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ORIGINAL ARTICLE

Ultra-shortened time-domain HRV parameters at rest and following exercise in athletes: an alternative to frequency computation of sympathovagal balance

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Abstract
Purpose The primary purpose of this study was to determine the accuracy of the standard deviation of normal-to-normal intervals (SDNN) to root mean square of successive normal-to-normal interval differences (RMSSD) ratio from 1-min recordings (SDNN:RMSSD$_{1-\text{min}}$) compared to criterion recordings, as well as its relationship to low-frequency-to-high-frequency ratio (LF:HF) at rest and following maximal exercise in a group of collegiate athletes.
Method Twenty athletes participated in the study. Heart rate variability (HRV) data were measured for 5 min before and at 5–10 and 25–30 min following a maximal exercise test. From each 5-min segment, the frequency-domain measures of HF, LF, and LF:HF ratio were analyzed. Time-domain measures of SDNN, RMSSD, and SDNN:RMSSD ratio were also analyzed from each 5-min segment, as well as from randomly selected 1-min recordings.
Result The 1-min values of SDNN, RMSSD, and SDNN:RMSSD provided no significant differences and nearly perfect intra-class correlations (ICCs ranged from 0.97 to 1.00, $p < 0.001$ for all) to the criterion measures from 5-min recordings. In addition, SDNN, RMSSD, and SDNN:RMSSD from the 1-min segments provided very large to nearly perfect correlations (r values ranged from 0.71 to 0.97, $p < 0.001$ for all) to LF, HF, and LF:HF, respectively, at each time point.
Conclusion The findings of the study suggest that ultra-shortened time-domain markers may be useful surrogates of the frequency-domain parameters for tracking changes in sympathovagal activity in athletes.

Keywords Heart rate variability · RMSSD · Time-domain · Cardiovascular-autonomic control · Athlete monitoring

Abbreviations

HRV	Heart rate variability
ECG	Electrocardiogram or electrocardiographic
HF	High frequency
LF	Low frequency
LF:HF	LF-to-HF ratio
RMSSD	Root mean square of successive normal-to-normal interval differences
SDNN	Standard deviation of normal-to-normal intervals
RMSSD:SDNN	RMSSD-to-SDNN ratio
PRE	Pre-exercise resting period
POST1	Period between 5- and 10-min post-exercise
POST2	Period between 25- and 30-min post-exercise

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ICC	Intra-class correlations
r	Pearson's correlation coefficient

Introduction

Frequency-domain analysis of heart rate variability (HRV) involves spectral decomposition of electrocardiographic (ECG) recordings often via fast Fourier transformation (Task Force 1996). The advantage of this method purportedly remains in its ability to capture the activities of both arms of the autonomic nervous system. For instance, high-frequency (HF) power falls within the spectrum range of 0.15–0.40 Hz and is considered to be a marker of parasympathetic activity (Task Force 1996). Low-frequency (LF) power falls within the range of 0.04–0.15 Hz and is considered to be influenced by both arms of the autonomic nervous system, as well as the baroreflex sensitivity (Task Force 1996; Billman 2013). Though controversy exists regarding the underlying physiological mechanisms of LF:HF (Billman 2013), it is widely utilized as a marker of sympathetic-to-parasympathetic (e.g., sympathovagal) balance (Task Force 1996).

In sport and exercise research, LF:HF has been suggested to have a number of scientific and practical implications for monitoring sympathovagal responses. For instance, it has recently been suggested as an objective marker for displaying autonomic changes following concussion (Senthinathan et al. 2017). Furthermore, an increased LF:HF has been suggested to reflect a shift towards sympathetic predominance and lowered parasympathetic modulation during functional and non-functional overreaching (Mourot et al. 2004; Iellamo et al. 2002). In addition, LF:HF is often studied in response to acute exercise to track the transition from sympathetic dominance to parasympathetic rebound during recovery (Parekh and Lee 2005). Moreover, baseline measures of LF:HF were strongly related to changes in maximal oxygen consumption and peak work load in response to 2 weeks of high-intensity interval training (Kiviniemi et al. 2015), as well as with peak power output during repeated maximal cycling sprints (Cataldo et al. 2016).

Unfortunately, the usefulness of the frequency-domain for measuring HRV outside of the laboratory is limited. The relatively complicated nature of power spectral analysis requires sophisticated software, expensive heart rate recording equipment, and extensive technical knowledge for interpretation. Furthermore, the frequency parameters may be unreliable for monitoring athletes on a day-to-day basis due to the sensitivity to changes in breathing rate (Saboul et al. 2014). In addition, 5-min recording duration was previously recommended for collecting an appropriate number of R–R intervals for spectral decomposition (Task Force 1996), which may not be a suitable time period for analyzing athletes in a time-constrained setting such as a sports facility. Therefore, simplified approaches for measuring HRV in field settings are needed (Saboul et al. 2016).

Alternatively, the root mean square of successive normal-to-normal interval differences (RMSSD) appears to have a number of advantages for HRV monitoring among athletes. For instance, RMSSD has been shown to provide accurate measures when recorded in segments of only 1 vs 5 min (Flatt and Esco 2016a, b; Esco and Flatt 2014). Furthermore, it appears to be less influenced by breathing rate, and can be calculated and interpreted with greater ease (Buchheit 2014). It is because of these features that RMSSD has been utilized by a number of authors for monitoring athletic responses to training (Esco and Flatt 2016; Flatt and Esco 2016a, b; Nakamura et al. 2015; Buchheit 2014). However, it is only considered to be parasympathetically mediated and hence not a specific indicator of sympathovagal balance, such as LF:HF.

