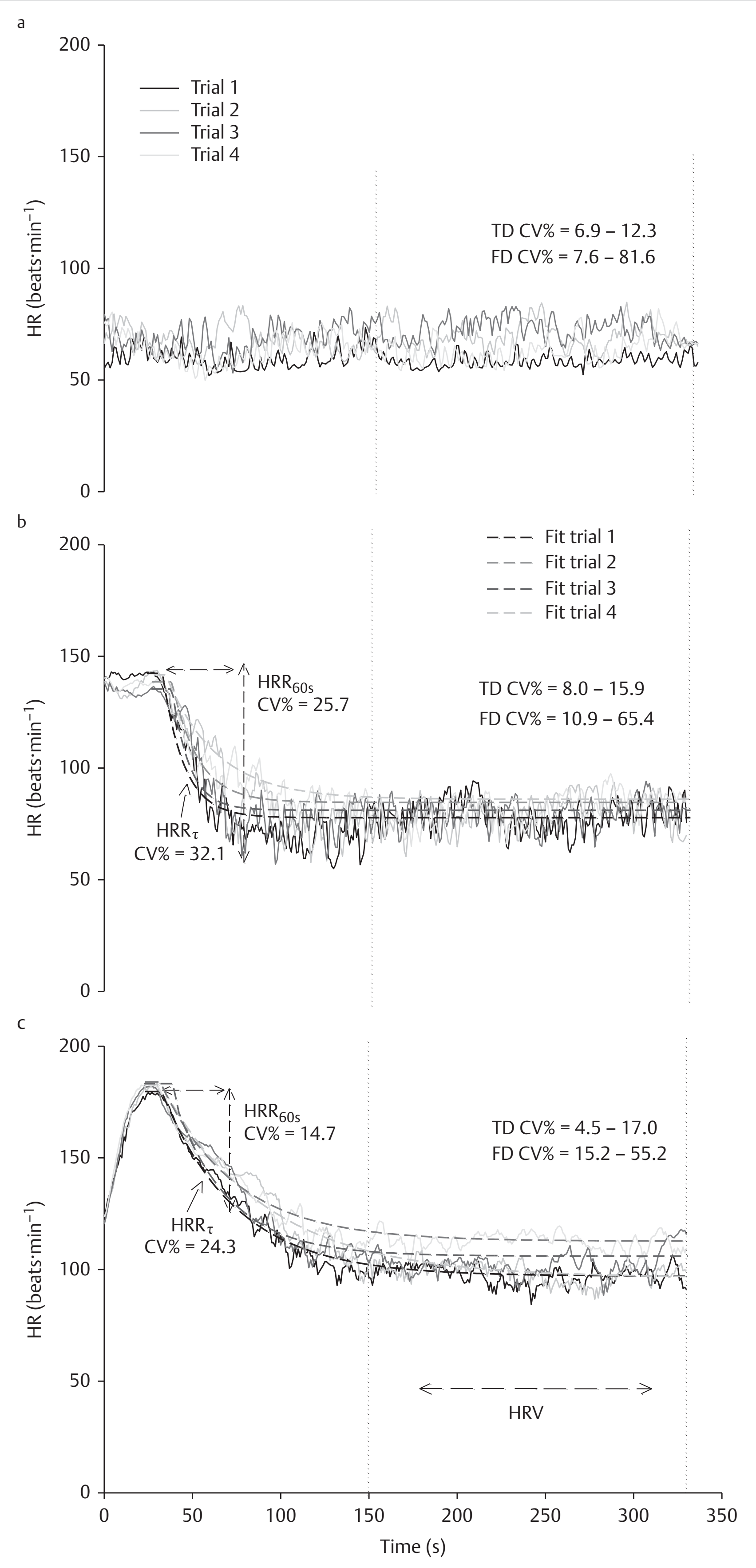

Fig. 1 Heart rate (HR) curve in a single representative subject over the 4 different trials during rest (**a**) and following submaximal (**b**) and supramaximal exercises (**c**). An example of HR recovery (HRR) and HR variability (HRV) indices determination is also presented (see "Methods" for details). CV for HRR_{60s} (absolute difference between the final heart rate at exercise end and the heart rate recorded 60 s later) and HRR_{τ} (time constant of HR decay) are presented as well as the range of CV for time domain (TD) and frequency domain (FD) indices.

