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IMAGE & SIGNAL PROCESSING

A New Algorithm to Reduce and Individualize HRV Recording Time

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Abstract

The aim of the present work was to propose a Smartphone algorithm to analyze, in real time, the evolution of Heart Rate Variability (HRV) in order to individualize and reduce the recording time according to the specificities of each user. During HRV recording, a new RMSSD value is calculated each time a new RR is captured. The recording process stops once an acceptable stability of HRV is reached. This new method was tested on 3 groups of 15 subjects (cardiac patients, sedentary employees and national-level athletes) and compared with the gold standard method (5 min HRV recording time). The RMSSD indices provided by the short method and by the gold standard method (respectively 62.1 ± 43.7 ms vs. 62.7 ± 44.1 ms) showed no significant differences. In addition, a very strong correlation was observed between RMSSD values obtained by the 2 methods ($n = 45$; R = 0.998; $p < 0.001$). Routine duration of the new method was significantly shorter with a time-savings of 2 min (178 ± 51 s vs. 300 s; $p < 0.05$). This new algorithm seems to adapt perfectly to each subject, and it can detect the stability phase for HRV measurements during the recording process. Algorithm provides an adapted and personal routine duration that can evolve each day depending on parameters such as fatigue or stress level that are known to influence HRV. This solution can be easily implemented in a smartphone application and seems particularly suitable for performing daily HRV monitoring in field conditions.

Keywords HRV · Smartphone application · Optimization · Individualization · Recording time · Monitoring

Introduction

The study of heart rate variability (HRV) has appeared in the scientific literature since the early 1980s [1, 2]. Initially focused on the medical field with cardiovascular diseases, HRV currently spans a wide spectrum ranging from high-level sport with overtraining prevention to psychology with burnout detection [3, 4]. HRV offers a noninvasive indicator of autonomic nervous system activity [5]. The responsiveness of HRV to stimulus like disease, aerobic training or mental workload is individual [6]. Therefore, recent work has highlighted the relevance of performing HRV monitoring during long-term follow-up [7–9].

As a consequence, specific methodology adapted to HRV monitoring has been discussed in the literature. For instance, pre/post or sporadic measures have been replaced by a minimum of 3 valid measurements per week [10]. Due to the relative noise of HRV recordings, several authors even suggest performing daily recordings to gain a true representation of an individual's physiological state [11, 12]. Considering the onerousness of protocol, several aspects can converge to simplify daily measurement implementation. First of all, some smartphone applications have been developed and scientifically validated to perform HRV monitoring at home or in the field [13–15].

Another way to simplify the implementation of a daily HRV follow-up is to reduce the recording time [16–18]. Traditional HRV methodology requires lengthy recording time periods of 10-min divided into a 5-min stability period followed by a 5-min HRV recording period for collecting an appropriate number of R-R intervals for spectral decomposition [2, 17]. This duration is justified by the fact that HRV

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recording should last for at least 10 times the wavelength of the lower frequency bound of the investigated component (i.e. Low Frequency boundary = 0.04 Hz ➔ wavelength duration = 25-s ➔ 10 period = 4-min 10-s) [2]. However, the frequency parameters have been demonstrated to be highly sensitive to changes in breathing rate [19]. Therefore, many studies have shown that RMSSD (Root Mean Square of the Successive Differences) is a suitable HRV index for field assessment as it is less influenced by breathing rate [3, 9, 20]. Performing HRV monitoring by focusing solely on RMSSD makes it possible to move away from the traditional methodology and reduce the recording time [18]. In this specific context, many studies have shown that a recording time of 5-min was reliable and sufficient [3, 21]. Moreover, some authors have shown that RMSSD can be accurately measured in segments of only 1 min versus 5 min [22, 23].

