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Validity and reproducibility of chest expansion measurement by a device using an ultrasonic sensor

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ABSTRACT

Background: Chest expansion is a type of physical examination used by physicians and physical therapists to diagnose various pulmonary diseases. Despite the fact that it can be performed using various equipment. However, it has some limitations while operating in the clinic. Therefore, a prototype device was developed.

Objectives: The study was carried out to assess the validity and reproducibility of a chest expansion measurement device using an ultrasonic sensor. Furthermore, the opinion to the device was gathered by the questionnaire.

Materials and methods: The study included 110 healthy subjects ranging in age from 20-60 years old. Two examiners measured upper, middle, and lower chest expansion independently and at random, and the measurements were repeated one day later. The Pearson correlation coefficients and Bland-Altman plotting were then used to assess validity and reproducibility. In addition, a questionnaire yielded suggestions from 10 experienced physical therapists.

Results: The results showed that the validity, as measured using Pearson's correlation coefficient, had a moderate association in the lower part (r=0.69, p<0.001), whereas the other levels had the lowest and lowest association. There was also a strong correlation between intra-observer reproducibility (upper and middle: r=0.81, lower: r=0.84, all p<0.001). According to the questionnaire responses, some aspects of the device's appearance should be improved.

Conclusion: The device's validity appears to be very low to moderate depending on the expansion levels measured. Additionally, the reproducibility is considerably high, while some details of the device need to be improved to maximize its efficiency.

Introduction

Chest expansion measurement was first described by Moll *et al*. in 1972.[1] It is a useful method for assessing disease conditions, such as asthma and chronic obstructive pulmonary disease (COPD),[2] as well as the effects of treatment techniques.[3,4] Commonly, it is measured as the difference between the thoracic girth measurement after maximal inspiration and at the end of maximal expiration.[1] Clinical measurements can be taken using simple methods that do not necessitate the use of complex devices, such as a cloth tape[5, 6] or a caliper.[7] Even if the method is simple, the validity of the measurable distance is dependent on various factors, including the equipment, the examiner's

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expertise, and the patient's cooperation. In the literature on chest expansion, it is mainly measured in a standing position.[1,2] However, according to the preceding facts, measurement will be difficult in the case of unconsciousness or an uncooperative patient, such as a patient with brain injury or spinal cord injury. It is also difficult in patients who have thoracic wall wounds or who have known or suspected infections that represent an increased risk of contact transmission. Currently, numerous inventions of devices used to measure chest wall dimensions[8-12] may compensate for the limitations discussed previously.

These devices, however, must be used in conjunction with other instruments, such as body markers, computers, camcorders, etc., which may not be suitable for clinical use. Based on the fact that the expansion was the length, a previously reported device for measuring length was adapted from an ultrasound sensor.[13,14] It consists of a transmitter and a receiver that can transmit and receive ultrasonic sound. The sensor's principle is to measure the time to flight of an ultrasonic soundwave from the sensor to a detected object. It provides noncontact range detection with high validity. It is unaffected by sunlight or dark materials.[15] Furthermore, it can be used without any other instruments. As a result, the researchers attempted to develop a chest expansion measurement prototype device using an ultrasonic sensor, and the current study was conducted to evaluate its validity and reproducibility in comparison to standard equipment. In addition, evaluating opinions on the device from experienced physical therapists was also conducted. The data provided will aid researchers to improve the device so that it can be used more effectively and alleviate the limitations of chest expansion measurement in some clinical conditions.

Materials and methods

The study was approved by the Khon Kaen University Ethical Committee (HE621260), and written informed consent was obtained from all subjects.

Developing the device

The device consists of two parts: the body, in which the set of sensors is located, and the standing part that fixes into the bed rail, as shown in Figure 1(A). It was produced by adapting twenty-five HC-SR04 ultrasonic sensors (version 1.0) and an aluminium structure. The sensor was a product of Cytron Technologies® Sdn. Bhd., Johor, Malaysia. The measurement range of the sensor is 2-400 cm and the precision is 0.3 cm.[15] The set of sensors consists of two ultrasonic transducers: the transmitter and the receiver. To measure chest expansion, device's body is set at a height of 60 cm above the mattress by fix the standing part to the bed's upper handrail, and the start button that is located on the body is pressed. The sensor will then transmit ultrasonic bursts one by one at a frequency of 40 kHz. The sound then travels through the air and finds the mattress or the subject's chest wall. After that, it bounces back to the module and the reflected wave is detected by the receiver. The time between the transmission and reception of the signal allows the processor board settled inside the device's body to calculate the distance. After that, the received distance is processed again to obtain the results from the calculations between several sensors installed to indicate the chest wall distance from side to side. Finally, the distance that represents the chest expansion is expressed on the LCD screen.

