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CRITERION VALIDITY AND ACCURACY OF A HEART RATE MONITOR

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ABSTRACT

Purpose. Heart rate (HR) monitors have recently started to use photoplethysmography, a technique which measures the light reflected by blood vessels and does not require the use of a chest strap. The aim of this study was to test the validity and accuracy of the Garmin® HR monitor, which measures HR at rest and during exercise utilizing the method of photoplethysmography.
Methods. The sample consisted of 28 males aged 18–32 years. Anthropometric measurements were collected and HR was concomitantly monitored with electrocardiography and with the Garmin® 735XT® device in 2 situations: at rest and during self-selected exercise. Descriptive statistics, linear regression, Bland-Altman plot, mean absolute error (MAE), and mean absolute percentage error (MAPE) were calculated for statistical analysis. Correlations between the HR measurement with electrocardiography and the Garmin® monitor at rest and during exercise were obtained ($r = 0.93$ and $r = 0.96$, respectively).
Results. The difference between Garmin® and electrocardiography HR values showed an error of –1.2 ± 3.3 bpm (rest), while the average error was positive at 0.7 ± 5.1 bpm. MAE and MAPE at rest equalled 2.2 ± 2.8 bpm and 3.3%, respectively. In addition, MAE and MAPE for exercise were 3.5 ± 3.8 bpm and 3.0%, respectively.
Conclusions. The Garmin Forerunner 735XT can be used at rest, as well as with walking and running activities of light, moderate, and vigorous intensities.
Key words: exercise, heart rate, heart rate monitor, photoplethysmography

Introduction

Heart rate (HR) has been used as an effective method of intensity control for prescribing aerobic exercises since the 1970s [1–4]. More recently, HR and the R-R interval have served as an indicator of cardiac prognosis [5], mental and physical fatigue [6, 7], fitness level [8], and the assimilation of physical training load in athletes. All these possibilities of use may qualify HR measures as essential in controlling the physical and mental state of individuals engaged in exercise programs.

There are several ways of measuring HR, from invasive to palpatory methods [2]. The method considered the gold standard to evaluate HR is the electrocardiogram (ECG) [2, 9]. However, despite being an excellent non-invasive technique of HR monitoring, the instrument is characterized by a high cost, limitations in high-intensity exercise monitoring (especially when performed outside the laboratory setting) [10], and dependence on trained individuals to interpret the results.

The first HR monitors were developed in the early 1980s in order to popularize the control of exercise intensity by permitting automated, real-time monitoring of this physiological variable [11] in different contexts. Research has shown excellent correlations ($r = 0.92 \pm 0.07$) between HR measures [12, 13] and the R-R interval [14–18], respectively obtained by monitors with pickup sensors attached on the chest and conventional ECG during rest [14–16, 18, 19] and exercise [12, 16, 17, 19].

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The emergence of smartphones and new technologies in the last decade has enabled the creation of apps and/or portable devices which can be used to measure HR and variables derived from the R-R interval [7]. Today, smartphones, wristbands, and watches, called wearable devices, use targeted blood vessel lights and measure HR [7, 20]. Photoplethysmography (PPG) is a simple, non-invasive, low-cost optical technique which can be used to make measurements on the skin surface and to detect blood volume changes in the vascular tissue bed. Its sensors can be attached to the fingers, wrists, forearms, upper arms, thighs, or legs [20–22]. Laboratory studies have demonstrated the accuracy and reliability of PPG for measuring HR in different exercise modes [23–30]. Other studies have compared different manufacturers or brands [23, 24, 27, 28, 31] and positioning the device on the wrist, arm, and chest. ECG is generally the gold standard for validity comparison, but 3 studies utilized a Polar HR monitor (M400, RS400, and RS800) as criteria comparison [27, 30, 32]. The results of the available research indicate validity classified as good to very good for rest (0.87 ± 0.14), elliptical effort (0.61 ± 0.27), walking (0.87 ± 0.09), running (0.82 ± 0.19), and cycling at light (0.73 ± 0.19) and moderate (0.62 ± 0.33) intensities. For practical purposes, the raw error ranged from 1 to 23 bpm, with an average of 7.3 ± 3.5 bpm. In addition, the validity tends to be lower at higher intensities [23–25, 28] and when utilizing distal measurement sites [23, 24].

