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Concurrent validity and accuracy of wrist-wearable devices to track heart rate during exercise in sedentary individuals

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ABSTRACT

Background: Heart rate (HR) is commonly used as an indicator to represent a change in oxygen consumption and energy expenditure during activities. Nowadays, HR is easily measured by low-cost wrist-wearable devices, but a few studies examine the validity and accuracy of these devices in sedentary people.

Objective: The study aimed to explore the concurrent validity and accuracy of low-cost wrist-wearable HR devices (The GT2e: approx. 4000 THB and Red Mi watch 2 lite: approx. 1000 THB) for measuring HR during exercise on a treadmill in people with a sedentary lifestyle.

Materials and methods: Seventy-six sedentary participants (60 female; 78.95%) were instructed to wear a Polar H7 while randomly wearing a watch on each hand. Participants were asked to walk or run on the treadmill for 40 minutes, including free-living activities, exercise, and HR recovery phases. Pearson's correlation coefficient was utilized to explain the levels of correlation (concurrent validity) of wrist wearable devices with the Polar H7. In contrast, the Bland-Altman method, Concordance correlation coefficient (CCC), and Mean Absolute Percentage Error (MAPE) were then used to determine the accuracy of wrist wearable devices.

Results: The GT2e had an excellent agreement with the Polar H7 in free-living activities, exercise sessions, and the HR recovery phase (CCC=0.88, 0.85 & 0.78, respectively) and strong correlation with the criterion measured; Polar H7 (r=0.79 - 0.88; p<0.001). While Red Mi watch 2 lite also had an excellent agreement and correlation in free-living activities and the HR recovery phase (CCC=0.88 - 0.85; r=0.79), but a moderate agreement was found in the exercise phase (CCC=0.55; r=0.61 [p<0.001]).

Conclusion: Both the GT2e and Red Mi watch 2 lite wrist-wearable devices could be used as alternative HR-measured devices to detect HR in sedentary people's daily lives. However, the GT2e wrist-wearable device was more valid and accurate in detecting HR than the Red Mi watch 2 lite.

Introduction

Heart rate (HR) is helpful in wide areas, including clinical medical care, pervasive health care, sports, and well-being centers. It was described as a critical indicator for detecting the efficiency of cardiovascular response and heart functionality during activity and exercise.[1-4] Thus, the introduction of HR-tracking-wearable-technology devices has become a new phenomenon for consumers and removes the burden of wearing an electrocardiograph (ECG) or chest straps, which is a standard measure for HR tracking, which is not comfortable or practical in some activities.[3,5] Hence, these consumer wrist-wearable HR

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trackers have already become popular for purchase and use.[3,6,7]

Wrist-wearable devices have begun incorporating heart rate measures using photoplethysmography (PPG) technology: this involves flashing green LED light through the skin to detect the expansion and contraction of wrist capillaries with each pulse.[6-8] Algorithms are then applied to estimate heart rate from that information continuously. With the expanding market in wearable activity monitors, the research community has been focused on validating the properties of PPG to detect outcomes among these devices. Several studies have demonstrated their validity and accuracy or agreement in the most famous brand and high-cost devices (i.e., Apple, Garmin, or Fitbit),[1,6-10,] but none at low-cost devices, which limits their application for clinical or research purposes.[11] Also, there is limited knowledge of the validity and accuracy of these low-cost devices to detect HR in sedentary individuals, whose numbers have been continuously increasing, particularly teenagers and adults (81% and 23%, respectively). WHOs reported that prolonged sitting or sedentary behaviors are linked to high risks of noncommunicable disease (NCDs) such as high blood pressure, type II diabetes, obesity, depression, or chronic heart disease.[12]

Therefore, the objective of this study is to evaluate the validity and accuracy of the heart rate estimates produced by low-cost wrist-wearable devices (<5,000 THB) compared to the gold standard (Polar H7) during treadmill training among sedentary individuals. The information summarized herein can be used to inform consumers and can aid researchers in having more options for selecting physical activity monitoring devices in study design.