Subjects for chest expansion measurement

Sample size of the first study was calculated for correlation analysis, based on the level of correlation coefficient =0.8, and estimated drop out of 10%.[16] One hundred and ten subjects between the ages of 20 and 60 were recruited. Personal information was gathered using a self-administered questionnaire. All subjects were healthy and had no medical conditions. Their BMIs were between 18.5-22.9 kg/m^2. In addition, they were asked to keep their normal physical activity while participating

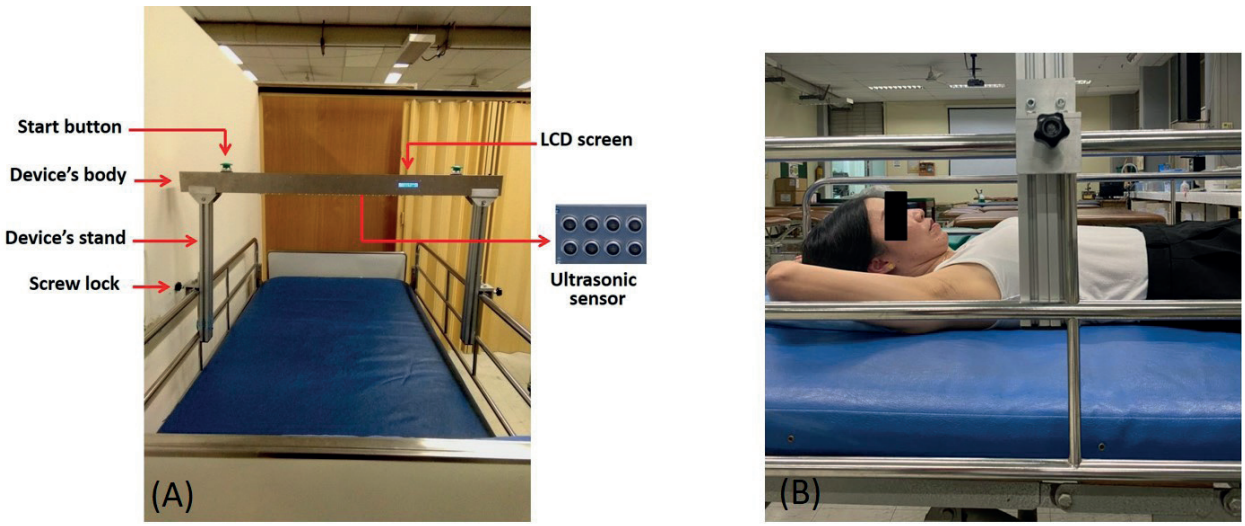

Figure 1. *Device's component (A) and the measurement position (B).*

in the study. Subjects were excluded if they had physical situations altering respiratory mechanics, i.e., scoliosis or kyphosis, or had a history of fainting while taking a deep breath or holding a breath, syncope of unknown origin, or a history of clavicle, rib, or sternum fracture less than six months prior.