Moreover, some authors recently highlighted the need for testing the technique and listed a number of factors which might influence HR evaluation with PPG, such as the thickness and type of skin, the type and intensity of activity performed [24, 28], speed and force of change of the segment which receives the device [23, 24], number of sensors and PPG colour available in the device, room temperature, emotional states of the subject evaluated [7, 20, 32], and use of different algorithms for obtaining HR.

The psychometric performance of HR monitoring with PPG was found to be brand- and model-dependent and these aspects need to be investigated case by case. For example, Boudreaux et al. [24] found a consistent validity of different brands of equipment, with Polar A360 ($r = 0.53$) at light intensity and Fitbit Blaze ($r = 0.12$), Fitbit Charge 2 ($r = 0.14$), Polar A360 ($r = 0.32$), Garmin Visosmart HR ($r = 0.06$), and TomTom Touch ($r = 0.38$) showing an inferior performance at moderate to vigorous intensity.

The traditional Garmin brand recently started selling a new version of its Forerunner line with the inclusion of other features (smallest size, connectivity resources, training resources, etc.), the measurement of HR with PPG with Elevated Technology®, and with the appeal of a more precise approach for sign reading and analysis in different environment contexts [33]. Considering the market share of this brand for amateur and professional training monitoring, as well as for research, associated with the non-existence of a previous validity study, the objective of this study was to verify the validity of the Garmin® 735XT® monitoring device for measuring HR at rest and during exercise.

Material and methods

Participants

This study included 28 male college students aged 18–32 years and was conducted from January to July 2017 at the Department of Physical Education, Federal University of Pernambuco (Table 1).

The sample was recruited through posters on the walls of the Department and dissemination in social networks. The inclusion criteria were age of 18–35 years and the absence of contraindications to aerobic exercises. Subjects who reported the use of any drug affecting cardiovascular responses were excluded from the study.

Experimental procedures

A quantitative and cross-correlation study was performed. Anthropometric measurements were obtained after signing the informed consent form. Body weight was measured with mechanical scales (Filizola®, Brazil) to the nearest 0.1 kg. Height was assessed with a stadiometer (Sanny®, Brazil) with an accuracy of 1 mm. The body weight and height were used to calculate the body mass index as follows: body weight (kg)/height^2 (m^2). Next, skinfold measurements (chest/pectoral, triceps, suprailiac, abdominal, and thigh) were obtained by using a skinfold calliper (Lange®, USA) with a precision of 0.5 mm and spring pressure of 10 g/cm^3. Circumferences (arm, chest, waist, abdomen, hip, thigh) were measured with a flexible metal tape measure (Sanny®, Brazil) to the nearest 0.1 cm. All anthropometric measurements followed the guidelines by the International Society for the Advancement of Kinanthropometry [34].

HR was measured with the Garmin® Forerunner 735XT® HR monitor with pulse PPG, which has built-in 'Elevate® technology,' according to the manufacturer

(Garmin, England), and by ErgoMET® ECG (HeartWare Ltda., Brazil). The Garmin® Forerunner 735XT® possesses 3 green LED (530 nm), 1 red LED (660 nm), and an infrared sensor (940 nm) to detect changes in blood flow during cardiac systole and diastole, allowing beat-by-beat HR calculation (https://www.garmin.co.in/garmin-technology/heart-rate/). In addition, according to the manufacturer, the monitor is equipped with ‘G-Sensors,’ which filter real-time fluctuations caused by arm movement during the activities, permitting the HR measurement without interferences. The ErgoMET® ECG has 10 input channels and 13 simultaneous leads (D1, D2, D3, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6, and CM5).

ECG monitoring was performed by using only a combination of 5 leads which were attached with 3M® electrodes (3M®, Brazil). The volunteer was asked to remove his shirt and to assume a standing or sitting position, after which the electrodes were placed (care was taken with the skin preparation: 70% alcohol asepsis and 360 sand-paper). The placement points for the 5 electrodes were then marked: clavicles, true last ribs, and above the manubrium of the sternum [2]. The cables of the electrodes were connected to their respective defined points. The volunteer was then asked to rest in dorsal decubitus for 10 min. HR measurements were simultaneously collected every 20 s on ECG and Garmin during this period. Therefore, we had 30 and 60 HR values per subject and device at rest and exercise, respectively.