Maximal graded exercise test and reliability of the submaximal and supramaximal exercises

Mean V_{IFT} was 19.1 ± 1.5 km.h^{-1}. Mean HR during Sub (138 ± 10, 139 ± 10, 138 ± 9 and 138 ± 12 beats.min^{-1}, $p=0.35$, corresponding to 69 ± 0.1 % of the participants' maximal HR), mean HR for Supra (173 ± 9, 174 ± 6, 172 ± 6 and 172 ± 6 beats.min^{-1}, $p=0.15$, corresponding to 88 ± 1 % of participants' maximal HR) and mean maximal power output for the Wingate test (750 ± 120, 754 ± 126, 770 ± 123, and 753 ± 118 W, $p=0.17$) were similar for the 4 consecutive trials. TE (CV) were 4.2 beats.min^{-1} (3.2 %) and 2.7 beats. min^{-1} (1.5 %) for mean Sub and Supra HR, respectively. A TE of 26 W (3.8 %) was observed for mean maximal power output during Supra.

Table 1 Number of recordings used to assess the reliability of each HR-derived index as a function of recording phase.

	Trial 1 Rest/Sub/ Supra	Trial 2 Rest/Sub/ Supra	Trial 3 Rest/Sub/ Supra	Trial 4 Rest/Sub/ Supra
total participants	n = 15	n = 15	n = 14	n = 11
HRR$_{60\,s}$	(n/a)/15/15	(n/a)/15/15	(n/a)/14/13	(n/a)/10/9
HRR$_{\tau}$	(n/a)/15/15	(n/a)/15/15	(n/a)/13/12	(n/a)/7/6
HRV indices	15/15/15	15/15/15	14/14/13	11/11/11

Data represent the total number of participants on each testing day for resting condition (Rest), submaximal (Sub) and supramaximal (Supra) exercises, as well as the number of measurements analysed for each condition as a function of each testing day. HRR$_{60\,s}$ is the absolute difference between the final heart rate at exercise end and the heart rate recorded 60 s later, HRR$_{\tau}$ is the time constant of the heart rate decay. n/a: not applicable, since HRR indices (i. e., HRR$_{60\,s}$ and HRR$_{\tau}$) could only be assessed following exercise

Short-term HRV reliability

HRV index values over the 4 consecutive trials at rest and following the 2 exercise bouts are reported in ▸ **Table 2**. Analysis of variance (one within factor, *day*) did not show any significant differences between the 4 consecutive measures at rest or following exercise (▸ **Table 2**). Reliability of HRV indices calculated at rest and following Sub and Supra are presented in ▸ **Table 3**. The reliability of spectral HRV indices was higher (inferred from lower CV values) at rest when compared with supra for LnHF (12.6 vs. 26.2 %; $p=0.02$) and LnLF (7.6 vs. 15.2 %; $p=0.03$). Conversely, a higher CV was observed at rest when compared with supra for mRR (11.1 vs. 4.5 %; $p=0.012$). No other between-condition differences were observed for the remaining indices.

Reliability of post exercise HRR indices

HRR index values over the 4 consecutive trials in both exercise intensities are reported in ▸ **Table 2**. There was no significant day effect for any of the measures (▸ **Table 2**). Reliability of HRR indices following both exercise intensities are presented in ▸ **Table 3**. There was no difference in CV following both exercise intensities (i. e., Sub vs. Supra; $p=0.10$ for HRR$_{60\,s}$ and $p=0.42$ for HRR$_{\tau}$).

Time-varying vagal-related HRV index

There was no day effect for any of the Ln rMSSD$_{30\,s}$ 30-s segments (e. g., at time = 30 s or 270 s, $p=0.28$ or 0.20 for Sub and

Table 2 Heart rate variability (HRV) and heart rate recovery (HRR) indices at rest (Rest) and following submaximal (Sub) and supramaximal (Supra) exercises during the 4 consecutive trials.

