EFFECT OF EXERCISE-INDUCED SHORT-TERM CHANGES IN BLOOD PRESSURE AND HEART RATE ON SMARTWATCH MEASUREMENT ACCURACY

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Abstract

Blood pressure (BP) is a key vital sign that many people around the world are increasingly monitoring continuously using smartwatches. It remains unclear whether smartwatches can fully replace traditional oscillometric cuff-based devices under real-world conditions. The aim of this study was to verify the accuracy of BP and heart rate (HR) measurements using smartwatches compared to a standard patient monitor before and after a short-term exercise. Twenty-seven participants underwent an experimental part divided into three phases: pre-exercise, exercise, and post exercise. BP and HR were measured simultaneously with a Samsung smartwatch Watch Active2 or Watch3 and a patient monitor Datex-Ohmeda S/5 two times before and four times after exercise. The results showed a slight deterioration in the accuracy of smartwatch blood pressure measurements after exercise compared to values measured before exercise (-0.3 ± 6.3 vs. 2.9 ± 8.8 for systolic BP and 1.0 ± 4.8 vs. 1.9 ± 5.7 for diastolic BP given as mean ± standard deviation). Furthermore, smartwatches underestimated high BP readings and overestimated low BP readings. On the other hand, measuring HR with smartwatches proved to be very accurate even after exercise (-0.8 ± 3.7 vs. 0.0 ± 2.5). The study confirmed the accuracy of smartwatch heart rate measurements but questioned the accuracy of smartwatch BP measurements taken at values far from the calibration point.

Keywords

smartwatch, wearables, blood pressure, heart rate, exercise

Introduction

Blood pressure (BP) is a key vital sign that is routinely monitored, and its regular assessment enables early detection of hypertension, a major risk factor for cardiovascular diseases [1]. Hypertension causes more than 10 million deaths worldwide every year, more than any other health risk [2]. In clinical practice, BP is often only measured during preventive checkups, typically once every 1–2 years. Since BP fluctuates throughout the day and is influenced by physical and psychological factors, such as white coat syndrome [3], isolated measurements taken at long intervals may be insufficient. Consequently, home monitoring using oscillometric cuff-based devices has become more widespread. However, the accuracy of these devices can be compromised by factors such as cuff size, incorrect placement of the cuff, system leakage, or inadequate compression of the limb [4]. Moreover, these devices only provide intermittent readings under resting conditions, which limits their ability to capture dynamic BP changes during daily life [4].

To address these limitations, cuffless BP measurement devices have emerged. These devices most commonly use photoplethysmography (PPG), which also enables estimation of heart rate (HR), oxygen saturation, and respiratory rate [5, 6]. The growing interest in smartwatch-based BP monitoring led to several validation studies examining their accuracy and reliability. Most focused on short-term accuracy over a single day, often using ambulatory BP monitoring. While some devices, such as Samsung Galaxy Watch3 [7] and InBodyWATCH [8], met the ISO 81060-2:2018 accuracy criteria (mean difference of ± 5 mmHg and standard deviation of ≤ 8 mmHg) [9], other devices, including earlier models such as the Samsung Galaxy Watch Active2 [10], had significantly worse accuracy.

Only a few studies have examined long-term accuracy. These studies indicated that measurement accuracy declines over time after calibration [11] and that cuff-calibrated devices perform better than

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calibration-free models, particularly in normotensive populations [12]. Despite ongoing technological progress and numerous validation efforts, it remains uncertain whether smartwatches can fully replace traditional cuff-based sphygmomanometers under real-world conditions [13].

The aim of this study was to verify the accuracy of blood pressure and heart rate measurements using a calibrated Samsung smartwatch compared to a standard patient monitor used in intensive care units before and after short-term exercise.