Materials and methods

Participants

A sedentary adult aged 18-25 from Srinakharinwirot University participated in this cross-sectional study from March to December 2022. Recruitment was carried out via posters and leaflets within the university and through word of mouth. Each participant went through a screening survey for sedentary behavior using a questionnaire, namely the Global Physical Activity Questionnaire (GPAQ; METs <600 mins/week).[13] The exclusion criteria were any conditions or disorders that might affect the ambulatory status–such as brain function disorders,[14] musculoskeletal pain (with an intensity of pain more than 5 out of 10 on a numerical pain rating scale),[15] deformities in the joints of the lower extremities, obesity (body mass index >29.9kg/m^{-2}),[16] having a cardiac pacemaker or cardiovascular or lung disease,[17] having tattoos around their wrists or forearms and inability to follow the research protocols of the study.[3]

The sample size estimation for the primary objective of the study (concurrent validity) was calculated from a pilot study (N=30), which sets the level of correlation (r) to 0.354-0.760 for each device and the α to 0.05; the findings indicated this study required 11-76 participants to obtain 90% power of the test. However, a systematic review study recommends that 50-99 participants are adequate to minimize selection bias for the study's secondary objective; the total sample size was hence 76 participants.[18] Then, eligible participants signed an informed consent document approved by the Srinakharinwirot University Ethics Committee in Human Research (SWUEC 417/2564) before participating.

Instruments

Criterion measures

The Polar H7 was selected as the gold standard for heart rate measurement in the current study.[8,14,19] The heart rate strap was attached at the distal sternum firmly against the skin and required continuous Bluetooth connection for HR readings from the Polar Beat application. In addition, this instrument has been studied regarding the validation and accuracy, which was reported to have a high correlation and agreement with ECG.[3]

Wrist-wearable devices

The present study examines 2 brands of low-price (<5,000 THB) wrist wearable devices that were easily purchased in the shop. They were GT2e (Huawei Technologies Co., Ltd., approx. 4,000 THB) and the Red Mi watch 2 lite (Xiaomi Inc., approx. 1,000 THB). Each device estimates heart rate from the wrist using PPG technology, but the number of PPG is different between the devices; the GT2e has 2 PPG and photodiodes, Red Mi watch 2 lite has only 1 PPG and photodiodes. Both require Bluetooth connection for HR recording from their application. Using a simple random method, participants were randomly instructed to wear a watch on the right or left wrist. Previous studies demonstrated no difference in the accuracy of the HR monitors based on which wrist they are worn on if individuals have no vascular disease.[1] Wrist-wearable devices were fastened tightly above the ulnar styloid [GT2e and Red Mi watch 2 lite on the right-hand sides for 46 and 30 participants, respectively].

Protocol

A novice assessor was trained in the methods for administering the treadmill and all devices and then practiced processing to record the outcomes in their own application via smartphone, with practice sessions lasting 60 minutes. In addition, preliminary studies were conducted on five subjects to ensure the smooth function of the protocol.

Participants were interviewed and assessed for their demographics (i.e., age, gender, and Body Mass Index [BMI]), vital signs, and wrist circumferences to ensure no wrist was too small for the watch strap. Once all devices were on, they were instructed to lay on the bed to measure resting HR (RHR). RHR was then converted to a target HR (THR) that was set at a moderate intensity using the formula from Karvonen: ([%Intensity x (HRmax-RHR)] + RHR).[20]

Exercise protocol

Participants were then asked to walk or run on the treadmill (ST 65 Digital Treadmill, Quinton, USA) over

40 minutes at different speeds (in mph) in a room with a controlled temperature of 25° Celsius. The 40-minute protocol began with the free-living activity phase; they were instructed to walk on the treadmill at self-selected speeds for 5 minutes. After the 5-minute free-living activity phase, the 30-minute exercise phase was started with speed increasing at 0.5 mph every 1 minute until the HR raised to their target (THR). They were instructed to walk fast or run at the same speed to maintain HR until the time was up. After completing the exercise, a 5-minute heart rate recovery phase was started with treadmill speed reduction. The treadmill speed was decreased equally every 1 minute until the speed was similar at the beginning of the session.