After collecting the data during rest, the subjects were invited to walk or run for 20 min with a 0% inclination (self-selected intensity). Next, 2 evaluators registered the numbers which showed up on the screens of the 2 devices during the exercise session on the treadmill. Neither the ECG (ErgoMET® ECG) nor the Garmin® (Garmin Connect®) software has a data export function, so we had to choose to view them directly on the devices’ screens.

The total time (20 min) of execution was divided into 4 moments (5 min each) to categorize the effort intensity during the exercise on the treadmill. We then calculated the average HR for each part, and estimated the exercise intensity on the basis of the Karvonen equation given below [35]. HRmax was assumed as 220 – age [36].

$$\text{Int\%} = (HR_{\text{Load}} - HR_{\text{Rest}}) / (HR_{\text{Max}} - HR_{\text{Rest}})$$

The exercise intensity was defined in accordance with the American College of Sports Medicine guidelines [35] as light (30% to 39%), moderate (40% to < 59%), and vigorous (> 68% to 89%). All tests were performed at an average temperature of 21 ± 0.6°C and controlled humidity.

Statistical analysis

The results were analysed by using descriptive statistics (distribution, mean, standard deviation). Data normality was verified by the Kolmogorov-Smirnov test.

We applied linear regression to determine validity (r and standard error of estimation [SEE]) and Bland-Altman plots with calculation of the respective bias and 95% limit of agreement (LoA) for each exercise intensity defined as described above. A correlation coefficient > 0.90 was classified as excellent, 0.75–0.90 as good, 0.60–0.75 as moderate, and < 0.60 as weak [37].

The total average percentage error was calculated as $HR_{\text{Garmin}} - HR_{\text{ECG}}$ divided by HR_{ECG} and multiplied by 100. We used the proposal by Nelson et al. [38], which establishes a 10% threshold to classify the validity of the devices. Mean absolute error (MAE) was calculated as the average absolute distance between the Garmin measurement and the ECG. Mean absolute percentage error (MAPE) relative to ECG was calculated for each wearable device by averaging the individual absolute percentage errors. Accuracy was established on the basis of the number of occurrences in which the difference between HR_{Garmin} and HR_{ECG} was ≤ 10% [26]. All analyses were implemented at rest and during exercise (light, moderate, and vigorous). The data were analysed with the Statistica for Windows software (v. 12) and the graphs were constructed with the GraphPad Prism 7.0 for Windows software. Statistical significance at $p < 0.05$ was adopted for all analyses.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the Research Ethics Committee of the Federal University of Pernambuco (No. 1.097.611).

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

The study included 28 male college students aged 18–32 years and was performed during the months

Table 1. General sample characteristics ($n = 28$)

Variables	Mean	Min	Max	Standard deviation
Age (years)	23.41	18.00	32.00	3.43
Body weight (kg)	74.30	59.00	96.00	8.67
Height (m)	1.76	1.65	1.98	0.08
BMI (kg/m^2)	23.90	19.00	27.50	1.92
Σ skinfolds*	11.76	5.00	26.00	4.54

BMI – body mass index
* Skinfold measurements involved chest, triceps, suprailiac, abdominal, and thigh skinfolds

from January to July 2017 at the Department of Physical Education, Federal University of Pernambuco (Table 1).

Figure 1 shows the correlations between HR values obtained with the Garmin® monitor and by ECG at rest (Figure 1A) and during exercise (Figure 1B). Both methods provided excellent correlation ($r = 0.93$ and $r = 0.96$, respectively) with SEE 3.3 and 5.1 bpm, respectively, at rest and during exercise. We found similar correlation values when analysed by intensity domain (light: $r = 0.87$, $p < 0.001$, SEE = 4.4 bpm; moderate: $r = 0.81$, $p < 0.001$, SEE = 5.6 bpm; vigorous: $r = 0.72$, $p = 0.0002$, SEE = 4.7 bpm).

