Measuring Arterial Oxygen Saturation Using Wearable Devices Under Varying Conditions

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INTRODUCTION: Recently developed wearable monitoring devices can provide arterial oxygen saturation (S_pO_2) measurements, offering potential for use in aerospace operations. Pilots and passengers are already using these technologies, but their performance has not yet been established under conditions experienced in the flight environment such as environmental hypoxia and concurrent body motion.

METHODS: An initial evaluation was conducted in 10 healthy subjects who were studied in a normobaric chamber during normoxia and at a simulated altitude of 15,000 ft (4572 m; 11.8% oxygen). S_pO_2 was measured simultaneously using a standard pulse oximeter and four wearable devices: Apple Watch Series 6; Garmin Fēnix 6 watch; Cosinuss° Two in-ear sensor; and Oxitone 1000M wrist-worn pulse oximeter. Measurements were made while stationary at rest, during very slight body motion (induced by very low intensity cycling at 30 W on an ergometer), and during moderate body motion (induced by moderate intensity cycling at 150 W).

RESULTS: Missed readings, defined as failure to record an S_pO_2 value within 1 min, occurred commonly with all wearables. Even with only very slight body motion, most devices missed most readings (range of 12–82% missed readings) and the rate was higher with greater body motion (range 18–92%). One device tended to under-report S_pO_2, while the other devices tended to over-report S_pO_2. Performance decreased across the devices when oxygenation was reduced.

DISCUSSION: In this preliminary evaluation, the wearable devices studied did not perform to the same standard as a traditional pulse oximeter. These limitations may restrict their utility in flight and require further investigation.

KEYWORDS: pulse oximeter, pilot, hypoxemia, altitude, aviation, spaceflight.

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With a global market size of approximately $40 billion in 2020, wearable technology is a growing industry with a broad impact that is likely to include the aerospace sector.[4] Wearable physiological monitoring devices, or 'wearables', are portable technologies intended to track physiological data such as calories burned, step count, heart rate, and, more recently, arterial oxygen saturation (S_pO_2). Owing to the accessibility and convenience of wearable technology, these devices have the potential to transform remote monitoring in patients at risk of hypoxemia, such as those with chronic obstructive pulmonary disease or COVID-19, and are marketed to consumers as a means of promoting health and well-being.

Aircrew are routinely exposed to mild-moderate hypoxia and, anecdotally, the use of wearables by pilots across general, commercial, and military operations is increasing. Wearable measurements of in-flight S_pO_2 are similarly appealing in other groups such as passengers, aeromedical patients, and skydivers.[1] The ability to detect worsening hypoxemia during flight is highly desirable as it is dangerous and can develop for many reasons, such as reduced cabin pressure, unpressurized flight at high altitudes, pre-existing or acute illness, physical exertion (e.g., helicopter rear crew), high G acceleration, and failure of oxygen delivery and life-support systems. In recent years this

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has been particularly topical in the setting of military fast-jet operations due to the possible contribution of hypoxia to unexplained physiological events. However, it is important to establish the performance of new technologies prior to safety-critical use. With regards to isolated S_pO_2 monitoring during flight, additional care is required as interpretation can be challenging or misleading even for accurate measurements; for example, in the presence of hyperventilation.[2]

While the accuracy of heart rate data from wearables has been well-reported, the ability to measure S_pO_2 is a newer feature and has not been comprehensively investigated.[8] Standard pulse oximeters used in medical practice utilize transmissive photoplethysmography (PPG), in which a light source and photodetector are located on opposite sides of a vascular bed (such as a finger or ear lobe) and the intensity of transmitted light of certain wavelengths is measured. The reliability of this technique is well established, but such devices tend to be somewhat obtrusive when used while performing other activities. In contrast, wearables are by their nature less obtrusive, but typically use the less established technique of reflective PPG, in which the light source and photodetector are positioned on the same side of a vascular bed and the intensity of reflected light is measured.[12] Wearables are also designed for S_pO_2 measurements to be made while completely stationary.

