Validation of heart rate measurement of Fitbit Charge 4 and Xiaomi Mi Band 5

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Submitted to: JMIR mHealth and uHealth
on: June 02, 2021

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Abstract

Background: Recent advances in mobile sensor technology have led to increased popularity of wrist-worn fitness trackers. The possibility to use a smartwatch as a rehabilitation tool to monitor patients' heart rate during exercise has won the attention of many researchers.

Objective: The aim of the study was to evaluate the accuracy and precision of HR measurement performed by two wrist monitors: Fitbit Charge 4 (Fitbit) and Xiaomi Mi Band 5 (Xiaomi).

Methods: 31 healthy volunteers were asked to perform a stress test on a treadmill. During the test their heart rate was recorded simultaneously by both wristbands and ECG at 1minute intervals. The mean absolute error percentage (MAPE), Lin's concordance correlation coefficient (LCCC) and Bland-Altman were calculated to compare precision and accuracy of heart rate measurements. The estimated validation criteria were MAPE < 10% and LCCC < .8

Results: The overall MAPE of the Fitbit device was 10.19% (±11.79%) and the MAPE of Xiaomi was (6.89 % ± 9.75). LCCC of Fitbit HR measurements was .753 (95% CI:0.717-0.785) and of Xiaomi – .903 (0.886-0.917). In both devices the precision and accuracy were decreasing with the increasing exercise intensity. Age, sex, height, weight, BMI did not influence the accuracy of both devices.

Conclusions: The accuracy of a wearable wrist-worn heart rate monitor varies and depends on the intensity of training. The decision concerning the application of such a device as a monitor during in-home rehabilitation should be taken with caution, as it may prove not reliable enough.

(JMIR Preprints 02/06/2021:30893)
DOI: https://doi.org/10.2196/preprints.30893

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Conclusions: The accuracy of a wearable wrist-worn heart rate monitor varies and depends on the intensity of training. The decision concerning the application of such a device as a monitor during in-home rehabilitation should be taken with caution, as it may prove not reliable enough.

Keywords: smart band, heart rate, wearable, validation

Introduction

Recent advances in mobile sensor technology led to increasing popularity of wrist-worn fitness trackers (smart bands, smartwatches). The market offers a number of devices which allow continuous measurement of heart rate (HR), step count, energy expenditure, saturation, sleep duration. More advanced medical algorithms include detecting atrial fibrillation, estimating heart rate variability to assess the autonomic nervous system or continuous glucose monitoring.[1]

The possibility to use wrist-worn monitors in medical research has been assessed in many validation studies and clinical trials. An analysis published in 2018 included 423 devices. Top 5 brands represented there were Fitbit, Xiaomi, Apple, Garmin and Samsung. A total number of 81 studies were identified in MEDLINE database, 61 validation/reliability studies and 20 data collection studies. 55 ongoing or planned studies were registered in Clinical Trials, 6 validation and 45 data collection studies.[2]

Accuracy of HR monitoring is crucial in monitoring physical activity and estimating energy expenditure. HR sensors in smart bands base on photoplethysmography (PPG). It is an optical technique that measures blood volume changes in the microvascular bed of tissue with each heartbeat. [3] Wrist monitors have recently been gaining a lot of interest as a potential telerehabilitation tool. A randomised controlled trial with smart bands in a home-based rehabilitation programme proved that it is non-inferior to traditional outpatient cardiac rehabilitation.[4]

The aim of the study was to evaluate the accuracy and precision of HR measurement performed by two wrist-worn monitors: Fitbit Charge 4 (Fitbit) and Xiaomi Mi Band 5 (Xiaomi).

Methods

Materials

Fitbit wristbands are widely used in medical research.[2] The advantage of Fitbit monitors is an opportunity to store training data not only on the Mobile Fitbit App, but also cloud-store in the Web App, which provides access to the fitness data by a third party, such as a physiotherapist or trainer. This may improve compliance and facilitate remote monitoring.

Xiaomi MI Band 5 is a very popular tool, especially thanks to its competitive price. Xiaomi connects with Google FIT, a mobile App collecting data from many different devices and applications.

Both devices were compared regarding their functionality (see Table 1).