	Trial 1	Trial 2	Trial 3	Trial 4	'Repetition' effect (p)
Rest					
mRR	807.70 ± 117.87	744.80 ± 113.75	762.70 ± 85.05	813.40 ± 114.11	0.052
Ln SDNN	4.41 ± 0.38	4.20 ± 0.49	4.33 ± 0.20	4.32 ± 0.36	0.47
Ln rMSSD	3.97 ± 0.55	3.60 ± 0.61	3.73 ± 0.28	3.84 ± 0.50	0.15
LnHF	6.87 ± 0.91	6.35 ± 1.05	6.46 ± 0.51	6.70 ± 0.89	0.35
LnLF	7.72 ± 0.72	7.53 ± 0.96	7.80 ± 0.46	7.42 ± 0.45	0.38
HFnu	0.32 ± 0.18	0.24 ± 0.06	0.22 ± 0.10	0.33 ± 0.12	0.10
LF/HF	3.25 ± 2.49	3.47 ± 1.34	4.66 ± 3.32	2.36 ± 1.37	0.13
Sub					
HRR$_{60s}$	41 ± 13	36 ± 15	33 ± 14	37 ± 9	0.15
HRR$_{\tau}$	30 ± 11	26 ± 8	26 ± 10	28 ± 11	0.64
mRR	646.45 ± 87.35	617.45 ± 69.41	628.09 ± 76.93	651.00 ± 84.81	0.27
Ln SDNN	3.84 ± 0.37	3.68 ± 0.40	3.77 ± 0.33	3.85 ± 0.42	0.41
Ln rMSSD	3.16 ± 0.59	2.81 ± 0.72	2.96 ± 0.63	3.11 ± 0.59	0.10
LnHF	5.70 ± 0.97	5.02 ± 1.33	5.20 ± 1.18	5.36 ± 1.13	0.11
LnLF	6.73 ± 0.87	6.21 ± 0.94	6.51 ± 0.94	6.59 ± 0.80	0.12
HFnu	0.27 ± 0.08	0.26 ± 0.18	0.22 ± 0.10	0.25 ± 0.14	0.66
LF/HF	3.05 ± 1.28	4.28 ± 2.54	4.19 ± 2.08	4.60 ± 3.81	0.31
Supra					
HRR$_{60s}$	34 ± 9	32 ± 8	35 ± 10	34 ± 9	0.57
HRR$_{\tau}$	88 ± 19	85 ± 25	78 ± 23	67 ± 17	0.23
mRR	507.90 ± 64.00	508.54 ± 58.40	512.81 ± 53.65	510.63 ± 49.17	0.97
Ln SDNN	3.15 ± 0.37	3.11 ± 0.37	3.18 ± 0.48	3.09 ± 0.61	0.92
Ln rMSSD	1.91 ± 0.69	1.87 ± 0.60	1.93 ± 0.58	1.85 ± 0.40	0.90
LnHF	1.19 ± 1.38	2.17 ± 1.36	2.21 ± 1.15	2.13 ± 0.75	0.57
LnLF	3.90 ± 1.18	3.94 ± 1.03	4.08 ± 1.10	4.15 ± 0.71	0.68
HFnu	0.13 ± 0.07	0.14 ± 0.06	0.14 ± 0.08	0.12 ± 0.02	0.72
LF/HF	8.35 ± 4.02	7.45 ± 4.20	7.39 ± 3.57	7.71 ± 2.32	0.89

Mean ± SD absolute difference between the final heart rate at exercise end and the heart rate recorded 60 s later (HRR$_{60\,s}$), time constant of heart rate decay (HRR$_{\tau}$), mean R-R interval (mRR), the natural logarithm of: the standard deviation of R-R intervals (Ln SDNN), the root square of the mean squared differences of successive R-R intervals (Ln rMSSD), high (LnHF) and low (LnLF) frequency power, the normalized unit in high frequency range (HFnu), and the sympathovagal balance index (LF/HF). n = 11 (except when n is lower please refer to ▸ **Table 1**)

Table 3 Measures of reliability for heart rate variability (HRV) and heart rate recovery (HRR) indices at rest (Rest) and following submaximal (Sub) and supramaximal (Supra) exercises.

