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Original Research Article

CAN LOW COST FINGERTIP PULSE OXIMETERS BE USED TO MEASURE OXYGEN SATURATION AND HEART RATE DURING WALKING?

Jonas LaPier [1], Megan Chatellier *[2].

[1] Research Assistant, Physical Therapy Dept., Eastern Washington University, Spokane, WA, USA.

*[2] Assistant Professor, Physical Therapy Dept., Eastern Washington University, Spokane, WA, USA.

ABSTRACT

Background: Measurement of oxygen saturation (SpO2) during activity and exercise is important for clinical treatment and prognostic decision-making, but oximeter error can be problematic. New generation fingertip pulse oximeters are readily available and inexpensive; therefore, their potential clinical applications are rapidly expanding. While the performance of new generation tabletop and handheld pulse oximeters has been evaluated, little information is available on the accuracy of fingertip pulse oximeters, especially during activity.

Purpose: The objective of this study was to determine if new generation low cost fingertip pulse oximeters provide accurate and consistent measurements of oxygen saturation (SpO2) and heart rate (HR) during walking.

Materials and Methods: Nine different fingertip oximeter models were evaluated during treadmill walking at one and two mph in healthy subjects (n = 32). Oximeter readings from both hands were simultaneously recorded and a 15 second electrocardiogram (ECG) strip was printed. Paired t-tests were used to determine differences in SpO2 measurements between oximeter pairs. An ANOVA was used to determine differences in HR measurements among oximeter pairs and ECG. Error rates were also calculated.

Results: A significant difference in SpO2 values was identified between oximeter pairs for two models when subjects walked at one mph. Additionally, a significant difference in HR values existed between oximeter pairs and the ECG for two models when subjects walked at one mph. No differences were found in SpO2 or HR measurements when subjects walked at two mph. Oximeter performance was better when measuring SpO2 than HR. Also, in this study pulse oximeters performed better when subjects walked at higher versus lower exercise intensities.

Conclusions: The results of this study suggest that accuracy and consistency of fingertip oximeter measurements are less than ideal during treadmill walking. Clinicians should use caution when interpreting HR values obtained with fingertip pulse oximeters during exercise.

KEY WORDS: Pulse oximeter, oximetry, oxygen saturation, heart rate, exercise, exercise-induced desaturation.

Address for correspondence: Megan Chatellier, Eastern Washington University PT Dept., 310 N Riverpoint Blvd, Box T, Spokane, WA 99202, Phone: (509) 828-1372, Fax: (509) 828-1389
E-Mail: functionaloutcomespt@gmail.com

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INTRODUCTION

Pulse oximeters are commonly used in medical settings to non-invasively measure arterial oxyhemoglobin saturation (SpO2) and heart rate (HR) at baseline and with therapeutic interventions [1-3]. They allow for vital continuous monitoring of oxygenation in patients with oxygen loading impairments such as chronic obstructive pulmonary disease and heart failure. While the performance of new generation tabletop and handheld pulse oximeters has been evaluated, little information is available on the accuracy of fingertip pulse oximeters [4-7].

New generation fingertip pulse oximeters are readily available and inexpensive therefore their potential clinical applications are rapidly expanding. Their low cost potentially increases global accessibility, which could have substantial implications for public health [8, 9]. These oximeters also allow clinicians to monitor SpO2 in many settings outside of the acute care hospital. Likewise, use of inexpensive fingertip oximeters may become an important tool in patient self-management of chronic diseases if they provide consistent, accurate measurements [10].

Pulse oximeters calculate SpO2 and HR by comparing the light absorbency values of oxyhemoglobin and deoxyhemoglobin when red and infrared wavelengths are emitted through blood vessels. For these wavelengths, hemoglobin is the primary source of light absorption; however, chromophores (such as melanin) and venous blood also absorb red and infrared light so it is important to isolate the arterial blood component.Photoplethysmography (PPG) measures the light-absorption increase due to arterial blood volume during systole. Measurement of PPG in both wavelengths allows for the arterial contribution of the total light absorbance to be calculated [3].

Monitoring oxygen saturation is important during activity and exercise in many patient populations [11-14], but oximeter error due to diminished distal perfusion and/or sensor movement can be problematic [2, 3]. Therefore, the purpose of this study was to determine if nine new generation low cost fingertip pulse oximeters provide accurate and consistent measurements of SpO2 and HR during treadmill walking.