In all activities, participants had the option of holding or releasing the treadmill bars as they needed.

Data acquisition and processing

The heart rate data were extracted in minute-by-minute format for all devices, including the Polar heart rate strap, the GT2e, and the Red Mi watch 2 lite, from the application. HR was recorded from the three devices after 2 minutes of every session. The HR data were summed individually for each of the protocol's three sessions.

Statistical analysis

Descriptive statistics were used to explain the demographics of participants as well as the findings of the study. The Kolmogorov-Smirnov test was used to estimate the normality of the data. Pearson's correlation coefficients (r) or the Spearman rank correlation coefficients (ρ) were utilized, which depend on their normality data, to explain the levels of correlation (concurrent validity) of both wrist-wearable devices and Polar H7. The strength of the correlation was defined as modest (r or ρ of 0.30-0.49), moderate (r or ρ=0.50-0.69), and strong (r or ρ>0.70). The levels of significant differences were set at p<0.05.[21]

Bland-Altman's analysis examined the differences between the means of measuring agreement.[22] This method uncovers any tendency for the variation to change with the magnitude of the measurement. Moreover, the Concordance Correlation Coefficient (CCC) was applied to obtain a measure of agreement for each device with the Polar H7. The level of the CCC was determined as modest (CCC<0.4), moderate (CCC=0.41-0.74), and strong (CCC>0.74).[23] In addition, Individual level measurement errors were evaluated with mean absolute percent errors (MAPE), which was calculated by averaging the individual absolute percent errors (i.e., |(criterion-estimation)/criterion|). An acceptable level of accuracy is indicated by a MAPE of less than 10%, while the MAPE is more than 10% but less than 25%, and the accuracy is poor.[24]

Results

Table 1 concludes the demographics of the participants. They were enrolled in the study and had an average age of approximately 21 years old with a BMI range of 16.23-29.73 kg/m^2, and most of them were female. HR data from the GT2e and the Red Mi watch 2 lite are summarized in Table 2. The Red Mi watch 2 lite underestimated HR in three protocol phases. The GT2e slightly underestimated HR in free-living activity and aerobic exercise, while it somewhat overestimated HR in HR recovery sessions.

Table 1. Demographic of participants.

Variables	N=76	Min/Max
Gender[a] (female)	60 (78.95)	-
Age[b] (years)	20.7±1.23	18/25
Weight[b] (kg)	54.68±10.89	40/90
Height[b] (cm)	162.35±6.89	151/183
Body mass index[b] (kg/m^2)	20.64±3.33	16.23-29.73
Self-selected speed[b] (m/s)	0.47±0.1	0.35-0.8
Aerobic exercise speed[b] (m/s)	2.25±0.44	1.51-3.52

Note: *[a]the variable is categorized as male/female,[b]data are presented using mean±SD.*

Table 2. Average heart rate in three sessions of wrist-wearable devices and PolarH7 (N=76).

Activities	Heart rate (beats/min)		
	Polar H7	GT2e	Mi
Free living activity	102.8±11.0	102.5±10.9	100.1±11.4
Aerobic exercise activity	139.0±11.0	138.2±11.3	134.3±13.6
Heart rate recovery	117.6±9.3	118.5±8.1	115.8±9.1

Note: *Mi: Red Mi watch 2 lite. All data are presented using mean±SD.*

The correlations between the wrist-wearable devices and the PolarH7 were strong in the free-living activity and HR recovery phase (p<0.01, Figure 1). Moreover, the correlations in aerobic exercise sessions were also strong in the GT2e (p<0.01, figure 1) but moderate in Red Mi watch 2 lite (p<0.01, Figure 1).