Recently developed wearables that can measure S_pO_2 include consumer-grade products such as the Apple Watch 6 (Apple Inc., Cupertino, CA, USA) and Garmin Fēnix 6 watch (Garmin Ltd, Olathe, KS, USA), which are marketed for 'general fitness and wellness purposes' rather than for medical use. In contrast, the commercially available in-ear ('hearable') Cosinuss° Two (Cosinuss GmbH, Munich, Germany) has undergone testing in clinical settings, although comparative data has not been published and it is not currently classified as a medical device, while the wrist-worn Oxitone 1000M (Oxitone Medical, Kfar Saba, Israel) is an FDA-cleared medical monitor intended for clinical use. The Garmin and Apple watches and Cosinuss° Two use reflective PPG, while the Oxitone 1000M uses transmissive PPG. There is little published research reporting S_pO_2 data from these devices. The Oxitone 1000M has been reported to provide accurate and precise S_pO_2 values when measured in a stationary state,[5] while a recent study conducted in a respiratory outpatient clinic reported the Apple Watch 6 appeared to be a reliable means of measuring S_pO_2 in this controlled setting, although there were occasional outlying values.[10] An earlier Garmin watch model (the Fēnix 5× Plus) was found to over-estimate S_pO_2 in volunteers studied in a normobaric chamber, especially at higher simulated altitudes, and it was noted that achieving a single measurement could take up to 3 min.[6] This highlights the potential for measurement failure to impact on performance—irrespective of its other qualities, a device that is unable to reliably achieve a timely reading is unlikely to be useful in the flight environment.

Although there is limited data and satisfactory performance cannot be assumed across the various technologies, these initial studies are generally encouraging with regards to use while stationary and under normoxic conditions. However, in-flight use does not necessarily allow such optimal conditions; achieving an absolutely motionless state can be challenging or impossible, and a lower range of S_pO_2 may well be encountered. To our knowledge, no previous studies have investigated the potential combined effects of hypoxia and concurrent body motion of any degree. This initial study aimed to undertake a preliminary evaluation of four leading wearable devices in measuring S_pO_2 under normoxic and hypoxic conditions while at rest and during relevant levels of body motion, including very minimal movement only marginally beyond a stationary state. The hypothesis was that their performance in measuring S_pO_2 would be the same as that of a standard pulse oximeter. Our aim was to generate preliminary results and provide a basis for the definitive studies that are ultimately required.

METHODS

Subjects

This study was conducted in healthy volunteers and was approved by the King's College London Research Ethics Committee. It was conducted in accordance with the Declaration of Helsinki. All subjects provided written informed consent.

Equipment

The study was undertaken in a normobaric altitude chamber (Sporting Edge, Basingstoke, UK) containing a cycle ergometer (Monark 818E, Monark Exercise, Vansbro, Sweden). Reference S_pO_2 was measured continuously at the left index finger using a standard pulse oximeter (Pulse Oximeter 7840, Kontron Instruments Ltd, West Sussex, UK) recorded via PowerLab 8/35 and LabChart 8.0 (AD Instruments, Oxford, UK) and was compared with data from an Apple Watch 6 (at the left wrist), Garmin Fēnix 6 watch, and Oxitone 1000M (at the right wrist) and a Cosinuss° Two (in the right ear). All wearables were attached and operated according to the manufacturer's instructions, and the Cosinuss° Two was fitted for size (small, medium, or large). Simultaneous heart rate measurements were recorded from all monitors in parallel with S_pO_2.

Procedure

Subjects attended the laboratory on 2 experimental days separated by a minimum of 24 h. The protocol was identical on each occasion except one day was conducted under normoxic conditions in room air (20.9% oxygen) and the other was conducted in hypoxic conditions at a simulated altitude of 15,000 ft (4572 m; 11.8% oxygen). This altitude was intended to extend nadir S_pO_2 values into the 70–80% range. The order of normoxia and hypoxia was counterbalanced and subjects were blinded to each condition. Following instrumentation, subjects entered the hypoxia chamber and completed 10 min of seated rest. They then cycled on the ergometer for 5-min periods at very low intensity (30 W) and at moderate intensity (150 W) separated by 5 min of seated rest. These periods of cycling were intended as a reproducible means of inducing very slight body motion (30 W) and moderate body motion (150 W), with the added