MATERIALS AND METHODS

This study used a within subjects design with repeated measures. The term oximeter pair was operationally defined as two different oximeters of the same model placed on the same finger of the opposite hand (i.e. index finger of right hand and index finger of left hand). Nine different fingertip oximeter models were evaluated in this study and are outlined in Table 1. Study fingertip oximeters ranged in price from approximately $20 to $200 USD and only one was not designated as Food and Drug Administration cleared. Eight of these oximeters used transmissive sensors and spring clip mechanism for fingertip attachment. The SPO Medical PulseOx 5500 used a reflectance sensor and had a soft shell sleeve for finger attachment.

Study Participants: Participants (n=32) were a convenience sample recruited from a university community. Inclusion criteria were: (1) age 21-75 years, (2) ability to walk on treadmill at slow speeds, (3) intact sensation, and (4) ability to provide informed consent. Exclusion criteria were: (1) diagnosis of peripheral arterial disease, peripheral venous disease, ischemic stroke, coronary artery disease, myocardial infarction, or diabetes, (2) resting HR over 120 bpm, (3) any contraindication for exercise participation as outlined by the American College of Sports Medicine Guidelines for Exercise Testing [15],or (4) diminished peripheral circulation. Diminished peripheral circulation was operationally defined as two or more of the following abnormal examination findings: cyanosis, digital clubbing, cool/cold skin temperature, capillary refill greater than three seconds, and pitting edema. All study procedures were performed with prior written informed consent from each participant. The Eastern Washington University Institutional Review Board for Human Subjects approved the study procedures and informed consent.

Protocol: After obtaining informed consent, participants underwent a basic health and screen to obtain baseline physiological data and information pertaining to their health. Skin on the upper extremities was screened for changes in color, integumentary disruption, scar tissue, and trophic changes. In addition, skin pigmentation was rated using the Fitzpatrick Skin Type Classification; the scale measures six skin types from the lightest, Type I (pale white, freckles, always burns, never tans), to the darkest, Type VI (deeply pigmented, dark brown to black, never burns, tans very easily) [16]. Sensory integrity of the upper extremities was examined for light touch in different nerve distributions. Next, a study investigator explained the testing procedures and demonstrated use of a pulse oximeter. Electrodes to monitor ECG (electrocardiogram) and measure HR were placed on the participant's chest under each clavicle (at midclavicular line) and on the left side of the abdomen (lateral to umbilicus).

First, participants walked at one mph on a treadmill (Trackmaster, Model TMX425C, Full Vision Inc., Newton, KS). Study investigators continually monitored the participants' vital signs (SpO2, HR, and ECG rhythm) and guarded them during treadmill walking. After five minutes of walking, two different oximeter models were placed on the index and middle finger with identical models on the opposite hand. After 30 seconds, oximeter readings were simultaneously recorded from both hands by two study investigators and a 15 second ECG strip was simultaneously printed. The order in which oximeters were tested and finger assignment (index or middle) were randomized and testing of all oximeters took approximately three minutes. This process was repeated five times until all oximeter models had been tested. Then, the treadmill speed was increased to two mph and after five minutes of walking, the entire process was repeated.

Statistical Analysis: Descriptive statistics and error rates for SpO2 and HR measurements were calculated. Paired *t*-tests were used to determined differences in SpO2 measurements between oximeter-pairs ($P < 0.05$). To determine differences in HR measurements among oximeter pairs and ECG, ANOVA and Tukey's Honest Significant Difference post hoc tests were used ($P < 0.05$). Error rates were calculated from the number of error readings obtained divided by the total number of possible data points. Statistical analyses were performed using Excel (Microsoft Corporation, Redmond, WA).