However, appropriate recording time may vary among subjects depending on their training status, pathology and/or stress level, and the influence of recording duration on the measurement error could change in different populations. Thus, it would be interesting to propose an individual HRV acquisition time adapted to the specificities of each person. Indeed, we think that there may be inter-individual differences in the ability to reach a plateau in heart rate parameters, in particular with heterogeneous populations like high-level athletes, heart failure patients or sedentary persons with mood disorder. In this respect, the aim of this study was to propose a smartphone algorithm to analyze, in real time, the evolution of RMSSD stability in order to optimize and reduce HRV recording time according to the specificities of the person.

Methods

Subjects

A total of 45 men were recruited divided into 3 distinct groups of 15 in order to cover the different HRV user profiles frequently presented by the literature. The first group (G-cardiac) consists of 15 patients, post myocardial infarction, who follow a guided exercise training protocol with HRV recordings during cardiac rehabilitation. The second group (G-sedentary) consists of 15 sedentary employees who perform HRV monitoring for stress follow-up. The third group (G-trained) consists of 15 national-level athletes who perform HRV monitoring for training optimization. The anthropometric characteristics of the subjects are presented in Table 1.

Protocol

Each subject was already familiar with HRV monitoring using a smartphone application. HRV Signal was recorded in the morning, on waking, in the supine position, in a quiet environment (low brightness, no sound) and with an empty stomach [3, 9]. The measurement was performed in spontaneous breathing for 5-min [20]. The data were collected using a Polar H7 chest strap (Polar electro, Oy, Finland). This system records RR intervals at a sampling frequency of 1000 Hz and provides reliable results comparable to other ECG recording systems [24]. Raw data (i.e. RR interval in ms) was transferred to a smartphone, with standard Bluetooth low energy protocol, for real-time analysis [24]. The protocol was approved by the ethical committee of France-Sud Est VI and was in accordance with the guidelines set by the Declaration of Helsinki. All the subjects gave their written informed consent.

HRV analysis

Data analyses were restricted to time domain indices and the only HRV marker used was the Root Mean Square of the Successive Differences between R-R intervals (RMSSD). RMSSD was chosen because it represents short-term HRV variability and especially vagal modulation [3]. In addition, RMSSD has been shown to be a suitable HRV index for field assessment as it is less influenced by breathing rate compared to frequency domain measures [9, 19, 20].

RMSSD was calculated with two different methods. First, we used the standard method of calculation with the entire 5-min HRV recording ($RMSSD_{5\text{-}min}$). Second, we used the new RMSSD calculation algorithm with an adjustable recording time ($RMSSD_{adjust}$).

Algorithm description

This new algorithm was implemented in a homemade Android application. It operates, live, from the beginning of the RR data recording. To ignore the disturbances caused by the installation procedure (i.e. click to start button, put the smartphone close to yourself, lie on the bed), the first 10 RR intervals are deleted. Thereafter, a routine is repeated in a loop as soon as a new RR interval is received:

– Calculate the current RMSSD value ($RMSSD_1$ with the first 2 RR values obtained, $RMSSD_2$ with the first 3 RR values obtained, … $RMSSD_i$ with the first $i + 1$ RR values obtained)
– Calculate the current coefficient of variation (CV) on a window composed of the last 20 RMSSD values obtained (the choice of window size is discussed below).
– Compare the current CV with a threshold of 0.5% (i.e. Current CV < 0.005, the choice of threshold value is discussed below).

Table 1 Anthropometric characteristics of all subjects ($n = 45$)

Group	n (sex)	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m^2)
G-cardiac Heart failure patients	15 (males)	52.3 ± 6.9	79.6 ± 12.2	174.2 ± 8.0	26.2 ± 3.2
G-sedentary Sedentary employees	15 (males)	30.3 ± 7.7[a]	75.4 ± 10.6	178.6 ± 8.0	23.6 ± 2.8[a]
G-trained National-level athletes	15 (males)	29.1 ± 6.1[a]	71.5 ± 7.8	179.1 ± 6.0	22.2 ± 1.6[a]
All subjects	45	37.2 ± 12.7	75.6 ± 10.6	177.3 ± 7.6	24.0 ± 3.1

[a] Different from G-cardiac ($p < 0.05$)

[b] Different from G-sedentary ($p < 0.05$)

– This routine stops as soon as the current CV is below the threshold.

