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The important role of time series stationarity for agreement of ultra-short-term heart rate variability in ski mountaineers: a case series

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Abstract

Study aim: The validity of ultra-short-term (≤1 min) heart rate variability (HRV) analysis in sports science remains debated. Previous studies have not established criteria for acceptable agreement or considered the role of signal stationarity. The aim of this study was to evaluate the agreement between HRV calculated based on RR intervals (RRi) from 5-minute (criterion) and shorter durations in elite athletes, with emphasis on the impact of signal stationarity.
Material and methods: Eight ski mountaineers underwent ECG recordings in a supine position. Criterion recordings were segmented into the first: 4-min, 3-min, 2-min, and 1-min intervals. HRV parameters (HR, RMSSD, RMSSD/mRR, lnRMSSD) were analyzed. Signal stationarity was assessed using the augmented Dickey-Fuller test. Agreement was evaluated using Bland-Altman analysis with the smallest worthwhile change defining acceptable differences and intraclass correlation coefficients.
Results: HR and natural logarithm of RMSSD (lnRMSSD) calculated from 4-min recordings showed clinically acceptable agreement with criterion. Three athletes exhibited non-stationary RRi in 1-min and 2-min recordings. These non-stationary recordings demonstrated higher bias in HRV parameters compared to stationary recordings. Heart rate microstructure (acceleration/deceleration patterns) remained unchanged across different recordings. Signal non-stationarity in shorter recordings may affect agreement between HRV parameters in athletes.
Conclusions: Ultra-short recordings (1-min) may not be reliable for all athletes or all HRV parameters. Individual variation in signal stationarity appears to be an important consideration. Practitioners should verify signal stationarity and define acceptable difference thresholds before adopting shortened recording protocols for HRV analysis.

Keywords: Heart rate variability – Ultra-short-term HRV – Stationarity agreement – Signal quality – Ski mountaineers

Introduction

Evaluation of cardiac autonomic nervous system modulation through analysis of heart rate (HR) and its variability (HRV) is receiving increased interest in sports science (Aubert et al., 2003, Lundstrom et al., 2023). A crucial research question is whether, and to what extent, the recording duration (time series length) can be shortened to extract information about resting cardiovascular variability, making it more convenient for athletes, while remaining in agreement with the accepted 5-min criterion. There are discrepant findings on the acceptable recording duration for calculation of time-domain root mean square of successive differences between adjacent normal RR intervals (RMSSD), or its log transformed version (lnRMSSD), from 2 min (Bourdillon et al., 2017) to 30 s (Chen et al., 2021), mostly favoring 1 min (Esco and Flatt, 2014, Pereira et al., 2016, Esco et al., 2018).

These discrepancies may have been caused by, inter alia, unreported differences in signal stationarity for 5-min and shorter recordings. Shortening time series length may

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affect stationarity, and non-stationarities significantly distort short-term HRV (Magagnin et al., 2011, Tarvainen et al., 2002). Additionally, the criteria for defining agreement between short- and ultra-short-term HRV parameters in athletes were not well defined: i) the maximum acceptable difference was not provided (Shaffer et al., 2020), and ii) authors have not reported whether it was exceeded by the limits of agreement (LoA) (Abu-Arafeh et al., 2016). Indeed, we found that despite the lack of significant differences and high intraclass correlation coefficient between 5-min and 1-min vagally mediated HRV in elite modern pentathletes, no parameter could be considered interchangeable once the LoA between them exceeded the smallest worthwhile change (Hoffmann et al., 2020).

The aim of this study was to assess, with emphasis on signal stationarity, the agreement between HRV parameters popular in sports science and properties of HR microstructure calculated based on traditional 5-min duration and shorter recordings performed at rest in athletes who practice ski mountaineering—a new Olympic winter sport (Schöffl et al., 2022, Bortolan et al., 2021).

Material and methods

A total of 11 elite, active ski mountaineering athletes licensed by the National Mountaineering Association participated in the study in the pre-season period. Results from 3 athletes were excluded due to: diagnosis of non-sinus atrial rhythm, second-degree atrioventricular blocks, and lack of stationarity for criterion 5-min RRi time series. Details on the study population and measurements were shown previously (Gąsior et al., 2024). Here, stationary-confirmed, 5-min RRi time series obtained using ECG examinations (Custo cardio 100, sampling frequency 1000 Hz; Custo med GmbH, Ottobrunn, Germany) performed under controlled conditions (supine) preceded by a 10-min stabilization period (supine), preprocessed using the coRRection software (Mikielewicz et al., 2025), were used.