RESULTS

Study participants were predominately Caucasian (94%) women (21 vs. 11 men) with a mean (±SD) body mass index of 24.4 ± 2.9 kg/m^2. Their age was 25.3 ± 3.1 years with a range of 21-33 years. Resting HR, SpO2, and blood pressure were 65.2 ± 14.1 bpm, 98.3 ± 1.2%, and 113 ± 24/71 ± 7 mm Hg, respectively. None of the study participants smoked or had a history of smoking. Skin types identified in study participants were 25% Type II (fair white), 40% Type III (cream white), and 30% Type IV (moderate brown) on the Fitzpatrick Scale. Tables 2 and 3 outline SpO2 means ± SD, differences and error rates for treadmill walking at one and two mph, respectively. The range of SpO2 means for one mph walking was 94.0% - 98.0% and for two mph walking was 96.0% - 97.6%. A significant difference was found in SpO2 values between oximeters pairs for two models (C and I), the Concord Emerald ($P = 0.002$) and SPO Medical PulseOx 5500 ($P = 0.046$), when subjects walked at one mph. No differences were found in SpO2 values between oximeters pairs when subjects walked at two mph. For both walking speeds, the greatest mean difference between SpO2 values was 1.7%. Error rates at one mph walking were as high as 12.5% and for two mph walking the greatest error rate was 4.7%.

Table 1: Fingertip pulse oximeter models and manufacturer information.

Oximeter ID	Name	Manufacturer
A	ChoiceMMed MD-300C12	Choice Electronic Technology Co., Ltd. Beijing, Hebei, China
B	Concord Black Ox*	Concord Health Supply Lincolnwood, Illinois, USA
C	Concord Emerald	Concord Health Supply Lincolnwood, Illinois, USA
D	Contec CMS-50DL	Contec Medical Systems Co., Ltd. Qinhuangdao, Hebei, China
E	FaceLake FL-100	FaceLake Lake Bluff, Illinois, USA
F	Nonin Onyx Vantage 9590	Nonin Medical Plymouth, Minnesota, USA
G	Santamedical SM-110	Santamedical Tustin, California, USA
H	Contec CMS50-D+	Contec Medical Systems Co., Ltd. Qinhuangdao, Hebei, China
I	SPO Medical PulseOx 5500	SPO Medical Equipment Ltd Sylmar, California, USA

*Not Food and Drug Administration cleared

Tables 4 and 5 outline HR means ± SD, differences and error rates for treadmill walking at one and two mph, respectively. The range of HR means for one mph walking was 79.0-96.5 bpm and for two mph walking was 85.9-101.5 bpm. There was a significant difference in HR values between oximeters pairs and the ECG for two models (C and H), the Concord Emerald ($P = 0.046$) and Contec CMS50-D+ ($P = 0.049$), when subjects walked at one mph.No differences

Table 2: Oxygen saturation mean ± SD, difference, and error rate during treadmill walking at 1 mph.

Oximeter ID	Unit #1 (%)	Unit #2 (%)	Δ (%)	Error (%)
A	97.1 ± 1.5	96.4 ± 2.3	0.7	1.6
B	95.9 ± 3.4	96.0 ± 3.4	0	6.3
C	97.3 ± 1.9	95.8 ± 3.5	1.5*	0
D	96.3 ± 2.5	94.8 ± 4.1	1.6	3.1
E	97.4 ± 1.9	97.3 ± 1.4	0	12.5
F	97.6 ± 2.9	97.0 ± 4.1	0.6	0
G	96.0 ± 5.0	96.1 ± 2.9	0.1	1.6
H	95.6 ± 4.4	94.0 ± 5.7	1.7	0
I	98.0 ± 0.8	96.8 ± 3.3	1.2*	3.1

Δ = Difference between means; *P < 0.05

Table 3: Oxygen saturation mean ± SD, difference, and error rate during treadmill walking at 2 mph.

Oximeter ID	Unit #1 (%)	Unit #2 (%)	Δ (%)	Error (%)
A	96.8 ± 2.7	96.4 ± 3.1	0.4	0
B	97.1 ± 2.8	96.9 ± 3.1	0.2	0
C	96.6 ± 3.7	96.4 ± 3.0	0.2	0
D	97.1 ± 5.8	96.0 ± 3.0	1.1	3.1
E	97.0 ± 2.2	97.0 ± 1.5	0	4.7
F	97.3 ± 2.2	97.2 ± 2.0	0.1	1.6
G	96.7 ± 3.7	96.3 ± 4.0	0.4	0
H	96.3 ± 3.5	96.2 ± 3.3	0.1	1.6
I	97.6 ± 1.1	96.9 ± 2.2	0.7	0

Δ = Difference between means; *P < 0.05

Table 4: Heart rate mean ± SD, difference, and error rate during treadmill walking at 1 mph.

