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Validity and reliability of different smartphones applications to measure HRV during short and ultra-short measurements in elite athletes

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ABSTRACT

Background and objective: Heart rate variability (HRV) has been proposed as a useful marker that can show the performance adaptation and optimize the training process in elite athletes. The development of wearable technology permits the measurement of this marker through smartphone applications. The purpose of this study is to assess the validity and reliability of short and ultra-short HRV measurements in elite cyclists using different smartphone applications.

Method: Twenty-six professional cyclists were measured at rest in supine and in seated positions through the simultaneous use of an electrocardiogram and two different smartphone applications that implement different technologies to measure HRV: Elite HRV (with a chest strap) and Welltory (photoplethysmography). Level of significance was set at $p < 0.05$.

Results: Compared to an electrocardiogram, Elite HRV and Welltory showed no differences neither in supine nor in seated positions ($p > 0.05$) and they showed very strong to almost perfect correlation levels ($r = 0.77$ to 0.94). Furthermore, no differences were found between short (5 min) and ultra-short (1 min) length measurements. Intraclass correlation coefficient showed good to excellent reliability and the standard error of measurement remained lower than 6%.

Conclusion: Both smartphone applications can be implemented to monitor HRV using short- and ultra-short length measurements in elite endurance athletes.

1. Introduction

Heart Rate Variability (HRV), defined as the analysis of the variability of successive R-R intervals, has been established as a variable to monitor and fine-tune the training process [1] and it has been shown to be a useful marker to assess the autonomic nervous system [2], which can reflect the performance adaptation and the fatigue induced by daily stressors or physical training [3]. Regarding elite athletes, who have less room for further increases in performance and large volumes of training and competition, the monitoring process is highly relevant to optimize training adaptation and to avoid a maladaptation process such as non-functional overreaching [4]. To date, several studies have implemented the use of HRV for the monitoring and optimization of the training process [5]. For instance, a body of literature has focused on the use of HRV to perform day-to-day training changes aiming to optimize the improvement of the performance of elite athletes [6–9].

In the last years there has been a simplification of HRV data collection thanks to the new technology that has been developed and the scientific evidence that has emerged. First, it has been suggested that ultra-short recordings (≤ 1 min) offer a valid measure of time-domain HRV when compared against standard length measurement [10–12]. Second, the increase of wearable devices and smartphone applications has allowed any person to record these variables [13–15]. These reasons allow for a better compliance with daily measurements of HRV because of their easy, fast, and friendly usage.

To date, different smartphone applications have been validated against gold standard electrocardiogram to measure HRV accurately [14–17]. However, these previous validation studies were carried out with sedentary or recreationally-trained athletes. Only one study included elite endurance athletes (three subjects of

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a total sample of twenty-six participants) [15]. In this regard, endurance-trained athletes have shown a higher vagal tone than the sedentary population which may cause a parasympathetic saturation during HRV recordings [4]. Thus, it remains unknown if the currently available smartphone application technology could monitor HRV accurately in highly endurance-trained individuals.

Therefore, the purpose of this study was to evaluate the validity of short- and ultra-short HRV measures with two different smartphone applications that implement different technologies to measure HRV: Elite HRV (with a chest strap) and Welltory (photoplethysmography).

2. Method

2.1. Experimental design

Four consecutive 5 min HRV recordings were taken in two positions (supine and sitting) with three different devices at the same time: a 12-lead electrocardiogram Holter F12plus (Schiller Medizintechnik GmbH, Baar, Switzerland), a smartphone app (Elite HRV) connected via Bluetooth to a validated chest strap (Polar H10, Polar Electro Oy, Kempele, Finland) [18], and a smartphone application that performs HRV recordings using photoplethysmography (PPG) technology (Welltory, New York, USA). The smartphone was the same for all the measurements (iPhone 11, Apple Inc., USA). Before each 5 min recording, a 1 min stabilization period was carried out [19].

2.2. Subjects

Twenty-six professional road cyclists participated in this study. All of them were members of Professional-continental or Professional cycling teams and completed a standardized medical screening form. Before taking part in this study, the participants were fully informed of the objectives of the study and provided a written informed consent. The study was approved by the ethical committee of BLINDED INSTITUTION (Ref: DPS.JSM.02.18) and was conducted to conform to the recommendations of the Declaration of Helsinki.