Methods

The prospective interventional study was conducted at the Faculty of Biomedical Engineering of the Czech Technical University in Prague (FBME CTU) in the Laboratory of Special Devices for Anesthesiology and Intensive Care. The protocol of the study was approved by the Ethics Committee of FBME CTU in Prague under number B3/2021. All participants signed an informed consent prior to enrolment in the study. The study was prospectively registered in the ClinicalTrials.gov database under the number NCT05302193.

Study participants and Experiment setup

A total of 27 healthy participants (13 men, 14 women) aged 15–52 years participated in the study. Exclusion criteria for participation in the study included severe cardiovascular or respiratory disease, pregnancy, diabetes or any acute illness. All participants were without major pathologies that would preclude participation in the study. The basic characteristics of the participants enrolled in the study are summarized in Table 1.

Upon arrival at the laboratory, each participant was first introduced to the experimental procedure and completed a personal questionnaire with general personal data, current health status and previous diseases. Subsequently, all participants were fitted with a smartwatch on their left wrist. The participants' BP was measured using two types of smartwatches, Galaxy Watch Active2 and Galaxy Watch3 (both Samsung Electronics Co., Ltd., Suwon, South Korea). Each type of smartwatch was used in two sizes: 40-mm or 44-mm case size for Galaxy Watch Active2 and 41-mm or 45-mm case size for Galaxy Watch3. The choice of smartwatch type (Watch Active2 or Watch3) was randomized, and the case size was chosen according to a participant's wrist size. Generally, the larger case size of the smartwatch was assigned to male participants, and the smaller case size of the smartwatch was assigned to female participants. In a single case, a smaller sized watch had to be fitted to a male participant due to a small wrist circumference. In addition to BP, HR was also measured with the smartwatch. A cuff of the Datex-Ohmeda S/5 patient monitor (Datex-Ohmeda, Inc, Madison, USA) was placed on the participant's right arm.

In the calibration part the smartwatch BP measurement was calibrated with the patient monitor according to the instructions in the Samsung Health Monitor mobile app. A participant's BP was measured three times consecutively, simultaneously with the smartwatch and the patient monitor, and the patient monitor readings were entered into the mobile app.

Experimental protocol

The calibration part was followed by a 25-minute experimental part divided into three consecutive phases: a pre-exercise phase, an exercise phase, and a post-exercise phase.

All BP and HR measurements were recorded during the pre-exercise and post-exercise phases using the smartwatch and the patient monitor simultaneously. During these measurements, participants were seated comfortably on a chair with a backrest, with their arms resting loosely on the table and their feet flat on the floor.

In the pre-exercise phase (0–7.5 min), BP and HR were measured twice, at 2.0 min and 5.5 min. This was followed by the exercise phase (7.5–12.5 min), during which participants cycled on a spinning ergometer with a standardized workload of 1 W/kg body mass. The purpose of this physical activity was to alter the monitored physiological parameters. Finally, in the post-exercise phase (12.5–25.0 min) BP and HR were measured four times, at 15.5, 17.0, 20.5, and 22.0 min. All time stamps are referenced to the onset of the experimental part. The entire experimental procedure including the preparation of a participant, calibration part, and experimental part took approximately 50 minutes.

Table 1: Summary characteristics of the participants in the study by assigned smartwatch.

Smartwatch type Galaxy	Case size (mm)	Number of participants (–)	Age (years)	Height (cm)	Weight (kg)
Watch Active2	44	6	32 (23–39)	184 (176–195)	81 (65–92)
Watch Active2	40	4	33 (23–52)	164 (159–172)	57 (52–62)
Watch3	45	6	29 (15–42)	181 (174–190)	81 (67–90)
Watch3	41	11	26 (23–43)	166 (158–180)	64 (51–77)

Data are given as a mean (minimum–maximum value).

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Data and statistical analysis

All BP and HR values were stored in the memory of the measuring devices and were also manually recorded in a log. All measured values were processed in Microsoft Excel (Microsoft, Albuquerque, USA) and MATLAB R2021a (MathWorks, Nattick, USA).