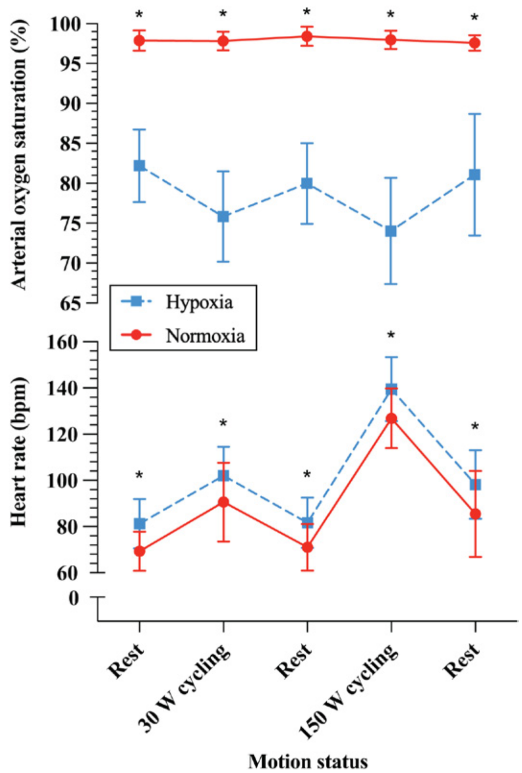

Fig. 1. Mean arterial oxygen saturation and heart rate at rest and cycling at 30 W and 150 W under normoxic (20.9% oxygen) and hypoxic (11.8% oxygen) conditions. Solid red lines and circles denote normoxia. Dashed blue lines and squares denote hypoxia. Asterisks denote a statistically significant effect of hypoxia ($P < 0.05$). Data are mean ± SD.

potential for exaggerating any hypoxemia.[13] Participants were instructed to remain otherwise still while cycling and there was minimal associated motion of the arms and head, especially at 30 W, which requires only very gentle pedaling. A further 5 min of seated rest concluded testing. For each period of rest and cycling, measurements of S_pO_2 and heart rate were recorded at three evenly spaced time points. A maximum of 1 min was allowed to obtain a reading from each device, after which a failed or 'missed' measurement was recorded.

Statistical Analysis

Data were normally distributed (Shapiro-Wilk test). The effect of hypoxia on S_pO_2 and heart rate was analyzed with paired *t*-tests (SPSS Statistics v.26, IBM, Armonk, NY, USA) using mean data for each period of rest or cycling (using S_pO_2 and heart rate data obtained from the reference pulse oximeter). The accuracy and bias of measurements from the wearable devices were tested against the reference pulse oximeter using paired *t*-tests, Bland Altman analyses (GraphPad Prism, v.26, San Diego, CA, USA), and mean absolute percentage error (MAPE) score. MAPE was calculated using the following equation: ((actual value – forecast value)/actual value)*100. Statistical significance was assumed at $P < 0.05$ and data are presented as mean ± SD.

RESULTS

There were 10 subjects (6 men and 4 women) with a mean age of 27 ± 6 yr, weight 75 ± 15 kg, height 1.74 ± 0.11 m, and body mass index 24 ± 3 $kg \cdot m^{-2}$. **Fig. 1** shows the effects of hypoxia and periods of cycling on the reference physiological data obtained using the standard pulse oximeter. S_pO_2 was significantly lower during hypoxia at rest [82 ± 3% vs. 98 ± 1%; $t(29) = 15.9$, $P < 0.001$], 30-W cycling [76 ± 6% vs. 98 ± 1%; $t(9) = 11.8$, $P < 0.001$], and 150-W cycling [74 ± 7% vs. 98 ± 1%; $t(9) = 12.2$, $P < 0.001$]. There was a small increase in heart rate during hypoxia compared with normoxia at rest [87 ± 14 bpm vs. 75 ± 15 bpm; $t(29) = 6.4$, $P < 0.001$] and similarly during 30-W cycling [102 ± 13 bpm vs. 91 ± 17 bpm; $t(9) = 3.4$, $P = 0.008$] and 150-W cycling [139 ± 14 bpm vs. 127 ± 13 bpm; $t(9) = 2.7$, $P = 0.026$].