Short-term (5-min) RRi time series were then segmented into shorter RRi, i.e. first: 4-min, 3-min, 2-min, and 1-min recordings. RRi series of different lengths were imported into PyBiOS (Silva et al., 2020) to calculate mean RR interval (mRR), HR, and RMSSD. The ratio between RMSSD and mRR was calculated and presented in percentages (RMSSD/mRR). Imported RRi series were not detrended using software tools. To analyze monotonic runs of accelerations (AR), decelerations (DR), and neutral runs (NR) (Piskorski & Guzik, 2011), HRAExplorer software (https://hraexplorer.com, accessed on 20.09.2024) was used.

The Kolmogorov–Smirnov test was applied to assess the normality of the data distribution. The RRi stationarity (the property where the statistical characteristics of a signal remain constant over time) was tested using the augmented Dickey-Fuller test for each athlete and for each RRi length. To estimate the effects of RRi time series length and stationarity of RRi on possible differences between HRV parameters, the repeated-measures analysis of variance (ANOVA) was conducted, with RRi length as the within-subject factor, stationarity as the between-subject factor, and Bonferroni correction applied for post hoc comparisons. Agreement between parameters calculated based on reference 5-min and shorter time periods was verified using a Bland-Altman plot with limits of agreement (LoA) (Abu-Arafeh et al., 2016). An agreement sufficient for the interchangeable use of two methods is suggested when the lower 95% confidence interval value from the intraclass correlation coefficient (ICC) exceeds 0.75 (Lee et al., 1989). The smallest worthwhile change (SWC) was calculated by multiplying the between-subject HRV standard deviation values by 0.2 and used to define the maximum allowed difference (MAD) between methods (Buchheit, 2018). Two methods were considered in agreement if the LoA did not exceed the SWC. Statistical analyses were performed using PQStat Software (v.1.8.4.138, Poznan, Poland). The graphics were prepared with the same software and using R version 4.4.1. The significance level for all tests was set at 0.05.

The study was approved by the Ethics Committee of the Higher School of Rehabilitation in Warsaw (Poland) (No. 103/2021, 20.02.2021) and followed the rules and principles of the Helsinki Declaration. All athletes provided written informed consent prior to data collection.

Results

Five-min stationary-confirmed RRi time series of 8 elite ski mountaineers (5 females, 3 males, 25 ± 8 years, 63 ± 11 kg, 171 ± 11 cm, 21 ± 2 kg/m^2 and career duration of 6 ± 4 years) were included in the statistical analysis. Visualization of RRi time series with stationarity assessment for rest condition is presented in supplementary materials in our previously published article. These materials allow one to identify which athletes had stationary 5-min RRi time series and analyze shorter segments visually (Gąsior et al., 2024). Lack of stationarity of the RRi data series of shorter duration was observed as follows: for the first 4 min in one athlete (#9 p = 0.116), for the first 3 min in one athlete (#9 p = 0.098), for the first 2 min in three athletes (#3 p = 0.448, #4 p = 0.101 and #5 p = 0.098), and for the first 1 min in three athletes (#3 p = 0.256, #4 p = 0.089, #5 p = 0.075). The same three athletes presented non-stationarity in the first 1-min and 2-min RRi segments. Therefore, ANOVA was performed twice with the between-subject factor "stationarity" (with 2 groups: a) athletes with stationary 5-min RRi and stationary first 1-min and 2-min RRi, and b) athletes with stationary 5-min RRi and non-stationary first 1-min and 2-min RRi) and with the within-subject factor RRi length with: i) five levels (5-min vs 4-min vs 3-min vs 2-min vs 1-min), and ii) four levels (5-min vs 4-min vs 3-min vs 2-min).

Table 1 presents the results of agreement statistics between HRV parameters calculated based on 5-min RRi length and shorter segments for the whole group.