2.3. Procedures

The Holter F12plus was chosen to register the electrocardiogram (ECG) signal. The gold standard measure for the quantification of R-R intervals is ECG, which registers each heartbeat. In this regard, the reference method for assessing R-R intervals in ambulatory conditions is an ECG Holter monitor [20,21]. Before recording the R-R intervals, the ECG electrodes were placed on the chest following the standard recommendations[19]: Six precordial electrodes were place in the standard position. To prevent signal disturbances, the two cranial limb electrodes were placed in the infraclavicular fossa on both sides. The caudal limb electrode was positioned halfway between the costal margin and the iliac crest in the left anterior axillary line while the other inferior electrode was placed on the lower abdomen ground. For the electrode placement, the skin of the participants was shaved and cleaned with alcohol rubs.

After the ECG electrode placement, the Polar H10 chest strap was fitted to the participants. Previous research has demonstrated the validity of this chest strap to measure R-R intervals [18]. Then, the chest strap was connected via Bluetooth technology to the Elite HRV application (version 5.2.1), which allows the recording and calculation of the most common HRV indexes.

The Welltory app (version 3.2.3) is a free smartphone application that allows the measurement of HRV data through PPG technology. PPG measures heart rate through the reflection of the illumination of the skin when a light-emitting diode is applied (e.g., the smartphone's camera flash) as local blood volume increases during cardiac systole, which reduces the light intensity and therefore detects the heart beats.

Before recording, a researcher placed 10 ECG electrodes, as well as the chest strap, on each subject. This researcher also instructed the participants to place the index finger of their right hand on the smartphone camera and flash for PPG measurement. The same researcher performed the recordings. The recordings were monitored on all three devices simultaneously. In the event of a recording failure in any of the devices, the recording was repeated again with the three devices simultaneously to avoid a desynchronized recording. The measurements took place in a quiet dark room with constant temperature and humidity conditions. After the recordings, raw R-R data were exported and analyzed with Kubios HRV software (version 3.2.0; Biosignal Analysis and Medical Image Group, Department of Physics, University of Kuopio, Kuopio, Finland) to obtain the HRV data [22]. The analysis and processing of the data were performed according to the standard criteria [2,23]. The files were corrected for ectopic beats and artifacts before the analysis using a medium level of artifact correction. The interpolation of the series was performed by a cubic spline interpolation method provided by the Kubios' software. A full description of the algorithm can be found elsewhere [24]. This is the recommended technique by the literature for artifact and ectopic beats corrections when examining R-R intervals [14,23]. The literature suggests to hold the 80% of normal R-R intervals for the further analysis, and for the present study, only the signals with less of a 20% of beats corrected were included in the analyses. However, previous research has shown statistical differences in low ratios of ectopic beats even after applying an interpolation method [25]. Therefore, caution must be exercised in the analysis of HRV recording in free-living conditions [26]. The first minute of the data obtained from the three measures (ECG, Elite HRV, and PPG) was then split up with the aim to compare the ultra-short length measurement against the full-length measurement of 5 min. The time-domain root mean of successive R-R interval differences (rMSSD) was chosen as the vagal index as it was the best indicator and the most practical one to use [27]. The data were transformed by taking the natural logarithm to allow for parametric statistical comparisons that assume a normal distribution (LnrMSSD). Despite we displayed the LnrMSSD data only, the data set generated during and analyzed during the current study, which includes the most common time- and frequency-domain variables, are available in the Elsevier repository, (DOI: 10.17632/d4kypz3m77.2).

2.4. Statistical analysis

Results are presented as mean ± standard deviation (SD). A Kolmogorov-Smirnov statistical test was used to confirm data normality. A one-way analysis of variance (ANOVA) was carried out using the smartphone application and the Kubios software to assess possible mean differences according to the length of the measurement (1 min vs 5 min) or according to the device used to measure HRV in the analysis. A Bonferroni posthoc test was also used to evaluate the pairwise comparison between the different measurement devices. Besides, the standardized differences or effect sizes (ES) at 95% CI between groups were expressed in Cohen's d units and interpreted as trivial (< 0.19), small (0.20–0.49), moderate (0.50–0.79), and large (> 0.80). [28] The strength of association between HRV measurements in 1 min and 5 min measurement length as well as with different devices were assessed by Pearson's correlation coefficient (r). To interpret these results, the thresholds were set as follows: trivial (< 0.09), small (0.10–.29), moderate (0.30–.49), high (0.50–.69), very high (0.70–.89), and almost perfect (> 0.90) [29]. Relative and absolute reliability among trials was assessed by the intraclass correlation coefficient (ICC) [30] and the

Table 1
Comparison of the gold-standard ECG and the Elite HRV and Welltory smartphone applications.

