Journal of Medical Systems (2019) 43:328
https://doi.org/10.1007/s10916-019-1478-z

MOBILE & WIRELESS HEALTH

Intra-Individual Variation of HRV during Orthostatic Challenge in Elite Male Field Hockey Players

Jason D. Vescovi[1]

Received: 6 August 2019 / Accepted: 11 October 2019

Abstract

The purpose of this study was to examine the intra-individual variation of heart rate variability (HRV) and heart rate using an orthostatic challenge in elite male athletes during a training camp. Heart rate (variability) was measured upon waking. Log-transformed HRV metrics were evaluated in three segments (first min discarded for stabilization): 0–3 min supine, 3–6 min supine, and standing. Heart rate was assessed while supine, 15 s after standing and average final 30 s standing (Rusko protocol). A RM-ANOVA compared intra-individual means, standard deviations (SD) and coefficients of variation (CV%) for HRV and heart rate. The intraclass correlation coefficient (ICC) and standard error of measurement (SEmeas) were used for relative and absolute reliability, respectively. Time and frequency domain HRV metrics had low variation (CV% <8.5%; SEmeas% ≤4.0%) for 0–3 min supine which was not improved during 3–6 min. Standing HRV had lower ICC and higher SEmeas than supine values. Variability and reliability outcomes for heart rate were comparable to log-transformed HRV metrics. This study uniquely describes the intra-individual variation of HRV metrics during an orthostatic challenge and demonstrated low variability in this cohort of elite male athletes. These data can be helpful for identifying when true individual changes occur for the autonomic nervous system indices in supine and standing positions.

Keywords Orthostatic challenge · LnRMSSD · Standard error of measurement · Reliable change index · Readiness

Introduction

Elite athletes (i.e., professional, Olympic) endure a substantial amount of stresses (e.g., training loads, competition demands, frequent/long-distance travel, etc.) as a part of their chosen profession. Keeping athletes healthy and avoiding non-functional overreaching or overtraining is important for achieving desired training adaptations and performances. Therefore, regularly monitoring objective, physiological markers is valuable for understanding how athletes are tolerating the imposed stresses. Heart rate variability (HRV) is increasingly being used as an indication of physiological fatigue or athlete readiness. Indeed, abnormal fluctuations of several time and frequency domain metrics are purported to help identify potential fatigue, illness or overuse scenarios [1, 2]. Knowing whether fluctuations in HRV are within or outside the expected variation will enable practitioners to make more accurate inferences about observed changes.

The expected variation for any assessment technique within a given population and in various contexts should be known to allow practitioners to determine if a true change has occurred [3]. This enables evidence-based decisions to be made when monitoring longitudinal data [4, 5]. The reliability of HRV metrics varies greatly between studies (e.g., coefficient of variation is 4–45%) [6, 7] and HRV outcomes are impacted by age [8], fitness status [9], posture [10], technology used [11] and respiration rate [12]. It has been demonstrated that multiple HRV metrics should be monitored in order to better appreciate individual characteristics [5] of elite athletes [13]. Thus, knowing the intra-individual variation in an applied setting is valuable for HRV analysis in high-performance sport.

Sports scientists using HRV in field-based settings need a simple, non-invasive method and reliable metrics that allow for meaningful interpretations to be made about the fatigue/readiness of an individual. The most widely used HRV

This article is part of the Topical Collection on *Mobile & Wireless Health*

✉ Jason D. Vescovi
VescoviJ@aol.com; http://orcid.org/0000-0003-2656-5109

[1] Faculty of Kinesiology and Physical Education, Graduate School of Exercise Science, University of Toronto, Toronto, ON, Canada

Published online: 27 October 2019

parameter in sport is the natural log of the root mean square of successive R-R interval differences (LnRMSSD) because it has demonstrated greater consistency than frequency domain metrics for day-to-day monitoring of athletes [14]. However, used in isolation, the LnRMSSD ignores other autonomic nervous system parameters that could add value to a HRV monitoring strategy within athletic populations [15]. Assessing the intra-individual variation for other HRV metrics is therefore warranted.

Another challenge for assessing the variation of HRV indices in athletic populations is posture. Measurements are often taken upon waking in a supine position but there is evidence that supine and standing HRV metrics are independent characteristics [16]. Additionally, researchers have assessed HRV while standing to address saturation [17], which can occur in individuals with low resting heart rate values (i.e., elite athletes) [18]. To date, the literature is lacking evidence about the intra-individual variability of HRV in elite male athletes while standing.

The primary purpose of this study was to determine the intra-individual variation of HRV metrics during an orthostatic challenge (supine to standing) in a group of elite male athletes in a field-based setting. Specifically, the study compared the intra-individual mean, standard deviation (SD) and coefficient of variation (CV%) for HRV metrics between postures. A secondary aim was to compare the intra-individual mean, SD and CV% for heart rate according to the Rusko protocol [19]. Lastly, the relative and absolute reliability of HRV metrics and heart rate was determined.

Methods

This paper is derived from an observational study with a men's national field hockey team during a pre-Olympic training camp. The study was approved by the University of Toronto Research Ethics Board (protocol #30586) and conforms to the Declaration of Helsinki. The procedures were verbally explained and informed consent was signed by the athletes.

