

ORIGINAL ARTICLE

Validity and Reliability of the Res-Rhythm: A Prototype Portable Respiratory Rate Measurement System in Healthy Subjects

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ABSTRACT

Respiratory rate is one of the important vital signs, typically assessed by observing the number of breaths per minute. This can result in measurement errors and variability between observers. Furthermore, commercially available respiratory rate measurement devices tend to be expensive. This study aimed to develop a portable prototype system for measuring respiratory rate, consisting of a chest belt sensor and a display application. Validity was tested by comparing it with a BIOPAC device, and reliability was tested using the retest method in 29 healthy volunteers with an average age of 21.61 ± 2.24 years. The test was conducted during a 5-minute rest period and a 5-minute exercise period, which involved marching in place, for a total of 10 minutes, repeated twice. Validity was analyzed using Pearson's correlation coefficient (r), and reliability was analyzed using the intraclass correlation coefficient (ICC) at the 95% confidence interval. The study found that the prototype device demonstrated very high validity during both rest ($r=0.94, p<0.001$) and exercise ($r=0.90, p<0.001$) when compared to the BIOPAC device. The average difference between the two devices was -0.35 ± 1.5 breaths per minute (2.01%) during rest and -0.81 ± 1.90 breaths per minute (4.18%) during exercise. When analyzing test-retest reliability, the prototype system showed good reliability (ICC=0.75, $p<0.01$) at rest and moderate reliability (ICC=0.57, $p<0.01$) during exercise. The average difference between the two measurements was -1.11 ± 3.89 breaths per minute (6.78%) at rest and -0.70 ± 4.50 breaths per minute (3.81%) during exercise. In conclusion, the prototype system demonstrated acceptable levels of validity and reliability. Additionally, it can be further developed into a portable respiratory rate measurement device for clinical and research applications.

Introduction

Respiratory rate (RR) is one of the vital signs that reflects the general physiological status of the body. RR can deviate from normal values, which vary across different age groups, when the body experiences illness or responds to internal stressors¹. Moreover, RR values measured during exercise can serve as an indicator for monitoring exercise intensity and fatigue, reflecting differences in individual exercise tolerance^{2,3}. Previous studies showed that RR can be used to predict cardiac arrest and diagnose the severity of pneumonia in children and adults, as well as in patients with coronavirus disease 2019 (COVID-19)^{4,7}. Clinically, RR is commonly measured by counting the number of breaths per minute, defined as one inspiration and one expiration, observed through chest expansion and relaxation. In addition, the assessor may evaluate the depth, rhythm, and breathing pattern to detect respiratory abnormalities. However, manual counting is prone to high variability between observers because it depends on the observer's skill and experience, as well as the duration of observation.

Consequently, RR measurements can differ even when taken from the same individual⁸.

To address these issues, RR measuring devices have been developed for convenience and to minimize measurement errors, using different approaches. Direct methods include the piezoelectric respiratory sensor, impedance pneumography, and capnography⁹⁻¹³. Indirect methods estimate RR from electrocardiograms (ECG) or photoplethysmograms (PPG)^{14,15}. However, these devices are not widely used in clinical practice due to their relatively high cost, complex installation, and bulky size, which limit portability and field application. Recently, a prototype portable device for heart rate and RR measurement with a mobile display application was developed in Thailand¹⁰. This prototype demonstrated accuracy in measuring RR compared to an ECG monitor. Nonetheless, it showed low sensitivity in detecting chest expansion, as users needed to breathe deeply to the level of the diaphragm for capturing respiratory signals. The sensor unit was relatively large, limiting its usability in field settings and during exercise. In

addition, the display program could report only waveforms and RR, without providing data on the inspiration-expiration duration parameters essential for evaluating breathing patterns and guiding respiratory training. The previous prototype employed a strain-gauge-based respiratory sensor connected via an IOIO-Q interface board, which detected thoracic circumference changes through variations in electrical resistance. In contrast, the current study utilized a piezoelectric (PZT) respiratory sensor integrated with an Arduino microcontroller, which detects chest wall motion by converting mechanical deformation into voltage signals. This piezoelectric configuration provides higher sensitivity and faster response compared with the strain-gauge sensor¹⁶, while the Arduino-based system enhances signal stability, portability, and wireless data acquisition. Furthermore, the present design allows real-time estimation of additional respiratory parameters, including the inspiration-to-expiratory (I:E) ratio, during dynamic exercise.