Chest expansion measurement

To evaluate the device's validity, chest expansion in the transverse dimension was measured by two different instruments: a 20-inch-scale Martin Breadth Caliper as the standard and the device. To evaluate the device's reproducibility, chest expansion was evaluated under two conditions. On the first visit (V_1), it was measured by two examiners: a professional (Ex_1) and a general (Ex_2) physical therapist whose order was random. On the second visit (V_2), it was only re-assessed by the Ex_1. The protocol is shown in Figure 2. Each subject was instructed to perform breathing exercises at three levels—the upper, middle, and lower chest-to maximise each level of expansion. Upper chest expansion was measured at the level of the third intercostal space.[5] Middle and lower chest expansion were measured at the level of the fourth intercostal space[17] and the level of the xiphoid process, respectively.[1,5,18] The test procedure was standardized, and the two examiners involved were trained in testing before the study started to avoid measurement errors. In this study, block randomization was employed using computer-generated random numbers for the examiners and the subjects. The subjects were divided at random into the caliper then device group (CD group) and the device then caliper group (DC group). All subjects were measured in a supine position with their hands placed on their head, as shown in Figure 1(B). For the caliper measurement, the chest expansion was measured by placing the C-shaped arm end over the left to right chest wall at the mid-axillary line.[1] For the device measurement, the chest expansion was measured by operating method that previously mention in the "developing the device" topic. Three trials at each level were measured, with a 5-minute rest between the levels. The best value was then selected. After resting for 15 minutes, the CD group and the DC group exchanged instruments. Finally, measurements using the device were repeated on V_2 one day apart by the Ex_1. All measurements in the study were conducted in a room with the temperature set at 26±2 °C to avoid environmental factors affecting the ultrasonic sensor's capability.

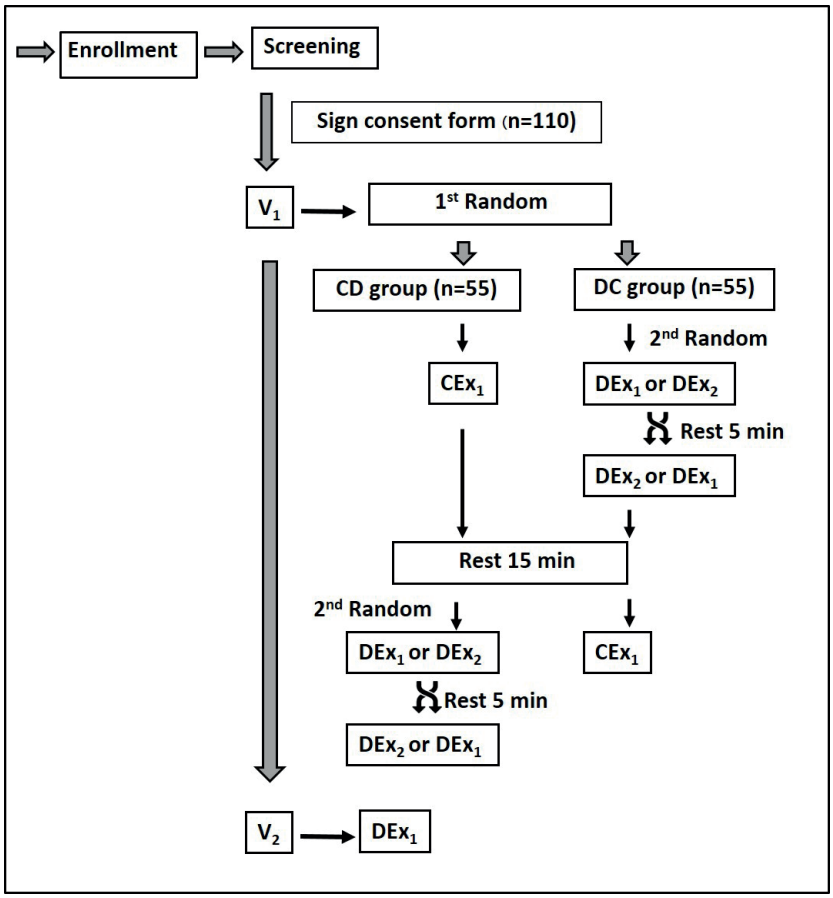

Figure 2 *Consort diagram of the study.*
V_1: First visit, V_2: second visit, CD group: caliper then device group, DC group: device then caliper group, CEx_1: caliper measured by professional physical therapist, DEx_1: device measured by professional physical therapist, DEx_2: device measured by general physical therapist.