Participants

Twenty-two members of a men's national field hockey team volunteered to participate (age 26.8 ± 3.4 yr; height 178.4 ± 6.3 cm; body mass 76.2 ± 7.4 kg). The players were weight stable throughout the event [20]; aerobically fit (YoYo IRT1–2668 ± 305 m); had typical on-field training volume of 10–15 h per week; and played high-level hockey for at least 7 years. The daily training environment was based at a centralized location and the team trained/competed together throughout the entire year. Average total and high-intensity distances in the centralized training environment were approximately 9775 and 1050 m, respectively and when double sessions were performed could be as high as 17 km and 2 km, respectively.

Design and procedures

Data were collected over 10 days during a training camp that included morning and afternoon sessions (Table 1). This was the final preparation event leading into the Rio Olympics, with matches played against nations with similar International Hockey Federation (FIH) world rankings. Morning heart rate measurements were captured on Day 2 and Days 5 through 10 (Days 3–4 were off). Upon waking (7–8 AM) each morning (after voiding their bladder) athletes were outfitted with a Polar RS800CX™ (Polar Electro, Kempele, Finland) heart rate monitor to assess HRV and returned to bed to complete a 10-min orthostatic challenge (7 min supine+3 min standing) [21]. No foods or fluids were consumed between waking and the orthostatic test. Players were verbally informed to stand after 7 min by the researcher. A metronome set to 1-Hz was placed in the room to help athletes achieve day-to-day consistency with breathing. Visual inspection of R-R peaks and troughs in HRV files indicated players had consistent breathing rates (~8 breaths per minute) in all files. The Polar RS800CX™ is valid and reliable for the measurement of R-R intervals with a resolution of 1 ms [22]. Data were transmitted from the chest strap to the watch, then files were downloaded from the watch (ProTrainer, Version 5.40.170), exported (.hrm file) and subsequently analyzed in Kubios (Version 2.2., Kuopio, Finland). An artifact correction (low or medium) was used to remove irregular heartbeats if necessary. No more than 2% of heartbeats in any single file required correction.

Measures

HRV parameters included: time domain–the square root of the mean squared difference of successive NN intervals (RMSSD, ms); frequency domain (fast Fourier transform)–high frequency power (HF; 0.15–0.4 Hz); low frequency power (LF; 0.04–0.15 Hz), LF:HF ratio, and total power (TP); and two calculated metrics from the Poincare analysis–the stress score (inverse of SD2 × 1000) and the stress score:SD1 ratio [23]. HRV metrics were analyzed from three sections of the orthostatic test after the first minute was discarded for stabilization [24]: 0–3 min (supine), 3–6 min (supine) and standing (excluding initial 30 s).

Heart rate during the orthostatic challenge was assessed according to the timepoints described in the protocol of Rusko [19], which included mean supine heart rate, heart rate after 15 s from standing and the mean heart rate during the final 30 s of standing.

Table 1 Overview of schedule and selected running demands

Day	Session		Running demands (daily totals)	
	Morning	Afternoon	Total distance (m)	HIR distance (m)
1	Light training	Match	12,167	1599
2	Light training	Match	12,496	1674
3	Off	Off	–	–
4	Off	Hard training	6704	754
5	Light training	Match	12,074	1607
6	Recovery	Match	8438	1623
7	Hard training	Light training	9725	1812
8	Match	Off	8092	1313
9	Light training	Match	12,749	1795
10	Off	Off	–	–

HIR high-intensity running (≥18 kph)

Statistical analysis

Statistical analyses were performed using SPSS (version 20.0). All HRV metrics were log-transformed to reduce bias from non-inform errors and enable parametric analysis to be performed. The stress score:SD1 ratio was first multiplied by 100 to ensure positive values when applying the log-transformation. A RM-ANOVA was used to compare intra-individual means, SD and CV% of HRV variables for the three segments of the orthostatic challenge described above. A RM-ANOVA compared intra-individual means, SD and CV% of heart rate values according to the time points of Rusko described above [19]. Bonferroni adjustments for post-hoc pairwise comparisons were used when significant main effects were observed. Cohen's *d* provided the effect size (ES) for all pairwise comparisons [25]. The ES were calculated from the ratio of the mean difference to the pooled standard deviation and considered trivial (<0.2), small (0.2–0.6), moderate (0.61–1.20), large (1.21–2.0), and very large (2.1–4.0) [26].

Relative and absolute reliability were assessed using the intraclass correlation coefficient (ICC) and standard error of measurement (SEmeas), respectively. A two-way mixed method ICC with absolute agreement was used and values were considered poor (<0.5), moderate (0.5–0.75), good (0.76–0.9), and excellent (>0.9) [27]. The SEmeas was calculated using the following formula: $SEmeas = \mathrm{SD}\sqrt{1-reliability}$; where SD is the standard deviation of the entire sample and reliability is Cronbach's alpha [28]. Mean-normalized SEmeas% was also calculated.

Results

Table 2 shows the intra-individual mean, SD and CV% of the HRV metrics during the orthostatic challenge. There was a difference for mean values between 0–3 min and 3–6 min supine segments for LnRMSSD, LnLF and LnSS:SD1 (trivial/small ES). Differences between supine and standing were observed for LnRMSSD, LnHF, LnLF:HF and LnSS:SD1 (large ES) as well as LnTP (moderate ES). In almost all cases, the intra-individual SD was similar between each segment of the orthostatic challenge with the exception of LnTP with 3–6 min greater than 0–3 min (moderate ES). In general, the intra-individual mean CV% for LnRMSSD and the frequency domain metrics were < 9% with higher values for 3–6 min (LnLF and LnTP) and standing (LnRMSSD) than 0–3 min (small/moderate ES). The intra-individual mean CV% for LnSS and LnSS:SD1 were greater during 3–6 min segment for 3 of the 4 comparisons (moderate ES).