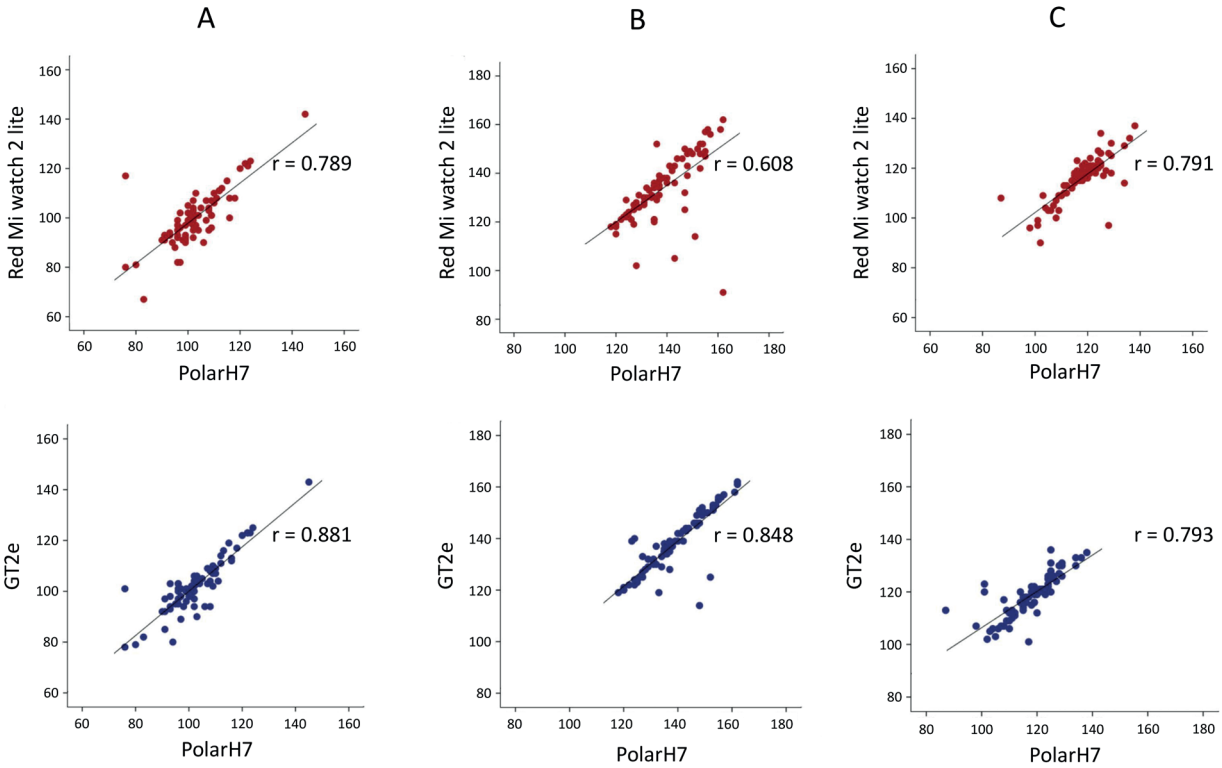

Figure 1. *Scatter plot for Pearson's correlation (r) of wrist-wearable devices-measured HR with PolarH7. A: free-living activity, B: exercise, C: heart rate recovery. The top panel indicates the results for heart rate from Red Mi watch 2 lite, and the bottom panel shows the results for heart rate from GT2e separately for the three activity sessions.*

The overall agreement between the GT2e and the PolarH7 was high across all three sessions. Still, the CCC of Red Mi watches 2 lite was reported as having moderate accuracy in the aerobic exercise phase. Moreover, both GT2e (2.02-3.43 %) and Red Mi watch 2 lite (3.32-5.04 %) had a whole-trial MAPE, and performance was also consistently acceptable for all three separate activities in terms of MAPE (Table 3). In the Bland-Altman plots, the data on the graph were uniformly and tightly scattered around the horizontal axis in both devices, particularly in the GT2e watch (Figure 2).