Recently, the SDNN:RMSSD ratio has been suggested as an appropriate surrogate to LF:HF (Wang and Huang 2012). However, the limited existing literature involves data primarily collected from 5-min segments, within non-athletic subjects, and under conditions that are not reflective of autonomic changes in response to exercise (Sollers et al. 2007; Balocchi et al. 2006). If ultra-short-term recordings of SDNN:RMSSD relate to LF:HF in athletes at rest and following exercise, then the time-domain metric could offer a simpler and more convenient approach for monitoring sympathovagal balance in field settings. Therefore, the primary purpose of this study was to determine the accuracy of ultra-shortened SDNN:RMSSD ratio from 1-min recordings compared to criterion 5-min recordings, as well its relationship to LF:HF at rest and in response to maximal exercise in a group of collegiate athletes. A secondary purpose was to determine the agreement of separate ultra-shortened measures of SDNN and RMSSD to the traditional recordings and frequency parameters. Due to the previous research involving non-athletic and clinical subjects under resting conditions and with lengthier recordings, it was hypothesized that the ultra-short-term time-domain parameter would provide accurate measures that relate to the frequency-domain at each time point; i.e., before exercise and after exercise.

Methods

Subjects

Twenty male athletes from the National Association for Intercollegiate Athletics participated in the study and provided written informed consent. The athletes (age = 21.7 ± 2.2 years, height = 185.7 ± 6.9 cm, weight = 82.1 ± 10.4 kg) were recruited from the University's soccer and basketball teams. All participants were apparently healthy, free from cardiopulmonary, metabolic, and orthopedic disorders according to health history questionnaires. Data collection for each participant occurred on any day of the week during the morning hours as close as possible to awakening from sleep (i.e., from 7:00 am to 11:00 am). Each participant was required to report to the laboratory following an overnight fast, though the consumption of a moderate amount of water was allowed. Participants were told to refrain from consuming stimulants (e.g., caffeine) or depressants (e.g., alcohol) and to avoid strenuous exercise for 24 h prior to data collection. The study was approved by The University of Alabama's Institutional Review Board for Human Participants and was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Procedures

The subjects performed a maximal graded exercise test via the Bruce Protocol to volitional fatigue on a Trackmaster treadmill (Full Vision, Inc., Carrollton, TX, USA). The staged protocol began at 1.7 mph at 10% grade with increasing work rate (speed and grade) every 3 min until volitional fatigue was reached.

For 10 min before and 30 min following the exercise test, each athlete was instructed to lay supine on an athletic training table in a dimly lit, climate controlled laboratory (i.e., temperature and humidity maintained at approximately 22.2 °C and 50%, respectively). During these time periods, heart rate and rhythm were assessed via ECG with three Ag/AgCl surface electrodes organized in a modified Lead II arrangement. The electrodes were connected to a Biopac MP100 data acquisition system (Goletta, CA, USA) that was interfaced with a Dell personal computer. The ECG data were collected at a sampling rate of 250 Hz. While a sampling rate of 250 Hz has been recommended as 'may be adequate' and higher sampling frequencies suggested as optimal (Task Force 1996), recent studies have suggested that HRV measures down-sampled to 125 Hz (Ellis et al. 2015) and lower (Mahdiani et al. 2015) showed to be accurate compared to higher sampling rates. This supports earlier reports that sampling rates greater than 125 Hz are sufficient for spectral analysis of healthy subjects (Abboud and Barnea 1995). Therefore, the 250 Hz sampling rate in this study is expected to be sufficient for the time and spectral analysis.

Three 5-min ECG epochs were used to analyze HRV from the following time points: the last 5-min of the pre-exercise resting period (PRE), and between minutes 5-to-10 (POST1) and 25-to-30 (POST2) of the post-exercise resting period. The participants were asked to pace their breathing rate with a metronome within a range of 10-to-12 breaths.min^{-1} (0.167–0.20 Hz) during a trial period before the ECG was recorded. The self-selected rate within this range for each participant was recorded and performed with the metronome which was visually checked by the investigators during all HRV recordings. This method was chosen to ensure a comparable breathing rate was performed during the pre- and post-recordings.

The three 5-min segments were visually inspected and non-sinus beats were removed and replaced by the adjacent normal cycle. If three or more ectopic beats were found within any 5-min segment, the participant was excluded from analysis ($n = 0$). The ECG segments were analyzed with the use of Kubios V2 HRV software (Biosignal Analysis and Medical Imagining Group at the Department of Applied Physics, University of Kuopio, Kuopio, Finland), an HRV analysis tool with a both time-domain, and frequency-domain analysis options (Tarvainen et al. 2014). Each ECG signal was converted to a tachogram, which plots the distance of each consecutive R–R interval in milliseconds on the *y*-axis against the time of recording in seconds on the *x*-axis. The R–R intervals were determined using the in-built Kubios functionality, which utilizes interpolation to improve the detection accuracy of these intervals. A power spectrum was created from the tachogram and separated into LF power (0.05–0.15 Hz) and HF power (0.15–0.40 Hz) via fast Fourier transformation (Task Force 1996). The LF:HF ratio was calculated as LF power divided by HF power. From each 5-min tachogram, SDNN and RMSSD were also calculated and recorded. The SDNN:RMSSD ratio was calculated as SDNN divided by RMSSD. Thereafter, SDNN and RMSSD parameters were recalculated from randomly selected pre- and post-exercise tachogram segments at intervals of 1-min ($SDNN_{1-min}$, $RMSSD_{1-min}$, respectively). $SDNN:RMSSD_{1-min}$ was calculated as $SDNN_{1-min}$ divided by $RMSSD_{1-min}$.