Oximeter ID	Unit #1 (bpm)	Unit #2 (bpm)	ECG (bpm)	Δ (bpm)	Error (%)
A	83.8 ± 13.6	79.0 ± 12.4	80.4 ± 11.8	4.8	1.6
B	83.1 ± 15.0	81.5 ± 15.3	81.3 ± 12.3	1.9	6.3
C	84.1 ± 13.4	91.2 ± 21.3	81.4 ± 11.9	9.8*	0
D	93.4 ± 34.8	83.5 ± 17.9	80.5 ± 11.6	13	3.1
E	80.0 ± 12.1	80.1 ± 13.3	81.0 ± 12.1	1	12.5
F	81.1 ± 11.6	80.0 ± 11.9	81.4 ± 11.8	1.4	0
G	79.5 ± 13.1	84.7 ± 12.2	81.1 ± 12.2	5.2	1.6
H	85.5 ± 28.5	96.5 ± 33.7	81.0 ± 11.9	15.5*	0
I	81.5 ± 12.1	83.0 ± 12.8	81.0 ± 12.4	2	3.1

Δ = Greatest difference among means; *P < 0.05

Table 5: Heart rate mean ± SD, difference, and error rate during treadmill walking at 2 mph

Oximeter ID	Unit #1 (bpm)	Unit #2 (bpm)	ECG (bpm)	Δ (bpm)	Error (%)
A	91.8 ± 16.4	91.8 ± 16.8	88.1 ± 13.3	3.7	0
B	91.4 ± 16.2	85.9 ± 15.9	88.4 ± 13.4	5.5	1.6
C	94.1 ± 21.1	91.7 ± 19.4	88.9 ± 12.8	5.2	0
D	95.9 ± 27.9	101.5 ± 28.0	87.6 ± 13.5	13.8	3.1
E	87.4 ± 14.8	86.1 ± 15.9	89.4 ± 13.5	3.3	6.3
F	86.5 ± 15.3	88.9 ± 12.2	88.3 ± 12.6	2.4	1.6
G	91.0 ± 14.4	91.9 ± 13.1	90.0 ± 12.8	1.9	0
H	94.1 ± 20.8	95.6 ± 24.9	88.6 ± 12.7	7	1.6
I	88.8 ± 12.2	92.2 ± 22.1	88.6 ± 12.8	3.5	0

Δ = Greatest difference among means; *P < 0.05

were found in HR values between bilateral oximeters when subjects walked at two mph. For both walking speeds, the greatest mean difference between HR values and the ECG was 15.5 bpm. Error rates at one mph were as high as 12.5% and for two mph walking the greatest error rate was 6.3%.

DISCUSSION

The results of this study suggest pulse oximetry accuracy and consistency is less than ideal during treadmill walking. Although we found a significant difference between SpO2 means for two oximeter models during treadmill walking at one mph, the greatest SpO2 difference was 1.5%. This is not a clinically important difference as most manufacturers state an accuracy of 2% which is the standard deviation of the differences between SpO2 and the in vitro measurement of saturated hemoglobin in arterial blood (SaO2) [3]. We found a clinically important difference (≥ 10 bpm) in HR for three oximeter models (C, D, and H) during treadmill walking. Two of the oximeter models tested, the Concord BlackOx (B) and FaceLake FL-100 (E), had high (>5%) SpO2 and HR error rates. Overall study results indicate that the pulse oximeters tested had good accuracy for SpO2 readings but not for HR in some models. Although there are other more accurate methods of measuring HR, pulse oximeters are frequently used in clinical settings to continuously monitor HR during activity, especially when ECG is not available. The frequent error readings found in some of the oximeter models tested may limit their clinical use.

Accurate pulse oximeter readings are especially difficult to obtain during activity and exercise. In a previous study analyzing the performance of these fingertip pulse oximeters when subjects were at rest, we found lower SpO2 differences, HR differences, and error rates than in the current study. The greatest SpO2 difference between bilateral oximeters was 0.7% and the greatest SpO2 error rate was 3.3%. The maximum HR difference between oximeters pairs or ECG was 2.1 bpm and the maximum error rate was 3.8% [17]. Other studies have evaluated the accuracy of pulse oximeters during movement or exercise but not specifically fingertip models [4,7,18].