Missed S_pO_2 readings were common for all devices, with a progressive increase in the percentage of missed readings with increasing cycling intensity (**Table I**). At rest, the percentage of

Table I. S_pO_2 Measurements: Number of Data Points, Percentage of Missed Readings, Mean Absolute Percentage Error and Percentage Accuracy for Each Device Measuring S_pO_2 at Rest and During Cycling at 30 W and 150 W.

	APPLE WATCH 6	GARMIN FĒNIX 6	COSINUSS° TWO	OXITONE 1000M
Number of data points				
Rest	160	160	160	160
30-W cycling	60	60	60	60
150-W cycling	60	60	60	60
Missed readings (% of total)				
Rest	2.5%	20%	11%	14%
30-W cycling	65%	65%	12%	82%
150-W cycling	95%	83%	18%	92%
Mean absolute percentage error				
Rest	−2.26	−2.19	2.66	−2.39
30-W cycling	−0.80	−3.92	2.06	−3.44
150-W cycling	−4.21	−9.89	3.33	−6.69
Accuracy (%)				
Rest	97.7	97.8	97.3	97.6
30-W cycling	99.2	96.1	97.9	96.6
150-W cycling	95.8	90.1	96.7	93.3

Table II. Heart Rate Measurements: Number of Data Points, Percentage of Missed Readings, Mean Absolute Percentage Error (MAPE) and Percentage Accuracy for Each Device Measuring Heart Rate at Rest and During Cycling at 30 W and 150 W.

	APPLE WATCH 6	GARMIN FĒNIX 6	COSINUSS° TWO	OXITONE 1000M
Number of data points				
Rest	160	160	160	160
30-W cycling	60	60	60	60
150-W cycling	60	60	60	60
Missed readings (% of total)				
Rest	0%	2%	7%	5%
30-W cycling	0%	2%	12%	67%
150-W cycling	0%	0%	20%	77%
Mean absolute percentage error				
Rest	1.05	0.8	7.64	2.56
30-W cycling	−7.51	7.91	0.51	9.71
150-W cycling	−2.33	29.41	45.14	33.32
Accuracy (%)				
Rest	98.95	99.2	92.36	97.44
30-W cycling	92.49	92.09	99.49	90.29
150-W cycling	97.67	70.59	54.86	66.68

missed readings ranged between 2.5% and 20%, while during very low intensity cycling at 30 W, when associated body motion was very minimal, most devices missed most readings (range 12–82%). During moderate intensity cycling at 150 W, the percentage of missed readings ranged between 18% and 95%. Overall, the percentage of missed readings was lowest for the Cosinuss° Two and highest for the Oxitone 1000M. MAPE and percentage accuracy were calculated and are shown in Table I. With increasing cycling intensity, MAPE increased and percentage accuracy decreased. The Apple Watch 6 displayed the highest percentage accuracy independent of motion status, while the Garmin Fēnix 6 showed the lowest percentage accuracy. Equivalent data for heart rate is shown in **Table II**. Missed heart rate readings were generally less frequent, while overall,

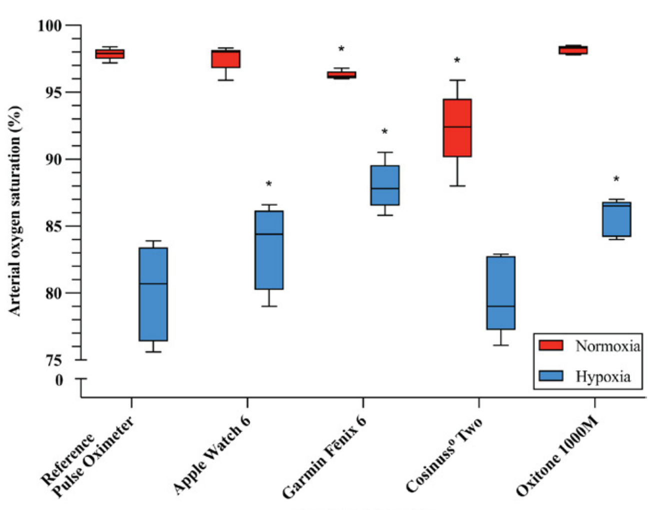

Fig. 2. Arterial oxygen saturation measured by the reference pulse oximeter and wearable devices during normoxia (red boxes) and hypoxia (blue boxes). Data are from all conditions combined (rest and cycling). The mean, interquartile range (boxes) and maximum and minimum values (bars) are shown. Asterisks denote a statistically significant difference ($P < 0.05$) between reference data obtained from the traditional pulse oximeter and data from the respective wearable devices.