Statistical analysis

Data were analyzed with SPSS Statistics version 22.0 (Chicago, IL, USA). Data normality was evaluated with a Shapiro–Wilk test, which determined that the assumption of normality was violated for the HRV parameters ($p < 0.05$). Therefore, natural log (ln) transformations were applied. Due to the skewed absolute values, only ln values were analyzed and reported. To determine if a change in each HRV metric occurred in response to the exercise test, repeated-measures analysis of variance with follow-up paired t tests were used. A Bonferroni adjusted *p* value was applied to the follow-up *t* tests to reduce the chances of obtaining a type I error when multiple pairwise tests were performed. This procedure involved dividing the *p* value by the number of comparisons that were made (i.e., $0.05/3 = 0.017$). Therefore, the adjusted alpha level for significance of the follow-up comparisons was determined as $p < 0.017$. To determine the agreement between the 1- and 5-min time-domain segments paired *t* tests and Cohen's d effect sizes were used to compare mean values, intra-class correlations (ICC), and the method of Bland–Altman was used to determine the limits of agreement. The magnitude of the effect sizes was interpreted by the use of Hopkin's scale (Hopkins 2000) as follows: 0–0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, > 2.0 = very large. Pearson product-moment correlation procedures were used to determine the relationship between the time-domain and frequency-domain parameters at each time point. Statistical significance for the correlation procedures was determined as $p < 0.05$. The thresholds used to qualitatively interpret the ICCs and Pearson correlations were based on Hopkins (2002) using the following criteria: r or ICC < 0.0–0.1 was trivial; 0.1–0.3 was small; 0.3–0.5 was moderate; 0.5–0.7 was large; 0.7–0.9 was very large; > 0.9 was nearly perfect.

Table 1 HRV changes from PRE, POST1, and POST2

	PRE	POST1	POST2
Frequency-domain (5-min recordings)			
LF	7.77 ± 1.00	3.95 ± 1.19*	5.69 ± 1.04*†
HF	7.63 ± 0.93	2.18 ± 1.56*	4.18 ± 1.59*†
LF:HF	0.14 ± 0.71	1.76 ± 0.73*	1.50 ± 1.22*
Time-domain (5-min recordings)			
SDNN	4.29 ± 0.46	2.22 ± 0.61*	3.12 ± 0.58*†
RMSSD	4.31 ± 0.51	1.60 ± 0.83*	2.60 ± 0.76*†
SDNN:RMSSD	0.02 ± 0.18	0.62 ± 0.44*	0.52 ± 0.42*
Time-domain (1-min recordings)			
SDNN	4.35 ± 0.55	2.33 ± 0.57*	3.16 ± 0.58*†
RMSSD	4.32 ± 0.59	1.65 ± 0.78*	2.60 ± 0.80*†
SDNN:RMSSD	0.03 ± 0.21	0.68 ± 0.40*	0.55 ± 0.44*

*Significantly lower from PRE ($p < 0.017$)

†Significantly higher than POST1 ($p < 0.017$)

Results

Table 1 shows the mean values for each HRV metric at PRE, POST1, and POST2. Similar trends were shown in LF, HF, SDNN, RMSSD, $SDNN_{1-min}$, and $RMSSD_{1-min}$ as each displayed a significant decrease ($p < 0.017$) at POST1 compared to PRE, followed by a significant increase at POST2 compared to POST1 ($p < 0.017$). The changes in LF:HF, SDNN:RMSSD, and SDNN:$RMSSD_{1-min}$ were also similar, with each showing a significant increase at POST1 compared to PRE ($p < 0.017$), and remained elevated but not statistically different at POST2 compared to POST1.

Table 2 shows the agreement statistics between the 1- vs 5-min time-domain segments. There were trivial mean differences between each time-domain parameter from ultra-shortened and conventional recordings across all three conditions. The ICCs of the relationships were *near perfect* to *perfect* (i.e., ranging from 0.97 to 1.00) across the time points. The Bland–Altman plots are shown in Fig. 1 for the SDNN parameters, Fig. 2 for the RMSSD parameters, and Fig. 3 for the SDNN:RMSSD parameters. The biases were near zero (ranging from 0.00 to 0.11) with small limits of agreement (ranging from ± 0.16 to ± 0.41) for all comparisons.