		Descriptive data		$F_{(1,78)}$	*p*	ES (95%CI)	r (95%CI)
Supine							
ECG	EliteHRV (k)	4.09 ± 0.64	4.12 ± 0.65	0.23	1.0	−0.06 (−0.50, 0.38)	0.87* (0.76, 0.93)
	Elite (app)		4.17 ± 0.67	0.57	1.0	−0.13 (−0.57, 0.31)	0.85* (0.74, 0.92)
	Welltory (k)		4.40 ± 0.49	2.19	0.30	−0.19 (−0.63, 0.25)	0.77* (0.61, 0.87)
	Welltory (app)		4.35 ± 0.69	1.80	0.70	−0.19 (−0.63, 0.25)	0.72* (0.53, 0.84)
Sitting							
ECG	Elite (k)	4.13 ± 0.47	4.13 ± 0.46	0.06	1.0	0.00 (−0.44, 0.44)	0.94* (0.88, 0.97)
	Elite (app)		4.15 ± 0.47	0.17	1.0	−0.04 (−0.48, 0.40)	0.93* (0.87, 0.96)
	Welltory (k)		4.32 ± 0.39	1.76	0.40	−0.44 (−0.88, 0.01)	0.92* (0.85, 0.96)
	Welltory (app)		4.38 ± 0.56	2.35	0.20	−0.48 (−0.92, 0.03)	0.86* (0.74, 0.92)

* $p < 0.01$;.
k: kubios analysed data.
app: smartphone application analysis.

Table 2
Comparison between standard 5 min and 1 min ultra-short recordings.

		1 min	5 min	$F_{(1,78)}$	p	ES (95%CI)	r (95%CI)
ECG	Supine	4.17 ± 0.60	4.09 ± 0.64	0.33	0.57	0.13 (−0.31, 0.57)	0.94* (0.89, 0.97)
	Seated	4.14 ± 0.47	4.13 ± 0.47	< 0.01	0.98	0.02 (−0.42, 0.46)	0.92* (0.85, 0.96)
Elite HRV	Supine	4.17 ± 0.69	4.12 ± 0.65	0.11	0.74	0.07 (−0.36, 0.51)	0.95* (0.90, 0.97)
	Seated	4.12 ± 0.46	4.13 ± 0.46	<0.01	0.96	−0.02 (−0.46, 0.42)	0.92* (0.85, 0.96)
Welltory	Supine	4.49 ± 0.55	4.40 ± 0.49	0.62	0.43	0.17 (−0.27, 0.61)	0.86* (0.75, 0.92)
	Seated	4.39 ± 0.41	4.32 ± 0.39	0.54	0.47	0.17 (−0.27, 0.61)	0.90* (0.82, 0.95)
$p < 0.01$							

standard error of measurement (SEM) [31], respectively. ICC values were interpreted as: excellent (> 0.90), good (0.75 to 0.90) and poor to moderate (< 0.75) [32]. SEM values lower than 10% were considered acceptable and the minimal detectable change (MDC) was calculated based on SEM values through the formula ($1.96 \times \text{SEM} \times \sqrt{2}$). To establish the agreement between the three HRV measurement devices, Bland–Altman analyses were performed for the LnrMSSD parameter[29]. This method geometrically illustrates the difference (and limits of agreement) between three measurement devices (i.e., Welltory smartphone application and Elite HRV smartphone application vs. ECG) against each method's mean[29]. All the analyses were performed using specific spreadsheets in Microsoft Excel (Microsoft, Seattle, USA) and JASP [33]. The level of statistical significance to reject the null hypotheses was set at $p < 0.05$.

