



A smartphone oximeter with a fingertip probe for use during exercise training: usability, validity and reliability in individuals with chronic lung disease and healthy controls

C. Chan^{a,b}, J.A. Inskip^{a,b}, A.R. Kirkham^a, J.M. Ansermino^{c,d}, G. Dumont^{c,d},
L.C. Li^{b,e}, K. Ho^f, H. Novak Lauscher^f, C.J. Ryerson^{a,g,i}, A.M. Hoens^b,
T. Chen^c, A. Garde^{c,h}, J.D. Roadⁱ, P.G. Camp^{a,b,g,*}

^a Centre for Heart Lung Innovation, University of British Columbia, Vancouver, Canada

^b Department of Physical Therapy, University of British Columbia, Vancouver, Canada

^c Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada

^d Department of Anesthesiology, Pharmacology and Therapeutics, University of British Columbia, Vancouver, Canada

^e Arthritis Research Canada, Richmond, Canada

^f Department of Emergency Medicine, University of British Columbia, Vancouver, Canada

^g Providence Health Care, St. Paul's Hospital, Vancouver, Canada

^h Department of Biomedical Signals and Systems, University of Twente, Enschede, The Netherlands

ⁱ Division of Respiratory Medicine, Department of Medicine, University of British Columbia, Vancouver, Canada

Abstract

Background and aim Telehealth is a strategy to expand the reach of pulmonary rehabilitation (PR). Smartphones can monitor and transmit oxygen saturation (SpO₂) and heart rate (HR) data to ensure patient safety during home-based or other exercise. The purpose of this study was to evaluate the usability, validity and reliability of a Kenek O₂ pulse oximeter and custom prototype smartphone application (smartphone oximeter) during rest and exercise in healthy participants and those with chronic lung disease.

Methods Fifteen individuals with chronic lung disease and 15 healthy controls were recruited. SpO₂ and HR were evaluated at rest and during cycling and walking. SpO₂ was valid if the mean bias was within $\pm 2\%$, the level of agreement (LoA) was within $\pm 4\%$; HR was valid if the mean bias was within ± 5 beats per min (bpm), LoA was within ± 10 bpm. Usability was assessed with a questionnaire and direct observation.

Results The smartphone oximeter was deemed easy to use. At rest, SpO₂ measures were valid in both groups (bias $< 2\%$, lower bound LoA -2 to 3%). During exercise, SpO₂ measurement did not meet validity and reliability thresholds in the patients with chronic lung disease, but was accurate for the healthy controls. HR recording during exercise or rest was not valid (LoA > 10 bpm) in either group.

Conclusions The smartphone oximeter did not record HR or SpO₂ accurately in patients with chronic lung disease during exercise, although SpO₂ was valid at rest. During exercise, patients with chronic lung disease should pause to ensure greatest accuracy of SpO₂ and HR measurement.

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Keywords: Chronic obstructive pulmonary disease; Oxygen saturation; Pulmonary rehabilitation; Telerehabilitation; Usability

Introduction

Despite high-level evidence regarding the benefits of pulmonary rehabilitation (PR), most people with chronic obstructive pulmonary disease (COPD) do not have access to

* Corresponding author at: Centre for Heart Lung Innovation, University of British Columbia, 166-1081 Burrard Street, Vancouver, Canada, V6Z 1Y6.

E-mail address: Pat.Camp@hli.ubc.ca (P.G. Camp).

a programme [1,2]. A lack of available PR programmes and low capacity to enrol participants in existing programmes are key factors limiting access [1,2]. Those living far away from PR programmes face geographic barriers, and mobility and transportation barriers significantly decrease the likelihood of attending or completing PR [3–5]. Patients may not be able to attend PR due to other factors, including disruption in their regular routine impacting other obligations or interests [6]. Therefore, physiotherapists and other members of the rehabilitation team need to find alternative ways to deliver PR.

Telerehabilitation is the delivery of home- or community-based rehabilitation using telehealth technology. It may provide a feasible option to hospital-based PR programmes by addressing the geographical barriers to access [7]. Telehealth technology encompasses any technology utilising telephone landlines, the Internet, or mobile or smartphones. Extensive research on the delivery of PR programmes using a telerehabilitation intervention is limited; however, studies using telehealth for COPD management demonstrate benefits. Systematic reviews by Polisena *et al.* [8] and Paré *et al.* [9] reported that using telehealth to monitor symptoms of patients with COPD reduced the rates of hospitalisation and emergency department use, and improved quality of life. A telehealth intervention study conducted by Stickland *et al.* created a pulmonary telerehabilitation programme for those living in rural communities, and found improvements in functional capacity and quality of life that were similar to those in a traditional PR programme [10]. However, this intervention required patients to travel to a health unit for telerehabilitation exercise and education; therefore, transportation barriers may still have been present. A recent randomised clinical trial of 36 patients with COPD by Tsai *et al.* [11] evaluated the benefits of a supervised, home-based, real-time video-conferencing pulmonary telerehabilitation programme. Live videos of patients exercising in their homes were transmitted to the hospital physiotherapist, who was also supervising participants in the hospital PR programme. The investigators found that their telerehabilitation programme resulted in increased exercise endurance, with excellent adherence to the programme (98%).