This study aimed to develop a prototype portable RR monitoring system, consisting of a respiratory belt sensor and a mobile application that displays respiratory parameters, including respiratory rate and inspiration-expiration duration, via portable electronic devices connected through Wi-Fi. The prototype was tested in healthy volunteers and compared with a BIOPAC device. This system may provide a basis for developing clinical and research applications for RR measurement.

Materials and Methods

Prototype development

This study developed a prototype portable respiratory rate monitoring system, named Res-Rhythm, which consisted of two main components, including a respiratory belt sensor that detects thoracic movements during breathing, and a display application (Figure 1). The system operates in three main steps: (1) A piezo-electric respiratory sensor, attached to a respiratory belt, detects signals from chest expansion and relaxation. These signals are transmitted to a microcontroller connected to a Wi-Fi network. (2) The sensor data are then sent to a server, where they are stored and processed using a Microsoft SQL Server database and PHP-based programs. (3) The processed data are displayed through an application accessible via an internet browser on the World Wide Web. The application presents respiratory-related variables, including respiratory waveform, respiratory rate, inspiration time, expiration time, and the I:E ratio.

Participants

This study recruited twenty-nine healthy volunteers (aged 20-60 years) through public announcements at Mae Fah Luang University and nearby communities. Individuals who expressed interest underwent screening using a questionnaire and a brief physical assessment to ensure that they met the inclusion criteria. The inclusion criteria were individuals with no self-reported or physician-diagnosed medical conditions, who were able to communicate effectively, and who could follow instructions. Exclusion criteria included those with a history of diagnosed respiratory diseases (e.g., asthma), cardiovascular diseases (e.g., ischemic heart disease, coronary artery disease, or valvular heart disease), chest or rib injuries with wounds or fractures located beneath the nipples or at the level of the sternum, neurological disorders affecting respiration (e.g., spinal cord injury, Guillain-Barré syndrome, amyotrophic lateral sclerosis, or myasthenia gravis), and movement disorders affecting standing or walking.

Validity and reliability testing

After providing written informed consent, volunteers appeared at the laboratory on a scheduled date. Upon arrival, participants were asked to rest in a seated position for at least 5 minutes. Personal information was collected, including sex, age, weight, height, body mass index, and medical history. Vital signs, including blood pressure, heart rate, respiratory rate, and body temperature, were measured over approximately 20 minutes to identify potential contraindications or precautions for exercise testing.

Following screening, participants were fitted with the prototype respiratory belt sensor and the BIOPAC device (BIOPAC MP36 Systems, Goleta, CA). Both straps were positioned below the nipples around the level of the fourth intercostal space, ensuring they did not overlap (Figure 2). Electrodes were applied to the chest wall to record lead II ECG. An arm cuff was placed on the left upper arm, and a finger plethysmography device was attached. All sensors were connected to a bedside monitor (Life Scope®, Nihon Kohden, Japan). Preparation took approximately 10 minutes. Tests were conducted individually in a quiet laboratory at a controlled temperature between 23-25 °C.