3. Results

No differences were observed ($p > 0.05$) in the results of the Elite HRV and the Welltory app when they were compared to the ECG gold standard both in supine and seated positions (Table 1). In addition, ES showed trivial effects (Cohen's $d < 0.19$) in the supine position in both smartphone applications and in the seated position for Elite HRV. Welltory showed small effects for the seated position. Correlation analysis showed a very strong to almost perfect correlation of both apps against the ECG gold standard. The results from the Bland–Altman plots showed that there was no apparent bias for the agreement in none of the two measurement devices (the Welltory app and the Elite HRV app) against the gold standard method ECG under neither of the two measurement conditions (supine and sitting) (Fig. 1).

The ANOVA showed no differences between the 5 min standard measurement and the 1 min ultra-short recording. In addition, ES showed trivial effects and the correlation coefficient ranged between very strong and almost perfect (Table 2).

The reliability analysis of the consecutive HRV measurements showed ICC values that ranged between very high to almost perfect (Table 3). The SEM values, as shown in Table 3, reported values lower than the limit of 10% in all the measurements.

Table 3
Reliability of the ECG, Elite HRV and Welltory.

	Mean change	ICC (90%CI)	SEM (%)	MDC (%)
Supine				
ECG	0.05	0.95 (0.87, 0.98)	3.66	10.16
Elite (k)	0.09	0.95 (0.88, 0.98)	3.46	9.60
Elite (app)	0.13	0.94 (0.84, 0.97)	4.16	11.52
Welltory (k)	0.09	0.81 (0.56, 0.92)	5.02	13.92
Welltory (app)	0.10	0.93 (0.83, 0.97)	4.50	12.46
Sitting				
ECG	0.02	0.87 (0.68, 0.95)	3.65	10.11
Elite (k)	0.03	0.87 (0.70, 0.95)	3.72	10.33
Elite (app)	0.04	0.87 (0.70, 0.95)	3.85	10.67
Welltory (k)	0.09	0.85 (0.64, 0.94)	3.27	9.06
Welltory (app)	0.13	0.93 (0.82, 0.97)	3.77	40.46

ICC: Intraclass correlation coeficient.
SEM: Standard error of the measurement.
MDC: Minimal detectable change.
k: kubios analysed data.
app: smartphone application analysis.

4. Discussion

The purpose of this study was to test the validity and reliability of different smartphone applications to measure HRV against an ECG gold standard in highly trained cyclists. Additionally, the validity and reliability of ultra-short measurements (1 min recordings) were tested against standard 5 min recordings. The main conclusion is that both, the Elite HRV and the Welltory apps, are valid and reliable to measure time-domain LnRMSSD during short (5 min) and ultra-short (1 min) recordings in both supine and seated positions. To the best of our knowledge, this is the first study to evaluate the validity and reliability of smartphone applications in elite endurance athletes.