In PR, physiotherapists measure oxygen saturation (SpO_2) and heart rate (HR) with a portable pulse oximeter, at rest and throughout the exercise session, to ensure that the intensity of exercise is both safe and effective. These measures provide feedback to physiotherapists and other members of the rehabilitation team who then titrate supplemental oxygen levels, reinforce breathing techniques or alter the exercise intensity based on the values. However, in a telerehabilitation setting, there is a greater expectation of independence on the part of the participant. The responsibility of monitoring parameters such as HR and SpO_2 is now shifted to the participant. This means that they are required to confidently measure and interpret SpO_2 and HR measurements

themselves, adjust their exercise accordingly, and be comfortable doing so. This was illustrated in the study by Tsai *et al.* [11]. Although the participants were supervised via the live video-conferencing, they were requested to measure HR and SPO_2 intermittently and adjust their exercise based on those values. Other telerehabilitation programmes that do not have real-time supervision may recommend that patients measure values and adjust exercise or oxygen levels themselves. However, using telehealth technology may be challenging for participants, depending on the complexity of the system. In a recent feasibility study by Paneroni *et al.* [12], pulmonary telerehabilitation was delivered using a videoconferencing platform, telephone calls and Bluetooth biomonitoring accessories. While the authors found that the telerehabilitation option improved health outcomes, the system used in that study was complex, and 61% of participants found the technology difficult to understand and not ‘user-friendly’ [12,13]. Conversely, in the study by Tsai *et al.* [11], the physiotherapist set up a much simpler system that only required a laptop, an oximeter and a cycle ergometer, with real-time video monitoring. The participants in the study by Tsai *et al.* found this system easy to use, and any problems could be dealt with during the session [14].

Over the last 5 years, there has been an exponential increase in mobile health applications (apps) for use on smartphone and tablet platforms that measure various biological indicators relevant to exercise [15]. Smartphones may have utility in a telerehabilitation setting as their use is increasing, they can record data, and they can provide feedback through displays, videos and phone connectivity [16]. However, as the pulmonary telerehabilitation setting shifts the responsibility of measurement from the physiotherapist on to the participant, it is important to assess if participants can use these systems. PR participants are typically older adults with multiple comorbidities [17–19] who may have less experience with smartphone technology [20], although two recent studies indicated that many participants would be willing to incorporate telehealth technology into PR if the necessary supports were in place [21,22]. In addition to ease of use, smartphone systems must also be accurate during rest and exercise settings.

In Canada, although other smartphone apps are available for measuring SpO_2 saturation, the Kenek O_2 oximeter (LionsGate Medical, Vancouver, Canada; hereafter ‘smartphone oximeter’), which retails for less than \$100CDN, is the only smartphone oximeter approved by Health Canada for use in medical settings and can therefore be recommended by healthcare professionals. However, it has not been assessed for use during exercise. Therefore, the aim of this study was to evaluate the usability and accuracy of this smartphone-based measurement system (O_2 oximeter finger probe and custom app) at rest and during exercise in healthy adults and in patients with chronic lung disease.

Methods

Participants

The chronic lung disease group consisted of 15 individuals awaiting or undergoing PR, or who had completed PR within the preceding 2 years. Inclusion criteria for this group were: between 35 and 90 years of age; English-speaking; 6-minute walk test distance >250 m measured within the past year; and physician diagnosis of COPD, interstitial lung disease or asthma. Potential participants in this group were excluded if they had experienced a respiratory infection or change in their respiratory medications in the 4 weeks prior to testing, had been diagnosed with dementia, had a hand injury or impairment, used a wheelchair for regular mobility, or required oxygen therapy to complete activities of daily living.

A control group of 15 English-speaking healthy adults aged between 35 and 70 years was recruited using poster advertisements in hospital and community centres in Vancouver. Healthy adult controls were included as a reference for the results related to ease of use of the smartphone and expected biometric parameters during exercise. Adults were determined as healthy for low-intensity exercise if they answered 'no' to all questions on the Physical Activity Questionnaire for Everyone [23,24], and reported no hypertension, cardiovascular disease or chronic lung disease. Impairments to the hands, limbs or torso that would interfere with exercise and the placement of study devices also excluded potential participants.

This study was approved by the University of British Columbia Research Ethics Board. All participants provided written informed consent. The study was completed between March 2014 and September 2016.

Smartphone oximeter

The Kenek O₂ pulse oximeter is the only smartphone-based pulse oximeter approved by Health Canada for use in medical settings. It consists of a finger probe and a downloadable app compatible for use with iPhone, iPad and iPod Touch systems (Apple Inc., Cupertino, CA, USA). Currently, there is no compatible app for Android devices. The probe is a hard plastic finger clip probe with rubber inserts surrounding the inside and sides of the probe. HR and SpO₂ signals are captured through the probe and transmitted to the smartphone *via* a cable inserted in the audio jack. The version of the smartphone oximeter used for this study displayed the photoplethysmography signal, and recorded and archived the HR and SpO₂ values.