Table 1. Results of agreement statistics between HRV parameters calculated based on RRi length criterion (5-min) and shorter segments

	Heart rate [bpm]	RMSSD [ms]	RMSSD/mRR [%]	lnRMSSD
5-min	63.9 ± 5.8	68 ± 43	7.0 ± 3.8	4.06 ± 0.60
SWC	1.2	8.7	0.8	0.12
4-min	64.1 ± 5.7	66 ± 39	6.9 ± 3.5	4.05 ± 0.56
Bias (LoA)	-0.2 (−0.9 – 0.4)	2 (−7 – 11)	0.1 (−0.7 – 0.9)	0.01 (−0.10 – 0.11)
ICC low. 95% CI	0.98	0.97	0.97	0.98
LoA<SWC	Yes	No	No	Yes
3-min	64.2 ± 5.6	66 ± 38	6.9 ± 3.4	4.07 ± 0.53
Bias (LoA)	-0.4 (−1.7 – 0.9)	2 (−10 – 14)	0.1 (−0.9 – 1.2)	0.01 (−0.18 – 0.17)
ICC low. 95% CI	0.96	0.95	0.95	0.95
LoA<SWC	No	No	No	No
2-min	64.4 ± 5.8	66 ± 37	6.8 ± 3.1	4.06 ± 0.52
Bias (LoA)	-0.6 (−1.3 – 0.1)	2 (−11 – 16)	0.3 (−1.3 – 1.8)	0.00 (−0.18 – 0.18)
ICC low. 95% CI	0.64	0.94	0.89	0.94
LoA<SWC	No	No	No	No
1-min	63.8 ± 6.2	63 ± 35	6.6 ± 3.1	4.02 ± 0.52
Bias (LoA)	0.1 (−1.8 – 1.9)	5 (−12 – 23)	0.5 (−1.1 – 2.0)	0.04 (−0.14 – 0.22)
ICC low. 95% CI	0.95	0.84	0.85	0.93
LoA<SWC	No	No	No	No
p (RRi length) 4 levels	0.023	0.097	0.099	0.906
p (RRi length) 5 levels	0.005	0.014	0.029	0.198

RMSSD – root mean square of successive R-R interval differences; mRR – mean RR interval; ln – log-transformed; SWC – smallest worthwhile change; LoA – limits of agreement; ICC – intraclass correlation coefficient; CI – confidence interval; RRi – RR intervals

A significant main effect of RRi length factor with 5 levels was observed for HR (F = 4.9, p = 0.005, post-hoc: first 1-min vs 2-min, p = 0.043), RMSSD (F = 3.9, p = 0.035, post-hoc: first 1-min vs 5-min, p=0.035) and RMSSD/mRR (F = 3.2, p = 0.029, nonsignificant post hoc analysis) whereas with 4 levels significance was observed only for HR (F = 4.0, p = 0.023, 2-min vs 5-min, p = 0.022). There was no significant main effect of RRi length factor for lnRMSSD. A significant main effect of stationarity was observed for RMSSD (F = 8.1, p = 0.029), RMSSD/mRR (F = 9.4, p = 0.022) and lnRMSSD (F = 7.6, p = 0.033). Athletes with non-stationary first 1-min and 2-min of RRi time series presented higher values of the mentioned parameters (Figure 1).

Figure 1 shows results of interactions between RRi length and stationarity for HRV parameters. Significant interactions with the 5-level RRi length factor (from 5-min to 1-min) were observed for HR, RMSSD, and RMSSD/mRR (F = 7.3, 2.9, 3.3, respectively) and with the 4-level RRi length factor (from 5-min to 2-min) for RMSSD and RMSSD/mRR (F = 4.4, 5.1, respectively). Significant differences between parameters calculated based on RRi with different lengths were observed for those with non-stationary first 1-min or non-stationary 2-min. There was no significant interaction for lnRMSSD.

The bias between HRV parameters increased as the time segment became shorter. LoA do not exceed the SWC for the whole group for HR and lnRMSSD calculated based on 4-min RRi (Table 1).

The Bland–Altman plots with bias and LoA for the whole group and separately for athletes with stationary and non-stationary first 1-min or 2-min RRi are presented in Figures 2 and 3, respectively. Bias was nominally lower in all parameters for athletes with stationary 5-min RRi and stationary first 1-min or 2-min RRi.