The Bland-Altman plot shown in Figure 2 illustrates the difference between HR values obtained with Garmin® and ECG at rest (Figure 2A) and during exercise by intensity (Figure 2B). We observed underestimation of HR at rest by –1.2 ± 3.3 bpm when the Garmin® 735XT® HR monitor was used. The average error during exercise was positive at 0.7 ± 5.1 bpm. We separately analysed light, moderate, and vigorous exercise bias and found the values of 0.2 ± 4.6 (LoA: –8.7 to 9.1), 0.9 ± 5.6 (LoA: –10.1 to 12.0), and 3.9 ± 5.0 (LoA: –5.9 to 13.7), respectively. MAE and MAPE at rest equalled 2.2 ± 2.8 bpm and 3.3%, respectively. In addition, MAE and MAPE during exercise were 3.5 ± 3.8 bpm and 3.0%, respectively.

We compared 810 pairs (ECG and Garmin 735XT) at resting condition and 1680 pairs during exercise within and including ± 5 bpm from ECG HR (Table 2) to analyse the accuracy of the devices. The accuracy with the Garmin Forerunner 735XT was 92% and 96.8% for rest and exercise, respectively.

Discussion

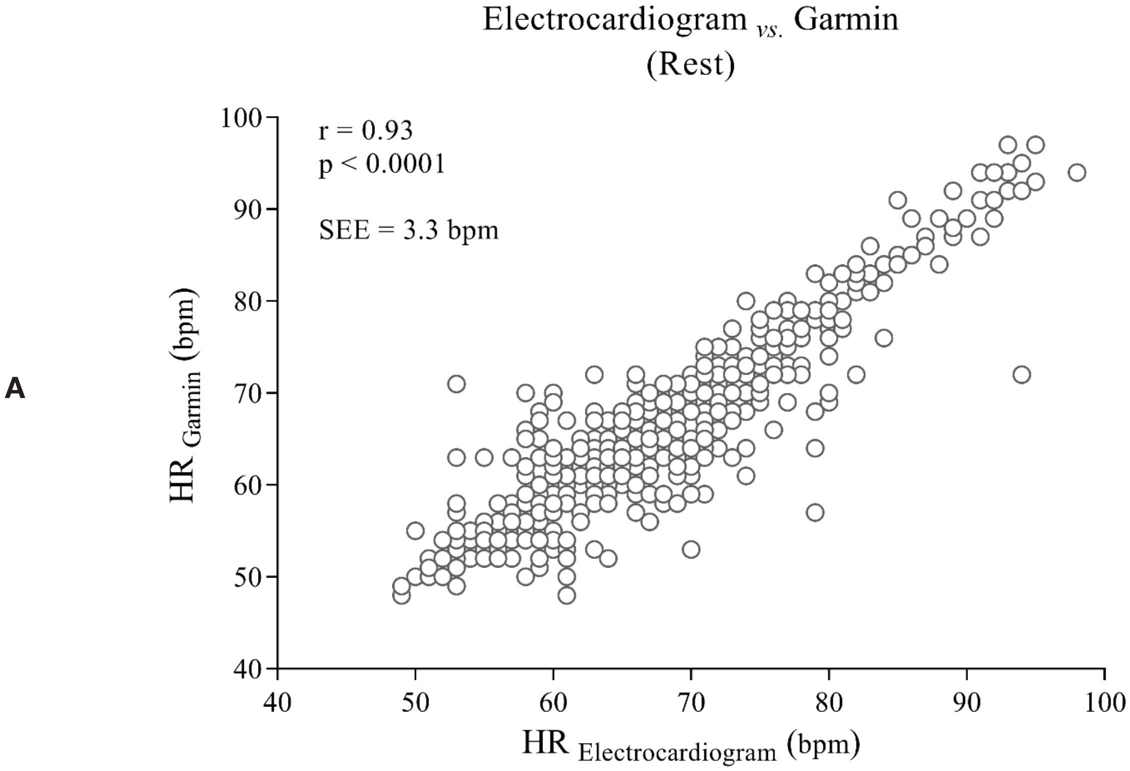
HR monitors with PPG technology have been widely used to measure HR, especially during physical exercise. The objective of this study was to test the validity and accuracy of the Garmin® 735XT® device at rest and in exercise conditions.