Procedures

Informed consent was obtained by participants reading and signing a document detailing the study protocol, risks and use of recorded measurements. Participants were also

given a copy of this document for their personal records. Next, baseline measurements of age, sex, height, weight, smoking status and history, smartphone experience, resting SpO₂ and resting HR were recorded. Participants were introduced to the smartphone system and given a maximum of 15 minutes to familiarise themselves with it using a standardised instruction manual that gave step-by-step instructions and pictures on setting up and operating the system. Participants were encouraged to only ask the researcher for prompts if absolutely necessary. Following this familiarisation period, they were asked to set up the finger probe, open the smartphone app, take their HR and SpO₂ measurements, and save their measurements while being video-recorded and timed. Instructions for this assessment were delivered using standardised flash cards that were the same for each participant. This was followed by completion of the Mobile Phone Usability Questionnaire (MPUQ) [25]. This study used 31 relevant items from the six-domain, 72-item yes/no MPUQ on ease of learning and use (14 items), helpfulness and problem-solving capabilities (two items), affective aspect and multimedia capabilities (eight items), commands and minimal memory load (two items), control and efficiency (four items), and typical tasks for mobile phones (one item) (see online supplementary material) [25]. The MPUQ was scored by reverse coding where relevant, and tallying the number of 'yes' responses and reporting the positive responses as a percentage of the total number of items.

Overall exercise test set-up

Two exercise tests were conducted: a cycle ergometer test and treadmill walking test. A Nonin 8500 pulse oximeter (Nonin Medical, Inc., Plymouth, MN, USA) was used as the reference device for SpO₂ measurements as it is non-invasive, approved for hospital settings, and is commonly used in PR. The reference standard for HR measurements was a 12-lead electrocardiogram (Cardiox, Columbus, OH, USA). Before the first exercise test, participants were fitted with a finger probe connected to an iPod Touch running the custom prototype app. The probe was placed on alternating hands for each participant. The Nonin 8500 pulse oximeter was then placed on the opposite hand. Finger probes were placed on the participant's index fingers. Nail polish and fake nails were removed to avoid measurement disturbances through the finger probes. In order to assess measurement reliability, each exercise test was repeated three times with rest breaks in between. All tests were completed within the same day.

Cycle ergometer test

Participants cycled on an electronically-braked cycle ergometer (Ergoline 800, SensorMedics, Yorba Linda, CA, USA) at 60–70 revolutions per minute at an intensity of 50 W, followed by a 3- to 5-minute rest break while seated on

the ergometer. This was repeated three times. The healthy controls cycled for 5-minute intervals, while patients with chronic lung disease cycled for 3-minute intervals. Borg's modified Rate of Perceived Exertion scale [26] was used to monitor exercise intensity at the end of each exercise set. Cycling intensity was reduced if participants scored >5 on this scale. SpO₂ and HR measurements were collected during the last 30 seconds of each resting period and 2 minutes into exercise by recording the measure displayed on the reference standard devices and the smartphone oximeter at a synchronised time. To reduce signal disturbances at the finger probes, participants were advised before and during exercise to keep a relaxed grip on the handle bar.

Treadmill test

After the cycle ergometer test, participants walked on a treadmill at 3 km/hour and 0% incline for 5 minutes (healthy controls) or 3 minutes (patients with chronic lung disease), followed by a 3- to 5-minute break in a sitting position in a chair. As with the cycle ergometer test, three sets of exercise and rest breaks were completed. Intensity was monitored and data were collected in the same fashion as in the cycle ergometer test (SpO₂ and HR measurements during the last 30 seconds of rest period and 2 minutes into exercise).

Data analysis

Data analysis was performed using R Version 3.2.2 [27]. Descriptive analyses were performed to summarise patient characteristics. Sample sizes of 15 people per group were based on 80% power to detect a significant correlation of 0.70 for HR and SpO₂ ($\alpha=0.05$). Validity of SpO₂ and HR measurements was assessed using mixed-effects Bland–Altman plots [28,29]. Plots differentiated between measurements taken during rest, cycle ergometer or treadmill test. Mean biases and limits of agreement (LoA) were compared with the manufacturer-stated error range of SpO₂ and HR measurements by the pulse oximeter to determine validity. Validity of SpO₂ was defined as measurements with a mean bias within $\pm 2\%$ and LoA within $\pm 4\%$ [30]. For patient safety, the lower bound LoA is particularly important. Validity of HR was defined as measurements with a mean bias within ± 5 beats/minute (bpm) and LoA within ± 10 bpm [30], with both upper and lower bounds important. Ninety-five percent confidence intervals (CI) for LoA were also calculated. Reliability of SpO₂ and HR measurements was determined by intraclass correlation coefficients (ICC) model 3 of several measurements (3,k) [31]. Three measures were taken in each condition; therefore, ICC (3,3) was used. An ICC >0.75 ($P<0.05$) demonstrated good reliability [32]. Separate analyses were performed for patients with COPD and healthy controls.

Table 1
Participant characteristics and lung function.