Table 3. Overall agreement data of wrist-wearable devices for heart rate estimation (N=76).

Activities	Mean diff[a]		95% LoA		MAPE	
	GT2e	Mi	GT2e	Mi	GT2e	Mi
Free living activity	- 0.32	- 2.68	-10.8 to 10.2	-16.9 to 11.60	3.43	5.04
Aerobic exercise activity	- 0.78	- 4.71	-12.8 to 11.3	-26.5 to 17.1	2.02	4.90
Heart rate recovery	- 0.96	- 1.79	-12.1 to 10.2	-13.4 to 9.8	2.70	3.32

Note: *LoA: limit of agreement, MAPE: mean absolute percentage error, Mi: Red Mi watch 2 lite, [a]mean difference was calculated using* $Mean_{wrist\text{-}wearable\ device}$ - $Mean_{PolarH7}$.

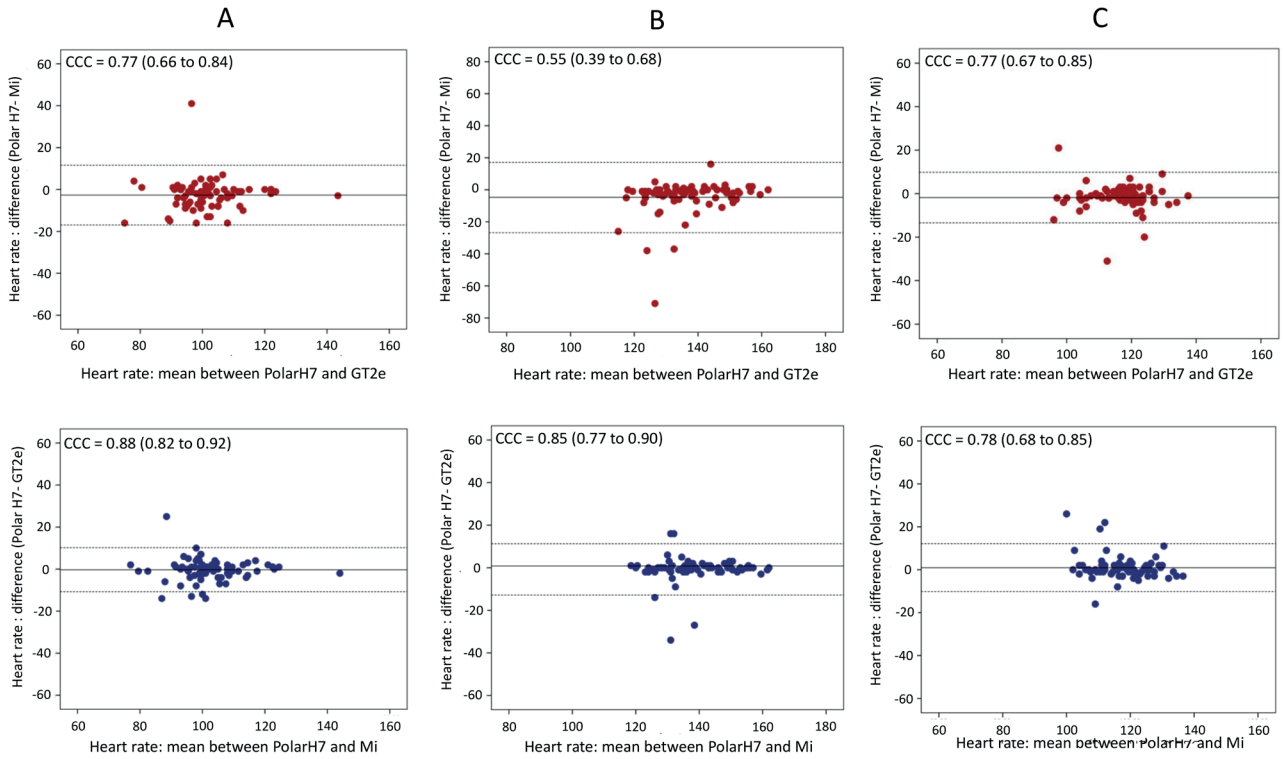

Figure 2. *Concordance correlation coefficient (CCC) and Bland-Altman plots comparing heart rate between wrist-wearable devices and PolarH7. Mi: Red Mi watch 2 lite, A: free-living activity, B: exercise, C: heart rate recovery. The top panel indicates the results for heart rate from Red Mi watch 2 lite, and the bottom panel shows the results for heart rate from GT2e separately for the three activity sessions.*