		Rest	Sub	Supra	'Condition' effect *(p)*
$HRR_{60\,s}$	TE (beats.min^{-1})		8 (7–10)	5 (4–6)	
	CV		25.7 (21.1–33.0)	14.7 (12.1–19.0)	0.10
HRR_{T}	TE (s)		7 (6–9)	20 (17–26)	
	CV		32.1 (26.0–46.3)	24.3 (20.0–32.7)	0.42
mRR	TE (ms)	79.72 (68.99–99.17)	48.92 (41.19–60.65)	23.30 (19.61–8.8)	
	CV	11.1 (9.3–14.0)	8.0 (6.7–10.0)	4.5 (3.8–5.7)*	0.01
Ln SDNN	TE (ms)	0.27 (0.22–0.33)	0.29 (0.24–0.36)	0.33 (0.28–0.41)	
	CV	6.9 (5.7–8.6)	8.4 (7.1–10.6)	11.7 (9.8–14.7)	0.23
Ln rMSSD	TE (ms)	0.40 (0.33–0.49)	0.39 (0.33–0.48)	0.27 (0.23–0.34)	
	CV	12.3 (10.3–15.5)	15.9 (13.2–20.1)	17.0 (14.1–21.5)	0.61
LnHF	TE (ms^2)	0.73 (0.62–0.91)	0.68 (0.58–0.85)	0.45 (0.38–0.57)	
	CV	12.6 (10.5–15.9)	15.2 (12.7–19.2)	26.2 (21.5–33.7)*	0.02
LnLF	TE (ms^2)	0.51 (0.43–0.64)	0.64 (0.53–0.79)	0.51 (0.43–0.63)	
	CV	7.6 (6.3–9.5)	10.9 (9.1–13.7)	15.2 (12.6–19.2)*	0.04
HFnu	TE	0.11 (0.09–0.13)	0.09 (0.07–0.11)	0.06 (0.05–0.07)	
	CV	52.0 (42.2–68.4)	41.6 (34.0–53.9)	44.0 (35.9–57.2)	0.52
LF/HF	TE	2.19 (1.84–2.72)	1.99 (1.67–2.47)	3.1 (2.6–3.9)	
	CV	81.6 (65.0–110.0)	65.4 (52.8–86.7)	55.2 (44.7–72.4)	0.08

Typical error of measurement (TE (90 % confidence limits; 90 % CL)), TE expressed as a coefficient of variation (CV, % (90 % CL)) calculated for the absolute difference between the final heart rate at exercise end and the heart rate recorded 60 s later ($HRR_{60\,s}$; beats.min^{-1}) and the time constant of heart rate decay (HRR_{T}; s), mean R-R intervals (mRR; ms), natural logarithm of standard deviation of R-R intervals (Ln SDNN; ms) and natural logarithm of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (Ln rMSSD; ms), natural logarithm high frequency power (LnHF; ms^2), natural logarithm low frequency power (LnLF ms^2), normalized unit in high frequency range (HFnu), and the sympathovagal balance index (LF/HF). * : significant difference vs. Rest. (n = refer to ▶ **Table 1**)

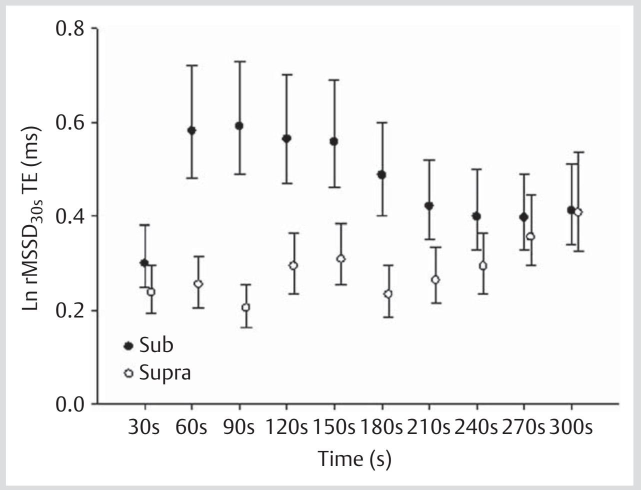

Fig. 2 Typical error of measurement (TE, with 90 % CI) for the time-varying vagal-related index (natural logarithm of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (Ln rMSSD), calculated for each of the 30-s segments of recovery and over the 5-min of seated recovery) calculated for the submaximal (Sub; closed circles) and Supramaximal (Supra, open circles) exercises. (n = refer to ▶ **Table 1**).

$p = 0.40$ or 0.57 for Supra). The reliability of Ln $rMSSD_{30\,s}$ is presented in ▶ **Fig. 2** and ▶ **Table 4**. No significant difference was found between the 2 conditions ($p = 0.60$).