The testing protocol included three stages: (1) Resting stage: Participants sat upright on a chair with back support and feet flat on the floor, breathing normally. RR from the prototype and BIOPAC device, as well as inspiration/

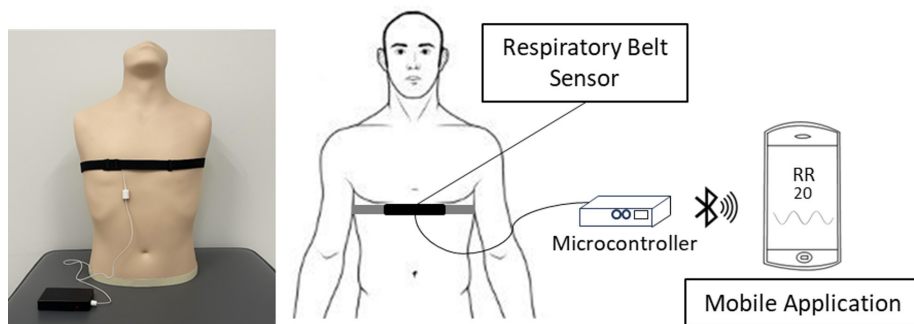


Figure 1 Prototype of a portable respiratory rate measuring system (Res-Rhythm)

expiration time and heart rate, were recorded at baseline (0 minute) and every minute for 5 minutes. (2) Exercise stage: At 6th minute, participants performed the Spot Marching Exercise (SME) by marching in place at a cadence of 70 steps per minute, with hip flexion of 70° and arm swing of at least 90°. This activity increased breathing rate to test the validity and reliability of the prototype during exercise. RR and heart rate were recorded at baseline (minute 0) and every minute for 5 minutes, continuing until minute 10. (3) Recovery stage: Participants rested for at least 30 minutes until RR, heart rate, and blood pressure returned to baseline. The testing protocol from stages (1) and (2) was then repeated.

Validity testing was performed by comparing mean RR values obtained from the prototype and the standard device during both the 5-minute resting and 5-minute exercise phases. Reliability testing was assessed by comparing mean RR values between the first and second trials during rest and exercise.

Statistical analysis

All data were analyzed using SPSS version 20.0, with a significance level set at $p \leq 0.05$. The Shapiro-Wilk test was used to assess data distribution. Descriptive statistics (frequency distribution, mean, standard deviation, and percentage) were applied to participant characteristics, including age, blood pressure, heart rate, respiratory rate, and body temperature at rest. Comparisons of RR between the prototype and the BIOPAC device were performed using a paired t-test for normally distributed data and the Wilcoxon signed-rank test for non-normally distributed data. To supplement the interpretation of the mean values, standard error of mean (SEM) was calculated as SD divided by the square root of the sample size ($SEM = SD/\sqrt{n}$). Validity analysis was conducted using Pearson's correlation coefficient (r): values of 0.00-0.30 indicated no correlation, 0.30-0.50 low correlation, 0.50-0.70 moderate

correlation, 0.70-0.90 high correlation, and 0.90-1.00 very high correlation. Agreement between devices was examined using the Bland-Altman test. For each comparison, the mean difference, the standard error of the mean difference, and the 95% limits of agreement were calculated to evaluate the magnitude and precision of measurement differences (SEdiff). Reliability analysis was achieved using intraclass correlation coefficients (ICC) from repeated tests, applying the ICC (3,1) model (two-way mixed-effects model, single measures) since there was only one assessor. ICC values less than 0.5 indicated poor reliability, while values from 0.5 to 0.74 indicated moderate reliability, values from 0.75 to 0.89 indicated good reliability, and values from 0.9 to 1.0 indicated excellent reliability. Agreement between the two test sessions was examined using the Bland-Altman test, including mean difference, SEdiff, and the 95% limits of agreement.

Results

Participant characteristics

A total of 29 healthy volunteers participated in this study, consisting of 11 males (37.93%) and 18 females (62.07%). The mean age of the participants was 21.61 ± 2.24 years, with an average body weight of 70.83 ± 17.32 kg, height of 165.38 ± 8.45 cm, and body mass index (BMI) of 25.75 ± 5.27 kg/m². The participants' average resting heart rate was 79.07 ± 11.54 beats per minute, while the average systolic and diastolic blood pressures were 111.75 ± 15.27 mmHg and 75.89 ± 11.68 mmHg, respectively.

Comparison of RR between the BIOPAC Device and the Prototype System

When comparing the mean RR between the standard device and the prototype system, no statistically significant differences were found during either the resting or exercise phases in both the first and second trials (Table 1).