Table 2 presents the percentages of AR, DR, NR, and DR/AR in different RRi length series. There were no significant changes in the percentage of mentioned runs between RRi series of different lengths.

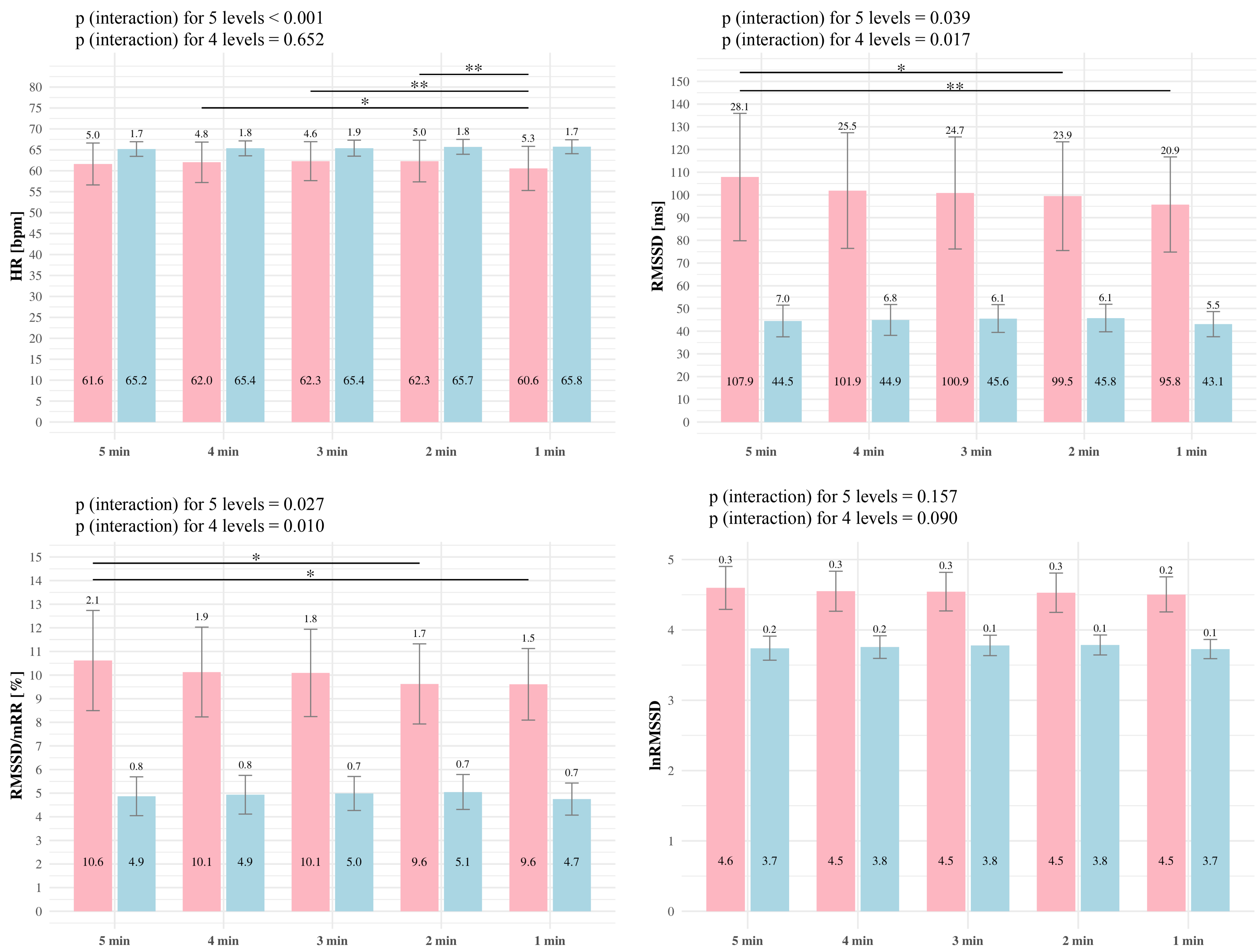

Figure 1. Comparison of mean ± SE for mean HR, RMSSD, RMSSD/mRR, and lnRMSSD parameters for 5-min, 4-min, 3-min, 2-min, and 1-min RR intervals between non-stationary (red bars) and stationary (blue bars) recordings; SE = SD/sqrt(N)