Table 3 shows the correlation coefficients of the relationships between time-domain (i.e., 5- and 1-min values) and frequency-domain parameters. The SDNN parameters were significantly related to LF at all three time points, with the strength of the relationships remaining stable throughout (r values ranged from 0.88 to 0.94). However, the relationship between the SDNN parameters and HF weakened from *nearly perfect* at PRE (0.93 and 0.93, respectively) to *very large* POST1 (0.81 and 0.77, respectively) and *large* to *very large* at POST2 (0.69 and 0.71, respectively), but each r value remained significant ($p < 0.001$). HF was significantly related to the RMSSD values at PRE, POST1, and POST2

Table 2 Comparison of the ultra-shortened (1-min) and 5-min time-domain HRV measures showing bias and limits of agreement (LoA), effect sizes, and intra-class correlations (ICC) with 95% confidence intervals

Value	Bias (LoA)	Effect size (interpretation)	ICC (95% CI)
PRE			
SDNN vs $SDNN_{1-min}$	0.05 ± 0.22	0.12 (trival)	0.99 (0.96–1.00)
RMSSD vs $RMSSD_{1-min}$	0.00 ± 0.22	0.02 (trival)	0.99 (0.97–1.00)
SDNN:RMSSD vs SDNN:$RMSSD_{1-min}$	0.05 ± 0.16	0.05 (trival)	0.93 (0.78–0.98)
POST1			
SDNN vs $SDNN_{1-min}$	0.11 ± 0.35	0.18 (trival)	0.98 (0.94–0.99)
RMSSD vs $RMSSD_{1-min}$	0.05 ± 0.41	0.06 (trival)	0.98 (0.95–0.99)
SDNN:RMSSD vs SDNN:$RMSSD_{1-min}$	0.06 ± 0.27	0.14 (trival)	0.97 (0.93–0.99)
POST2			
SDNN vs $SDNN_{1-min}$	0.04 ± 0.25	0.07 (trival)	0.99 (0.97–1.00)
RMSSD vs $RMSSD_{1-min}$	0.01 ± 0.35	0.00 (trival)	0.99 (0.97–1.00)
SDNN:RMSSD vs SDNN:$RMSSD_{1-min}$	0.01 ± 0.35	0.07 (trival)	0.99 (0.97–1.00)

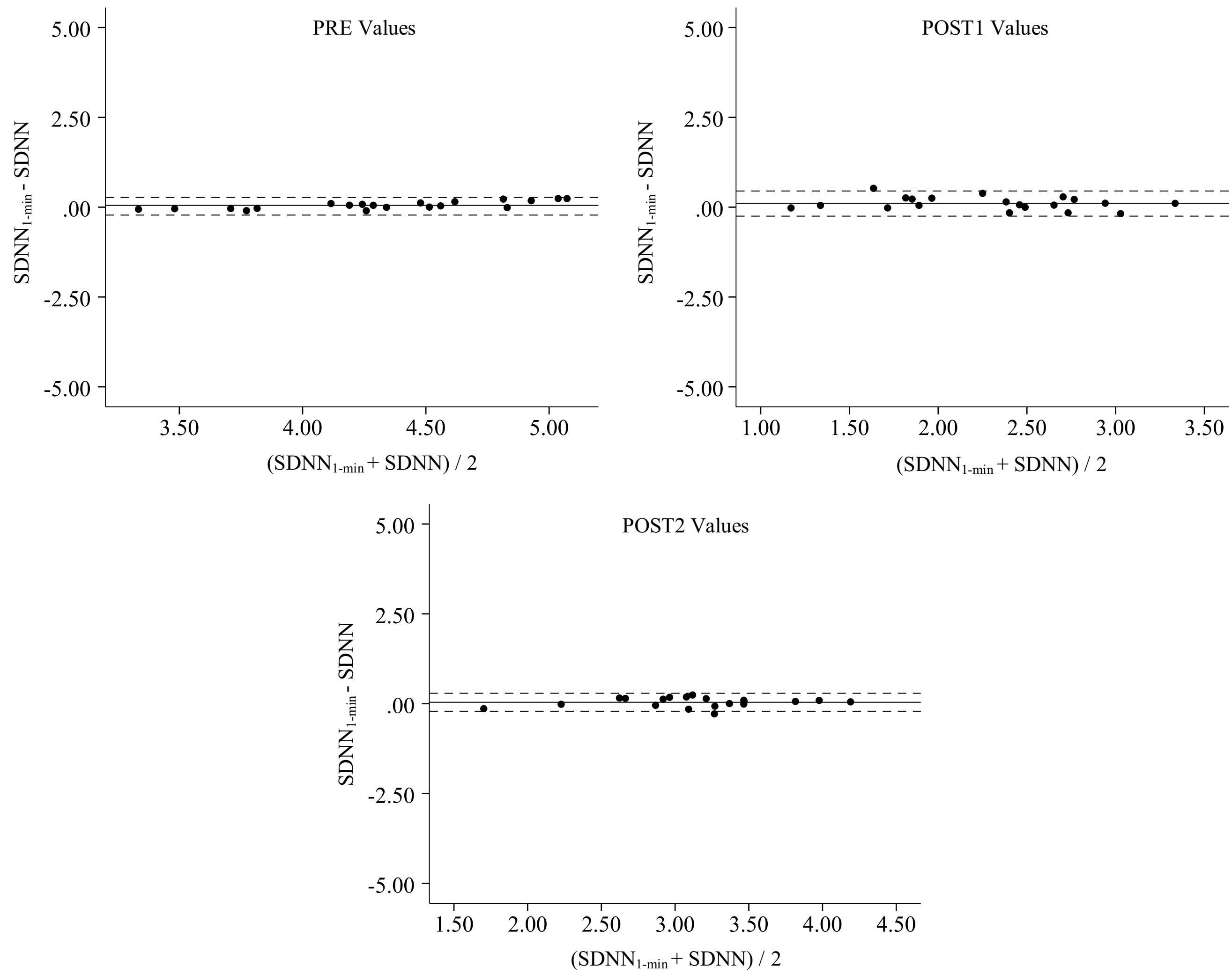

Fig. 1 Bland–Altman plots comparing the ultra-short-term $SDNN_{1-min}$ and criterion at pre-exercise (PRE), 5–10 min post-exercise (POST1), and 25–30 min post-exercise (POST2). The solid line represents the mean difference and the 2 outside dashed lines represent the upper and lower limits of agreement (±1.96 SD of the mean difference)