Discussion

The PPG in wrist-wearable devices has been known regarding the validity and accuracy of HR estimation. However, the existing evidence mostly involved the most famous and high-cost devices (i.e. Apple watch or Garmin), but none at low-cost devices such as Huawei or Xiaomi. The current findings revealed that the GT2e had high correlations to a criterion measure (PolarH7) (r=0.79-0.88; p<0.01) and highly acceptable accuracy (CCC=0.78-0.88; MAPE=2.02-3.43%) in all phases. While Red Mi Watch 2 lite was also strongly correlated (r=0.79; *p*<0.01) and acceptably accurate (CCC=0.77; MAPE 3.32 and 5.04%) in only free-living activity and heart rate recovery phases, but it showed moderate correlation (r=0.61; *p*<0.01) and accuracy (CCC=0.55; MAPE=4.9) in exercise activity as compared to PolarH7. These findings provide precise data regarding the properties of both devices to estimate HR, which can be used as a proxy and alternative devices for HR measurement. The findings were coherent with previous studies; other studies have examined the validity of other famous and high-cost commercially available HR monitors with PPG heart rate features.[1-3,8] In addition, a small MAPE and overall range were close to what we observed.[5-10]

However, the present study found that the GT2e strongly correlated with criterion measures to calculate HR in the exercise phase, but a moderate level was found in Red Mi watch 2 lite. These may be because the GT2e has the numbers of PPG and photodiodes equal to the high-cost HR watch,[11] The GT2e uses two green infra-red light-emitting-diodes (LED) paired with light-sensitive photodiodes to detect the amount of blood flowing through the wrist. The Red Mi watch 2 lite has only one red LED and photodiode. The two infrared lights and photodetector used in the GT2e may help its software filter any unwanted noise, which may increase the validity and accuracy of GT2e in measuring HR. Furthermore, a previous study reported that the green light used in GT2e is more common due to its higher absorption by hemoglobin than the red light used in Red Mi watch 2 lite. This could result in a stronger signal for the HR watch to detect changes in blood flow.[25] In addition, the watch's morphology and PPG's position and photodiodes of GT2e are like those with high validity and accuracy (i.e., Apple watch 7 or Garmin Forerunner).[3,18,26]

Data from the current study provide low-cost alternative devices for detecting HR in several phases of exercise. The number of PPG and photodiodes, as well as the colors of PPG used in wrist-wearable devices, should be considered before purchasing these low-cost devices, as these factors may interfere with the validity and accuracy of the HR measuring device.

Limitation

Indoor treadmill running could have different outcomes than running outside or on uneven ground. Future studies should be conducted to determine the effect of the exercise environment on HR. In addition, the

participants in the current study were allowed to either hold or release the treadmill bar during the protocol, which may affect the function of PPG and photodiodes. This information was in the same line with previous research, which reported changes in HR at exercise intensities, as arm movement which increases during high exercise intensity can interfere with data signaling.[27] Therefore, readers should be cautious about applying this information to other conditions of exercise that may require different arm positions such as exercise using a stationary bicycle.

Conclusion

The low-cost wrist-wearable device was a potential HR measurement in daily exercise. However, the GT2e wrist-wearable device was more valid and more accurate in detecting HR during exercise on a treadmill in sedentary people than the Red Mi watch 2 lite due to the number of PPG and photodiode and the color of PPG in the device.

Conflict of interest

The authors declare no conflict of interest regarding the publication of this paper.

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