Table 2. Results for percentages of AR, DR, NR, and DR/AR ratio calculated based on different RRi lengths

	DR1%	DR2%	DR3%	AR1%	AR2%	AR3%	NR1%	DR/AR
5-min	11 ± 8	16 ± 10	14 ± 12	8 ± 4	16 ± 10	12 ± 6	2 ± 2	0.99 ± 0.02
4-min	11 ± 7	17 ± 10	15 ± 12	8 ± 3	16 ± 10	12 ± 6	2 ± 2	0.99 ± 0.02
3-min	10 ± 6	16 ± 10	15 ± 12	8 ± 4	15 ± 11	12 ± 6	2 ±2	0.99 ± 0.02
2-min	11 ± 7	17 ± 11	14 ± 10	8 ± 4	14 ± 10	14 ± 7	2 ± 3	1.00 ± 0.04
1-min	12 ± 7	17 ± 10	13 ± 11	9 ± 6	17 ± 9	12 ± 4	2 ± 3	0.97 ± 0.05
p (RRi length)	0.748	0.908	0.370	0.695	0.370	0.386	0.966	0.134
p (interaction)	0.980	0.438	0.764	0.504	0.555	0.581	0.256	0.494

DR – decelerations runs; AR – accelerations runs; NR – neutral runs; RRi – RR intervals