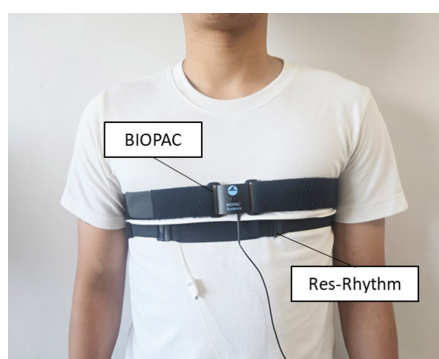


Figure 2 Setup of the respiratory belt sensor of Res-Rhythm and BIOPAC device on a subject for validity and reliability testing.

Table 1 Comparison of respiratory rate between the BIOPAC device and the prototype of the portable respiratory rate measuring system (Res-Rhythm)

Variables	BIOPAC device		Res-Rhythm		<i>p</i> -value
	Mean ± SD	SEM	Mean ± SD	SEM	
Measurement 1					
At rest					
- Respiratory rate (breaths/min)	16.83 ± 3.21	0.60	16.54 ± 3.94	0.73	0.270
- Inspiratory time (seconds)	-	-	1.46 ± 0.31	0.06	-
- Expiratory time (seconds)	-	-	2.30 ± 0.65	0.12	-
- I:E ratio	-	-	1:1.61	-	-
During exercise					
- Respiratory rate (breaths/min)	19.28 ± 2.91	0.54	18.41 ± 3.35	0.62	0.058
- Inspiratory time (seconds)	-	-	1.27 ± 0.21	0.04	-
- Expiratory time (seconds)	-	-	1.99 ± 0.46	0.09	-
- I:E ratio	-	-	1:1.59	-	-
Measurement 2					
At rest					
- Respiratory rate (breaths/min)	17.88 ± 4.07	0.76	17.45 ± 4.73	0.88	0.172
- Inspiratory time (seconds)	-	-	1.37 ± 0.46	0.09	-
- Expiratory time (seconds)	-	-	2.28 ± 0.93	0.17	-
- I:E ratio	-	-	1:1.76	-	-
During exercise					
- Respiratory rate (breaths/min)	19.70 ± 3.50	0.65	18.92 ± 4.90	0.91	0.055
- Inspiratory time (seconds)	-	-	1.13 ± 0.32	0.06	-
- Expiratory time (seconds)	-	-	2.09 ± 0.54	0.10	-
- I:E ratio	-	-	1:1.93	-	-

Data were analyzed using the paired t-test; $p < 0.05$ was considered statistically significant. Abbreviations: I, inspiratory time; E, expiratory time; SD, standard deviation; SEM, standard error of the mean.

Validity testing

Analysis of validity between the two devices using Pearson's correlation coefficient showed that respiratory rate values from the prototype and the BIOPAC device were very highly correlated both at rest ($r=0.94$, $p<0.001$) (Figure 3A) and during exercise ($r=0.90$, $p<0.001$) (Figure 3B). The mean difference in respiratory rate between the two devices at rest was -0.35 ± 1.5 breaths per minute (2.01%), with a standard

error of the difference of 0.28 and limits of agreement at the 95% confidence interval ranging from -3.30 to $+2.60$ breaths per minute (Figure 3C). During exercise, the mean difference between the two devices was -0.81 ± 1.90 breaths per minute (4.18%), with a standard error of the difference of 0.35 and limits of agreement at the 95% confidence interval ranging from -4.50 to $+2.90$ breaths per minute (Figure 3D).