Table1. Features and specifications of Fitbit Charge 4 and Xiaomi MI Band 5

	Fitbit Charge 4	Xiaomi Mi Band 5
Price	149.95 Euro	≈ 40 Euro
Battery life	Up to 7 days	Up to 14 days
GPS	+	-
PPG HR monitor	+ (measured in 1 s intervals)	+
Syncing	Bluetooth, NFC	Bluetooth
Operating system	Android, iOS	Android, iOS
Sleep Tracking	+	+
All-day activity Tracking	steps, distance, calories, activity time	steps, calories, activity time
Training mode	yes	yes
Automatic Exercise Recognition	yes	no
Waterproof	Up to50 m	Up to 5 ATM
Application	yes	yes
Payments	yes	no
Smartphone notifications	yes	yes
Google FIT App	no	yes
Internet Application	yes	no

Study protocol

Study participants were asked to perform a treadmill stress test in line with the Bruce protocol. The Bruce protocol consists of 3-minute stages. Each stage the speed and incline increase (Table 2).

Table 2. Bruce protocol

Stage	Speed (km/h)	Incline (%)
1	2.7	10
2	4.0	12
3	5.5	14
4	6.8	16
5	8.0	18
6	8.9	20

During exercise all participants wore the Xiaomi wristband on the right hand and the Fitbit wristband on the left hand. Exercise was preceded by a 3-minute resting period (stage 0) and followed by a 3-minute recovery period.

Stress tests were performed on a treadmill with Cambridge Heart, HeartWave II 4.1.0 software. ECG was continuously monitored by 12 electrodes placed on the chest with Manson-Likar modification. ECG HR was a gold standard, to which wristbands' HR measurements were compared.

Stress tests were continued until the submaximal HR limit was achieved. The HR limit was automatically calculated by the HearTwave software. At a request of a participant the stress test was continued until the maximum HR limit (220-age) was reached or until maximum exhaustion occurred.

During stress tests, at rest and recovery HR was simultaneously recorded from ECG and both wristbands every minute.

The study was approved by the local Medical University Ethical Board (nr: KB-0012/150/2020).

Participants

31 healthy Caucasian volunteers were enrolled in the study. Inclusion criteria were: age >18 years, no prior cardiovascular disease and no contradictions to perform a stress test. The participants comprised an age-diverse group (18-70 years) of 21 men and 10 women. All of them were physically active on a regular basis. Basic information on the participants and stress test results are shown in (Table 3).

Table 3. Participants' characteristics and stress test results

	Total	Female	Male
N	31	10	21
Age (years)	28 (18-71)	27.5 (23-54)	32 (18-71)
Height (cm)	177.7 (+-14.62)	168 (+-4.5)	181.9 (+-6.3)
BMI (kg/m^2)	23.5 (20.1-37.1)	22 (20-23)	24 (21-37.1)
Peak HR (BMP)	164.7 (+-19.9)	161.1 (+-13.8)	166.5 (+-22.4)
%HR MAX	88.8 (+-8.5)	85.1 (+-6.8)	90.6 (+-8.7)
METs	14.3 (+-3)	12.7 (+-1.2)	15 (+-3.2)

Legend: N – number of participants, BMI - body mass index, Peak HR - maximum HR achieved during stress test, BPM - beats per minute, % HR MAX - percentage of calculated maximal HR *achieved during stress test; METs - estimated metabolic equivalents achieved during stress test*

Some of the measurements were lost due to technical problems. In 29 cases the stress test was terminated after the HR limit was achieved. In one case exercise was stopped because of high blood pressure, while in another because of some technical problems with the treadmill. 3 participants wore only the Fitbit wristband because of organisational reasons.

Statistical analyses

The statistical analyses were performed using STATISTICA 13.3 and IBM SPSS Statistics software.

To test the accuracy of devices for each pair of HR measurements Absolute Error (AE) and Absolute Percentage Error (APE) were calculated according to the following formulas:

$$AE = \left| HR_{EKG} - HR_{devive} \right|$$

$$APE = \left| \frac{HR\,EKG - HR\,device}{HR\,EKG} \right| * 100\ \%$$

The Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) were also calculated. MAPE <10% was considered reliable. [5,6]

A correlation between AE and quantitative data (age, height, body mass, BMI) was calculated (Spearman correlation coefficient). Differences in AE between groups regarding sex and stage of exercise were calculated using the U Mann Whitney test, the Kurskal Wallis test and post hoc tests. *P*< .05 was considered statistically significant.