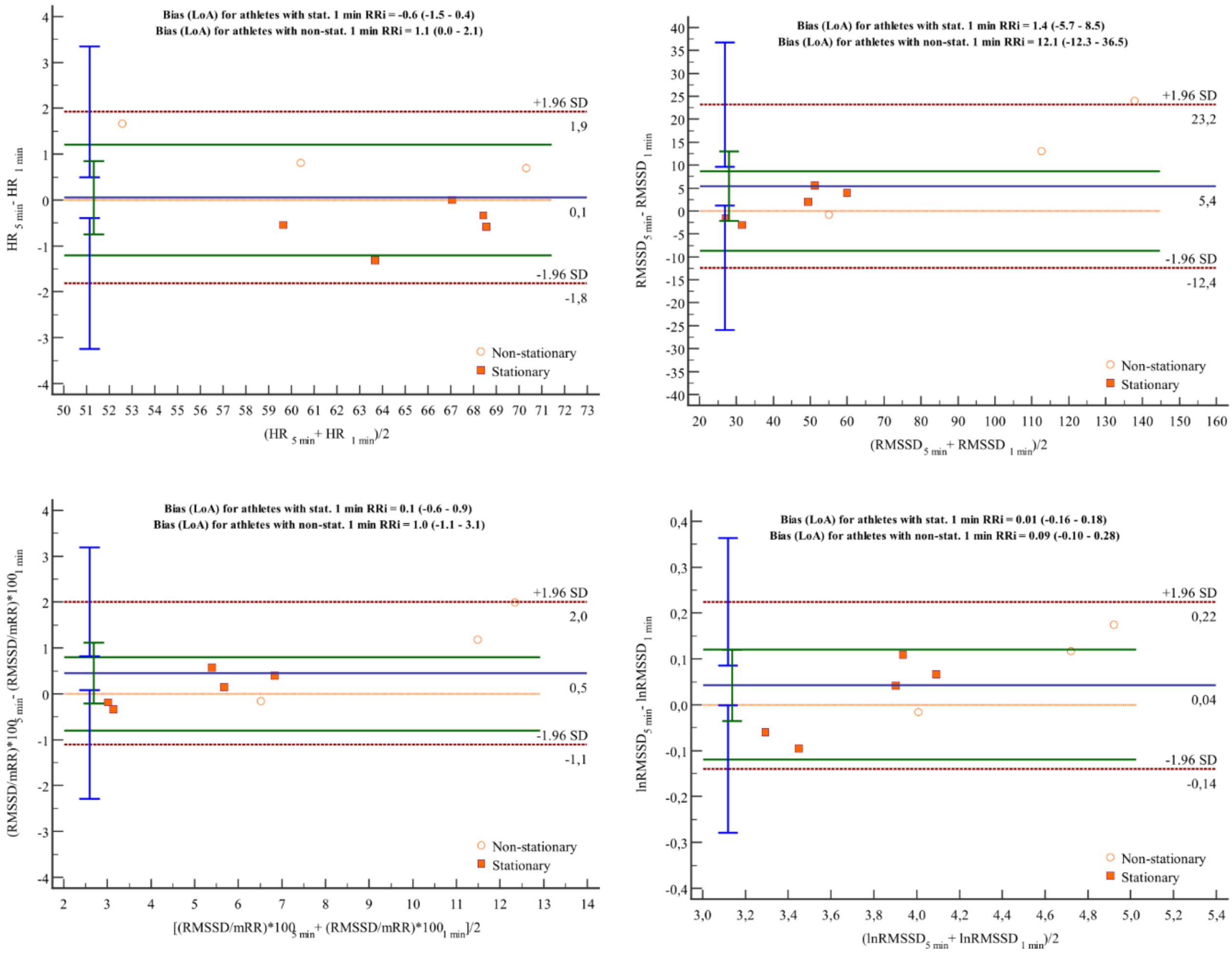

Figure 2. Bland–Altman plots for short-term (5-min) and ultra-short-term (1-min) parameters calculated for athletes who presented stationary or non-stationary RRi from the first 1 min of recordings. The blue whiskers indicate the confidence intervals for the LoA, while the green whisker denote the confidence intervals for the LoA. The green lines represent the SWC

Discussion

The agreement between HRV parameters commonly used in sports science, calculated based on the short-term criterion duration and ultra-short-term first minute of recordings performed at rest in a supine position in ski mountaineers was statistically sufficient, but clinically unacceptable, as all analyzed parameters calculated based on the first minute showed LoA with 5-min criterion parameters that exceeded the defined a priori MAD. Only HR