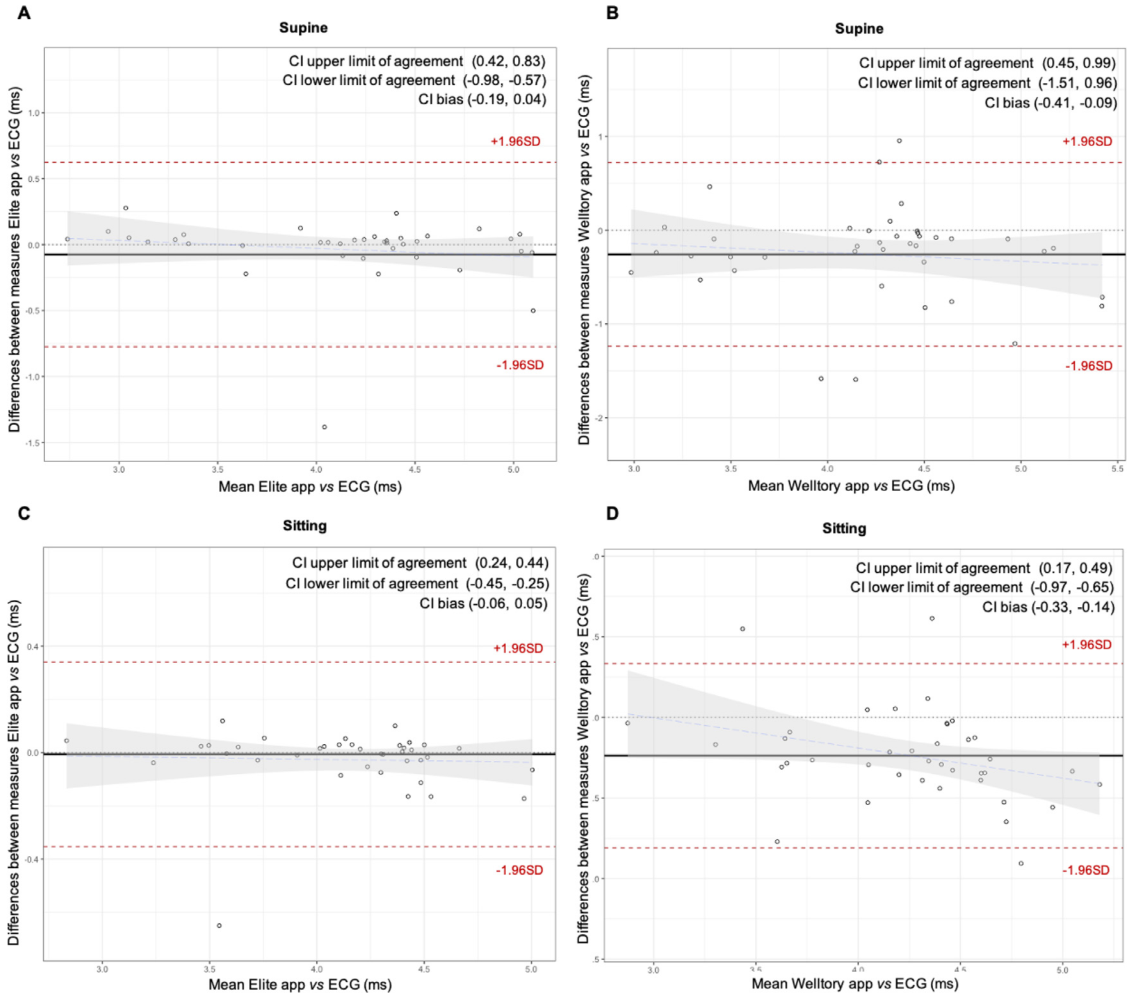

Fig. 1. Agreement (Bland-Altman plots, panels A and B supine position and C and D sitting position) between values of ECG vs Elite app and ECG vs Welltory app.

In this study, the validity of the Elite HRV and Welltory apps were analyzed by 1. comparing the HRV analysis performed by the smartphone applications against the ECG gold standard analysis, and 2. comparing the analysis performed with the Kubios software using the raw data of the different smartphone applications against the ECG gold standard analysis. The results of the present study revealed that there were no statistical differences between ECG and Elite HRV and Welltory smartphone applications in any of the analyses both in supine and in seated positions (Table 1).

Elite HRV showed trivial ES and ranged between a very strong and an almost perfect correlation in the analysis performed by the smartphone application and the analysis performed using the Kubios software (Table 1). These results confirmed previous results of another study with recreational athletes that did not find differences in rMSSD and found an almost perfect correlation against ECG. [17] Furthermore, our study was performed with participants in two different body positions (supine and seated) and previous studies suggested that for highly trained endurance athletes, the supine position can lead to a parasympathetic saturation that affects the measurement and the seated position could be more appropriate for daily assessment in this population [4]. Indeed, the seated position showed a slightly greater correlation (> 0.90) than the supine position against the gold standard in both analyses (Table 1). Therefore, this study design could be more appropriate to evaluate the validity of this smartphone application in a highly trained population and it confirms the suitability of Elite HRV to assess HRV. To note is that this study included a 1 min stabilization period before each measurement, which is reported to be the minimum measurement length to obtain a valid and reliable time-domain HRV measurement, [34] while the previous studies did not include this stabilization period.