Table 3 includes the ICC of HRV metrics and were, in general, slightly greater for supine 0–3 min than 3–6 min; with standing having the lowest values. The ICC was excellent for LnRMSSD, LnHF and LnSS:SD1 in both supine segments; whereas it was good-to-excellent for the other HRV metrics. ICC was considered good for all standing HRV metrics.

Table 3 also has the SEmeas (SEmeas%) for HRV metrics. The majority of metrics had SEmeas% ranging from 2.2–6.6%, except for LnSS:SD1 which were 7.8–9.4%. The LnRMSSD, LnLF, LnHF, and LnTP tended to have slightly larger SEmeas% in the standing position; whereas the calculated metrics from Poincare had somewhat similar SEmeas% between postures.

Figure 1 displays the intra-individual variation for heart rate. There were differences between each mean intra-individual heart rate value (all pairwise $p < 0.001$, $d > 2.6$) and CV% was the lowest for the first 15 s standing (pairwise $p = 0.04$, $d = 1.05–1.10$). No differences for the SD were found (main $p = 0.175$, $d = 0.33–0.59$). The ICC for intra-individual mean values were good to excellent. The SEmeas (SEmeas%) for supine, first 15 s standing and final 30 s standing were 1.6 (3.0%), 1.9 (2.0%), and 2.5 (3.4%) bpm, respectively.

Table 2 Intra-individual variation of heart rate variability metrics

		Intra-individual values				p value (Cohen's d, 95% CI)		
		0–3 min	3–6 min	Standing	Main	0–3 min vs 3–6 min	0–3 min vs stand	3–6 min vs stand
LnRMSSD	Mean	4.40 ± 0.52	4.32 ± 0.54	3.72 ± 0.39	<0.001	0.120 (0.15, −0.45-0.74)	<0.001 (1.48, 0.75–2.07)	<0.001 (1.27, 0.57–1.86)
	SD	0.26 ± 0.10	0.28 ± 0.10	0.29 ± 0.10	0.194	0.319 (0.20, −0.78-0.40)	0.306 (0.30, −0.88-0.31)	1.00 (0.10, −0.69-0.50)
	CV (%)	6.1 ± 2.9	6.7 ± 2.9	8.1 ± 2.9	0.021	0.227 (0.21, −0.79-0.40)	0.015 (0.69, −1.26-0.05)	0.081 (0.48, −1.06-0.14)
LnLF	Mean	8.73 ± 0.75	8.50 ± 0.77	8.44 ± 0.58	0.001	<0.001 (0.30, −0.30-0.89)	0.148 (0.43, −0.17-1.02)	1.00 (0.09, −0.50-0.68)
	SD	0.51 ± 0.18	0.58 ± 0.21	0.49 ± 0.19	0.036	0.051 (0.36, −0.95-0.24)	1.00 (0.11, −0.49-0.70)	0.483 (0.45, −0.16-1.04)
	CV (%)	6.0 ± 2.6	7.0 ± 3.0	5.8 ± 2.2	0.019	0.021 (0.36, −0.94-0.25)	1.00 (0.08, −0.51-0.67)	0.457 (0.46, −0.15-1.05)
LnHF	Mean	7.25 ± 1.17	7.14 ± 1.22	5.84 ± 0.92	<0.001	0.173 (0.09, −0.50-0.68)	<0.001 (1.34, 0.66–1.97)	<0.001 (1.20, 0.54–1.82)
	SD	0.57 ± 0.19	0.61 ± 0.23	0.61 ± 0.19	0.688	1.00 (0.19, −0.78-0.41)	1.00 (0.21, −0.80-0.39)	1.00 (0.00, −0.59-0.59)
	CV (%)	8.3 ± 3.7	8.9 ± 4.0	10.5 ± 3.3	0.059	1.00 (0.16, −0.74-0.44)	0.051 (0.63, −1.22-0.01)	0.157 (0.44, −1.03-0.17)
LnLF:HF	Mean	1.23 ± 0.15	1.22 ± 0.17	1.48 ± 0.18	<0.001	0.780 (0.06, −0.53-0.65)	<0.001 (1.51, 0.81–2.15)	<0.001 (1.49, 0.79–2.12)
	SD	0.10 ± 0.04	0.12 ± 0.06	0.12 ± 0.06	0.126	0.704 (0.39, −0.98-0.21)	0.208 (0.39, −0.98-0.21)	1.00 (0.00, −0.59-0.59)
	CV (%)	8.4 ± 2.9	9.4 ± 4.0	8.2 ± 3.6	0.318	0.424 (0.29, −0.87-0.31)	1.00 (0.06, −0.53-0.65)	0.542 (0.32, −0.29-0.90)
LnTP	Mean	9.39 ± 0.79	9.29 ± 0.83	9.03 ± 0.28	0.032	0.264 (0.12, −0.47-0.71)	0.046 (0.61, −0.01-1.20)	0.210 (0.42, −0.19-1.01)
	SD	0.41 ± 0.16	0.53 ± 0.19	0.45 ± 0.20	0.016	0.011 (0.68, −1.28-0.06)	1.00 (0.22, −0.81-0.38)	0.501 (0.41, −0.19-1.00)
	CV (%)	4.5 ± 2.0	5.9 ± 2.6	5.0 ± 2.2	0.011	0.007 (0.60, −1.20-0.01)	1.00 (0.24, −0.83-0.36)	0.611 (0.37, −0.23-0.96)
LnSS	Mean	1.91 ± 0.37	1.96 ± 0.42	2.08 ± 0.27	0.049	0.361 (0.13, −0.72-0.47)	0.077 (0.52, −1.12-0.09)	0.351 (0.34, −0.93-0.26)
	SD	0.23 ± 0.10	0.29 ± 0.10	0.22 ± 0.09	0.043	0.071 (0.60, −1.19-0.02)	1.00 (0.11, −0.49-0.69)	0.114 (0.74, 0.11–1.33)
	CV (%)	11.7 ± 3.9	14.9 ± 4.6	11.0 ± 4.5	0.023	0.052 (0.75, −1.35-0.13)	1.00 (0.17, −0.43-0.75)	0.037 (0.86, 0.22–1.46)
LnSS:SD1	Mean	2.46 ± 0.87	2.59 ± 0.93	3.31 ± 0.65	<0.001	0.026 (0.14, −0.73-0.45)	<0.001 (1.11, −1.72-0.45)	0.001 (0.90, −1.50-0.26)
	SD	0.45 ± 0.18	0.52 ± 0.19	0.50 ± 0.19	0.111	0.106 (0.38, −0.97-0.23)	0.922 (0.27, −0.86-0.33)	1.00 (0.11, −0.49-0.69)
	CV (%)	18.9 ± 5.8	21.0 ± 8.5	15.8 ± 6.8	0.037	0.333 (0.29, −0.88-0.31)	0.100 (0.49, −0.12-1.08)	0.030 (0.68, 0.06–1.27)