	Patients with chronic lung disease	Healthy controls
Number of participants (<i>n</i>)	15	15
Age (years)	67 (11)	47 (7.5) ^{***}
Sex (female:male)	7:8	10:5
Height (cm)	165 (11)	167 (10)
Weight (kg)	72 (18)	74 (16)
Smoking status		
Active	2 (13%)	1 (7%)
Ex-smoker	9 (60%)	6 (40%)
Never smoker	4 (27%)	8 (53%)
Smoking history (pack years)	23 (22)	2 (4) ^{**}
Resting oxygen saturation (%)	94 (4)	96 (1)
Resting heart rate (beats/minute)	79 (11)	68 (15) [*]
Chronic lung disease		
Asthma	3 (20%)	–
COPD	11 (73%)	–
ILD	2 (13%)	–
Lung function		
FEV ₁ (l)	1.6 (0.6)	Not tested
FEV ₁ % predicted	63.5 (25.6)	Not tested
FVC (l)	3.1 (1.0)	Not tested
FVC % predicted	86.8 (17.9)	Not tested
FEV ₁ /FVC	56.7 (19.0)	Not tested

COPD, chronic obstructive pulmonary disease; ILD, interstitial lung disease; FEV₁, forced expiratory volume in 1 second; FVC, forced vital capacity. Resting heart rate and oxygen saturation were recorded with the Nonin 8500 pulse oximeter.

Data are presented as mean (SD).

^{***} $P<0.0001$.

^{**} $P<0.005$.

^{*} $P<0.05$.

Results

Participant characteristics

Fifteen participants with chronic lung disease and 15 healthy controls completed the study (Table 1). Participants with chronic lung disease were older and had more pack-years of smoking history than healthy controls. The majority of participants with chronic lung disease had COPD (11/15, 73%). Among the healthy controls, the majority of participants used smartphones daily (10/15, 67%). In contrast, the majority of participants with chronic lung disease had never used a smartphone (12/15, 80%).

Usability of the smartphone oximeter

Both groups were able to assemble the probe, open and close the app, and save their measurements with relative ease. In general, the patients with chronic lung disease took longer than the healthy controls to complete all the tasks, but all tasks took less than 1 minute to perform for both groups (Table 2). The usability and ease of setting up the app and probe, and navigating within the app itself was rated highly by both groups. The MPUQ had an overall score of 93% in the healthy controls and 88% in the patients with chronic

Table 2
Task performance measures and usability using the smartphone oximeter.

Task	Patients with chronic lung disease Time (seconds)	Healthy controls Time (seconds)
1. Get to smartphone home screen and select the app	18 (5 to 131)	10 (2 to 18)
2. Exit the application	9 (4 to 28)	3 (2 to 4)
3. Assemble and connect probe to smartphone	39 (1 to 101)	19 (15 to 24)
4. Insert smartphone into the armband and put armband on	44 (1 to 72)	19 (11 to 33)
5. Put on probe, re-open app, begin recording data	26 (11 to 68)	10 (6 to 25)
6. Identify oxygen saturation and heart rate	6 (1 to 17)	6 (2 to 17)
7. Take off probe and remove armband from arm	15 (8 to 39)	9 (5 to 20)
8. Remove smartphone from armband and stop recording	7 (1 to 31)	7 (3 to 9)
9. Exit application and turn off smartphone	16 (4 to 106)	11 (3 to 17)
Usability questionnaire ^a	Patients with chronic lung disease 'Yes' response (%)	Healthy controls 'Yes' response (%)
Ease of learning and use		
Question 5. Does the system have all the functions and capabilities you would expect it to have?	80%	100%
Question 6. Are the colour coding and data display compatible with typical smartphones?	60%	93%
Question 10. Does using the system require a lot of mental effort?	20%	0%
Affective aspect and multimedia properties		
Question 19. Is the system attractive?	87%	80%
Question 20. Do you feel confident using the system?	80%	100%
Question 22. Do you feel excited when using the system?	47%	60%
Question 23. Would you miss the system if you no longer had it?	47%	53%
Question 24. Would you be proud of this product?	80%	80%
Control and efficiency		
Question 28. Has the system at some time stopped unexpectedly?	20%	7%
Question 29. Is the amount of information displayed on the screen adequate?	80%	93%
Question 31. Is it easy to operate with one hand?	80%	100%

Median (range) time (in seconds) to complete specific tasks among patients with chronic lung disease and healthy controls, and results from the adapted Mobile Phone Usability Questionnaire.

^a Selected questions, based on 80% or fewer of respondents from either group answering positively.

lung disease. The largest frequency of negative responses was reported for affective aspect and multimedia properties, which asked questions about 'attachment' to the product and the design interface (Table 2).

Validity and reliability

The SpO₂ measurement was valid in healthy controls at rest and during both exercise tests based on predetermined thresholds for validity, with mean biases between 0% and 1%, and LoA between $\pm 3\%$ and ± 3.8 (Table 3 and Fig. 1), and had modest reliability during both the cycle ergometer and treadmill tests (Table 4).

SpO₂ measurements were also valid at rest in the patients with chronic lung disease, with mean bias of 1% and LoA $\pm 4\%$. However, during exercise, the smartphone oximeter had values above the acceptable threshold measures (Table 3, Fig. 2). Reliability for SpO₂ measurements was 0.54 ($P < 0.001$) and 0.33 ($P = 0.005$) for the cycle ergometer and treadmill tests, respectively (Table 4).