Experienced physical therapists and the questionnaire

The second sample consisted of 10 experienced physical therapists who were invited to participate in the study through purposive sampling. All had been working at a hospital for more than two years. The instrument was a two-part self-administered questionnaire. The first part was divided into three questions. The first question dealt with the structure of the device and gathered opinions about its material, strength, weight and size, and overall appearance. The second question elicited feedback on device stability, safety, portability, and ease of use. The last question assessed opinions on device cleaning and storage, as well as overall satisfaction. In this part, each physical therapist was asked to rate their satisfaction on a five-point Likert scale ranging from 1 ("disagree") to 5 ("strongly agree"). Furthermore, the second part required all of them to include any additional suggestions or comments about the device. Following the demonstration of device usage, the questionnaire was distributed and collected within seven days by asking respondents to return it via postal mail. Following that, all suggestions were compiled.

Statistical analysis

Descriptive information, i.e. the general characteristics of the subjects and the opinions expressed in the questionnaires, are presented in the form of percentages. Data are expressed as the mean±SD. The statistical analysis was performed using the STATA programme version 10.5 software. Pearson's correlation analysis and Bland–Altman plotting were performed for the assessment of validity and reproducibility. Values of $p<0.05$ were considered to indicate statistical significance.

Results

Personal information about the subjects is depicted in Table 1. To evaluate the device's validity, the correlation between the caliper-measured expansion and the device is shown in Table 2. Between the upper and middle chest expansions, the lowest and lowest correlations were found. The lower chest expansion, on the other hand, had a medium correlation, and these patterns were seen in both examiners (Table 2). For reproducibility, a good correlation between device measurements taken on different trial visits by the Ex_1 was 0.81 ($p<0.001$) for the upper and the middle, and 0.84 ($p<0.001$) for the lower chest expansion. The sample of Bland-Altman plots between the two instruments and two trial visits by the Ex_1 are shown in Figures 3(A) and 3(B). As this shows, almost all of the values are within a mean±2SD deviation.

Table 1. General characteristics of the subjects for chest expansion measurement (n=110).

Characteristics	Mean (min-max)
Male: Female [n (%)]	25: 85 (23%: 77%)
Age (years)	32.0±12.8 (20-58)
Body weight (kg)	56.1±6.72 (44.4-78.2)
Height (cm)	161.6±7.77 (146.0-185.0)
BMI (kg/m2)	21.5±1.58 (18.0-22.9)
Waist circumference (cm)	73.9±7.88 (58.0-90.0)
Hip circumference (cm)	93.2±5.36 (78.0-109.0)
WHR	0.79±0.07 (0.66-0.94)

Note: *Values are mean±SD unless otherwise indicated. BMI: body mass index, WHR: waist-to-hip ratio.*

Table 2. Chest expansion and device correlation.

		Upper	Middle	Lower
Expansion (cm)	Caliper	1.15±0.29	1.34±0.43	2.97±0.88
	(min-max)	(0.6-2.2)	(1.0-3.0)	(1.2-5.0)
	Device Ex_1V_1	1.49±0.31	2.15±0.53	3.47±1.35
	(min-max)	(0.9-2.5)	(1.1-3.5)	(0.6-8.9)
	Device Ex_1V_2	1.64±0.33	2.38±0.54	4.17±1.51
	(min-max)	(0.9-2.6)	(1.2-4.0)	(1.1-10.0)
Correlation	Ex_1V_1	0.10	0.20	0.69
(*p* value)		(0.302)	(0.033)	(<0.001)
	Ex_2V_1	-0.19	-0.02	0.42
		(0.503)	(0.847)	(<0.001)
	Ex_1V_2	0.01	0.11	0.65
		(0.922)	(0.263)	(<0.001)

Note: *Data expressed in mean±SD. Ex_1: professional physical therapist, Ex_2: general physical therapist, V_1: the first visit and V_2: the second visit.*