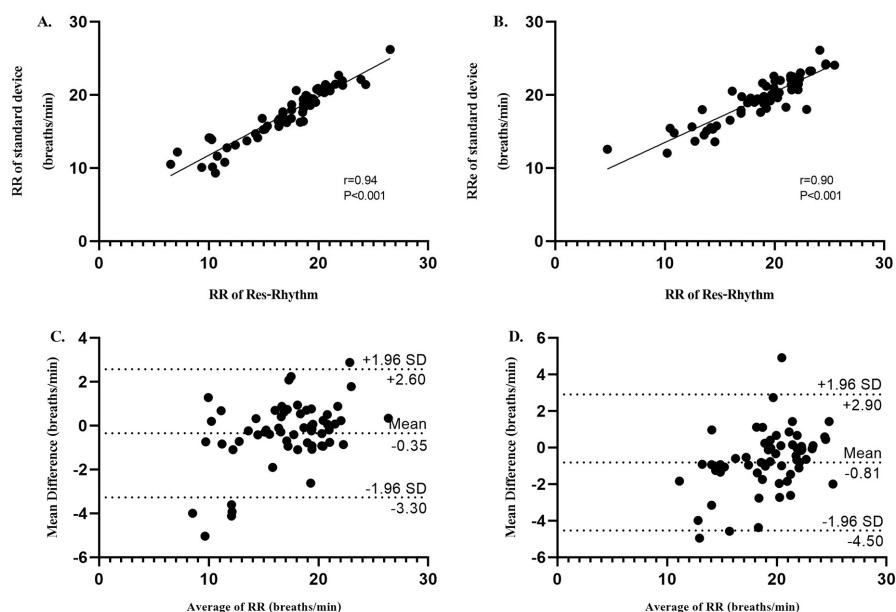


Figure 3 Correlations (A, B) and Bland–Altman plots (C, D) comparing respiratory rate (RR) measurements obtained from the BIOPAC device and the prototype of the portable respiratory rate measuring system (Res-Rhythm) at rest (A, C) and during exercise (B, D).

Reliability testing

Analysis of the test–retest reliability of the prototype portable respiratory rate monitoring system, performed twice during rest and exercise using the intraclass correlation coefficient (ICC), demonstrated that the prototype showed good reliability at rest and moderate reliability during exercise (Table 2). The mean difference in respiratory rate between the two test sessions at rest was -1.11 ± 3.89 breaths

per minute (6.78%), with a standard error of the difference of 0.72 and limits of agreement at the 95% confidence interval ranging from -8.73 to $+6.50$ breaths per minute (Figure 4A). During exercise, the mean difference was -0.70 ± 4.50 breaths per minute (3.81), with a standard error of the difference of 0.84 and limits of agreement at the 95% confidence interval ranging from -9.60 to $+8.20$ breaths per minute (Figure 4B).

Table 2 Reliability of the prototype of the portable respiratory rate measuring system (Res-Rhythm)

Variables	Mean $\pm$ SD	ICC (95% CI)
Respiratory rate at rest (breaths/min)		
Measurement 1	16.54 $\pm$ 3.94	0.75*
Measurement 2	17.45 $\pm$ 4.73	(0.47 - 0.88)
Respiratory rate during exercise (breaths/min)		
Measurement 1	18.41 $\pm$ 3.35	0.57*
Measurement 2	18.92 $\pm$ 4.90	(0.10 - 0.80)

ICC, intraclass correlation coefficient; 95% CI, 95% Confidence Interval; SD, standard deviation; *Statistically significant difference at $p<0.05$.

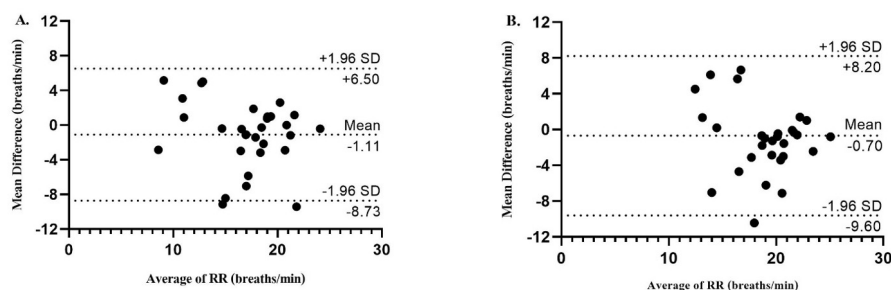


Figure 4 Bland–Altman plots comparing respiratory rate measurements obtained using the prototype of the portable respiratory rate monitoring system between the first and second measurements at rest (A) and during exercise (B).