The $RMSSD_{adjust}$ value is calculated, as soon as the loop is stopped, using all the RRs already registered. Figure 1 shows a schematic version, step by step, of the previously described algorithm.

Threshold and window size choices

CV threshold and window size values are closely linked. By design, they both influence the final results of $RMSSD_{adjust}$ with the "reliability versus time" paradox. Decreasing the CV threshold leads to reducing the measurement error of the $RMSSD_{adjust}$ compared to the $RMSSD_{5\text{-min}}$ but at the same time, this increases routine duration. Conversely, decreasing the window size leads to increasing the $RMSSD_{adjust}$ measurement error but also reduces routine duration. In order to find an optimum response to the "reliability versus time" paradox, we simulated different pairs of CV threshold and window size values with the 45 HRV recording files (32 different CV threshold values from 0.001 to 0.1 and 51 different window size values from 10 to 60 for a total of 1632 different pairs). From each of the 1632 simulated pairs, we obtained 1632 data points of routine duration values versus measurement error values that we plotted in Fig. 2.

The aim of this calculation was to determine the shortest recording time while having an acceptable average error. That is why we focused on the 10 data points just below the 5% error line with the shortest routine duration (i.e. data points circled in black on Fig. 2). These 10 data points showed an average CV threshold value of 0.0054 ± 0.0013 and an average window size value of 19.9 ± 4.2. Consequently, we chose a CV threshold value of 0.5% and a window size value of 20.