The HR measurements in the healthy controls were not valid at rest or during exercise based on predetermined thresholds, as LoA were all greater than ± 10 beats/minute (Table 3, Fig. 1). However, good reliability was demonstrated, with ICC values of 0.88 and 0.90 for the cycle ergometer and treadmill walking tests, respectively (Table 4). Similarly, HR measurements in the patients with chronic lung disease were above the predetermined thresholds of 5 bpm and LoA ± 10 bpm, although the HR measurements during both the cycle ergometer test and the treadmill test were reliable (Table 4).

Discussion

This study shows the results of a Health Canada-approved smartphone-based pulse oximeter that can be used to monitor SpO₂ and HR. The smartphone device and app were judged to be acceptable and easy to use by patients with chronic lung disease and healthy controls. At rest, the smartphone oximeter was valid with modest reliability for measuring SpO₂ in patients with chronic lung disease and healthy controls. However, the system did not meet predetermined SpO₂ validity thresholds, and had poor or moderate reliability during exercise. Similarly, HR recording using the smartphone oximeter did not meet predetermined validity thresholds, and had moderate to good reliability based on ICC(3,3) calculations. The presence of chronic lung disease was not a factor with the measurement of HR, as similar results were found in both groups.

PR programmes for patients with COPD have demonstrated significant improvements in mortality [33], exercise capacity [33–35], health-related quality of life [33–35] and perceived dyspnoea [36]. Monitoring SpO₂ periodically during exercise is important to ensure patient safety, prevent oxygen desaturation and reduce the potential of tissue dam-

Table 3
Mean biases and limits of agreement for measurements of oxygen saturation (SpO₂) and heart rate (HR).

Test			Patients with chronic lung disease	Healthy controls
Rest	SpO ₂ (%)	Bias (SD)	1.4 (1.9)	0.4 (1.9)
		UB 95% LoA (95% CI)	5.1 (3.3 to 6.9)	4.2 (2.4 to 6.0)
		LB 95% LoA (95% CI)	-2.4 (-4.2 to -0.6)	3.4 (1.6 to 5.2)
	HR (beats/minute)	Bias (SD)	-3.2 (7.0)	-1.6 (15.2)
		UB 95% LoA (95% CI)	11.0 (4.2 to 17.8)	28.7 (14.1 to 43.3)
		LB 95% LoA (95% CI)	-17.3 (-24.0 to -10.5)	-31.9 (-46.5 to -17.4)
Cycle	SpO ₂ (%)	Bias (SD)	-0.1 (4.5)	0.5 (1.8)
		UB 95% LoA (95% CI)	8.9 (4.6 to 13.2)	4.0 (2.3 to 5.7)
		LB 95% LoA (95% CI)	-9.1 (-13.4 to -4.8)	-3.03 (-4.7 to -1.3)
	HR (beats/minute)	Bias (SD)	-29.3 (25.2)	-16.4 (25.1)
		UB 95% LoA (95% CI)	21.1 (-3.1 to 45.3)	33.8 (9.6 to 57.9)
		LB 95% LoA (95% CI)	-79.7 (-103.9 to -55.5)	-66.7 (-90.8 to -42.5)
Tread-mill	SpO ₂ (%)	Bias (SD)	1.6 (4.5)	0.9 (1.6)
		UB 95% LoA (95% CI)	10.6 (6.3 to 14.8)	4.1 (2.6 to 5.7)
		LB 95% LoA (95% CI)	-7.3 (-11.6 to -3.0)	-2.4 (-4.0 to -0.8)
	HR (beats/minute)	Bias (SD)	-34.3 (25.4)	-4.0 (9.4)
		UB 95% LoA (95% CI)	16.4 (-8.0 to 40.8)	14.8 (5.8 to 23.8)
		LB 95% LoA (95% CI)	-85.0 (-109.4 to -60.6)	-22.7 (-31.7 to -13.7)

CI, confidence interval; LB, lower bound; LoA, limits of agreement; SD, standard deviation; UB, upper bound.

Mean biases and LoA were calculated in three conditions: at rest, 2 minutes into exercise on the cycle ergometer, and 2 minutes into exercise on the treadmill. Validity of SpO₂ was defined as measurements with a mean bias within $\pm 2\%$ and LoA within $\pm 4\%$ [24]. Validity of HR was defined as measurements with a mean bias within ± 5 beats/minute and LoA within ± 10 beats/minute [24].

Table 4
Reliability scores for oxygen saturation (SpO₂) and heart rate (HR) measurements.

Test		Patients with chronic lung disease		Healthy controls	
		ICC	<i>P</i> -value	ICC	<i>P</i> -value
Cycle	SpO ₂	0.54	<0.001	0.65	<0.001
	HR	0.58	<0.001	0.88	<0.001
Treadmill	SpO ₂	0.33	0.005	0.68	<0.001
	HR	0.64	<0.001	0.90	<0.001

Intraclass correlations (ICC (3,3)) were calculated for SpO₂ and HR in the two exercise conditions. An ICC >0.75 (*P* < 0.05) was considered to demonstrate good reliability [26].

age due to hypoxia [37–39], and is recommended in the guidelines of the American Thoracic Society/American College of Chest Physician [40]. Patients with SpO₂ < 88% during exercise will typically receive supplemental oxygen therapy or may titrate their existing supplemental oxygen [39]. Therefore, measurement of SpO₂ is important for these patients and for the physiotherapists who supervise exercise in PR programmes [39]. Unlike cardiac rehabilitation, in PR, HR is not used routinely to develop an exercise prescription, but can be used as an additional measure of patient safety [39].