Discussion

To the best of our knowledge, this is the first study to compare the reliability of parasympathetic-mediated HR-derived indices, such as resting HRV and postexercise HRR and HRV indices, after exercise bouts of varying intensity. These reliability results offer researchers and practitioners a starting point by which they may assess the smallest worthwhile change or difference in HRV and HRR variables [18]. Moreover, we have shown the independent effects of the recording conditions (i.e., seated at rest or following submaximal or supramaximal exercises) on the reliability of most of these indices.

Table 4 Measures of reliability for the time-varying recovery index (Ln $rMSSD_{30\,s}$) following submaximal (Sub) and supramaximal (Supra) exercises.

	Sub	Supra
Ln rMSSD30s	20.03 (16.49–25.69)	22.73 (18.47–29.80)
Ln rMSSD60s	29.08 (23.85–37.51)	20.57 (16.75–26.90)
Ln rMSSD90s	24.04 (19.79–30.85)	15.89 (12.98–20.66)
Ln rMSSD120s	22.11 (18.23–28.32)	15.91 (13.00–20.68)
Ln rMSSD150s	22.00 (18.13–28.16)	17.19 (14.03–22.38)
Ln rMSSD180s	20.61 (17.00–26.34)	13.47 (11.03–17.46)
Ln rMSSD210s	18.59 (15.36–23.70)	17.24 (14.07–22.45)
Ln rMSSD240s	17.50 (14.47–22.29)	20.06 (16.34–26.22)
Ln rMSSD270s	16.43 (13.60–20.90)	24.56 (19.94–32.28)
Ln rMSSD300s	16.81 (13.91–21.40)	27.62 (21.70–38.49)

Coefficient of variation (CV (90 % confidence limits; 90 % CL)) calculated for the time-varying vagal-related index (natural logarithm of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (Ln rMSSD)), was calculated for each of the 30-s segments of recovery and over the 5 min of seated recovery), (n = refer to ▶ **Table 1**)

Previously published reliability studies [5, 25, 29] have described the reliability of these measurements using, among other measures, the intraclass correlation coefficient (ICC). However, the ICC does not provide an index of the expected trial-to-trial noise in the data, but rather reflects the ability of a test to differentiate between individuals [36]. Hopkins [16] therefore argues that the typical error of measurement is the most appropriate measure of reliability. Typical error of measurement represents the noise occurring from trial-to-trial, which might confound the assessment of real changes in repeated measures [16], such as those that may occur after an endurance training intervention (e.g.,

[7]). To allow for appropriate comparisons to be made with the present study's findings, the typical error of measurement (expressed as a CV) was thus estimated from published literature where possible. Classification of reliability indices as low, moderate or high for HRV measures is currently lacking, and those currently offered in the literature do not have strong evidence [33]. Therefore, caution must be taken when using such arbitrary thresholds for reliability levels [1]. Indeed, the most reliable tests are not necessarily the most effective and practical for monitoring physiological adaptations in athletes [20]. Therefore, to assess the usefulness of a measurement, it is appropriate to compare the CV with the smallest worthwhile difference (when comparing different populations) or change (training studies) for the considered measure [19]. As long as the CV is smaller than the smallest worthwhile difference or change, the measure is likely capable of assessing between-group differences and training-induced changes, and is therefore deemed to be of interest. For example, postexercise vagal-related indices (e.g., Ln rMSSD) as assessed from the last 3 min of the 5-min recovery following a submaximal exercise, has been shown to be increased by 17% after an endurance training program [7], which is substantially higher than half of the presently observed inter-day error of measurement (i.e., Sub Ln rMSSD's half CV = 7.9%; ▸ **Table 3**).

Reliability of short-term HRV indices

The present CV values (4–17%, 7–27% and 41–82%, for time domain, spectral and ratio indices, respectively) are in agreement with previous studies investigating resting and postexercise HRV indices [10,29,32,34]. At rest, CV calculations derived from short-term recordings in the supine position with free breathing have been reported to range from 3 to 37% for time domain indices (i.e., Ln SDNN and Ln rMSSD, [29,32,34]). Higher CV values have been reported for spectral indices (i.e., LnLF and LnHF, CV ranging from 11 to 46%), and even higher for ratio indices (i.e., CV for HFnu and LF/HF ranged from 27 to 79%, [29,32]). The negative impact of spontaneous breathing on the (high) CV observed in the present study cannot be discarded, since paced breathing is generally thought to improve the reliability of HRV indices [33]. However, a recent study has also shown that the reliability of (log-transformed) spectral indices was not affected by breathing modalities (i.e., free or controlled) [24].