We evaluated the systolic BP, diastolic BP, and HR before and after exercise. The mean and standard deviation of the differences between the individual smartwatch and patient monitor BP measurements were assessed according to the ISO 81060-2:2018 standard [9] using the following two criteria: According to the first criterion, the mean difference between the BP values measured by the test device and the reference device must be within or equal to ± 5.0 mmHg with a standard deviation no greater than 8.0 mmHg [9]. For the second criterion, the variability (standard deviation) in the average differences between the test device and the reference device, which were calculated for each individual, must stay below a certain limit with the exact acceptable values provided within the ISO standard [9]. For HR measurements, the absolute mean difference of up to 5 beats/min is acceptable [14].

Differences between smartwatches and patient monitor measurements were analyzed using a linear mixed-effects model. The dependent variable was defined as the paired difference between devices (smartwatch − monitor) for each measurement. Systolic and diastolic BP were analyzed in separate models. To account for repeated measurements within subjects, a random intercept for subject was included. Time was modeled as a categorical fixed effect with five levels: a baseline level, representing the two pre-exercise measurements (treated as equivalent), and four post-exercise levels, representing successive measurements after exercise. Smartwatch type was included as an additional fixed effect. P-value less than 0.05 was considered statistically significant.

The data obtained during the pre-exercise and post-exercise phases were evaluated separately using Bland-Altman plots, a method for analyzing the agreement between two different methods of measurement of the same variable, i.e. the smartwatch and patient monitor. The 95% limits of agreement were calculated as the mean difference ± 1.96 standard deviations of the pooled measurements. In addition, the data were visualized using scatter plots of the measuring differences between the smartwatch and the patient monitor vs. BP changes from the calibration point as given in the IEEE Standard for Wearable, Cuffless Blood Pressure Measuring Devices [15].

Results

During the whole experimental procedure, a total of 162 pairs of systolic and diastolic BP values were measured from 27 participants. Eight percent of systolic BP readings were hypotensive (< 100 mmHg), 85% were normotensive and 7% were hypertensive (> 140 mmHg). Twenty-one percent of diastolic BP readings were hypotensive (< 60 mmHg), 76% were normotensive and 3% were hypertensive (> 85 mmHg). The HR was successfully measured in 22 participants with 132 pairs of values ranging from 48 to 104 beats/min.

During the exercise phase, systolic BP values increased by an average of 7 mmHg, diastolic BP values increased by an average of 5 mmHg, and HR values increased by an average of 10 beats/min. These values were calculated as the difference between the maximum post-exercise value and the mean pre-exercise value.

Table 2 summarizes the differences between the smartwatch and the patient monitor for the measurements taken in pre- and post-exercise phases. The first criterion of the ISO standard assessing the overall mean difference and standard deviation was met for both systolic and diastolic BP measured before and after exercise, except for the standard deviation for the systolic BP after exercise, which exceeded the maximum acceptable limit by 0.8 mmHg. The results met the second criterion of the ISO standard for both systolic and diastolic BP measurements evaluated before and after exercise together. The standard deviation of the averaged paired determinations per subject of the smartwatch and of the patient monitor was 5.5 mmHg for systolic BP (for a mean difference of 1.8 mmHg, the maximum acceptable standard deviation is 6.71 mmHg) and 3.6 mmHg for diastolic BP (for a mean difference of 1.6 mmHg, the maximum acceptable standard deviation is 6.76 mmHg).

Table 2: Comparison of smartwatch measurements and a reference patient monitor before and after exercise.