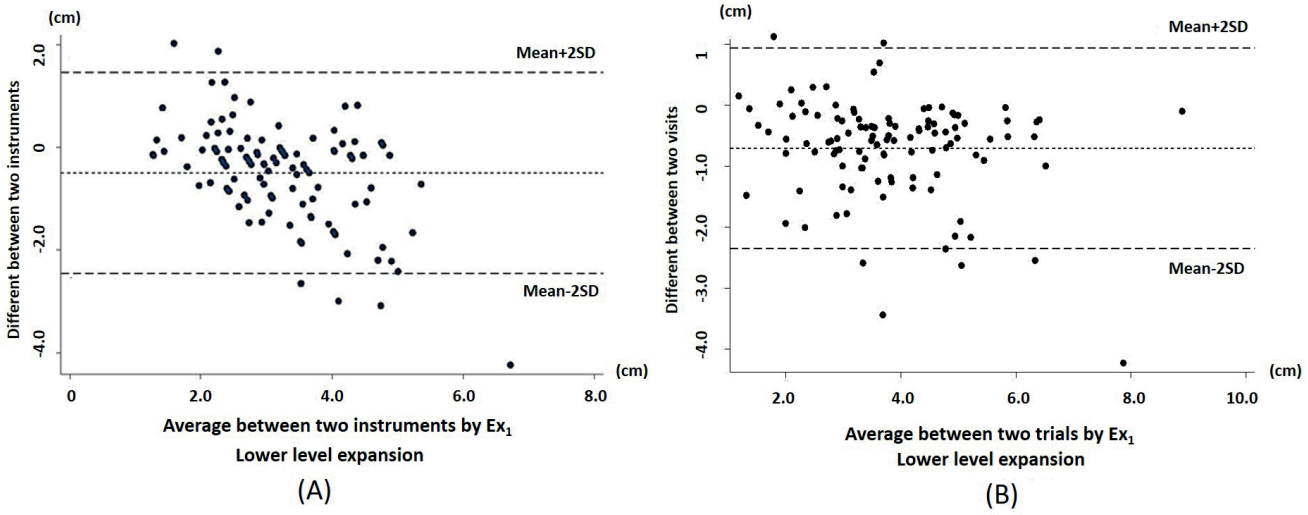

Figure 3. *Bland-Altman plots of the lower-level expansion between the two instruments (A) and two trial visits (B) by the* Ex_1.

Ten experienced physical therapists provided their opinions on the device. Almost all (80%) strongly agreed with the device's material, which is made from aluminum. Furthermore, 70% and 60% of them strongly agreed on the device's strength and stability, respectively. Only 60% of them agree with its weight and size and ease of use. Furthermore, they strongly agreed and agreed with the device's safety and ease of cleaning and storing on a half-to-half basis. However, almost all of them indicated that the devices were difficult to transport (neutral 50%, slightly disagree 40%). Furthermore, it should improve its overall appearance (40% agree and 30% neutral) and overall satisfaction (20% strongly agree and 80% agree). The interesting additional suggestion and comment from the last section included the charging component should be adapted outside the device. It would be preferable if it could be easily adjusted up to the bed's headboard or down to the footboard. One opinion suggested that it may not appear sufficiently like a medical device if the material is made with a carbon or fiber frame.

Discussion

Validity and reproducibility are two of the key features of evaluation instruments. The present study found that Pearson's correlation coefficients of intra-examiner reproducibility were considerably high. Almost all values in the Bland-Altman plots were within a 2SD deviation of the mean. However, the validity was unsatisfactory. These findings might be explained by the following reasons.

According to the capability of the invented device, one by one, the twenty-five HC-SR04 transmitters emit a high-frequency sound at 40 kHz. The sound then travels through the air and finds the mattress or the subject's chest wall. After that, it bounces back to the module. Based on the product user's manual, even though the sensor is capable of excellent performance, it has some limitations.[15] First, its limitations are related to the object's size and the distance between the sensors. The sensor and the object must be no more than 4 m or less than 2 cm apart, and the object must be no smaller than 0.3 cm in order to reflect enough sound waves back to the sensor. The object evaluated in the study was the thorax; therefore, the factor attributed to the device's validity may not be accounted for by the object's size. Additionally, the device's stand was designed to be able to adjust the distance above the bed's lower handrail to a maximum of 50 cm. In the study, the device's stand was installed by attaching it to the bed's upper handrail. Therefore, device's body was set 60 cm above the mattress to provide a comfortable space for the subject's body size. As a result, the sensor's distance from the chest wall was within the measurement range.