Only one study has previously assessed the reliability of HRV indices following submaximal exercise, and reported CV values of 29% and 64% for SDNN and rMSSD, respectively [10]. The lower values shown in the present study (8.4% Ln SDNN and 15.9% Ln rMSSD) could be related to the log-transformation of the data, as well as the higher number of repeated trials (4 vs. 2). Conversely, the CV for spectral and ratio indices were higher in our study compared with Buchheit et al. [10] (15 and 44% vs. 7 and 27%). While reasons for these differences remain unclear, between-trial differences in factors, such as mood, alertness, and mental activity, which are difficult to control, could account for the different reliability levels reported [33]. The discrepancies in these results could also be related to differences in age between the study populations (i.e., adolescents vs. adults) [27].

Former and present study data combined suggest that time domain indices are likely more reliable than spectral and ratio indices when inferred from short-term recordings, as well as at rest as following exercise. The impact of recording conditions was likely index-dependent. Spectral indices at rest were associated with higher reliability compared with postexercise ones, while there was no clear between-condition difference for time domain indices. The influence of respiration, which is likely to affect the (peak) frequency of the power density of R-R oscillations [3], might partly explain the differences in reliability observed (time domain indices being less likely affected by differences in respiratory rate) [31].

Reliability of postexercise heart rate recovery indices

The reliability of postexercise HRR indices (i.e., CV: 15–32%) was in agreement with previous results [5,10]. Studies assessing postexercise HRR index reliability following submaximal exercise reported CV values ranging from 8 to 18% for HRR_{60s} [5,10,25] and from 14 to 21% for HRR_{τ} [5,10]. Following a maximal graded exercise test, Bosquet et al. [5] reported a CV of 27% for HRR_{60s} and 21% for HRR_{τ}. The lowest CV (8%) for HRR_{60s} was noted in Lamberts et al. [25] study while assessing the day-to-day variation in HRR_{60s} over 5 consecutive days following submaximal exercise. Consequently, we suggest that the day-to-day variation in HRR over consecutive days may present lower CV values than in the case of a test re-test conducted over longer periods (i.e., 72 h [5] or 1 week interval [10]). Regarding the influence of exercise intensity on the reliability of HRR indices, we observed a tendency towards a decrease in CV with increases in exercise intensity (e.g., 26 vs. 15% for HRR_{60s}, $p = 0.10$), which was in accordance with Lamberts et al. [25]. This contrasts however with the findings reported by Bosquet et al. [5], which indicated a lower CV for HRR_{60s} after submaximal compared with a maximal graded exercise (17 vs. 27%). These inconsistencies might be related to the nature of the exercise. In our study for example, the Wingate test probably elicited a greater anaerobic participation than a graded maximal exercise eliciting the maximal oxygen uptake [5], which may have led to a greater metabolite accumulation. This is likely associated with greater autonomic perturbation [14], and in turn, with a slower HRR, which tends to be relatively less variable than a faster HRR. Future studies using larger sample sizes are needed to assess the influence of age, training status and disease state on the reliability of resting heart rate variability and postexercise parasympathetic reactivation indices.

Limitations

It is first worth mentioning that reliability of the vagal-related indices from the present study was only assessed in moderately-trained healthy young males. Therefore care should be taken when interpreting and applying our results in other populations (e.g., elderly, disease or highly-trained athletes). Moreover, since breathing patterns could influence the (peak) frequency of the power density of R-R oscillations [3]), it is unknown how ventilation patterns actually influenced the reliability of postexercise HRV indices. The reduced sample size in this study (n = 15), as well as the lack of randomization between exercises, should also be acknowledged as a potential limiter.