Phase	Systolic pressure (mmHg)		Diastolic pressure (mmHg)		Heart rate (beats/min)	
	MD	SD	MD	SD	MD	SD
pre-exercise	-0.3	6.3	1.0	4.8	-0.8	3.7
post-exercise	2.9	8.8[+]	1.9	5.7	0.0	2.5

MD–Mean Difference, SD–Standard Deviation
[+] indicates non-compliance with the requirements of the standard ISO 81060-2:2018

For the systolic BP at baseline under resting conditions, there was no significant difference between smartwatches and monitor measurements (mean difference -0.31 mmHg, p = 0.809). Following exercise, a time-dependent bias emerged. No significant difference was observed immediately after exercise at time 15.5 s (p = 0.545), but then the smartwatch showed significantly higher value compared to the monitor. The estimated mean differences were approximately

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2.9 mmHg at 17.0 s (p = 0.050), 5.4 mmHg at 20.5 s (p < 0.001), and 4.9 mmHg at 22.0 s (p = 0.001). There was no evidence that smartwatch type influenced measurement bias (p = 0.658). Similarly, there was no significant difference in diastolic BP (p = 0.260), but there was a significant difference after exercise (p = 0.022). The HR readings from the smartwatch and the patient monitor did not differ either before (p = 0.093) or after exercise (p = 0.999).

Bland-Altman plots for systolic (Fig. 1A) and diastolic BP (Fig. 1B) show an increase in the mean difference between the smartwatch and the patient monitor in the post-exercise phase compared with the pre-exercise phase. The interval between the 95% limits of agreement that reflects the variance in the differences was wider after exercise than before exercise for both systolic and diastolic BP. On the other hand, the Bland-Altman plot for HR in Fig. 3A shows a higher accuracy of HR measurement after exercise than before exercise. Scatter plots in Fig. 2 show systematically higher values of measured BP by smartwatches for values lower than the smartwatch calibration point and, conversely, lower values of measured BP by smartwatches for values higher than the smartwatch calibration point. The scatter plot for HR in Fig. 3B shows no systematic dependence.

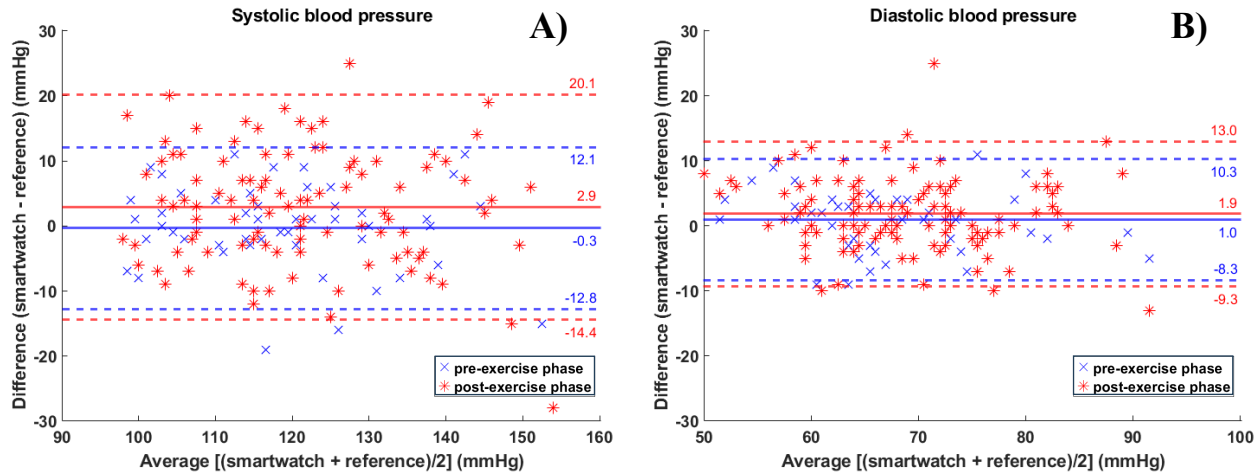

Fig. 1: The Bland-Altman plots for the systolic (A) and diastolic (B) BP show a slight deterioration in the accuracy of smartwatch BP measurements in the post-exercise phase (red color) compared with the pre-exercise phase (blue color). The solid line is the mean difference of the measurements, and dashed lines are the 95% limits of agreement.