with *nearly perfect r* values (0.94–0.97) being displayed at each time point. At PRE, the 5- and 1-min RMSSD values were significantly and *very largely* related to LF ($r=0.72$ and 0.70, respectively), with stronger, *nearly perfect* r values shown at POST1 ($r=0.95$ and 0.90, respectively) and *very larger* values at POST2 ($r=0.79$ and 0.79, respectively). LF:HF significantly correlated to both 5- and 1-min SDNN:RMSSD values at each time point, with the strongest and *very large r* values shown at PRE ($r=0.87$ and 0.89, respectively) and POST2 ($r=0.86$ and 0.86, respectively). In addition, the 5- and 1-min SDNN:RMSSD parameters were significantly ($p<0.001$) and *very largely* correlated to HF at POST1 ($r=-0.72$ and -0.71, respectively) and POST2 ($r=-0.78$ and -0.78), but not at PRE ($r=-0.33$ and -0.30, respectively), and were only *moderately* significantly correlated to LF at POST1 ($r=-0.52$ and -0.49, respectively).

Discussion

The purpose of this study was to determine the accuracy of ultra-shortened time-domain measures (i.e., SDNN, RMSSD, and SDNN:RMSSD ratio) from 1-min recordings compared to conventional recordings, as well as their relationships to frequency-domain parameters at rest and in response to maximal exercise in a group of collegiate athletes. The findings of the study showed similar responses to the bout of exercise with the time and frequency-domain HRV variables. Furthermore, $SDNN_{1-min}$, $RMSSD_{1-min}$, and $SDNN:RMSSD_{1-min}$ were accurate compared to their criterion measures and were strongly related to LF, HF, and LF:HF, respectively, from 5-min recordings at rest and following maximal exercise. Therefore, the ultra-shortened markers may be useful surrogates of the frequency-domain