These results suggest that if a smartphone-based app is used during exercise, the measurements obtained may not be accurate. Users may need to stop or slow down their exercise when measuring SpO₂ to ensure greatest accuracy. During exercise, vigorous movement likely increases artifacts and decreases the accuracy of the system compared with reference values. While this conclusion fits with recommendations for monitoring SpO₂ during exercise in PR using regular clinical oximeters [41] (as clinical oximeters were initially designed for bedside use), it may be difficult for patients to remember

as the smartphone app displays the measurement readings continuously. Therefore, further efforts to reduce the influence of motion artifacts on measurement readings in portable oximeters are needed.

Telemonitoring interventions in patients with chronic lung disease have been shown to be: feasible [9]; associated with good compliance [9]; effective in improving quality of life [8]; and can reduce hospitalisations by early detection of changes in symptoms [8,9]. Although the majority of patients with chronic lung disease in this study were not smartphone users, they were able to navigate the system easily and the usability scores were >85%. However, the low prevalence of smartphone use among this cohort of patients raises the question of the likelihood of smartphone monitoring in PR being widely adopted in the near future. Previously, the authors reported that patients want to be able to monitor their bioparameters in order to adjust exercise intensity or titrate their supplemental oxygen, if necessary [21]. The ability of a smartphone system to monitor SpO₂ accurately may aid in enhancing confidence in patients'