Abbreviations: RMSSD root mean sum of squared differences, *LF* low frequency, *HF* high frequency, *LF:HF* low:high power ratio, *TP* total power; *SS* stress score, *SS:SD1* stress score:SD1 ratio; *SD* standard deviation, *CV* coefficient of variation

Table 3 Standard error of measurement and intraclass correlation coefficient

	0–3 min		3–6 min		Standing	
	SEmeas (%)	ICC (95% CI)	SEmeas (%)	ICC (95% CI)	SEmeas (%)	ICC (95% CI)
LnRMSSD	0.11 (2.6%)	0.961 (0.927, 0.983)	0.12 (2.8%)	0.958 (0.922, 0.982)	0.20 (5.3%)	0.822 (0.669, 0.921)
LnLF	0.23 (2.6%)	0.928 (0.866, 0.968)	0.30 (3.5%)	0.896 (0.803, 0.955)	0.34 (4.0%)	0.776 (0.579, 0.903)
LnHF	0.25 (3.4%)	0.963 (0.931, 0.984)	0.26 (3.7%)	0.960 (0.924, 0.982)	0.33 (5.6%)	0.897 (0.807, 0.954)
LnLF:HF	0.05 (4.0%)	0.925 (0.860, 0.967)	0.06 (4.8%)	0.912 (0.833, 0.962)	0.07 (4.5%)	0.903 (0.815, 0.958)
LnTP	0.22 (2.3%)	0.936 (0.871, 0.975)	0.23 (2.5%)	0.942 (0.889, 0.975)	0.31 (3.4%)	0.792 (0.601, 0.913)
LnSS	0.11 (5.7%)	0.932 (0.870, 0.971)	0.13 (6.6%)	0.928 (0.866, 0.968)	0.13 (6.1%)	0.858 (0.735, 0.937)
LnSS:SD1	0.19 (7.8%)	0.960 (0.925, 0.982)	0.23 (8.8%)	0.947 (0.900, 0.977)	0.31 (9.4%)	0.839 (0.700, 0.928)

Abbreviations: *RMSSD* root mean sum of squared differences, *LF* low frequency, *HF* high frequency, *LF:HF* low:high power ratio, *TP* total power, *SS* stress score, *SS:SD1* stress score:SD1 ratio, *SEmeas* standard error of measurement, *ICC* intraclass correlation coefficient, *CI* confidence interval

Among the heart rate differences (i.e., supine-15 s, supine-30 s, 15 s–30 s), supine-15 s had the largest intra-individual mean values (pairwise $p < 0.001$, d = 3.17–3.62) and smallest CV% (pairwise $p < 0.001$, d = 1.79–2.20). Intra-individual SD values were similar among heart rate differences (main $p = 0.76$, d ≤ 0.60). The ICC were considered good to excellent for the differences in heart rate values. The SEmeas (SEmeas%) for supine-15 s, supine-30 s, and 15 s–30 s were 2.2 (5.6%), 2.6 (13.5%), and 2.8 (14.0%) bpm, respectively.

Discussion

The outcomes from this field-based, observational study demonstrate four key aspects of HRV and heart rate within the current context. First, time and frequency domain metrics had low intra-individual variation (CV% <8.5%, SEmeas% ≤4.0%) during the first 3 min and excellent relative reliability (ICC >0.92). Second, reliability was not improved beyond 3 min of supine HRV measures; therefore, a seven-minute orthostatic challenge (1 min stabilization+3 min supine+