Practical application

HRV and HRR indices are widely used to assess the adaptation of cardiac autonomic function to short- and long-term exercise [7]. Since a greater parasympathetic activity is usually associated with a better recovery state [23] and readiness to perform [7,23], the monitoring of cardiac autonomic activity represents a promising tool to individualize training contents [23] and potentially prevent injuries and/or overload. Tracking changes in vagal-related indices in general or clinical populations is also likely of great interest given the association between lowered parasympathetic activity and cardiac disease and risk of sudden cardiac death [35]. We propose that calculating the typical error of measurement and assessing the smallest worthwhile change is necessary in order to evaluate real or meaningful changes after an acute bout of exercise or an exercise intervention. Hopkins et al. [18] suggest a cut-off point of half of the coefficient of variation as being important for detecting the smallest worthwhile change in athletes, irrespective of the level of group homogeneity [18]. While present data suggests that exercise intensity (i.e., submaximal and supramaximal) does not influence the reliability of HRR indices, the use of submaximal exercise might be preferred [11], since 1) it is associated with greater signal stability during exercise and recovery (▶ **Table 1**) and 2) represents a non-exhaustive exercise that can be easily and frequently implemented into the training schedules of both athlete and patient populations alike.

Conclusion

Short-term reliability of resting heart rate variability and post-exercise parasympathetic reactivation indices (i.e., heart rate recovery and heart rate variability) following either submaximal or supramaximal exercise showed large discrepancies in markers of reliability, a factor which should be taken into account when attempting to assess meaningful changes or differences in these indices. Finally, when assessing postexercise heart rate measures, the use of submaximal exercise is encouraged as it is associated with greater signal stability and is easily implemented in an athlete's training schedule.

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References

1 *Atkinson G*, *Nevill AM*. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 1998; 26: 217–238

2 *Billman G*. Aerobic exercise conditioning: a nonpharmacological antiarrhythmic intervention. J Appl Physiol 2002; 92: 446–454

3 *Blain G*, *Meste O*, *Bermon S*. Influences of breathing patterns on respiratory sinus arrhythmia in humans during exercise. Am J Physiol Heart Circ Physiol 2005; 288: 887–895

4 *Bloomfield D*, *Magnano A*, *Bigger JJ*, *Rivadeneira H*, *Parides M*, *Steinman RC*. Comparison of spontaneous vs. metronome-guided breathing on assessment of vagal modulation using RR variability. Am J Physiol Heart Circ Physiol 2001; 280: 1145–1150

5 *Bosquet L*, *Gamelin FX*, *Berthoin S*. Reliability of postexercise heart rate recovery. Int J Sports Med 2008; 29: 238–243

6 *Buchheit M*, *Al Haddad H*, *Millet G*, *Lepretre PM*, *Newton M*, *Ahmaidi S*. Cardiorespiratory and cardiac autonomic responses to 30–15 intermittent fitness test in team sport players. J Strength Cond Res 2009; 23: 93–100

7 *Buchheit M*, *Chivot A*, *Parouty J*, *Mercier D*, *Al Haddad H*, *Laursen PB*, *Ahmaidi S*. Monitoring endurance running performance using cardiac parasympathetic function. Eur J Appl Physiol 2010; 108: 1153–1167

8 *Buchheit M*, *Gindre C*. Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load. Am J Physiol 2006; 291: H451–H458

9 *Buchheit M*, *Laursen PB*, *Ahmaidi S*. Parasympathetic reactivation after repeated sprint exercise. Am J Physiol Heart Circ Physiol 2007; 293: 133–141

10 *Buchheit M*, *Millet G*, *Parisy A*, *Pourchez S*, *Laursen PB*, *Ahmaidi S*. Supramaximal training and post-exercise parasympathetic reactivation in adolescents. Med Sci Sports Exerc 2008; 40: 362–371

11 *Buchheit M*, *Papelier Y*, *Laursen P*, *Ahmaidi S*. Noninvasive assessment of cardiac parasympathetic function: post-exercise heart rate recovery or heart rate variability? Am J Physiol 2007; 23: H8–H10

12 *Goldberger J*, *Challapalli S*, *Tung R*, *Parker M*, *Kadish A*. Relationship of heart rate variability to parasympathetic effect. Circulation 2001; 103: 1977–1983

13 *Goldberger J*, *Le FK*, *Lahiri M*, *Lahiri M*, *Kannankeril PJ*, *Ng J*, *Kadish AH*. Assessment of parasympathetic reactivation after exercise. Am J Physiol 2006; 290: H2446–H2452