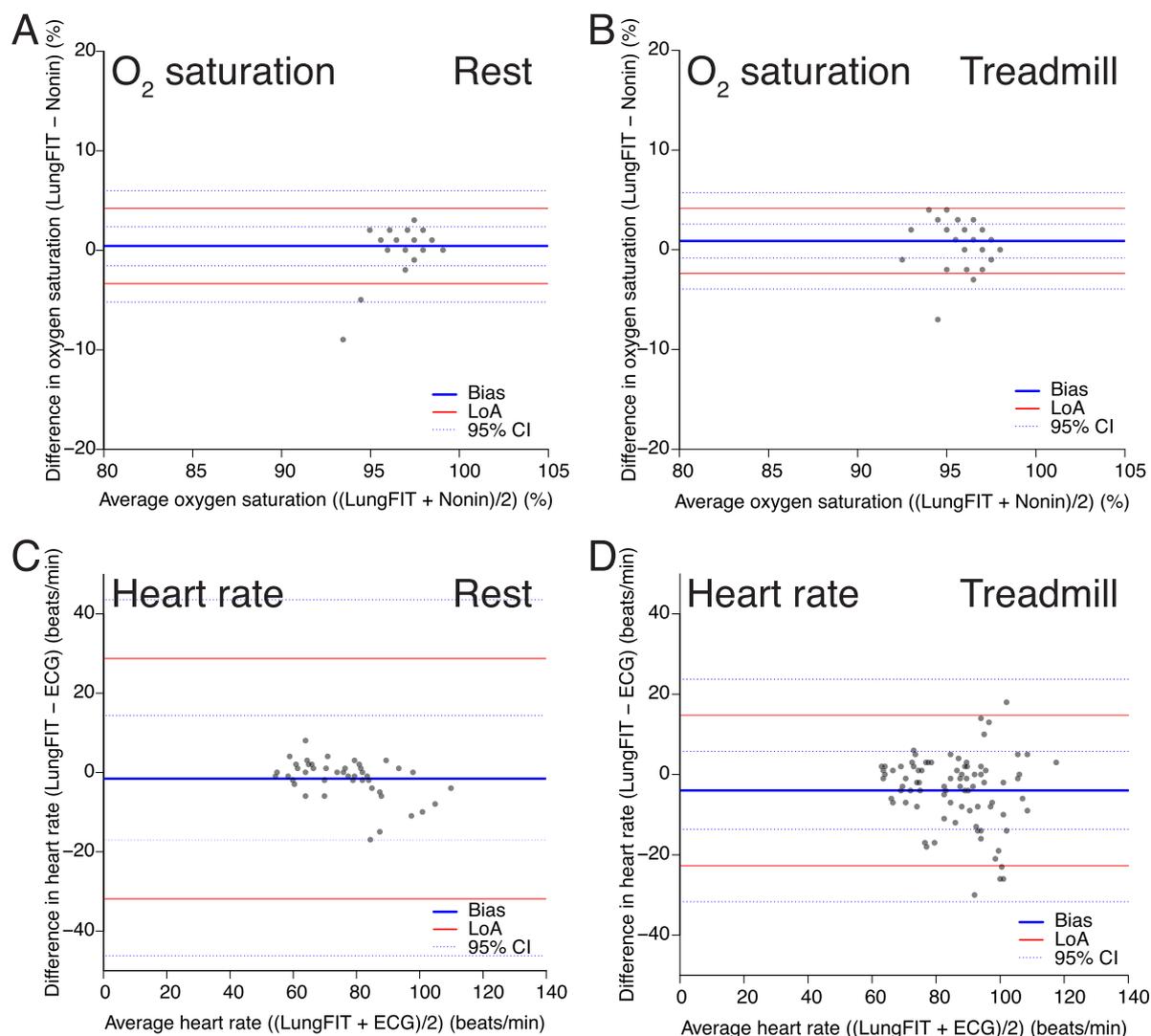


Fig. 1. Bland–Altman plot of the smartphone oximeter and reference measurement of oxygen saturation and heart rate at rest and during exercise in healthy controls. Oxygen saturation was tested in healthy control participants at rest (A) and 2 minutes into exercise on the treadmill (B). Heart rate was also measured at each time point (C, D). In each plot, the solid blue line represents the mean difference or bias over three trials. Solid red lines represent limits of agreement (LoA) over three trials. Dashed blue lines represent the 95% confidence intervals for the LoA. Each black data point represents a subject's measurement difference between the test probe and the reference value (Nonin 8500 pulse oximeter or 12-lead electrocardiogram). Three trials were performed per person in each condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

monitoring of their parameters and adjusting exercise accordingly.

As more apps become available, and the age of current smartphone users and smartphone use increases in Canada and worldwide [42,43], the smartphone platform may eliminate the need for multiple telemonitoring devices and be useful in PR settings. However, there is also a need for patients to understand the limitations of any monitoring device, and to incorporate other self-assessments during exercise, including level of dyspnoea and ratings of perceived exertion, especially in settings where exercise is unsupervised.

Functionality and usability factors can affect adherence and clinical impact as complicated apps can deter use [44]. Users may have a wide range of familiarity with smartphone apps and pulse oximeter probes; therefore, this smartphone

system must be simple enough to use so that even those with lower smartphone dexterity understand how to use it (both patients and healthcare professionals). A prototype version of the smartphone oximeter was used by healthcare professionals in Canada and Uganda, who scored 82% and 78% on the MPUQ, respectively [45]. Although there may be concerns about difficulty in using smartphones in an older population, the participants in the current study indicated that, with a short training period, there was no difficulty in using the system.

Limitations

There were limitations to this study. Patients and controls were not matched on characteristics such as age, sex or smoking history. Participants were supervised throughout