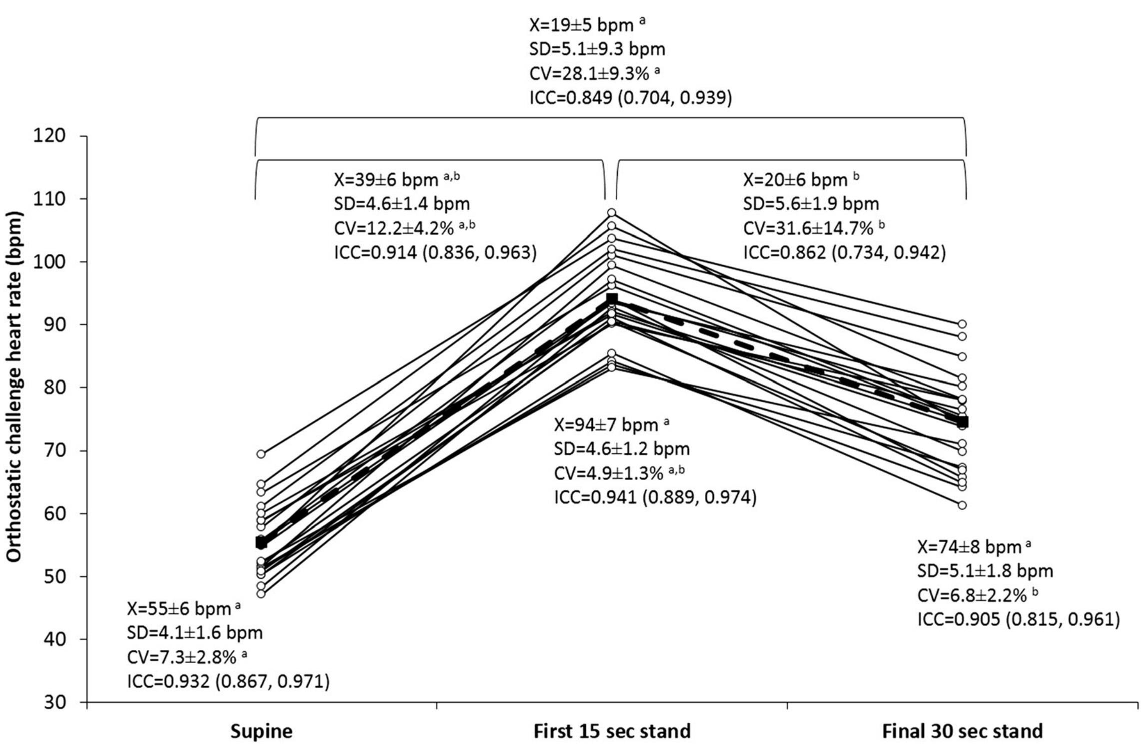

Fig. 1 Heart rate and delta values during orthostatic challenge. Solid line (open circles) are individual athletes and dashed line (solid squares) are mean values. Abbreviations: X (mean); SD (standard deviation); CV (coefficient of variation); ICC (intra-class correlation coefficient, 95% CI). Variables with the same superscript are statistically different from each other (see Results for ES)

3 min stand) is sufficient if this protocol is desired. Third, standing HRV metrics had lower relative (ICC) and higher absolute (SEmeas) reliability than HRV while supine. Lastly, intra-individual variation (CV%, ~5–7%) and reliability (ICC, >0.90 and SEmeas%, <3.5%) for heart rate were comparable to the log-transformed HRV metrics; however, the delta values for heart rate were less reliable and had greater variability.

The most commonly used HRV metric within sport is LnRMSSD. The current outcomes demonstrated similar resting supine values as well as relative changes from supine to standing (i.e.,~20% decrease) when compared to previous research in male athletes [4, 10, 21]. The observed intra-individual CV% was marginally lower in the supine than standing position and similar to previous research in male rugby players [29]. The reported mean difference in LnRMSSD between 'overtrained' and control athletes was about 0.20–0.25 ms (in supine and standing conditions) [21], highlighting a potential challenge for detecting the signal through the noise when attempting to use a dichotomized approach. However, these are group level differences and so the current intra-individual outcomes provide supportive evidence for using LnRMSSD to identify weekly fluctuations.

Frequency domain metrics are also used to detect fatigue within high-performance environments [16]. Several research groups have demonstrated that supine and standing values of LF and HF were suppressed in elite athletes who were classified as 'fatigued/overtrained' [16, 21]. The relative differences observed in these studies were ~45–60% (raw) and ~6–9% (log-transformed) of 'non-fatigued' athletes, which is near the intra-individual CV% found in the current group of athletes. There is often little change in mean LnLF values during the orthostatic challenge, but parasympathetic activity is inhibited while standing and thus LnHF is reduced. The current group of athletes had a mean positional LnHF difference of ~20%; similar to values for 'non-fatigued' athletes (18%) and less than 'fatigued' and 'overtrained' athletes (25–32%) [16, 21]. The current outcomes could also be influenced by the suppressive influence of low breathing rate on HF since controlled/slow breathing requires conscious effort [30]. Yet, breathing with a metronome has been shown to substantially reduce CV% of LF and HF [31]. The variation for the LnLF and LnHF in each posture were low and the changes between posture is aligned with previous research; so, practitioners will need to make decisions about which metrics to include in their environment and know that breathing rate must be considered when interpreting outcomes.

The stress score and stress score:SD1 ratio were recently proposed as indices of sympathetic activity and sympathovagal balance, respectively [23]. Based on an initial analysis with male athletes, the 75th percentiles were used to establish 'alert' values (>8 for stress score; >0.2 for stress score:SD1, log-transformed 2.1 and 3.0, respectively) [23] and subsequently shown to exceed these thresholds during pre-season soccer training [32]. The mean log-transformed data for the supine stress score is aligned with other researchers [33] (~2.3 ± 0.3) but with slightly higher CV% values than previously reported (90 CI, 4.9–7.3%). Those outcomes were also from field-based assessments taken during the season and in conjunction with the current results demonstrate the potential utility of LnSS as a sympathetic marker.