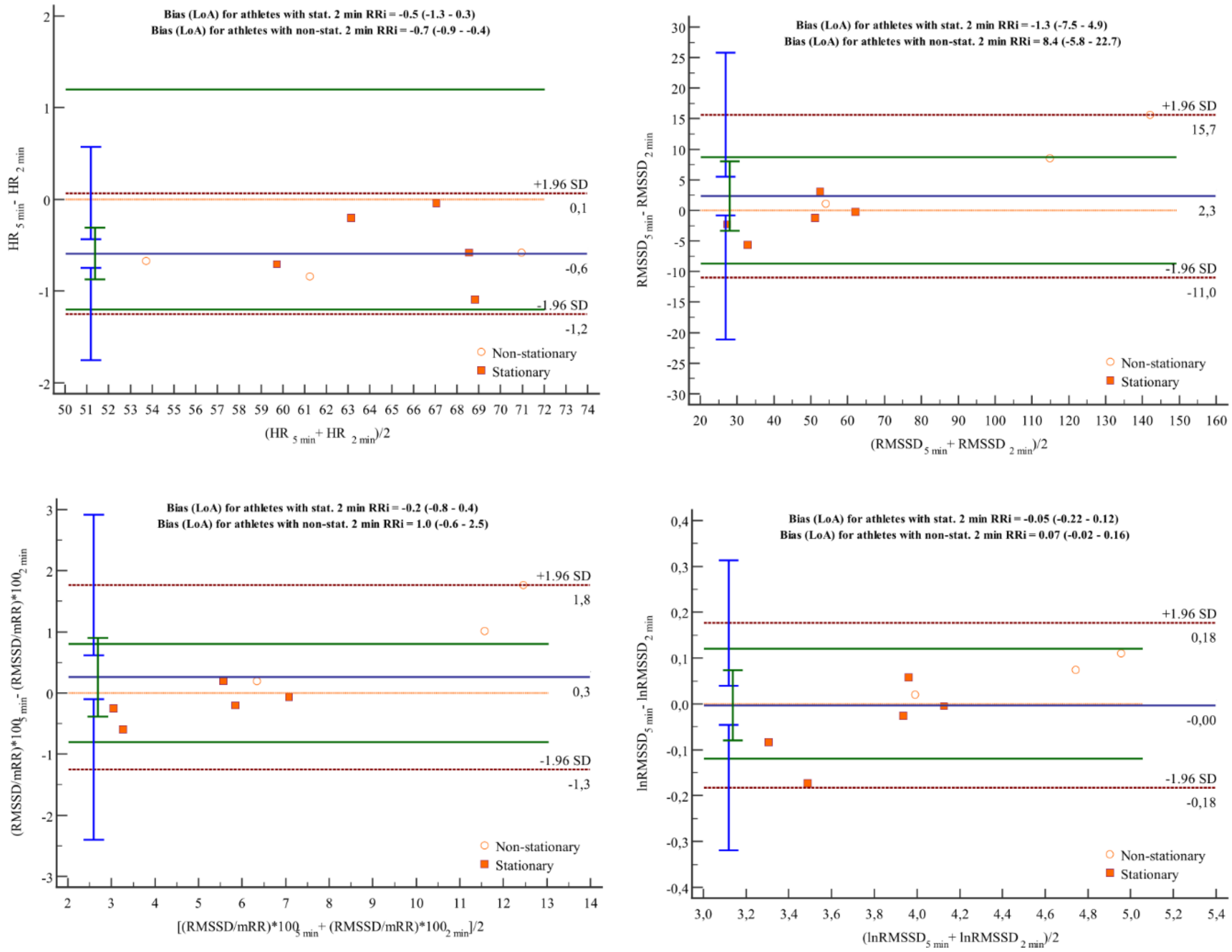

Figure 3. Bland–Altman plots for short-term (5-min) and ultra-short-term (2-min) parameters calculated for athletes who presented stationary or non-stationary RRi from the first 2 min of recordings. The blue whiskers indicate the confidence intervals for the LoA, while the green whiskers denote the confidence intervals for the LoA. The green lines represent the SWC

and lnRMSSD calculated based on 4-min RRi time series presented a satisfactory, clinically acceptable agreement with the parameters derived from the 5-min recordings. Shortening RRi time series length to the first 1 min or first 2 min was associated with a lack of signal stationarity for 3 out of 8 athletes. Bias between HRV derived from the short-term criterion and ultra-short-term recordings was nominally higher for athletes with non-stationary first 1-min or 2-min RRi.

Authors of previous studies revealed that the 1-min RMSSD or lnRMSSD displays strong agreement with those derived from 5-min recordings in athletes (Chen et al., 2021, Esco and Flatt, 2014, Pereira et al., 2016, Esco et al., 2018). The coefficient of variation of lnRMSSD required at least 2-min recordings after a 5-min stabilization period to provide valid HRV measures in futsal players (Chen et al., 2020). A 2-min recording duration in the supine position is acceptable for RMSSD, while a time series length of 1 min led to deteriorated HRV results. The authors suggested that 1 min is sufficient to obtain a steady signal prior to the appropriate analysis (Bourdillon et al., 2017). Chen et al. (2021) reported that the 1-min lnRMSSD from post-stabilization periods presented an acceptable agreement with morning resting 5-min lnRMSSD but also that the stabilization process seems to be unnecessary in futsal players during camps. Nevertheless, in the mentioned studies, the MAD between parameters calculated based on criterion and shorter RRi time series and analysis of whether the MAD was exceeded by the LoA were not provided. Thus, an important key item for reporting agreement analysis was missing (Abu-Arafeh et al., 2016). Consequently, the criteria for defining practically acceptable agreement between ultra-short-term and criterion HRV parameters in athletes were not well defined. Calculation of MAD or the smallest worthwhile change as a fraction of the standard deviation (most commonly from 0.2 to 0.5) is common, but the choice of standard deviation (within-athlete versus between-individual) should be context-specific (Lindberg et al., 2022, Bonetti & Hopkins, 2010). In the presented study, the MAD was calculated using the method/formula suggested by Buchheit for physiological data in athletes (Buchheit, 2018). The Bland-Altman method calculates mean bias and 95% LoA (expecting these limits to include 95% of differences between measurement methods), providing an appropriate approach to determine whether one measurement technique can substitute for another (Myles & Cui, 2007). Proper validation of new measurement methods for medical practice requires comparison with gold standard techniques using appropriate statistical approaches rather than relying solely on correlation analysis (Ranganathan et al., 2017). We demonstrated, using the Bland-Altman analysis with MAD determined *a priori*, that only HR and lnRMSSD from the first 5-min and 4-min recordings performed in rest conditions can be considered interchangeable, at least in elite ski mountaineers.