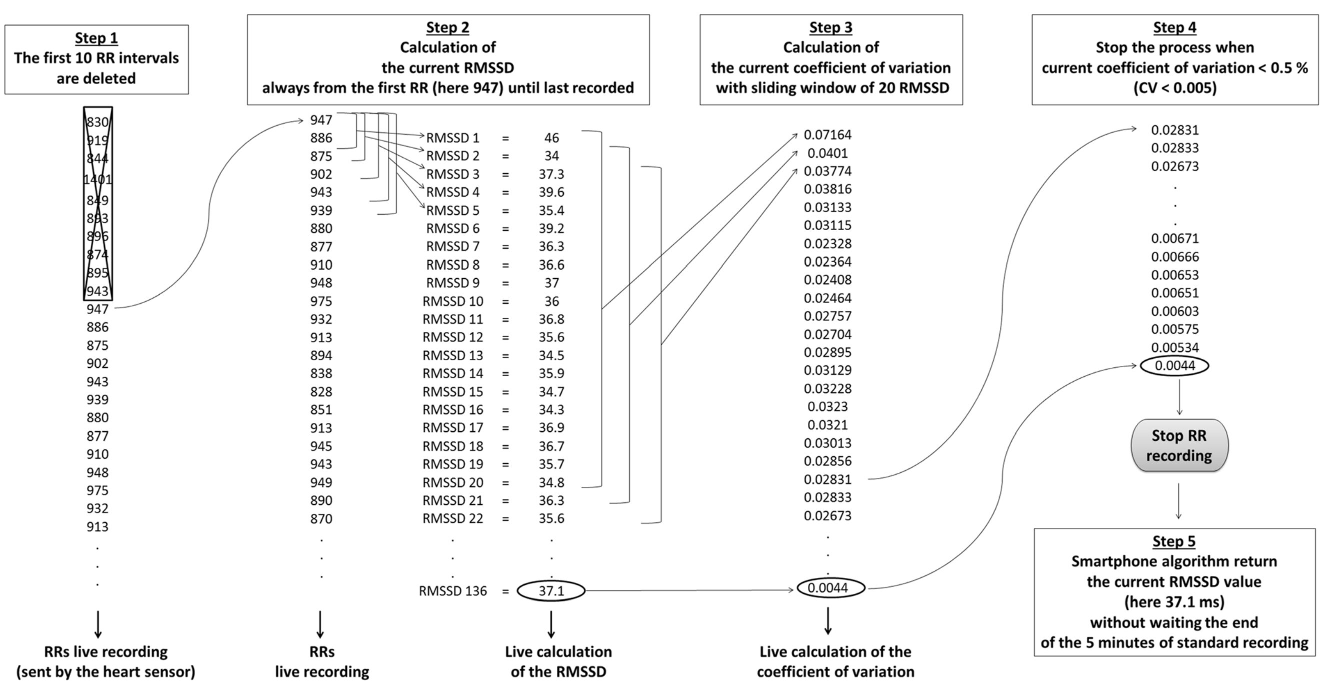

Fig. 1 Step-by-step description of the smartphone embedded algorithm used to calculate the HRV recording time

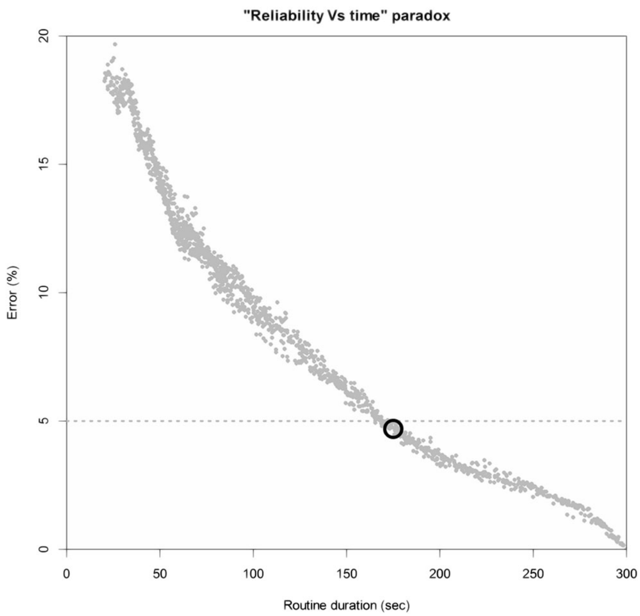

Fig. 2 Routine duration Vs. measurement error simulated with 1632 pairs of different windows size and coefficient of variation threshold

Statistical analysis

All values were expressed as means ± standard deviation. The normality of data was tested with the Shapiro–Wilk test. Data were normally distributed. Thus, a paired Student's t test was used in order to (1) examine the difference in RMSSD values found by the two methods ($RMSSD_{5\text{-}min}$ vs. $RMSSD_{adjust}$), (2) examine the difference in time duration of the two methods ($RMSSD_{5\text{-}min}$ vs. $RMSSD_{adjust}$). In addition, we performed a single factor ANOVA to (1) compare all anthropometric characteristics of each group presented in Table 1 and (2) compare all results obtained by each group presented in Table 2. If the means of the 3 groups were significantly different, we performed post hoc analysis with an unpaired Student's t test for all pairs of groups (i.e. G-cardiac vs. G-sedentary, G-cardiac vs. G-trained and G-sedentary vs. G-trained) in order to examine the difference in each group.

Pearson's correlation coefficient was used to study the relationships between the RMSSD values obtained with each method ($RMSSD_{5\text{-}min}$ vs. $RMSSD_{adjust}$). In addition, agreement between the two methods was examined by Bland and Altman plot [25]. The plot was drawn showing the mean difference between RMSSD values estimated by $RMSSD_{adjust}$ method and calculated by the reference method (i.e. $RMSSD_{5\text{-}min}$ method) against the mean of the two methods. The bias was estimated by the mean difference (M) and the standard deviation (SD). Statistically, 95% of the differences lie between M ± 1.96*SD (agreement limits). In addition, heteroscedasticity was tested. The data were analyzed using StatSoft software (Statistica 7.1, StatSoft, Inc., USA) and the statistical significance was set at $p < 0.05$.