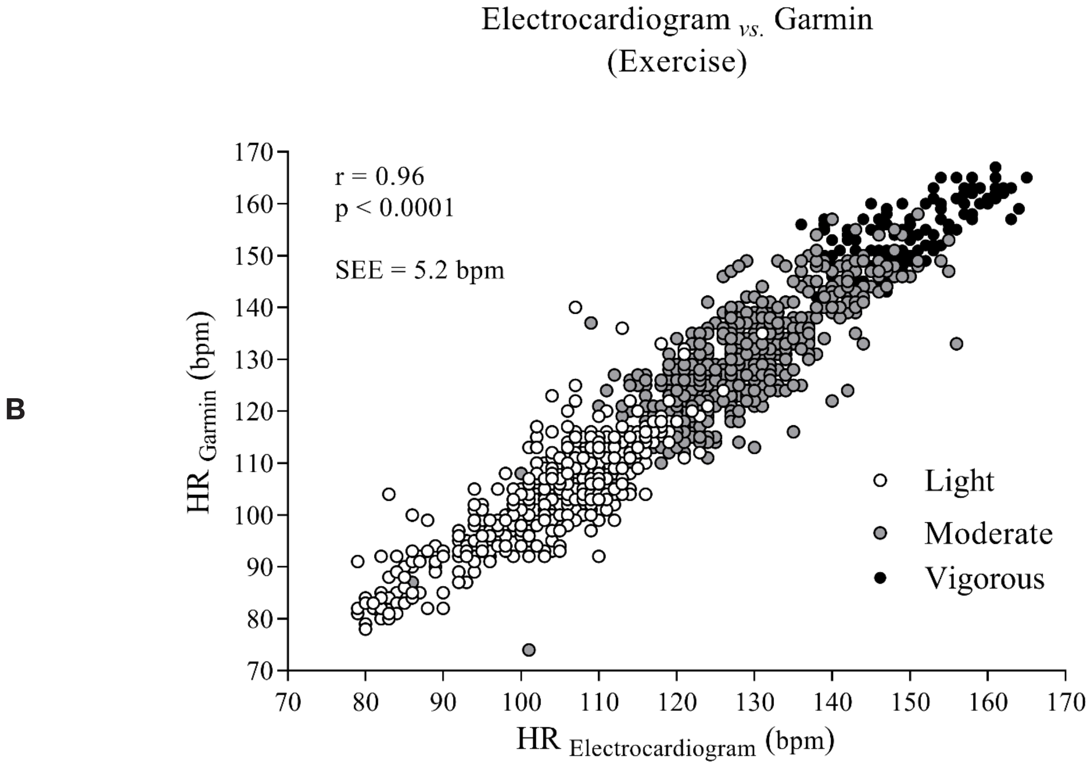
The correlations between HR values obtained with the Garmin® 735XT® and ECG were excellent both at rest ($r = 0.93$, $p < 0.001$) and during exercise ($r = 0.96$, $p < 0.001$). The correlation values considering only rest and walking or running activity on a treadmill and the studies which used ECG [23–25, 28, 29, 31, 39] or the Polar HR monitor or H7/H10 strap [26, 27, 30, 32, 40] as the gold standard were similar (ECG: $r_{\text{mean}} = 0.93$ at rest, $r_{\text{mean}} = 0.91$ during exercise; Polar HR monitor or H7/H10 chest strap: $r_{\text{mean}} = 0.94$ at rest, $r_{\text{mean}} = 0.92$ during exercise). Despite the recognized validity of the Polar HR monitor and H7/H10 chest strap for measuring HR and its variability, we believe that it is not a gold standard. Thus, although the correlations found in the aforementioned studies are very high, we believe that these results can be challenged. Some studies have tested activities other than rest and walking/running on a treadmill and revealed that the exercise intensity and arm movements reduce the validity of the HR monitor with PPG, suggesting caution in its use [23–25, 31, 32].