Regarding Welltory, these results suggest that this app is valid to perform ultra-short recordings using PPG technology (Table 1). This result is relevant because, in a field setting, it could be easier to implement the use of PPG than a chest strap to register daily HRV measurements. To the best of the authors' knowledge, this is the first validated app that allows free download and usage options that does not require another device (i.e., a chest strap). The present findings seem to be consistent with a previous study in another smartphone application that implements PPG technology which found an almost perfect correlation against ECG [15]. However, the correlation coefficient was greater in the other study than in the present study and the ES showed moderate effects although there were no statistical differences (Table 1) against the ECG gold standard. This difference could be due to the fact that probably both smartphone applications implement different algorithms to detect the RR intervals and this fact could lead to some slight differences in the HRV data. Despite these differences, the Welltory app could be an appropriate option to register daily measurements HRV based on its easiness and friendly use through the camera of the smartphone instead of a conventional chest strap and could lead to greater compliance with the monitoring process. Another point in favor of the use of Welltory is that it is a free code application for Android (https://github.com/Welltory/measure-stress-hrv-android) or iOS (https://github.com/Welltory/measure-stress-heart-rate-ios) that allows the connection of third-party applications through application programming interfaces.

No significant differences were found ($p > 0.05$) between short (5 min) and ultra-short (1 min) recordings in either the supine or the seated positions (Table 2). Additionally, the ES between both measurements was trivial (Cohen's $d < 0.2$). The Pearson's moment correlation values were almost perfect in all the measurements ($r > 0.9$), except for Welltory in the supine position, which showed a very strong correlation ($r = 0.86$). Our results follow those reported previously using ECG and other smartphone applications that used PPG [15] or near-infrared spectroscopy [16] to measure HRV. Although previous articles have validated the use of the Elite HRV app, [14,17] those articles analyze the validity of 5- and 10 min recordings, while our study is the first to demonstrate the validity of ultra-short recordings with this smartphone application. Additionally, Bland–Altman plots revealed a good agreement for the magnitudes of bias and 95% LoA between the PPG finger monitor Welltory app and Elite app with Polar H10 chest strap vs. ECG (Fig. 1). The confidence intervals obtained for the bias and the limits of the agreement show that there are no differences between any of the two measurement positions (supine and sitting) for the Elite app vs ECG system.

In this study, an excellent ICC (0.95) in conjunction with an SEM lower than 10% in the supine position (Table 3) suggested the reliability of the gold standard in the supine position. This is the standard procedure to measure HRV using ECG in resting conditions. Interestingly, the results obtained from a seated position showed lower ICC values (0.87) than in supine. Although this value is deemed as good reliability, further research should focus on the proper position to assess HRV because previous research has recommended the seated position in highly-trained endurance athletes and in population with low resting heart rate due to a possible parasympathetic saturation [4].

Finally, different limitations need to be considered. First, the correction of ectopic beats and artifacts from the files was performed according to the recommendations of the previous literature [14,23]. However, the data correction method implemented by Elite HRV app and Welltory app are not known by the authors. For this reason, the authors were not able to compare the signal correction methods of each tool and it is possible that it contributed to a bias in the HRV signal analysis. Further research may explore the impact of different artifact correction methods from the different smartphone apps to ensure a proper signal analysis processing. Second, several articles have shown that the PPG sensors are able to report HRV accurately but the assumption that the pulse rate variability measured by PPG, and HRV are the same physiological marker is imprecise [35]. This is because the pulse wave needs a period of time to travel from the heart to the finger (pulse wave transit) and this time may vary during the heartbeats of the recording depending on different factors. For example, a recent study found that pulse rate variability responds to cold exposure differently to HRV in peripheral sites like the finger [36]. Despite this study did not find differences between ECG and Elite HRV (that directly measure HRV) and Welltory (that implements PPG technology), further research should explore the effect of pulse wave transit in smartphone applications and wearables when their measures are compared against ECG.

Concerning the smartphone applications, to the best of our knowledge, this is the first study to assess the reliability of Elite HRV and Welltory to measure HRV. These results showed similar levels of reliability than the ECG gold standard (Table 3) with ICC values ranging from good to excellent and all SEM values under 10% (the highest SEM value is 5.02). Thus, it seems that both smartphone applications can be implemented to register daily HRV measurements in endurance athletes using the HRV.

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Declaration of Competing Interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

CRediT authorship contribution statement

M. Moya-Ramon: Conceptualization, Data curation, Writing – original draft, Project administration. **M Mateo-March:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **I. Peña-González:** Data curation, Formal analysis, Writing – review & editing. **M. Zabala:** Conceptualization, Data curation, Writing – review & editing. **A. Javaloyes:** Writing – original draft, Writing – review & editing, Project administration, Funding acquisition.

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