Results

As shown in Table 2, RMSSD values provided by the 2 methods ($RMSSD_{5\text{-}min}$and$RMSSD_{adjust}$) were not significantly different for the total population and for the 3 groups tested independently. Routine duration of $RMSSD_{adjust}$ method was significantly lower than $RMSSD_{5\text{-}min}$ method for the entire population (178 ± 51 s vs. 300 s; $p < 0.05$) and for the 3 groups tested independently (respectively 185 ± 49 s; 153 ± 47 s and197 ± 49 s for G-cardiac; G-sedentary and G-trained vs. 300 s; $p < 0.05$).

Recording duration (%):$RMSSD_{adjust}$ duration expressed in percent of $RMSSD_{5\text{-}min}$ duration (i.e. % of 300 s).

Two-by-two group comparisons showed that RMSSD values of G-trained are greater than RMSSD values of G-cardiac and G-sedentary whatever the methods ($RMSSD_{adjust}$ and $RMSSD_{5\text{-}min}$). Conversely, there was no significant difference between each group for absolute and relative measurement errors ($RMSSD_{adjust}$ vs. $RMSSD_{5\text{-}min}$)

Table 2 $RMSSD_{adjust}$ Vs $RMSSD_{5\text{-}min}$: relative error and recording duration ($n = 45$)

Group	RMSSD 5-min (ms)	RMSSD adjust (ms)	Absolute error (ms)	Relative error (%)	Recording duration (sec)	Recording duration (%)
G-cardiac Heart failure patients	38.2 ± 9.5	38.0 ± 10.3[†]	1.6 ± 1.5	4.5 ± 4.5	185 ± 49	62 ± 16
G-sedentary Sedentary employees	45.3 ± 24.5	46.3 ± 24.7[†]	2.2 ± 1.7	5.3 ± 3.2	153 ± 47	51 ± 16
G-trained National-level athletes	102.9 ± 51.2[ab]	103.8 ± 51.4[†ab]	3.2 ± 2.4	3.5 ± 2.7	197 ± 49	66 ± 16
All subjects	62.1 ± 43.7	62.7 ± 44.1[†]	2.3 ± 2.0	4.4 ± 3.6	178 ± 51	59 ± 17

[†] No significant difference from$RMSSD_{5\text{-}min}$

[a] Different from G-cardiac ($p < 0.05$)

[b] Different from G-sedentary (p < 0.05)

and for $RMSSD_{adjust}$ recording duration expressed in seconds or in percentage of $RMSSD_{5\text{-}min}$ duration (i.e. % of 300 s).

As presented in Fig. 3, there was a very strong correlation between RMSSD values for each subject obtained by $RMSSD_{5\text{-}min}$ method and $RMSSD_{adjust}$ method ($n = 45$; $R = 0.998$; $p < 0.001$).

The Bland and Altman plots presented in Fig. 4 show that x-axis values of all groups were heterogeneously distributed and the differences (i.e. y-axisvalues) were normally distributed. The bias between $RMSSD_{5\text{-}min}$ and $RMSSD_{adjust}$ was very small: 0.59 ms. Except for three values, all of the differences between $RMSSD_{5\text{-}min}$ and $RMSSD_{adjust}$ were within the limit of agreements (M ± 1.96 SD). According to heteroscedasticity results, there was no relationship between the mean values and difference values.

Discussion

The aim of the present study was to propose a new method of individualizing HRV recording time according to the evolution of RR stability of each person. The first main finding of this work was that this new method makes it possible to obtain reliable RMSSD values similar to the values calculated with the gold standard method and to reduce the standard recording time by over 2 min. Secondly, this new method can easily be implemented in HRV smartphone applications to be used autonomously, at home, as part of regular HRV monitoring.

Currently, the $RMSSD_{5\text{-}min}$ method used in the present study to obtain baseline RMSSD values is considered as gold standard in the specific context of daily HRV monitoring [3, 21]. The range of RMSSD values found in the present study are in agreement with the literature. More precisely, RMSSD average values close to 38.2 ± 9.5 ms (G-cardiac), 45.3 ± 24.5 ms (G-sedentary) and 102.9 ± 51.2 ms (G-trained) have already been reported in other studies for patients with heart failure [26], sedentary employees [27] and athletes [20].