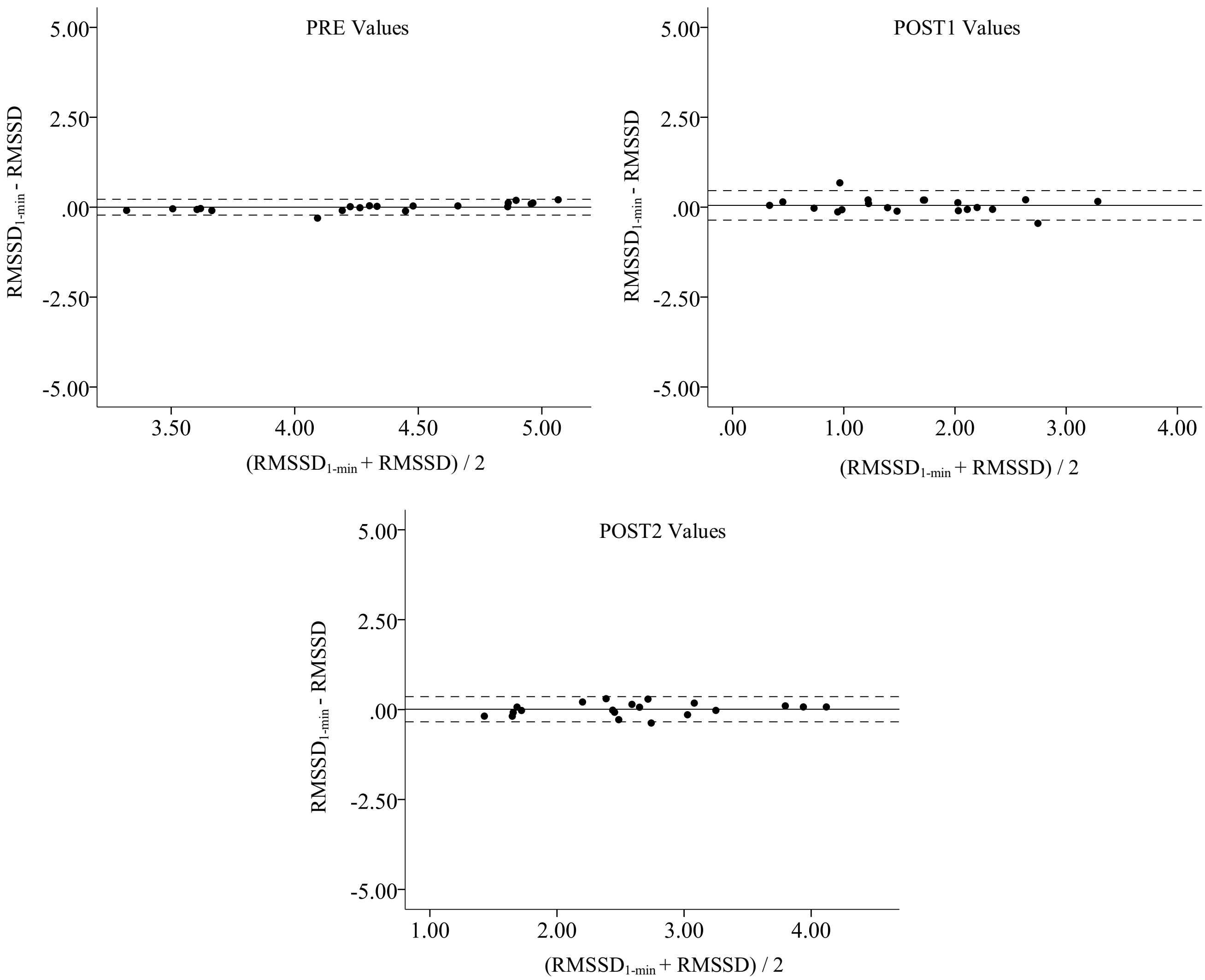

Fig. 2 Bland–Altman plots comparing the ultra-short-term $RMSSD_{1-min}$ and criterion at pre-exercise (PRE), 5–10 min post-exercise (POST1), and 25–30 min post-exercise (POST2). The solid line represents the mean difference and the 2 outside dashed lines represent the upper and lower limits of agreement (±1.96 SD of the mean difference)

parameters for tracking acute changes in sympathovagal activity in athletes.

Traditionally, LF was considered an index of sympathetic modulation (Pagani et al. 1984), while HF as a marker of parasympathetic control (Task Force 1996). However, more current research suggests that both LF and HF are influenced mostly by parasympathetic control, albeit to a lesser extent in the former (Billman 2013). Therefore, depressed LF and HF power were expected at POST1, when vagal modulation is depressed, with increasing trends toward baseline at POST2, as indicative of parasympathetic rebound. However, the increases in LF:HF ratio during the post-exercise time points suggest that a greater magnitude of decline occurred with the denominator (i.e., HF) compared to the numerator (i.e., LF). Thus, the increased LF:HF ratio during the post-exercise periods lends support for it serving as a non-invasive indicator of sympathovagal balance (Task Force 1999), due to the shift in sympathetic predominance during this time-frame. In fact, LF:HF was elevated at POST1 and POST2, with no significant difference between the two time points. This finding may possibly be related to the extended time that is required for the return of sympathetic activity toward baseline following intense exercise (Goulopoulou et al. 2009; Parekh and Lee 2005).

In support of others (Flatt and Esco 2016a; Esco and Flatt 2014; Nussinovitch et al. 2011; Salahuddin et al. 2007), time-domain measures from ultra-short-term recordings of only 1 min provided excellent agreement to the criterion measures recorded from the 5 min segments. The novelty of the current study, however, specifically relates to the potential usefulness of SDNN:RMSSD. Similar to the two statistical parameters used as isolated markers, the ratio also showed