Table 2. Summary of Garmin 735XT accuracy

Condition intensity	Number of pairs (C)	Garmin accuracy* (%)	Mean difference ± *SD* (bpm)	MAE ± *SD* (bpm)	MAPE ± *SD* (%)
Rest	840 (774)	92.1	–1.2 ± 3.3	2.2 ± 2.8	3.4 ± 4.6
Exercise (all)	1680 (1627)	96.8	0.7 ± 5.2	3.5 ± 3.9	2.9 ± 3.2
Exercise (light)	735 (707)	96.2	–0.2 ± 4.6	3.0 ± 3.4	2.9 ± 3.2
Exercise (moderate)	810 (789)	97.4	0.9 ± 5.6	3.8 ± 4.1	3.0 ± 3.3
Exercise (vigorous)	135 (131)	97	–3.9 ± 5.0	4.6 ± 4.4	2.9 ± 2.8

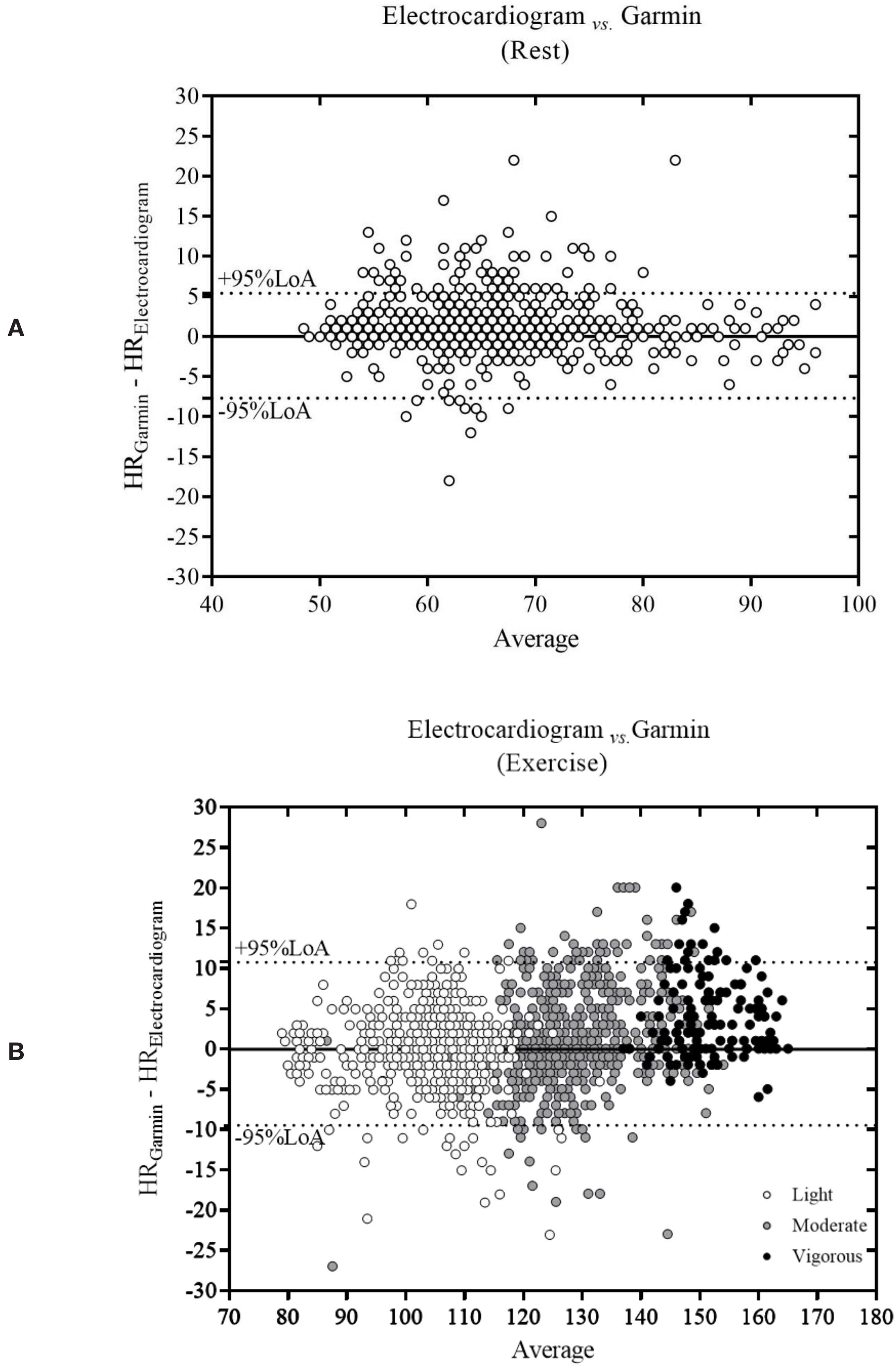
(C) – number pairs concordance between electrocardiography and Garmin
MAE – mean absolute error, MAPE – mean absolute percentage error
* Accuracy – within and including ± 5 bpm, % accuracy is the percentage of occurrences where HR measured with the Garmin device was within and including ± 5 bpm from the ECG HR value