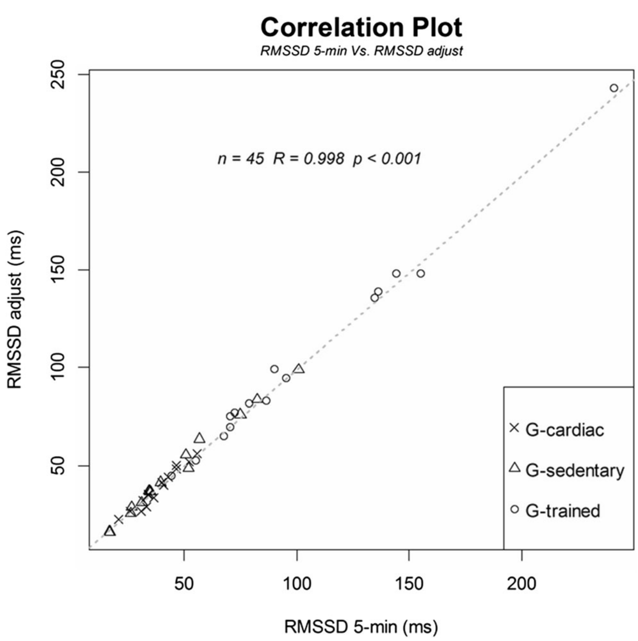

Fig. 3 Correlation plot between RMSSD 5-min Vs RMSSD adjust (n=45, R=0.998, p<0.001)

While the recording time of $RMSSD_{5\text{-}min}$ method was identical for each of the 45 subjects (300 s), the recording time of $RMSSD_{adjust}$ method was very different among the subjects with a minimum duration of 98 s, an average time of 178 s and a maximum of 287 s. It is important to note that the minimum recording time found is in line with a previous study suggesting a total recording time of 2 min composed of 1 min of HR stabilization and 1 min of actual analysis [23]. The average recording time calculated in the present study is in perfect agreement with a recent study which concluded that 3 min was the minimal window duration for accurate HRV recording [18]. Additionally, the maximum recording time is in line with the current gold standard for HRV recording (i.e. 5 min) [3, 21]. The differences between subjects in recording time could arise from the fact that the responsiveness of HRV to stimulus is individual [6]. In the same way, our results show that HRV stabilization is also individual. The new $RMSSD_{adjust}$ algorithm seems to adapt perfectly to each subject, and has a real adaptation ability to detect the initiation of the stability phase for HRV measurements during the recording process. We believe that this individualized recording time is a positive advantage, especially in the context of fatigue evaluation and training design. $RMSSD_{adjust}$ algorithm provides an adapted and personal response that can evolve each day depending on parameters such as fatigue or stress level that are known to influence HRV [2, 3, 28].

Comparatively to the $RMSSD_{5\text{-}min}$ method, the new $RMSSD_{adjust}$ algorithm leads to an absolute means error of 2.3 ± 2.0 ms (being 4.4 ± 3.6%). In addition, this new method is very strongly correlated with the gold standard method ($r = 0.998$; $p < 0.001$). Our results are in line with a recent study that finds an error of 15.69 ms and a correlation of 0.97 (i.e. $r^2 = 0.95$) between RMSSD segment of 3 min (0 to 3) and gold standard RMSSD of 5 min recorded in the supine position [18]. A measurement error of less than 5% seems quite acceptable and the Bland and Altman plot also shows that the error is randomly distributed (Bias = 0.59 ms). Therefore, this may be linked to the fact that daily errors may sometimes be positive or negative from one recording to another during a continuous individual follow up. Recent works have shown that HRV values averaged over 7 days provides superior methodological validity for assessing workload adaptation [11, 12]. In this context, we can assume that the sum of the $RMSSD_{adjust}$ errors over 7 days tends to zero and the HRV trend line obtained with this new method will be very close or similar to the HRV trend line obtained with the traditional method.