To test the reliability of both fitness trackers Lin concordance correlation coefficient (LCCC) was calculated. LCCC>.8 was considered good agreement. [7]

The Bland-Altman analysis was performed to determine agreement between each device and ECG.

All data with normal distribution was presented as mean +- SD (standard deviation). Nonparametric data was presented as median and an interval between minimum and maximum value.

Results

A total number of 556 pairs of data were obtained for Fitbit and 509 pairs for Xiaomi.

An AE for each pair of HR measurements was calculated. The overall MAPE of the Fitbit device was 10.19% (±11.79%) and did not meet validation criteria. The MAPE of Xiaomi was lower (6.89 % ± 9.75) and fulfilled validation criteria.

Because AE for both devices did not have a normal distribution, median AE was compared between devices. The overall median AE was significantly lower for Xiaomi comparing to Fitbit, both in stage 1.2 as well as 4 (Table 4).

Table 4. Comparison between Fitbit and Xiaomi error rates

	FITBIT					XIAOMI					
	N	MAE (BMP)	Median AE (BPM)	MAPE (%)	Median APE (%)	N	MAE (BMP)	Median AE (BPM)	MAPE (%)	Median APE (%)	*P*
Total	557	12.84 ±16.55	6 (0-98)	10.19 ±11.79	5.17 (0-63)	509	7.99 ±10.61	4 (0-82)	6.89 ±9.75	3.95 (0-115)	<.001
Male	391	12.59 ±16.70	5 (0-90)	9.92 ±11.67	4.92 (0-63.01)	391	7.74 ±10.90	4 (0-82)	6.73 ±10.35	3.85 (0-115)	<.001
Female	166	13.46 ±16.21	7 (0-98)	10.83 ±12.09	6.08 (0-62.42)	118	8.82 ±9.58	5 (0-44)	7.40 ±7.46	4.84 (0-38.58)	.0528
Stage 0	93	7.56 ± 8.45	5 (0-54)	8.69 ±9.06	5.33 (0-47.37)	84	8.08 ±10.65	5 (0-69)	10.58 ±17.14	5.67 (0-115)	.86
Stage 1	90	12.81 ±12.04	8 (0-46)	12.20 ±11.27	8.51 (0-63.01)	81	4.58 ±4.73	3 (0-28)	4.80 ±5.32	3.53 (0-34.15)	.001
Stage 2	93	11.78 ±13.96	6 (0-57)	10.17 ±11.66	5.38 (0-50)	84	6.68 ±7.33	4.5 (0-34)	5.99 ±5.77	4.37 (0-23.13)	.0012
Stage 3	90	14.71 ±19.60	5 (0-98)	10.61 ±13.36	3.88 (0-62.42)	81	7.38 ±8.01	4 (0-29)	5.53 ±5.91	2.88 (0-23.01)	.14
Stage 4	70	21.47 ±21.67	16 (1-79)	13.16 ±12.31	10.11 (0.57-53.02)	67	8.73 ±11.38	4 (0-51)	5.52 ± 7.28	2.53 (0-37.22)	.0012
Stage 5	25	21.6 ±26.23	6 (0-85)	11.97 ±12.88	3.33 (0-54.49)	25	12.72 ±16.19	5 (0-61)	7.41 ±9.92	2.76 (0-40.67)	.4
Stage 6	6	1.67 ±4.08	0 (0-10)	0.89 ±2.18	0 (0-5.35)	6	46.5 ±30.32	42.5 (13-82)	25.7 ±16.87	23.6 (7.22-45.05)	.017
Rest	90	9.2 ±14.84	4 (0-90)	7.15 ±10.51	3.36 (0-55.9)	81	8.33 ±8.81	6 (0-41)	7.03 ±7.81	4.42 (0-39.58)	.38

Legend: Stage 0-1 - stages of a stress test, N – number of pairs of measurements, AE – absolute error, MAE – mean absolute error, APE – absolute percentage error, MAPE – mean absolute percentage error, BPM – beats per minute

Analysing each device separately, there were no differences in AE regarding sex (p=.125 for Fitbit, p=.098 for Xiaomi). Fitbit's AE was significantly higher in stage 4 comparing to stage 0 and recovery. Xiaomi AE did not differ between stages. Because of a small number of measurements in stage 6 (only 2 participants achieved that stage), they were not included in separate calculations.