SEE – standard error of estimation

Figure 1. Dispersion of heart rate (HR) values obtained with electrocardiogram and with Garmin at rest (A) and during exercise by intensity (light, moderate, vigorous) (B)



LoA – limit of agreement

Figure 2. Bland-Altman heart rate (HR) difference with Garmin and electrocardiography at rest (A) Wand during exercise by intensity (light, moderate, vigorous) (B)

Regarding the walking and running activities on a treadmill, studies by Claes et al. [29], Jo et al. [28], Delgado-Gonzalo et al. [26], Boudreaux et al. [24], Parak and Korhonen [31], and Gillinov et al. [23] attest that HR monitors with PPG technology lose accuracy in the case of activities which require arm movement, as well as when the intensity increases, regardless of brand/manufacturer. Boudreaux et al. [24] and Gillinov et al. [23] emphatically state that HR monitors with PPG are not medical devices and that monitors with chest straps should be preferred when accurate HR measurements are necessary.

In our study, we reported SEE of –1.2 ± 3.3 bpm (rest) and 0.7 ± 5.1 bpm (exercise) between the Garmin® HR monitor and ECG. Several studies have shown a similar average SEE [28, 30, 32, 40] in only analysing activities of rest and walking/running on a treadmill. However, very wide confidence intervals (> 30 bpm) were found when other categories such as cycling, elliptical effort, and intense activities were analysed [23, 25, 28, 29].

MAE and MAPE values for rest and exercise in our study were similar (< 10%) to those in other studies which tested the validity of devices with PPG [24, 25, 29, 38]. Regarding the accuracy, our values were also in accordance with other studies [25, 26, 30, 31]. However, some of these studies tested more than 1 device and under different conditions (graded exercise test on a treadmill and/or cycle ergometer) [24, 25]. It is important to highlight that MAPE decreased with increasing intensity in graded exercise test on a treadmill or cycle ergometer.

Considering the difference between HR monitors with PPG and ECG at rest and during walking/running on a treadmill, possible factors which can influence measurement errors include skin type and thickness, type and intensity of the activity performed, speed and force of change of the segment that receives the device, amount of light and LED colours available in the HR monitor, room temperature, and emotional state of the subject [7, 20, 32]. Regarding the type of skin, Hermand et al. [30] and Spierer et al. [32] confirm that the darker the skin, the larger the measurement error. However, Hermand et al. [30] found no differences between skin types in soccer athletes. The authors speculated that the hot and humid environment of the region (India) may have increased peripheral vasodilatation, facilitating the measurement regardless of skin type. With reference to other interfering factors, Lee et al. [41] demonstrated the influence of PPG colour on the accuracy and reliability of HR measurements. The authors concluded that green LED should be chosen for the devices, as they showed fewer artifacts as compared with the other colours, as well as lower bias and standard deviation values.

The present study results interpretation must consider its limitations. First, we adopted a self-selection type of intensity regulation of exercise. This approach limited exploring different exercise domains by all volunteers presenting different morphological and physiological characteristics. Our strategy to collect data at 20-s intervals combined real-time ECG data with an 8.1 ± 3.1 s average HR obtained with Garmin. This mismatch data synchronization could, at least in part, explain the error observed in this and other studies.

Conclusions

The results indicate that the Garmin® device has good validity indicators for measuring HR at rest. The results for light, moderate, and vigorous exercise imply that the Garmin® monitor HR evaluation has high correlation values with the gold standard measurement, low MAE and MAPE values, and acceptable accuracy. Thus, the Garmin® Forerunner® 735XT® can be used at rest, as well as in walking and running activities of light, moderate, and vigorous intensities, considering an error in HR estimation by the ECG of 3.4 ± 4.6%, 2.9 ± 3.2%, 3.0 ± 3.3%, and 2.9 ± 2.8%, respectively.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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