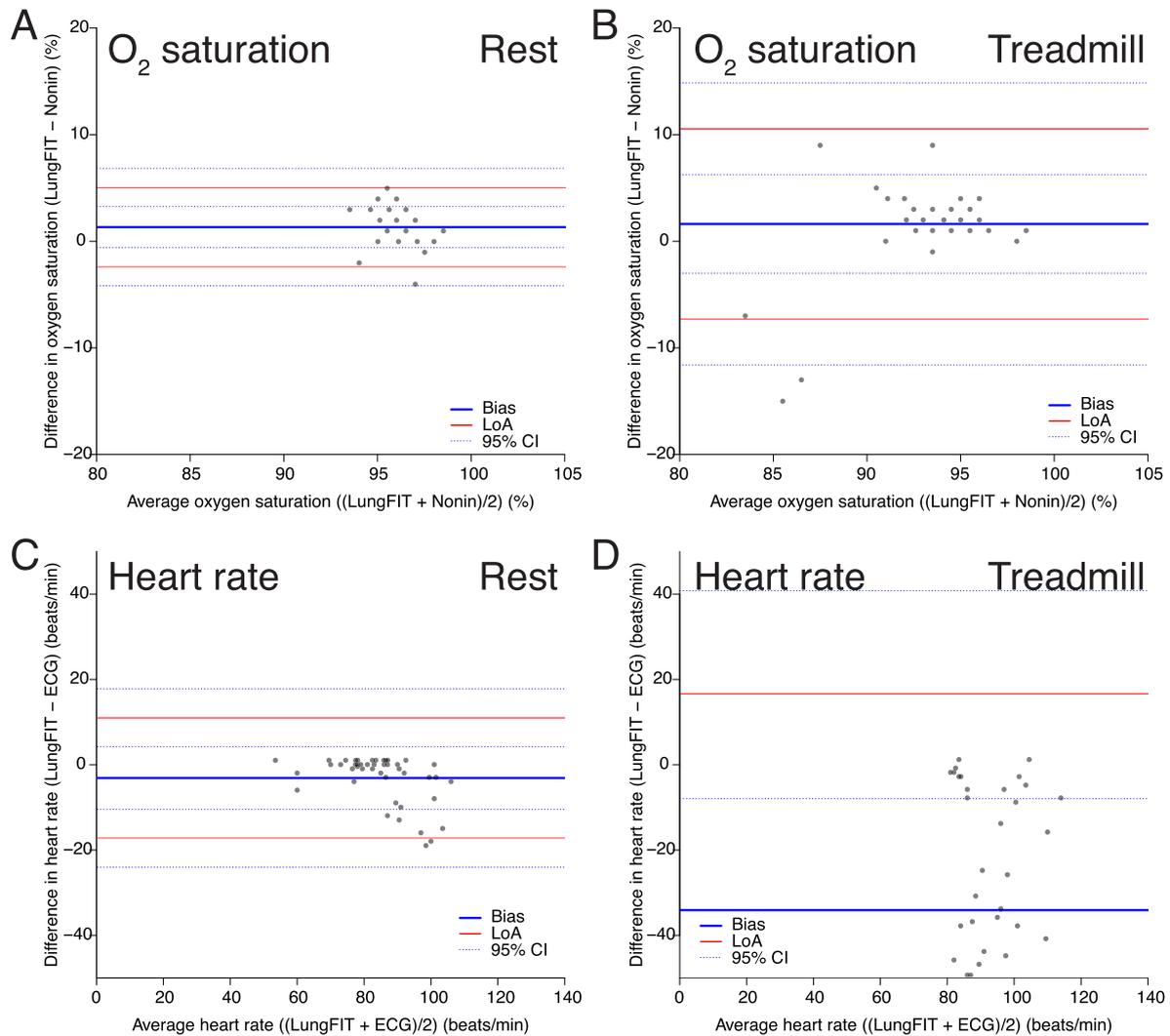


Fig. 2. Bland–Altman plot of the smartphone oximeter and reference measurement of oxygen saturation and heart rate at rest and during exercise in patients with chronic lung disease. Oxygen saturation was tested in participants with chronic lung disease at rest (A) and 2 minutes into exercise on the treadmill (B). Heart rate was also measured at each time point (C, D). In each plot, the solid blue line represents the mean difference or bias over three trials. Solid red lines represent limits of agreement (LoA) over three trials. Dashed blue lines represent the 95% confidence intervals for the LoA. Each black data point represents a subject's measurement difference between the test probe and the reference value (Nonin 8500 pulse oximeter or 12-lead electrocardiogram). Three trials were performed per person in each condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the study, and performed the HR and SpO₂ measurements on the same day that they were taught how to use the device. It is possible that the ease of use may have been different if the orientation and testing occurred on separate days, or if the use of the device was unsupervised. The study was also performed in a clinical environment free of distractions, which may represent a more idealised scenario than during everyday use. Therefore, it might be slightly more challenging for individuals to use the smartphone oximeter when faced with other distractions. However, given the ease of use and reasonable time that it took participants to use the system, it is not anticipated that this would deter individuals.

Simultaneous, single readings of HR and SpO₂ were measured on all devices. Increased accuracy may have been seen if several measurements had been collected over a period of

5–10 seconds and the median values had been used. However, the authors wished to emulate the typical clinical PR environment, where single readings are typically used and recorded. SpO₂ values were compared with those from the handheld Nonin pulse oximeter, which has been approved for use in medical settings and is used commonly in PR. However, motion artifacts may have affected the reference device. The smartphone device was not compared with a true gold standard of SpO₂, namely the arterial oxygen saturation level (SaO₂). However, accurate measurement of SaO₂ during exercise requires an indwelling arterial sampling line and rapid analysis of the sample, which was prohibitive in this setting.

Smartphone devices were provided for participants to use. Indeed, much of the research in the field of health mobile

technologies assumes that people are able and interested in purchasing devices to support their health. However, the cost of purchasing these devices is prohibitive for some patients, so adoption of this type of technology would potentially exclude a portion of the potential target users if the equipment was not included in the service provision. The rapid advance of smartphone devices and apps can mean that new versions have been launched during the research process. Indeed, new versions of the smartphone oximeter have included more signal processing to reduce the impact of motion artifacts on measurement. Nevertheless, the present findings related to ease of use, and the need to consider the impact of motion artifacts and the need for signal processing to remove artifacts are likely to remain important considerations.

Next steps for telerehabilitation and remote patient monitoring in chronic lung disease

There is a considerable need to improve access to PR as only a small portion of patients living with chronic lung disease have access. The provision of regulatory-approved devices that are user-friendly and accurate is a necessary step in the more widespread adoption of technologies to monitor patient data, including exercise parameters. While smartphones have the potential to measure, store and transmit biometric data, they are not the only technology that could aid in the delivery of telerehabilitation. Other potential systems, including video-conferencing, patient recording and subsequent transmission of data *via* online sites, and wearable trackers may also be useful and deserve further study. In addition, while this study provides evidence on the monitoring of SpO₂ and HR in a clinical laboratory setting, there are many other components of PR (education, behavioural modification, healthcare provider and peer support, follow-up, communication) that also warrant development and evaluation in a telehealth setting.

Conclusion

In conclusion, this study found that although the Kenek smartphone oximeter was easy to use, it could not measure SpO₂ or HR accurately during exercise in patients with chronic lung disease. If used during exercise, activity should be paused briefly in order to ensure the most accurate measurement.

Ethical approval: UBC Research Ethics Board (H13-03091).

Conflict of interest: None declared.

Funding: Funding was provided by a Canadian Institutes of Health Research Catalyst Grant.

Key messages

- Tele-technology offers tools that can enhance and support pulmonary rehabilitation programs, especially for those who do not have access.
- Smartphone applications may be useful to monitor patients during exercise, for example by monitoring heart rate (HR) and oxygen saturation (SpO₂) with a finger probe connected to the smartphone.

New Knowledge

- A smartphone oximeter can be used to take measurements during aerobic exercise, and were rated “usable” by study participants.
- A smartphone application takes accurate measurements of SpO₂ at rest in healthy individuals and people with COPD, but not during exercise. Heart rate was not accurately measured during rest or exercise.
- Exercise should be paused in order to obtain the most accurate readings of SpO₂ and HR when using the smartphone application.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.physio.2018.07.015>.

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