Only a weak correlation (r<.2) between Fitbit AE and height (positive), BMI (negative) and age (negative) was found. Xiaomi AE weakly correlated with age (positive), body mass (negative) and height (negative).

Figure 1 shows the scatterplots of pairs of HR measurements (ECG and Fitbit and ECG and Xiaomi). LCCC of Fitbit HR measurements was .753 (95% CI:.717-.785) and of Xiaomi .903 (.886-.917). Again, Fitbit did not fulfil validation criteria in any stage. LCCC of both devices decreased with increasing intensity of physical performance (Table 5).

Table 5. Lin's Concordance Correlation Coefficient (LCCC)

	Fitbit (LCCC, 95% CI)	Xiaomi (LCCC, 95% CI)
Total	.753 (.717-.785)	.903 (.886-.917)
Stage 0	.757 (.655 - .831)	.675 (.542 - .774)
Stage 1	.3 (.139 - .446)	.912 (.867 - .942)
Stage 2	.408 (.250 - .545)	.795 (.704 - .861)
Stage 3	.228 (.075 - .371)	.730 (.612 - .816)
Stage 4	.176 (.04 - .305)	.660 (.518-.766)
Stage 5	.051 (-.161 - .259)	.455 (.209 - .647)
Recovery	.651 (.517 - .753)	.851 (.783 - .899)
Women	.688 (.605 - .756)	.887 (.842 - .919)
Men	.774 (.743-.809)	.906 (.887 - .922)

Legend: LCCC – Lin's concordance corelation coefficient, CI – confidence interval

The Bland-Altman analysis revealed that Fitbit has a tendency to underestimate HR values with a mean difference of 9.348 BPM. Xiaomi does not show any tendency in estimating HR, with a mean difference of 1.639. Bland-Altman plots are shown in Figure 2. Dots outside the red lines correspond to extreme error values.

Discussion

Principal Results

The aim of the study was to validate HR measurements of 2 wrist-worn monitors: Fitbit Charge 4 and Xiaomi Mi Band 5. This is the first study evaluating these 2 models.

In our study the Fitbit device did not fulfil the presumed validation criteria. The overall MAPE and MAPE on every stage of exercise were>10% and were lower only at rest and recovery. However, it should be considered to use median instead of mean values, as they better represent nonparametric data. Both smart bands had median APE <10%. Fitbit's overall LCCC and LCCC at every stage were <.8. Xiaomi Mi Band 5 performed better with the overall MAPE 6.89% and LCCC .903.

Comparison with Prior Work

Available studies evaluating Fitbit devices most often assess Fitbit Charge 2, Fitbit Charge HR, Fitbit Blaze and Fitbit Surge. Reference methods are ECG [8-9] or Polar chest strap [5,7,10], which is a validated tool to estimate HR.

Most studies evaluating Fitbit devices report a lower MAPE than in our study. Dooley E. et al. [5] validated Fitbit Charge HR during exercise on a treadmill. The lowest MAPE occurred during the resting period (2.38%). In the study of Stahl et al. [10] Fitbit's Charge HR overall MAPE was 6.2%. Results of other validation studies reveal that the accuracy and reliability of fitness trackers decrease with increasing physical activity [5,10,11], which is consistent with our results. Fitbit Charge 2 was validated during cycling and resistance exercise. Across all intensities a decrease in agreement and precision was noticed (MAPE 4.43% and ICCC .92 at rest, MAPE 38.24% and LCCC .12 during intensive exercise.)[11] Some studies show the lowest agreement during moderate exercise, and it is getting better with more intense physical activity.[8]

Moreover, correlations between the gold standard and device readings differ depending on the activity type. Jo et al [9] assessed the reliability of Fitbit Charge HR during different activities:

cycling, walking, running, arm raises, planks and lunges. The Pearson's product moment correlation was the lowest while doing lunges (r=.28) and planks (r=.26). Fitbit blaze correlated the best with Polar Chest strap HR at rest (LCCC .89), during exercise on a treadmill (.76) and was the lowest on an elliptical trainer (LCCC .58), the overall LCCC was .67.[7]