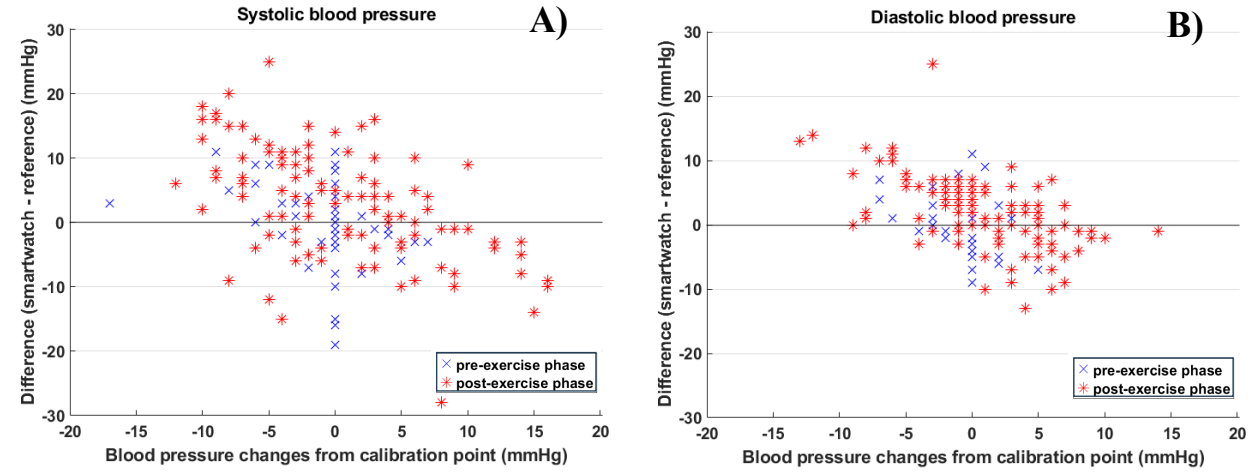

Fig. 2: The scatter plots of differences between smartwatches and reference as a function of change in BP from calibration point for the systolic (A) and diastolic (B) BP demonstrate a systematic overestimation of BP values lower than the smartwatch calibration point and an underestimation of values higher than the calibration point. This pattern is more evident in the post-exercise phase (red color) than in the pre-exercise phase (blue color).

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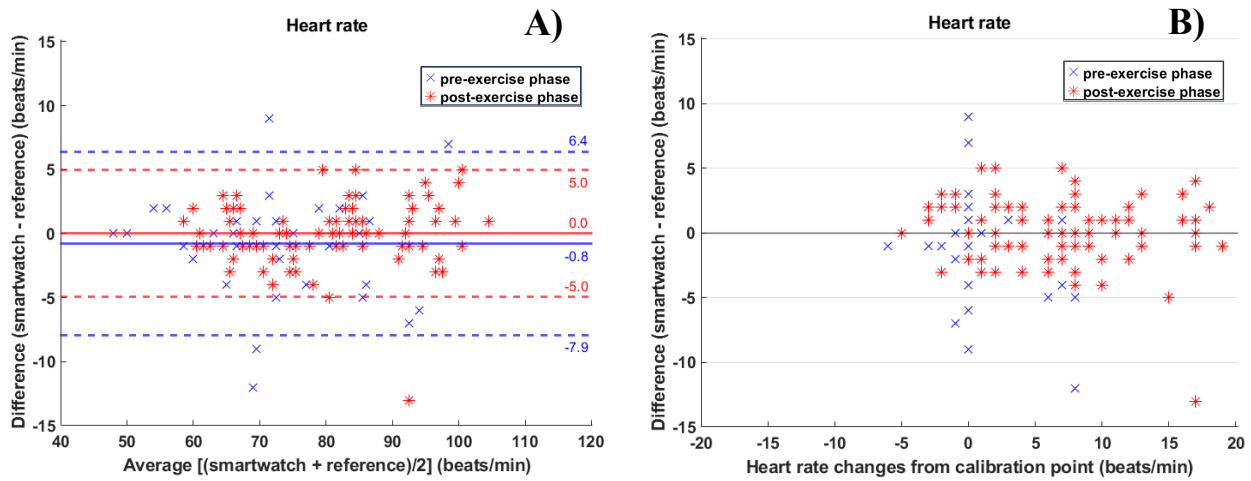