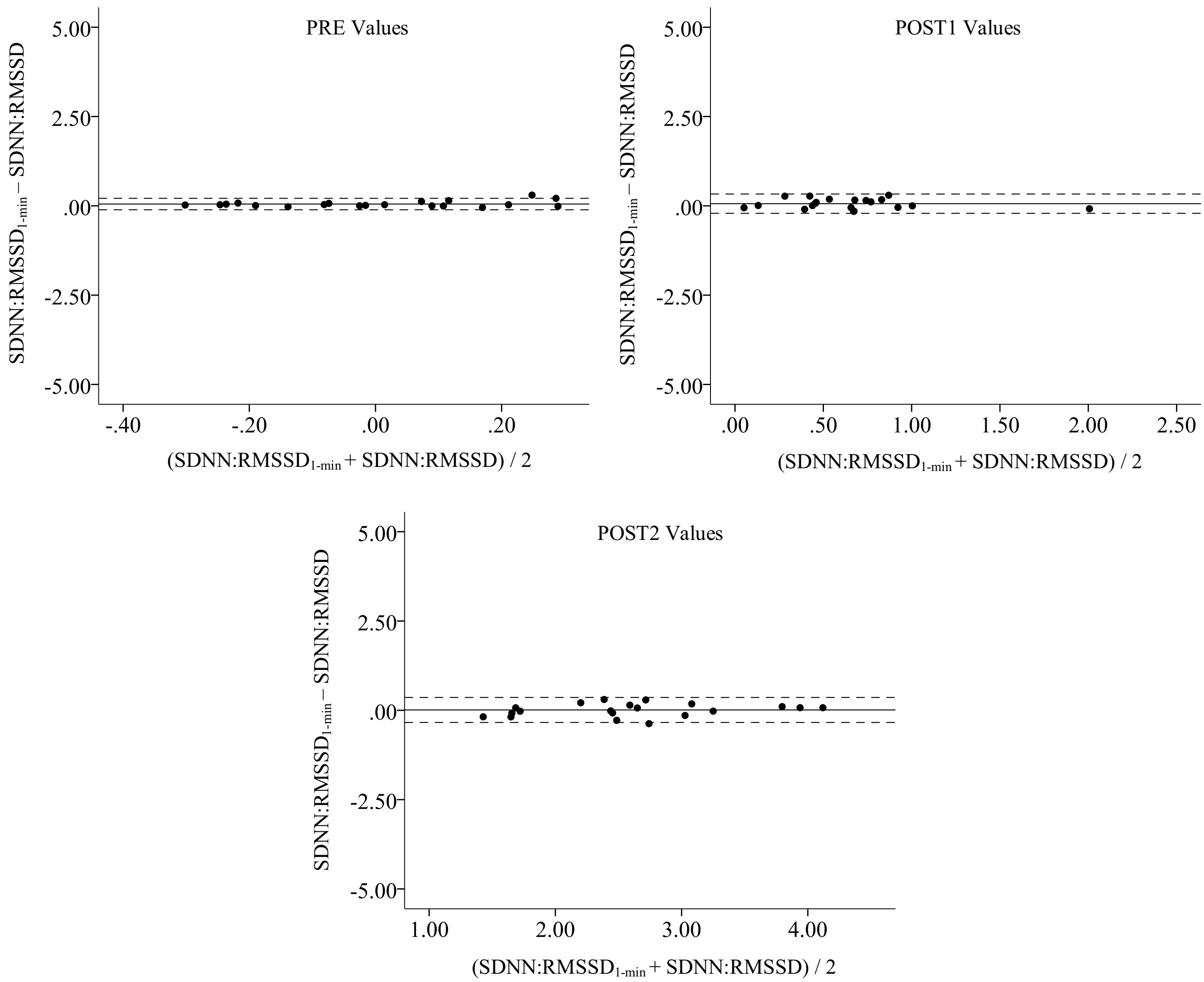

Fig. 3 Bland–Altman plots comparing the ultra-short-term $\text{SDNN:RMSSD}_{1-\text{min}}$ and criterion at pre-exercise (PRE), 5–10 min post-exercise (POST1), and 25–30 min post-exercise (POST2). The solid line represents the mean difference and the 2 outside dashed lines represent the upper and lower limits of agreement (± 1.96 SD of the mean difference)

excellent agreement between the 1- and 5-min recordings at each time point. As a noteworthy addition, strong correlations existed between the three ultra-short time-domain measures and the three frequency-domain parameters. The strongest correlation to $\text{SDNN}_{1-\text{min}}$ appeared to be LF power at each time point, whilst the strongest correlation to $\text{RMSSD}_{1-\text{min}}$ was HF power at each time point. Others have reported similar findings as nocturnal measures of HRV showed strong correlations between SDNN and LF and between RMSSD and HF (Otzenberger et al. 1998). It is because of these relationships that SDNN:RMSSD has been suggested previously as a surrogate to LF:HF in clinical patients and healthy individuals (Sollers et al. 2007; Balocchi et al. 2006). These findings are extended with the current study, though the investigation is the first to show the strong relationships following a bout of exercise, among an athletic sample, and with the ultra-shortened recordings of $\text{SDNN:RMSSD}_{1-\text{min}}$. These are novel aspects as athletes tend to display significantly higher HRV compared to non-athletes. Furthermore, LF:HF is often evaluated in the post-exercise period during a time when the risk of untoward cardiovascular events from dysrhythmic causes is heightened due to disturbance in sympathovagal balance (Parekh and Lee 2005). In addition, post-exercise HRV may be superior to analyzing resting conditions for monitoring athletic training status as it could reveal enhanced exercise recovery with training (Buchheit et al. 2008, 2007; Javorka et al. 2002). Due to the current findings, SDNN:RMSSD measured from only 1-min segments may provide a more time-efficient alternative to LF:HF ratio for tracking the changes in sympathovagal balance in response to exercise, and perhaps training, in athletes.

Table 3 Correlation coefficients of the relationship between the selected time- and frequency-domain parameters at before (PRE) and at 5–10 min (POST1) and 25–30 min (POST2) of the exercise test

	LF	HF	LF:HF
PRE			
SDNN	0.90† (*nearly perfect*)	0.93† (*nearly perfect*)	0.06 (*trivial*)
$SDNN_{1-min}$	0.88† (*very large*)	0.93† (*nearly perfect*)	0.02 (*trivial*)
RMSSD	0.70† (*very large*)	0.97† (*nearly perfect*)	− 0.25 (*small*)
$RMSSD_{1-min}$	0.70† (*very large*)	0.97† (*nearly perfect*)	− 0.29 (*small*)
SDNN:RMSSD	0.30 (*small*)	− 0.30 (*small*)	0.88† (*very large*)
$SDNN:RMSSD_{1-min}$	0.35 (*moderate*)	− 0.30 (*small*)	0.89† (*very large*)
POST1			
SDNN	0.92† (*nearly perfect*)	0.81† (*very large*)	0.22 (*small*)
$SDNN_{1-min}$	0.89† (*very large*)	0.77† (*very large*)	0.19 (*trivial*)
RMSSD	0.95† (*nearly perfect*)	0.97† (*nearly perfect*)	− 0.53* (*large*)
$RMSSD_{1-min}$	0.90† (*nearly perfect*)	0.94† (*nearly perfect*)	− 0.51* (*large*)
SDNN:RMSSD	− 0.52* (*moderate*)	− 0.72† (*very large*)	0.71† (*very large*)
$SDNN:RMSSD_{1-min}$	− 0.49* (*moderate*)	− 0.71† (*very large*)	0.72† (*very large*)
POST2			
SDNN	0.94† (*nearly perfect*)	0.69† (*large*)	0.10 (*trivial*)
$SDNN_{1-min}$	0.92† (*nearly perfect*)	0.72† (*very large*)	0.15 (*trivial*)
RMSSD	0.79† (*very large*)	0.94† (*nearly perfect*)	− 0.55* (*large*)
$RMSSD_{1-min}$	0.79† (*very large*)	0.96† (*nearly perfect*)	− 0.58* (*large*)
SDNN:RMSSD	− 0.16 (*trivial*)	− 0.78† (*very large*)	0.86† (*very large*)
$SDNN:RMSSD_{1-min}$	− 0.20 (*trivial*)	− 0.78† (*very large*)	0.86† (*very large*)