Another limitation is that the ultrasound wave generated by the sensor used in the study was classified as low-frequency ultrasound (20-200 kHz), which is usually applied in industrial and therapeutic applications.[19] Although the sensor's functionality is not affected by light or color. However, it was limited by the shallow reflective surface angle (<15 degrees), which meant that the sound wave could not be reflected back towards the receiver.[15] Moreover, there is the surface of the object to consider. Based on the theory of sound, there are many different phenomena leading to a loss in strength and distortion of the signal between the transmitter and receiver. These phenomena include reflection and transmission at the boundaries between media, attenuation in the media and loss in received sound energy due to dispersion.[20] To avoid false detection of the boundary of the chest wall by the shoulder, all subjects were measured in the supine position with their hands on their heads. They also provided a white cotton tank top that fit their bodies and allowed the female subjects to wear their bras. Given these circumstances, it was obvious that their bras almost covered the measurement areas. As a result, the device's poor validity, particularly at the upper and middle levels, could be explained by the bra fabric transmitting the sound wave and then attenuating the reflection to the sensor. In accordance with the clinical situation, the patients' chest expansion was measured while wearing only a hospital

patient gown. To validate this possibility, the next study will be conducted only on male subjects or on both genders, but only in the context of wearing hospital patient attire.

Previous studies have reported the greatest expansion was found at the lower level.[5,6,21] Notably, these patterns were discovered in the current study. Under normal physiological conditions, the upper ribs more move upward than outward; however, the lower ribs have more freedom of motion, this contributed to the lower level's broadening expansion.[22,23] It was observed that the mean expanded value at the upper chest level was 1.15 cm and the minimum value was 0.6 cm, while the sensor resolution was 0.3 cm. Based on the limitations of the sensor, less movement might have the potential to affect device validity. In addition, the device measured the transverse dimension of the chest wall, whereas the upper ribs move more upward than outward; this additional fact may have contributed to the study's lowest and lowest of the Pearson's correlation found at upper and middle chest level. Furthermore, during measurement, the lower level of the male subjects was only covered by the tank top, whereas some of the female subjects were also covered by their bras. This condition could be related to the medium level of the correlation finding at the lower level. As a result, not only the further study that was mentioned earlier but also a sensor replacement with a higher validity ultrasonic sensor generation or additional with another sensor type will be performed to achieve greater validity.

The researchers agree with the experienced physical therapist's that suggested to improve the device. For the usage, the device's stand should be redesigned so that it can be easily moved up to the headboard or down to the footboard by adjusting along the bed's handrail. In addition, because the battery was installed inside the device's body, it could not be moved to charge outside. According to this suggestion, the researcher will widen the charger slot to make it easier to plug in and disconnect the battery cable. For the structure, the size and weight should be smaller and lighter to enhance its portability to carry around when used in the clinic. Although, the aluminum structure might be suitable to be strong, lightweight, durable, and resistant to corrosion when cleaning. However, it should be noted that the higher the number of sensors, the greater the number of processor boards. As a result, the number of sensors and apparatus located in the body accounts for nearly all the device's weight. Furthermore, in conjunction with the previously discussed HC-SR04 sensor, the researchers intend to minimize its limitations to improve its validity, reduce its overall weight and size, and improve its appearance.

Study limitations

There were four limitations in the study. Firstly, based on the fact that measuring thoracic expansion during a clinical workout in the unconscious or even in those with mobility problems or muscle weakness, such as quadriplegia patients or patients with myasthenia gravis or Amyotrophic Lateral Sclerosis, etc., is difficult because they cannot be upright. According to the preceding condition, the supine position was chosen in the study to mimic the problems encountered while performing in the clinic, despite the fact that it limited the motion of the chest to expand. Secondly, there was no statistical test involve in the reliable tests of the professional examiner. Thirdly, the study was unable to validate that the cloth absorbed ultrasound waves through the bare skin. This is because clinical measurements of chest expansion are taken while wearing clothing. Lastly, to conduct the study, subjects with a normal BMI were used. As a result, for other body sizes, the validity may be different, and the results may differ from those found in this study.

Conclusion

Based on the results, it is possible to conclude that, while the device's reproducibility with an ultrasonic sensor is quite high, its validity appears to be very low to moderate, depending on the expansion levels measured. Furthermore, the sensor should be modified to improve its validity, and the device's overall appearance should be improved to maximize its aesthetics.

Conflicts of interest

The authors declare no conflicts of interest.

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