Fig. 3: The Bland-Altman plot (A) and scatter plot of differences between smartwatches and reference as a function of change in HR from calibration point (B) for the HR show the accurate measurement of HR by smartwatches in the post-exercise phase (red color) compared with the pre-exercise phase (blue color). In Fig. 3A, the solid line is the mean difference of the measurements. Dashed lines are the 95% limits of agreement.

Discussion

The results of this study indicate a slight deterioration in the accuracy of blood pressure measurements obtained by Samsung smartwatches following short-term exercise-induced changes in BP. In contrast, heart rate measurements remained in good agreement with those obtained from the reference patient monitor. The observed decline in BP measurement accuracy after exercise was evident in the Bland–Altman plots (Fig. 1) and was further supported by the linear mixed-effects model analysis.

Following exercise, smartwatch BP measurements exhibited a measurable bias relative to the reference patient monitor, whereas little to no systematic difference was observed under resting conditions. In addition, the variability of the differences increased after exercise, indicating a greater likelihood of substantial discrepancies in individual measurements. Nevertheless, the observed performance remained within the requirements of the ISO standard, with the exception of the standard deviation for systolic BP in the post-exercise phase. Furthermore, the linear mixed-effects model revealed that, beginning with the second post-exercise measurement, the smartwatch consistently reported significantly higher BP values than the reference monitor. This finding may suggest a slower response of the smartwatch algorithm to the gradual decline in BP following exercise.

Considering the accuracy of BP measurement by the reference patient monitor and smartwatches, and the clinical significance of the measured differences, the increase in the mean differences of BP measurements between smartwatches and the patient monitor by 3.2 mmHg for systolic BP and 0.9 mmHg for diastolic BP does not seem to be of practical significance. However, the scatter plots in Fig. 2 demonstrate that the smartwatches were unable to correctly measure BP values farther away from the calibration point and reported values closer to the original calibration point. That is, they underestimated higher BP values and overestimated lower BP values, consistent with the findings reported by [16]. Figures 3A and 3B confirmed the high accuracy of the smartwatch HR measurements, with even more accurate results after exercise, possibly due to the larger number of measurements.

The main limitation of this study is the small number of participants, and the small number of measured data pairs of smartwatch and reference readings compared to the requirements of the ISO standard. We measured 27 participants and evaluated 162 data pairs, the ISO standard requires at least 85 participants and 255 data pairs [9]. Further, while we met the ISO standard requirement of at least 5% hypotensive participants, we did not meet the requirement of 20% pre-hypertensive and hypertensive participants. Another limitation is that the measured data show only a small increase in measured BP and HR after exercise compared to values before exercise, so the accuracy of the measurements was not tested in extreme values or values very distant from the BP calibration point. We emphasized a standardized measurement position, i.e., participants had to change position from the bike to the chair after the exercise and had to put on the BP cuff again. This delay led to relaxation of the participants. A more intense and prolonged exercise could profoundly increase BP and HR.

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Conclusion

We compared blood pressure and heart rate measurements by Samsung smartwatches with a standard patient monitor before and after a short-term exercise. The accuracy of the smartwatch blood pressure measurements was worse after exercise than before exercise, but this worsening was practically insignificant. The heart rate measurements were very accurate in both situations. The results also demonstrated that watches underestimate deviations in actual blood pressure from the blood pressure during smartwatch calibration. However, the apparent agreement observed in this study should be interpreted in light of the aforementioned limitations and does not necessarily imply reliable performance under conditions with greater blood pressure variability.

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