*Significant at $p < 0.05$

†Significant at $p < 0.001$

Interestingly, SDNN:RMSSD also provided significant and negative correlations to LF and HF during the post-exercise periods, but no significant correlation was shown at PRE. It is difficult to provide a precise rationale to explain these findings. However, the results may be related to the transient decrease in parasympathetic with a concomitant increase in sympathetic activity following physical stress. The decline in parasympathetic activity following exercise likely contributed to decreases in both LF and HF (Billman 2013), while a shift toward sympathetic predominance may have increased SDNN:RMSSD (Wang and Huang 2012). These significant negative correlations probably arise from the maximal nature of the graded exercise test. Maximal whole-body exercises are related to high mobilization of central command, anaerobic metabolism, and plasma metabolites, all of which contribute to the depression in the vagal cardiac activity and persistent sympathetic activity (Buchheit et al. 2007). It remains to be elucidated whether the negative correlations between SDNN:RMSSD and both LF and HF will be noted post-low intensity exercise (i.e., below the first ventilatory threshold) that does not elicit a large contribution of anaerobic metabolism and practically unchanged post-exercise HRV (Seiler et al. 2007).

Ultra-short-term RMSSD has been considered as the most appropriate time-domain indicator for monitoring athletic performance (Buchheit 2014). This marker is the primary HRV parameter used in mobile devices and has been shown to track athletic performance and predict outcomes (Esco et al. 2017b, 2016; Flatt et al. 2017b, a). However, it is mainly mediated by parasympathetic modulation (Task Force 1996) and not an indicator of sympathovagal balance. This is supported in the current findings that RMSSD was near perfectly correlated to HF at all time points, but presented a weak (at PRE) to moderate (at POST1 and POST2) correlation to LF:HF. However, SDNN offers many of the same conveniences as RMSSD as it is easily calculated and interpreted, as well. Therefore, the SDNN:RMSSD when analyzed from 1-min recordings may provide a convenient marker of sympathovagal balance and could serve as a complimentary addition to the ultra-shortened RMSSD to provide a more robust assessment of autonomic modulation at rest and following exercise.

The current study did not analyze HRV responses over a long-term training season and no training status indicator was used. Therefore, future research is needed to determine if $SDNN:RMSSD_{1-min}$ can be used as a surrogate of the frequency-domain parameters for tracking changes in sympathovagal activity in athletes throughout a training season. However, because of the findings of strong correlations between $SDNN:RMSSD_{1-min}$ and LF:HF at three very different time points of cardiac-autonomic status (i.e., PRE, POST1, and POST2), we feel that the ultra-shorted time-domain marker of sympathovagal balance has potential to be used for long-term monitoring of training adaptation. Though the novel findings of the current study provide an important first step, future longitudinal research is needed regarding the efficacy of ultra-short SDNN:RMSSD$_{1-\min}$ for monitoring chronic training adaptation. In addition, the study only employed one physical stressor (i.e., exercise). Given the complicated reflexive nature of the autonomic nervous system to various physiological and psychological stimuli, additional research is needed to verify the capacity of the ultra-shortened measures to detect dynamic changes in response to other stressors that were not accounted for in the study. Furthermore, the study did not include a direct assessment of autonomic modulation, such as a pharmacological or surgical intervention, since determining the specific physiological mechanisms underlying the ultra-shortened parameters were beyond the scope.

In conclusion, the findings of the study show that SDNN, RMSSD, and SDNN:RMSSD when measured from ultra-short-term recordings of only 1-min significantly correlate with the measures collected from 5-min recordings before and following a bout of maximal exercise. Therefore, only a 1-min period is needed to suitably record these three time-domain parameters, which allow for a more convenient approach to measuring HRV in field settings. Furthermore, they showed strong correlations to LF, HF, and LF:HF, respectively, measured from 5-min recordings. Considering the need to simplify HRV assessment for field use (Saboul et al. 2016), the ultra-short-term time-domain parameters may be convenient alternatives to the more complex and time consuming frequency-domain method for measuring HRV in athletes. In addition, SDNN:RMSSD$_{1-\min}$ may provide a simple, yet more complete HRV profile when collected in addition to the parasympathetic-derived variable of RMSSD. However, additional research is needed to better understand the precise autonomic mechanisms underlying this metric and whether it is capable of reflecting longitudinal changes in training load and recovery status in athletes.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The study was approved by The University of Alabama's Institutional Review Board.

Research involving human and animal participants The research involved human participants. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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