Fitbit Blaze was evaluated in population of patients diagnosed with cardiovascular disease during various activities: at rest, cycling, walking on a treadmill (MAPE 6.6%, LCCC .88 at rest, MAPE 8.6%, LCCC .76 on a treadmill and MAPE 8.4% and LCCC .72 during cycling).[12]

There is definitely less data regarding Xiaomi fitness trackers, and it assesses Xiaomi Mi Band 2. In our study generally Xiaomi correlated better with ECG and showed lower error than Fitbit, but also showed worse outcomes during intensive exercise. In the study by Hsueh-Wen et al. [6] the overall MAPE was 8.85%. Authors divided participants into two groups: young and elderly (>65 years) and did not find a significant difference in reliability between them. However, LCCC was .73 in both age groups, and that was below the designated threshold. LCCC also differed depending on the activity type and reached lowest values in the younger group during cycling (.29) and exercise on an elliptical trainer (.32). In another study evaluating Xiaomi Mi Band 2 MAPE was 12% (±13%) at rest, but the applied methodology was different than usual and was based on manual recording of HR. [13]

We did not find any co-factors altering reliability, such as sex, age, height, weight and BMI, which is consistent with previous results [7,10]. Shcherbina et al. reported a higher error rate for males than for females across all evaluated devices, including Fitbit Surge.[14] In our study we observed higher error rates and lower corelation coefficients among females, but the differences between sex groups for both devices were not statistically significant. In both devices some extreme errors were spotted, occurring more often with higher HR values. Chow et al. [6] noticed that extreme readings were unpredictable, unexpected and transient. From our experience, the most important precaution taken to avoid extreme readings is proper adjustment of the wristband to the size of the wrist.

Limitations

Our study has some limitations. First of all, participants differed in age, but most of them were 20-30 years old, so basing on our results it is impossible to determine the reliability in older patients. However, in previous studies no difference in reliability between younger and older patients was observed.[6] Secondly, according to calculations made by other authors, 8 [6] -25 [7,15] pairs of data are a minimum number necessary to gain statistical significance when calculating LCCC. Because the duration of the stress test was different for every participant, there are far fewer observations at higher exercise intensities. Some authors suggest that a different methodology, i.e. acquiring data second by second, be superior to minute-by-minute observations, as more data to analyse is collected in the same period of time [9]. Thirdly, the exercise protocol used in our study is designed to reach the maximum HR limit in a short period of time – it is possible that after stabilising HR both devices would prove to be more reliable.

Conclusions

Both devices revealed a certain degree of error, which in our case was more considerable in the Fitbit device. Taking into account our results, as well as results of previous studies, the decision concerning the use of wrist-worn monitors in home-based rehabilitation should be taken with caution. The reliability of both devices decreases during exercise and at high HR values some extreme errors occur, which is crucial when deciding whether training can be continued or not. Moreover, not all devices give the opportunity to remotely control training progress. We are convinced that a home-based rehabilitation programme with a wristband as a HR monitor may be considered in the case of patients with low cardiovascular risk after proper instructions how to use it and interpret the results.

Acknowledgements

Ethics approval: The study was approved by the Pomeranian Medical University Ethical Board (nr: KB-0012/150/2020).

Funding: The study was funded by the Cardiology Clinic Foundation. The Foundation covered costs of buying wristbands and preparing the article, including language proofreading.