There are several possible causes of oximeter measurement inaccuracy during activity and exercise. One source is movement artifact, specifically the result of sensor movement on the skin [18, 19]. Also, exercise causes increased sympathetic activity which results in vasoconstriction, diminished distal arterial perfusion, and a weaker PPG signal. Because exercise increases venous return, the amount of venous blood remaining in the fingertip decreases thereby altering the oximeter's background light absorbance measurement and reducing accuracy [19, 20]. There is little consensus among previous studies on the effects of exercise on pulse oximeter accuracy [18, 19, 21]. Motion tolerant technology exists and uses digital signal processing to reduce signal noise [22, 23]. However, it was not present in any of the inexpensive fingertip oximeter models tested in our study.

Surprisingly, we found less difference in mean values and lower error rates for SpO2 and HR at two mph walking than one mph walking. These results suggest movement artifact is not predominantly responsible for the observed oximeter inaccuracy and that vascular adjustments are an important factor. Although at the moment of measurement subjects held their hands still, whole body movement during walking was still greater at the faster speed than the slower speed. McGovern et al. [21] hypothesized that SpO2 measurements would be more accurate at higher than lower exercise intensities because of increased cardiac output; however, study results did not support their hypothesis. Martin and colleagues [24] analyzed pulse oximetry and co-oximetry in eleven endurance athletes and found less measurement bias (%SpO2 - %SaO2) at higher exercise intensities than lower exercise intensities. Finger perfusion may improve as a result of intensity dependent responses: increased local metabolic factors, increased body temperature, or a combination of these responses. At the onset of exercise and at low intensities, activation of the sympathetic nervous system causes systemic vasoconstriction. To increase blood flow to metabolically active areas, the exercise pressor reflex responds to mechanical and chemical stimuli to decrease sympathetic-mediated vasoconstriction resulting in increased blood flow [20, 25]. Also, as core body temperature increases, blood is shunted to the periphery in order to dissipate heat. Other studies have shown the negative influence of cold inducing vasoconstriction and the positive influence of heat inducing vasodilation on oximeter performance [26, 27].

Study results should be interpreted cautiously due to several study limitations. We tested only young healthy non-smoking subjects with good perfusion and normal oxygen saturations (>90%); however, this also means the tested oximeters had the greatest potential for success. We speculate that oximeters performing poorly in this population would also perform poorly or worse in patients who smoke, have diminished perfusion, have arterial oxygen saturations below 80%, or a combination of these factors. Another limitation of our study was the lack of direct co-oximetry measurements of blood arterial oxygen saturation as the criterion of SpO_2 arterial oxygen saturation, but others have also examined pulse oximeter performance without co-oximetry [4, 6, 18, 27]. In addition, all study participants had light skin pigmentation so results cannot be extrapolated to individuals with dark skin. Probe type oximeters may overestimate SaO_2 under hypoxic conditions in dark skinned individuals [28, 29], but no comparable data is currently available for fingertip oximeters. A potentially confounding variable in our study was that the order of exercise intensity was not randomized and subjects always walked on a treadmill at one mph then two mph. Because order of intensity was not randomized, it is impossible to definitively determine whether improved pulse oximeter accuracy is intensity dependent or time dependent.

Further investigations are needed to fully elucidate the usefulness of inexpensive fingertip oximeters. Future exercise studies should randomize order of exercise intensity and evaluate methods to reduce motion artifact such as reinforcing the fingertip oximeter attachment mechanism or using a remote/wireless probe. Fingertip oximeter accuracy and consistency must also be evaluated when blood oxygen saturations are less than 90% either induced artificially in healthy subjects or in patients with oxygen loading impairments.

CONCLUSION

This study assessed nine new generation fingertip pulse oximeters using oximeter pairs on bilateral hands and ECG measurement of HR. Oximeter performance was more accurate when measuring SpO2 and less accurate when measuring HR. In this study, pulse oximeters also performed better when subjects walked at higher exercise intensities, than lower exercise intensities. Measurement of SpO2 during activity and exercise is important for clinical treatment and prognostic decision-making. Use of inexpensive fingertip oximeters may become an important tool in patient self-management of chronic diseases if they provide consistent, accurate measurements.

ABBREVIATIONS

SpO2 - Arterial oxyhemoglobin saturation (measured by pulse oximeter)
HR- Heart rate
PPG - Photoplethysmography
ECG - Electrocardiogram
SaO2 - Arterial oxyhemoglobin saturation (measured directly)

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Conflicts of interest: None

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