Discussion

This study aimed to develop a prototype portable RR monitoring system and evaluate its validity compared with a BIOPAC device, as well as its reliability from repeated measurements in 29 healthy volunteers. The findings demonstrated that the RR values obtained from the prototype and the BIOPAC device did not differ significantly, both at rest and during exercise. Moreover, the prototype exhibited high validity and moderate-to-good reliability, suggesting that it could be further developed for use in respiratory monitoring.

The validity testing of this study involved comparison with a BIOPAC device that uses the same principle of RR measurement: an elastic respiratory belt sensor that detects mechanical forces from thoracic expansion and relaxation during breathing. Testing was conducted both at rest and during exercise to determine whether the new prototype could perform consistently under different conditions of physical activity. The results showed a very high correlation between the two devices, indicating the strong validity of the prototype. These findings are consistent with a previous study by Yuenyongchaiwat et al.¹⁰, which developed and tested a similar respiratory measuring device against a bedside monitor that calculated RR from ECG signals. They reported a high correlation and a mean difference of -0.23 breaths per minute, comparable to the mean difference of -0.35 breaths per minute in the present study. This suggests that the current prototype achieves a comparable level of validity. However, unlike the previous study, which did not test during exercise, the present study demonstrated that the prototype maintains validity during increased physical activity levels. In comparison, Singh et al.¹² developed an RR monitor using impedance pneumography and reported a mean difference of 0.05 breaths per minute compared with observer-based breath counting. Although this shows smaller differences, their reference standard relied on manual counting, which is prone to higher variability, unlike the sensor-based standard device used in the present study.

The reliability testing indicated that the prototype system demonstrated good reliability at rest, reflecting stable measurement performance in static conditions. This finding is consistent with Nazari et al.¹⁷, who reported good-to-excellent reliability of chest-strap-based RR monitors, both at rest and during treadmill exercise. In this study, reliability during exercise was moderate, which may be

explained by the type of exercise employed. While Nazari et al.¹⁷ used treadmill running, where thoracic movement is primarily driven by breathing, the current study applied SME involving arm swinging and hip flexion¹⁸. Such movements may have caused additional tension in the chest wall muscles and mechanical artifacts that interfered with sensor detection, thereby reducing reliability during exercise. It is also possible that these motion-induced artefacts affected the estimation of I:E ratio. The greater upper-body movement during SME could have distorted the respiratory waveform, leading to differences in the calculated I:E ratio between the two exercise bouts. Therefore, the inconsistency in I:E ratio (1:1.59 vs 1:1.93) may not fully reflect true changes in breathing pattern but rather the influence of motion artefacts on the chest sensor signal. Nevertheless, the mean differences of RR between the two trials remained within acceptable limits in the Bland–Altman plots.

The prototype portable RR monitoring system in this study may provide a practical basis for developing accurate devices for both research and clinical applications. However, certain limitations must be addressed in future work. First, reliability during physical activity requires improvement, possibly through the development of sensors optimized for capturing respiratory signals during dynamic movement or enhanced signal-processing algorithms within the application to reduce motion artifacts. Second, the stability and transmission range of wireless signals between the sensor and the receiver should be improved, which would enable broader application in diverse monitoring environments. In addition, future studies should include other populations, such as older adults, patients with respiratory or cardiovascular diseases, or populations requiring close RR monitoring.

Conclusions

The newly developed prototype of a portable respiratory rate monitoring system demonstrated good validity and reliability compared with a BIOPAC device. These findings suggest that the prototype could serve as a foundation for the further development of accurate respiratory monitoring systems for future clinical and research use. Future studies should focus on improving sensor design and signal-processing algorithms to enhance measurement accuracy, particularly during dynamic conditions.

Ethical statement

The study was approved by the Mae Fah Luang University Ethics Committee on Human Research (protocol code EC 23115-25; approval date: 21 August 2023). Informed consent was obtained from all participants or their legal representatives.

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