This is the first study to report on the stress score and stress score:SD1 ratio while standing and highlights two important points. First, there was no difference between supine and standing LnSS, whereas the LnSS:SD1 ratio was elevated. This could be reflective of a greater influence of parasympathetic inhibition on increased heart rate while standing rather than augmented sympathetic outflow. Second, standing values had similar variation as supine measurements. While these preliminary data provide supportive evidence for including the stress score and stress score:SD1 ratio into an overall HRV profile, the utility of these particular metrics to help assess fatigue/readiness in elite athletes requires further investigation.

Heart rate rapidly increased during the initial 15 s of standing (Δ~40 bpm) before decreasing to ~75 bpm during the final 30 s (i.e., Δ~20 bpm between supine and stable standing values). This aligns with others who reported mean absolute differences between supine and standing of 16 to 27 bpm in athletes [10, 34]. Based on research with male cross country skiers [19], when heart rate during the final 30 s of an orthostatic test (standing) increases ≥10 bpm above normal it has been anecdotally suggested to be an indicator of mal-adaptation or possible impending illness. More recently, researchers reported that resting heart rate (supine and standing) was elevated approximately 15% (~7–10 bpm) in 'fatigued' athletes [16]. The mean intra-individual SD during supine and standing in the current group of players was between 4 and 5 bpm. Therefore, if an increase of 7–10 beats is indeed indicative of fatigue, mal-adaption, or illness in athletes, then it can be easily detected beyond the noise of these measurements.

The ICC and SEmeas were included as measures of relative and absolute reliability, respectively. Supine LnRMSSD, supine frequency domain metrics and the three absolute heart rate values demonstrated excellent ICC and low SEmeas% (≤4.0%). These were substantially better than values reported for a group of college students (male and female) for several non-transformed time domain, frequency domain and Poincare HRV metrics (ICC = 0.45–0.53; SEM% = 26–39%) [35]. However, the current outcomes showed similar reliability to 3-day LnRMSSD from the Brazilian Rugby team during a national team camp (ICC = 0.90, SEmeas% = 7.65%) [36] and highlights that elite male team-sport athletes have less intra-individual variation than the general college students. A practical approach to integrate reliability outcomes and evaluate if a true change has occurred for a given individual is the reliable change index (RCI) [37]: RCI $= \frac{\Delta i}{\sqrt{2(SEmeas)^2}}$;

where Δi is the change value from one time point to the next and an outcome exceeding 1.96 indicates a true change has occurred. For example, if an athlete had a change in supine resting heart rate of 6 bpm or 4 bpm, then the RCI would be 2.58 and 1.72, respectively, indicating the threshold for identifying a true change is likely only for the delta of 6 bpm.

Breathing rate has been shown to influence HRV in some [12, 38], but not all [39], studies, where paced breathing improves HRV reliability [40]. It was not mandatory for the current athletes to follow a specific, paced breathing rate. However, the metronome provided a way for each athlete to find their own comfortable pace that could be repeated each morning. Considering good reliability was shown for time domain, frequency domain, and Poincare analysis HRV metrics in both postures it would be prudent to state that having intra-individual, day-to-day consistency in breathing rate is likely more important rather than insisting on a particular (fixed) breathing rate for everyone. Nevertheless, the slow breathing rates in the current group of players may have influenced HF [30] and is a consideration when collecting data and interpreting outcomes.

A limitation to this study is that it occurred during a pre-Olympic training camp. It is plausible the demands might have been different from what these athletes normally experienced and resulted in atypical HRV outcomes. However, the current participants were highly fit (YoYo IRT1 ~2600 m) and accustomed to the types of training/competition loads experienced during this event. Indeed, the average daily total and high-intensity running distances in the current training camp (~10 km and ~1.5 km, respectively) were slightly elevated compared to a daily single-session (~9.8 km and ~1.0 km) but substantially lower than a daily double-session (~17 km and ~2.0 km) within the centralized daily training environment. Moreover, despite weekly total and high-intensity running distances being markedly greater (2.25–2.50x and 2.50–3.0x, respectively) for two consecutive weeks, there were no changes reported for mean (~4.4) or CV% (~5–7%) LnRMSSD in a group of elite male rugby sevens players during a pre-Olympic training camp [29]. Finally, the current group of players had heart rate and HRV values similar to 'non-fatigued' athletes [16, 21]. Taken together, it is unlikely the outcomes were impacted by athletes being 'fatigued/overtrained'; nevertheless, it is prudent that these data be applied to similar contexts.

These outcomes indicate that most log-transformed HRV indices and non-transformed heart rate values from an orthostatic challenge provide outcomes with low intra-individual variation and excellent relative reliability. Since no improvements in variability or reliability were observed for 3–6 min, a seven-min orthostatic protocol could be used (1 min stabilization+3 min supine+3 min stand) if desired. The SEmeas, in conjunction with the RCI could be used to determine if a true change has occurred for an individual athlete using HRV metrics in supine and standing positions (regardless if the test is performed using an orthostatic protocol or a single posture). For practitioners that want to include a greater dimensional analysis of HRV, the current findings demonstrate similar variation between time and frequency domain characteristics with slightly higher variation for Poincare derived metrics.

Acknowledgments Thanks to the athletes for participating and the coaches for their support.

Funding information This study was funded by the Research Program in Applied Sport Sciences from the Ministry of Tourism, Culture and Sport (Ontario, Canada).

Compliance with ethical standards

Conflict of interest Author JDV declares that he has no conflict of interest.

Ethical approval 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.