14 *Goulopoulou S*, *Heffernan K*, *Fernhall B*, *Yates G*, *Baxter-Jones AD*, *Unnithan VB*. Heart rate variability during recovery from a Wingate test in adolescent males. Med Sci Sports Exerc 2006; 38: 875–881

15 *Harriss DJ*, *Atkinson G*. International Journal of Sports Medicine – Ethical Standards in Sport and Exercise Science Research. Int J Sports Med 2009; 30: 701–702

16 *Hopkins WG*. Measures of reliability in sports medicine and science. Sports Med 2000; 30: 1–15

17 *Hopkins WG*. Reliability from consecutive pairs of trials (Excel spreadsheet). Sportscience 2000; http://sportsci.org/

18 *Hopkins WG*, *Hawley JA*, *Burke LM*. Design and analysis of research on sport performance enhancement. Med Sci Sports Exerc 1999; 31: 472–485

19 *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

20 *Hopkins WG*, *Schabort EJ*, *Hawley JA*. Reliability of power in physical performance tests. Sports Med 2001; 31: 211–234

21 *Imai K*, *Sato H*, *Hori M*, *Kusuoka H*, *Ozaki H*, *Yokoyama H*, *Takeda H*, *Inoue M*, *Kamada T*. Vagally mediated heart rate recovery after exercise is accelerated in athletes but blunted in patients with chronic heart failure. J Am Coll Cardiol 1994; 24: 1529–1535

22 *Inbar O*, *Bar-Or O*, *Skinner J*. The Wingate Anaerobic Test. Champaign, IL: Human Kinetics; 1996

23 *Kiviniemi AM*, *Hautala AJ*, *Kinnunen H*, *Tulppo MP*. Endurance training guided individually by daily heart rate variability measurements. Eur J Appl Physiol 2007; 101: 743–751

24 *Kobayashi H*. Does paced breathing improve the reproducibility of heart rate variability measurements? J Physiol Anthropol 2009; 28: 225–230

25 *Lamberts RP*, *Lemmink KA*, *Durandt JJ*, *Lambert MI*. Variation in heart rate during submaximal exercise: implications for monitoring training. J Strength Cond Res 2004; 18: 641–645

26 *Lamberts RP*, *Swart J*, *Capostagno B*, *Noakes TD*, *Lambert MI*. Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. Scand J Med Sci Sports 2010; 20: 449–457

27 *Leicht AS*, *Allen GD*. Moderate-term reproducibility of heart rate variability during rest and light to moderate exercise in children. Braz J Med Biol Res 2008; 41: 627–633

28 *Maeder MT*, *Ammann P*, *Rickli H*, *Brunner-La Rocca HP*. Impact of the exercise mode on heart rate recovery after maximal exercise. Eur J Appl Physiol 2009; 105: 247–255

29 *Nunan D*, *Donovan G*, *Jakovljevic D*, *Hodges LD*, *Sandercock GR*, *Brodie DA*. Validity and reliability of short-term heart-rate variability from the Polar S810. Med Sci Sports Exerc 2009; 41: 243–250

30 *Parouty J*, *Al Haddad H*, *Quod M*, *Leprêtre 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: 483–490

31 *Penttila J*, *Helminen A*, *Jartti T*, *Kuusela T*, *Huikuri HV*, *Tulppo MP*, *Coffeng R*, *Scheinin H*. Time domain, geometrical and frequency domain analysis of cardiac vagal outflow: effects of various respiratory patterns. Clin Physiol 2001; 21: 365–376

32 *Salo TM*, *Voipio-Pulkki LM*, *Jalonen JO*, *Helenius H*, *Viikari JS*, *Kantola I*. Reproducibility of abnormal heart rate variability indices: the case of hypertensive sleep apnoea syndrome. Clin Physiol 1999; 19: 258–268

33 *Sandercock GR*, *Bromley PD*, *Brodie DA*. The reliability of short-term measurements of heart rate variability. Int J Cardiol 2005; 103: 238–247

34 *Sinnreich R*, *Kark JD*, *Friedlander Y*, *Sapoznikov D*, *Luria MH*. Five minute recordings of heart rate variability for population studies: repeatability and age-sex characteristics. Heart 1998; 80: 156–162

35 *Task Force*. Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation 1996; 93: 1043–1065

36 *Weir JP*. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005; 19: 231–240