from rest to 150-W cycling, MAPE increased and percentage accuracy decreased.

Fig. 2 shows all recorded S_pO_2 data (at rest and while cycling) for each of the respective devices during normoxia and hypoxia. Under normoxic conditions, when values were successfully obtained, the S_pO_2 data from the Apple Watch 6 [$t(4) = 0.5898$, $P = 0.6$] and Oxitone 1000M [$t(4) = 1.215$, $P = 0.3$] were not significantly different from reference data obtained from the traditional pulse oximeter. However, S_pO_2 readings from the Garmin Fēnix 6 [$t(4) = 4.867$, $P = 0.008$] and Cosinuss° Two [$t(4) = 3.964$, $P = 0.017$] were significantly different from the corresponding reference data. During hypoxia, the Cosinuss° Two [$t(4) = 0.3653$, $P = 0.7$] was the only device to provide S_pO_2 measurements that were not significantly different from the reference data; the Apple Watch 6 [$t(4) = 8.025$, $P = 0.001$], Garmin Fēnix 6 [$t(4) = 4.094$, $P = 0.015$], and Oxitone 1000M [$t(4) = 3.812$, $P = 0.019$] data were significantly different from the reference data. Equivalent data for heart rate is shown in the supplementary online appendix (**Fig. A1**, found with the online version of this article or at https://doi.org/10.3357/AMHP.6078sd.2023).

Overall, when normoxic and hypoxic measurements were combined, the Apple Watch 6, Garmin Fēnix 6, and Oxitone 1000M all tended to over-report S_pO_2 both at rest and while cycling, while the Cosinuss° Two tended to under-report S_pO_2 (**Fig. A2**, found with the online version of this article or at https://doi.org/10.3357/AMHP.6078sd.2023). Compared with the reference S_pO_2 data, the Apple Watch 6 had the smallest mean bias (rest: 1.7 ± 2.1%; 30-W cycling: 1.2 ± 3.4%; 150-W cycling: 1.9 ± 2.3%), while the Cosinuss° Two had the largest mean bias (rest: −2.9 ± 3.0%; 30 W: −1.5 ± 3.7%; 150 W: −6.5 ± 5.2%). The Oxitone 1000M over-reported S_pO_2 with a higher mean bias (rest: 2.0 ± 1.8%; 30 W: 3.4 ± 3.8%; 150 W: 5.3 ± 6.5%) during cycling compared with at rest (Fig. A2). Equivalent data for heart rate is shown in the supplementary online appendix (**Fig. A3**, found with the online version of this article or at https://doi.org/10.3357/AMHP.6078sd.2023).

DISCUSSION

This preliminary study of four wearable devices indicates that, across a range of S_pO_2 values and levels of body motion, the ability of each of the respective devices to measure S_pO_2 diverged substantially from that of a traditional pulse oximeter. A high proportion of readings were recorded as 'missed' when the device failed to provide a measurement within 1 min, which would be considered a potentially critical operational failure in many aviation contexts. Missed measurements were common even at rest for most devices and none were able to reliably provide S_pO_2 measurements during cycling at moderate or even low intensity, when associated movement of the rest of the body was very minimal. The Apple Watch 6 had the highest accuracy with a potentially acceptable bias when S_pO_2 values were achieved, but the device missed the majority of readings in the presence of very slight body motion, and missed nearly all readings when body motion was at a moderate level. These wearable devices are designed for S_pO_2 measurements to be taken in a stationary state, but this is likely to be difficult or impossible to achieve during flight operations. Measurements were frequently missed even when there was only the slightest body motion and it is, therefore, questionable whether these devices would be able to obtain measurements reliably in many real-world settings, including aerospace environments.