Authors' contributions: MJ with MTJ recruited participants, performed stress tests and collected data. MJ and RMK analysed and interpreted data. MJ was a major contributor in writing the manuscript. RMK, MPP and JK co-wrote and revised the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest

None declared

Abbreviations

AE absolute error

AEP absolute error percentage

BMI body mass index

BMP beats per minute

CI confidence interval

ECG electrocardiography

GPS global positioning system

HR heart rate

LCCC Lin's Concordance Correlation Coefficient

MAE mean absolute error

MAPE mean absolute percentage error

METs metabolic equivalent of task

NFC near-field communication

PPG photoplethysmography

SD standard deviation

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Supplementary files

Figures

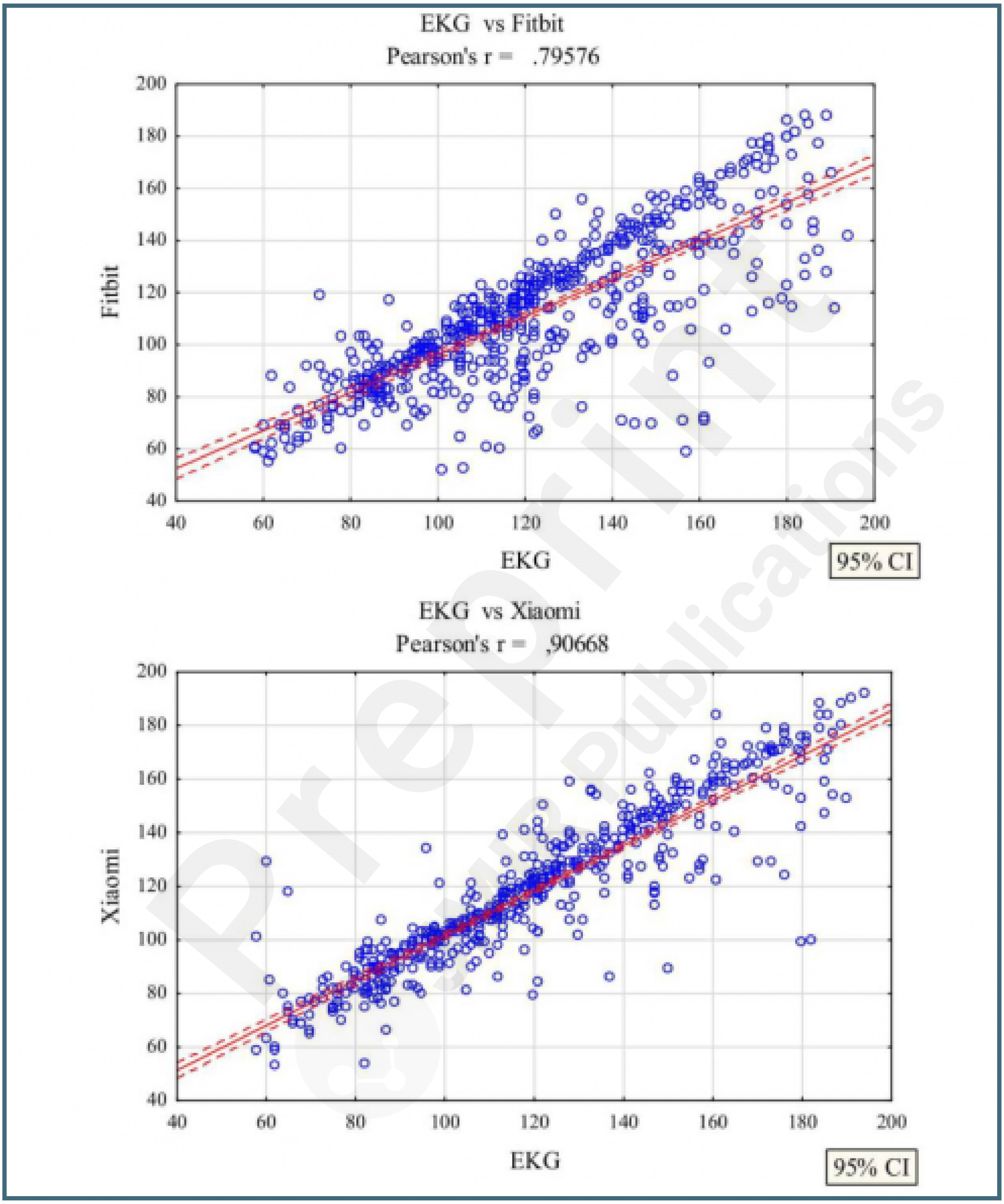
Figure 1. Scatterplots and Pearson’s correlation coefficient.

Figure 2. Bland-Altman plots.

Supplementary Files

Figures

Scatterplots of ECG recordings and Pearson's correlations.



Bland-Altman plots.