By design, we constituted 3 very heterogeneous groups of subjects in order to test the new $RMSSD_{adjust}$ method with

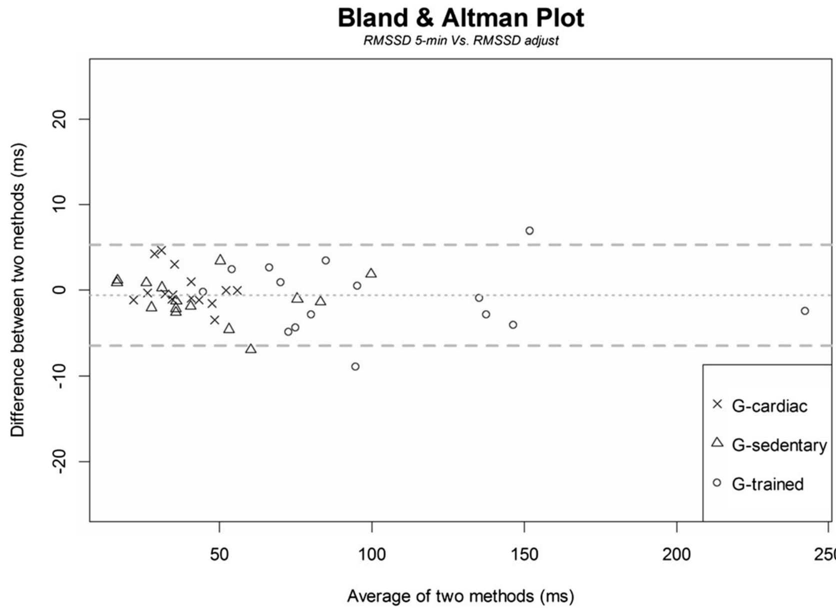

Fig. 4 Bland & Altman plot between RMSSD 5-min Vs RMSSD adjust (*n*=45)

various populations. G-cardiac was older than the other two groups and had a higher BMI. We can also assume that there were cardiovascular differences between each group. In this respect, RMSSD results obtained by both methods were in line with our previous suppositions since G-trained (athletes) showed a significant higher RMSSD level than other groups (G-cardiac and G-sedentary) [28]. Despite these multiple and diverse significant differences between the groups, there were no significant differences for the absolute error and routine duration of the new $RMSSD_{adjust}$ method. This indicates that the new $RMSSD_{adjust}$ method adapts correctly to each individual and is reliable for heart rate failure patients, sedentary employees and national-level athletes.

During this study, we had to choose two parameter values for the $RMSSD_{adjust}$ algorithm: the window size and the CV threshold. As discussed in the Methods section, these two parameters directly influence algorithm reliability and duration (i.e. absolute error and recording time). On the basis of 1632 simulations, we tested many pairs of different window sizes and CV threshold values (Fig. 2). Finally, a compromise between reliability and time led to a window size of 20 RMSSD and a CV threshold of 0.005 (0.5%). It is important to note that other window size and CV threshold values would have led to different results (shorter recording time with a greater measurement error or longer recording time with a lower measurement error). In the specific context of HRV monitoring, we believe that this is the most appropriate compromise and it has led to reliable results with a significant reduction in recording time of about 2 min (i.e. 3 min Vs 5 min). Our results and conclusions are in agreement with the literature [18]; however, in another context, it could be possible to modify these 2 parameters to better address the subject's specificities and the aim of the study.

Conclusion

The present work proposes a new algorithm to individualize and reduce HRV recording time. Based on RR stabilization analysis, it provides RMSSD results similar to the gold standard methodology with a reduced recording time adapted to each person (mean recording time of 2 min 58 s). This solution can easily be implemented in a smartphone application and seems particularly suitable for performing daily HRV monitoring in field conditions.

Compliance with ethical standards

Research involving human participants The protocol was approved by the ethical committee of France-Sud Est VI (number 2015-A01755–44). In addition, all procedures performed in studies involving human participants were in accordance with the 1964 Helsinki declaration and its later amendments.

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

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