Discrepancies in reported acceptable ultra-short-term recording durations may result from a lack of information on signal stationarity in both the 5-min criterion and shorter recordings. Non-stationarities significantly distort short-term HRV (Magagnin et al., 2011, Tarvainen et al., 2002). Non-stationarity could be removed using, e.g., detrending methods, but such procedures affect measures of variability and complexity (Berry et al., 2020). Detrending algorithms (e.g. smoothness priors approach, polynomial fitting, or wavelet-based methods) are commonly used to reduce the influence of aperiodic non-stationary components in RRi data. However, they may introduce spurious complexity patterns that do not reflect true cardiac autonomic function, potentially leading to different clinical interpretations of the same physiological data (Tarvainen et al., 2002). Routine application of stationarity assessment of cardiac time series was underlined in the early 1990s (Weber et al., 1992). Non-stationarity of RRi time series during non-steady-state conditions, such as exercise or recovery (Berry et al., 2021), as well as stationarity during controlled conditions such as supine rest, may be expected. In our opinion, stationarity of RRi time series recorded commonly daily by athletes in the morning during controlled, repeated conditions (Schneider et al., 2018, Iizuka et al., 2020) should be routinely verified to distinguish intended (due to, e.g., fatigue) from unintended (measurement error) changes in HRV. In the present study, for example, athlete #3 presented a difference between 5-min RMSSD derived from stationary RRi and first-minute RMSSD calculated based on non-stationary RRi of 24 ms with, importantly, stable and non-altered respiratory rate. In contrast, differences between short-term and ultrashort-term RMSSD were between −3 and 6 ms in athletes with a stationary first minute of RRi time series. Importantly, the SWC for RMSSD was 9 ms.

Shortening time series length may result in a loss of information related to slower dynamics compared to criterion time series length (Volpes et al., 2022). Changes in HR microstructure, i.e., percentages of AR, DR, NR, and DR/AR ratio, were not associated with recording duration and stationarity status. Therefore, it seems that shortening time series length corresponded with the stationarity deprivation, affecting regularity rather than the complexity of cardiovascular dynamics.

Several methodological constraints may limit the external validity of these findings. First, the homogeneous small sample of elite ski mountaineers represents a specific athletic population with potentially distinct cardiovascular adaptations and autonomic modulation patterns that may not be representative of broader athletic populations. Second, the examination of supine resting recordings limits the applicability of the findings to field-based HRV assessments, where postural influences, environmental factors, and measurement conditions may differ. Third, given that many clinical and performance applications of HRV monitoring occur in post-exercise or orthostatic challenge contexts, the absence of these conditions in the current protocol may limit the translational relevance of the stationarity findings to real-world monitoring scenarios. Sample size is a critical determinant of stationarity time series test performance. The augmented Dickey-Fuller test and related unit root tests typically test the null hypothesis of a unit root (non-stationarity), while the Kwiatkowski-Phillips-Schmidt-Shin test and some newer tests reverse the burden of proof, testing the null hypothesis of stationarity. The augmented Dickey-Fuller, used to test for stationarity of the data in the present study, and the Kwiatkowski-Phillips-Schmidt-Shin test – the most popular tests – are unreliable in small samples (Schlitzer, 1995). It may be worthwhile exploring the use of other alternative tests (e.g., wavelet-based) that showed improved power or size properties in specific contexts (Rhif et al., 2019) in the future.

Without defining the a priori maximum allowed difference and verification of signal stationarity, caution is required before considering HR, RMSSD, RMSSD/mRR, and lnRMSSD calculated based on ultra-short (1-min) recordings as interchangeable with these parameters calculated based on a short-term (5-min) period. Verification of the tendency of shorter segments of RRi time series toward non-stationarity during controlled conditions, along with assessing the smallest worthwhile change in HRV parameters, may help practitioners diagnose fatigue, non-functional overreaching, or overtraining states.

Conflict of interest: Author state no conflict of interest

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