The reduction in the performance of wearables in the presence of any movement of the body is attributable to motion artifact. As technology advances and becomes progressively miniaturized, this more readily exposes the PPG signal to noise such as motion artifact and movement of the PPG sensor that alters the direction in which the light signal is emitted. This is particularly pertinent when the motion artifact frequency corresponds with that of the PPG signal (0.5–5.0 Hz). Typically, motion artifact noise relates to a frequency of 0.01–10 Hz, thus regularly overlapping with the PPG band.[7]

A further factor to be considered is the potential for variation in peripheral circulation to affect S_pO_2 measurements. Poor perfusion can cause a decrease in the ratio of arterial to venous blood at the sensor location, reduced venous saturation through a larger oxygen extraction ratio, and lower pulse amplitude. In addition, motion artifact can have a more profound impact when pulse amplitude is suppressed as it exerts a greater influence on the PPG signal.[9] Poor perfusion could conceivably have lowered the S_pO_2 readings of the wrist-worn wearables in this study if a redistribution of blood flow to the exercising muscles in the lower limbs occurred. However, this seems unlikely as any such effect would also have applied to the reference pulse oximeter, and we note that the Cosinuss° Two (situated in the ear) was the only device to consistently under-report S_pO_2.

The performance of wearables in measuring S_pO_2 has only been investigated in a small number of studies in which data was obtained at rest.[5,6,10] A perfectly motionless state provides optimal conditions and may explain the more favorable comparative data obtained with the Apple Watch 6,[10] Oxitone 1000M,[5] and the predecessor Garmin Fēnix 5× Plus watch.[6] The latter study also explored the effect of reducing inspired oxygen concentration and demonstrated a larger bias at a simulated altitude of 12,000 ft (3658 m) compared with lower altitudes.[6] In the current study we observed a decrease in the performance of S_pO_2 measurements under hypoxic conditions compared with during normoxia in all four wearable devices. Pulse oximeter performance is known to be reduced at lower S_pO_2 values[11] and, in this context, the possibility that wearables may be additionally unreliable when oxygenation is lower, such as at altitude, warrants particular caution regarding their use in aerospace operations.

This study had several limitations. The sample size was intended to allow an initial preliminary evaluation of multiple wearables across varying conditions. The results are preliminary in nature and are intended to serve as the basis for more definitive research. Subjects were young and healthy and were primarily from a white ethnic background, precluding any analysis of the effect of skin pigmentation.[3] Cycling does not replicate actual in-flight conditions and was used as a reproducible surrogate for relevant levels of body motion, as this is the aspect of pedaling that has the potential to impair readings from wearable devices. The protocol did not target associated metabolic activity, which is not directly related to the function of wearable monitors. It should be noted hardware and software for these technologies remain under continuing development and improvement. Furthermore, consumer grade products such as the Apple Watch 6 and Garmin Fēnix 6 carry disclaimers that S_pO_2 readings are not intended for medical use and associated product information acknowledges various factors may affect measurements, including a user's individual anatomy, the fit of the device, and ambient light conditions.

Wearable technology is rapidly advancing and, with further development, the ability to measure S_pO_2 unobtrusively offers great potential to be useful in a multitude of settings, including as a means of early detection of hypoxemia in clinical populations. This could encompass ambulatory and outpatient settings as well as ward-based, perioperative, and critical care medicine. Ultimately, wearable-derived S_pO_2 data may likewise offer benefits as in-flight tools, whether for pilots, passengers, aeromedical patients, rear crew, or skydivers. Based on this preliminary study, we suggest further research and development is required before this can be generally recommended. Future investigations may consider ways to minimize movement-associated noise infiltrating reflective PPG signals and should encompass relevant populations and environmental conditions, including actual in-flight measurements.

In summary, while wearable devices offer great promise, in this preliminary study the four wearable devices investigated did not perform to the same standard as a traditional pulse oximeter for S_pO_2 measurements. Limitations associated with varying conditions, including minimal body motion, may well apply in real-world settings, including aviation and spaceflight, and further research into the use of wearables in these domains is required.

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