References

1. Le Meur, Y., Pichon, A., Schaal, K., Schmitt, L., Louis, J., Gueneron, J., Vidal, P. P., and Hausswirth, C., Evidence of parasympathetic hyperactivity in functionally overreached athletes. *Med. Sci. Sports Exerc.* 45(11):2061–2071, 2013. https://doi.org/10.1249/MSS.0b013e3182980125.
2. Schmitt, L., Regnard, J., Parmentier, A. L., Mauny, F., Mourot, L., Coulmy, N., and Millet, G. P., Typology of "fatigue" by heart rate variability analysis in elite Nordic-skiers. *Int. J. Sports Med.* 36(12):999–1007, 2015. https://doi.org/10.1055/s-0035-1548885.
3. Wright, A., Hannon, J., Hegedus, E. J., and Kavchak, A. E., Clinimetrics corner: A closer look at the minimal clinically important difference (MCID). *J. Man Manip. Ther.* 20(3):160–166, 2012. https://doi.org/10.1179/2042618612Y.0000000001.
4. Schafer, D., Gjerdalen, G. F., Solberg, E. E., Khokhlova, M., Badtieva, V., Herzig, D., Trachsel, L. D., Noack, P., Karavirta, L., Eser, P. et al., Sex differences in heart rate variability: A longitudinal study in international elite cross-country skiers. *Eur. J. Appl. Physiol.* 115(10):2107–2114, 2015. https://doi.org/10.1007/s00421-015-3190-0.
5. Plews, D. J., Laursen, P. B., and Buchheit, M., Day-to-day heart rate variability (HRV) recordings in world champion rowers: Appreciating unique athlete characteristics. *Int. J. Sports Physiol. Perf.*:1–19, 2016.
6. Cipryan, L., Within-session stability of short-term heart rate variability measurement. *J. Hum. Kinet.* 50:85–92, 2016. https://doi.org/10.1515/hukin-2015-0146.
7. Farah, B. Q., Lima, A. H., Cavalcante, B. R., de Oliveira, L. M., Brito, A. L., de Barros, M. V., and Ritti-Dias, R. M., Intra-individuals and inter- and intra-observer reliability of short-term

heart rate variability in adolescents. *Clin. Physiol. Funct. Imaging* 36(1):33–39, 2016. https://doi.org/10.1111/cpf.12190.
8. Armstrong, R. G., Kenny, G. P., Green, G., and Seely, A. J., Diurnal variation in heart rate variability before and after maximal exercise testing. *Chronobiol. Int.* 28(4):344–351, 2011. https://doi.org/10.3109/07420528.2011.559674.
9. Aubert, A. E., Beckers, F., and Ramaekers, D., Short-term heart rate variability in young athletes. *J. Cardiol.* 37(Suppl 1):85–88, 2001.
10. Abad, C., Kobal, R., Kitamura, K., Gil, S., Pereira, L., Loturco, I., and Nakamura, F., Heart rate variability in elite sprinters: Effects of gender and body position. *Clin. Physiol. Funct. Imaging* 37(4): 442–447, 2017. https://doi.org/10.1111/cpf.12331.
11. Baek, H. J., and Shin, J., Effect of missing inter-beat interval data on heart rate variability analysis using wrist-worn wearables. *J. Med. Syst.* 41:147, 2017. https://doi.org/10.1007/s10916-017-0796-2.
12. Song, H. S., and Lehrer, P. M., The effects of specific respiratory rates on heart rate and heart rate variability. *Appl. Psychophysiol. Biofeedback* 28(1):13–23, 2003.
13. Kiviniemi, A. M., Tulppo, M. P., Hautala, A. J., Vanninen, E., and Uusitalo, A. L., Altered relationship between R-R interval and R-R interval variability in endurance athletes with overtraining syndrome. *Scand. J. Med. Sci. Sports* 24(2):e77–e85, 2014. https://doi.org/10.1111/sms.12114.
14. Plews, D. J., Laursen, P. B., Kilding, A. E., and Buchheit, M., Evaluating training adaptation with heart-rate measures: A methodological comparison. *Int. J. Sports Physiol. Perf.* 8:688–691, 2013.
15. Pichot, V., Roche, F., Gaspoz, J. M., Enjolras, F., Antoniadis, A., Minini, P., Costes, F., Busso, T., Lacour, J. R., and Barthelemy, J. C., Relation between heart rate variability and training load in middle-distance runners. *Med. Sci. Sports Exerc.* 32(10):1729–1736, 2000.
16. Schmitt, L., Regnard, J., Desmarets, M., Mauny, F., Mourot, L., Fouillot, J. P., Coulmy, N., and Millet, G., Fatigue shifts and scatters heart rate variability in elite endurance athletes. *PLoS ONE* 8: e71588, 2013. https://doi.org/10.1371/journal.pone.0071588.
17. Kiviniemi, A. M., Hautala, A. J., Kinnunen, H., Nissila, J., Virtanen, P., Karjalainen, J., and Tulppo, M. P., Daily exercise prescription on the basis of HR variability among men and women. *Med. Sci. Sports Exerc.* 42(7):1355–1363, 2010.
18. Kiviniemi, A. M., Hautala, A. J., Seppanen, T., Makikallio, T. H., Huikuri, H. V., and Tulppo, M. P., 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.* 287(5):H1921–H1927, 2004. https://doi.org/10.1152/ajpheart.00433.2004.
19. Rusko, H. K., Harkonen, M., and Pakarinen, A., Overtraining effects on hormonal and autonomic regulation in young cross-country skiers. *Med. Sci. Sports Exerc.* 26:S64, 1994.
20. Vescovi, J. D., and Watson, G., Variability of body mass and urine specific gravity in elite male field hockey players during a pre-olympic training camp. *Int. J. Sport Nutr. Exerc. Metab.*:1–20, 2018. https://doi.org/10.1123/ijsnem.2018-0121.
21. Hynynen, E., Uusitalo, A., Konttinen, N., and Rusko, H., Cardiac autonomic responses to standing up and cognitive task in overtrained athletes. *Int. J. Sports Med.* 29(7):552–558, 2008. https://doi.org/10.1055/s-2007-989286.
22. Williams, D. P., Jarczok, M. N., Ellis, R. J., Hillecke, T. K., Thayer, J. F., and Koenig, J., Two-week test-retest reliability of the polar(R) RS800CX to record heart rate variability. *Clin. Physiol. Funct. Imaging.*, 2016. https://doi.org/10.1111/cpf.12321.
23. Naranjo Orellana, J., de la Cruz, T. B., Sarabia Cachadina, E., de Hoyo, M., and Dominguez Cobo, S., Two new indexes for the assessment of autonomic balance in elite soccer players. *Int. J. Sports Physiol. Perf.* 10:452–457, 2015. https://doi.org/10.1123/ijspp.2014-0235.
24. Flatt, A. A., and Esco, M. R., Heart rate variability stabilization in athletes: Towards more convenient data acquisition. Clin. Physiol. Funct. Imaging 36(5):331–336, 2016. https://doi.org/10.1111/cpf.12233.
25. Cohen, J., Statistical power analysis for the behavioral sciences. 2nd edition. Hillsdale: Erlbaum, 1988.
26. Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J., Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.* 41(1):3–13, 2009.
27. Koo, T. K., and Li, M. Y., A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J. Chiropr. Med.* 15(2):155–163, 2016. https://doi.org/10.1016/j.jcm.2016.02.012.
28. McManus, I. C., The misinterpretation of the standard error of measurement in medical education: A primer on the problems, pitfalls and peculiarities of the three different standard errors of measurement. *Med. Teach.* 34(7):569–576, 2012. https://doi.org/10.3109/0142159X.2012.670318.
29. Flatt, A. A., and Howells, D., Effects of varying training load on heart rate variability and running performance among an Olympic rugby sevens team. *J. Sci. Med. Sport* 22:222–226, 2019. https://doi.org/10.1016/j.jsams.2018.07.014.
30. Sasaki, K., and Maruyama, R., Consciously controlled breathing decreases the high-frequency component of heart rate variability by inhibiting cardiac parasympathetic nerve activity. *Tohoku J. Exp. Med.* 233:155–163, 2014.
31. Driscoll, D., and Dicicco, G., The effects of metronome breathing on the variability of autonomic activity measurements. *J. Manipulative Physiol. Ther.* 23:610–614, 2000. https://doi.org/10.1067/mmt.2000.110944.
32. Naranjo, J., De la Cruz, B., Sarabia, E., De Hoyo, M., and Dominguez-Cobo, S., Heart rate variability: A follow-up in elite soccer players throughout the season. *Int. J. Sports Med.* 36(11): 881–886, 2015. https://doi.org/10.1055/s-0035-1550047.
33. Proietti, R., di Fronso, S., Pereira, L. A., Bortoli, L., Robazza, C., Nakamura, F. Y., and Bertollo, M., Heart rate variability discriminates competitive levels in professional soccer players. *J. Strength Cond. Res.* 31(6):1719–1725, 2017. https://doi.org/10.1519/JSC.0000000000001795.
34. Rave, G., and Fortrat, J. O., Heart rate variability in the standing position reflects training adaptation in professional soccer players. *Eur. J. Appl. Physiol.* 116(8):1575–1582, 2016. https://doi.org/10.1007/s00421-016-3416-9.
35. Gisselman, A. S., D'Amico, M., and Smoliga, J. M., Optimizing inter-session reliability of heart rate variability - the effects of artefact correction and breathing type. *J. Strength Cond. Res.*, 2017. https://doi.org/10.1519/JSC.0000000000002258.
36. Nakamura, F. Y., Pereira, L. A., Esco, M. R., Flatt, A. A., Moraes, J. E., Cal Abad, C. C., and Loturco, I., Intraday and Interday reliability of ultra-short-term heart rate variability in Rugby union players. *J. Strength Cond. Res.* 31(2):548–551, 2017. https://doi.org/10.1519/JSC.0000000000001514.
37. Christensen, L., and Mendoza, J. L., A method of assessing change in a single subject: An alteration of the RC index. *Behav. Ther.* 15: 305–308, 1986.
38. Yildiz, M., and Ider, Y. Z., Model based and experimental investigation of respiratory effect on the HRV power spectrum. *Physiol. Meas.* 27:973–988, 2006. https://doi.org/10.1088/0967-3334/27/10/004.

39. Gasior, J. S., Sacha, J., Jelen, P. J., Zielinski, J., and Przybylski, J., Heart rate and respiratory rate influence on heart rate variability repeatability: Effects of the correction for the prevailing heart rate. *Frontiers in Physiology* 7:356, 2016. https://doi.org/10.3389/fphys.2016.00356.
40. Pinna, G. D., Maestri, R., Torunski, A., Danilowicz-Szymanowicz, L., Szwoch, M., La Rovere, M. T., and Raczak, G., Heart rate variability measures: A fresh look at reliability. *Clin. Sci.* 113: 131–140, 2007. https://doi.org/10.1042/CS20070055.