BPR MCS Bulletin of Pioneering Researches of Medical and Clinical Science

Bulletin of Pioneering Researches of Medical and Clinical Science

Available online: https://bprmcs.com
2022 | Volume 2 | Issue 1 | Page: 126-133

Assessing VO2max and Pulse Oximetry Accuracy in Wearable Devices

Jonas K. Weber[1]*, Franz Müller[1], Anna L. Schmidt[1]

[1]Department of Internal Medicine and Clinical Sciences, University of Heidelberg, Heidelberg, Germany.

Abstract

As wearable devices become more widespread and technologically advanced, verifying their accuracy is critical to ensure they provide reliable data for practical use. This study investigated how accurately the Garmin fēnix 6 estimates VO2max and measures blood oxygen saturation (BOS) via pulse oximetry in a general population sample. The study included healthy adults, both physically active and sedentary, for VO2max testing (n = 19) and pulse oximetry assessment (n = 22). VO2max values from the fēnix 6 were compared to a gold-standard metabolic system using a graded exercise test and outdoor running. BOS readings from the device under normal and low-oxygen conditions were compared against a clinical-grade pulse oximeter. Analyses included descriptive statistics, error evaluation, correlation assessment, equivalence testing, and bias evaluation, with validation benchmarks defined as a concordance correlation coefficient (CCC) > 0.7 and mean absolute percentage error (MAPE) < 10%. VO2max estimates from the fēnix 6 aligned closely with laboratory measurements (30 s average MAPE = 7.05%; Lin's CCC = 0.73), whereas BOS readings were unreliable under all conditions tested (combined conditions MAPE = 4.29%; Lin's CCC = 0.10). The Garmin fēnix 6 provides reasonably accurate VO2max estimates, suggesting usefulness for fitness tracking and research purposes, but its BOS measurements are insufficiently precise for clinical or altitude monitoring. These results emphasize the necessity of validating wearable devices before relying on them for health or research applications.

Keywords: Biometric technology, Activity monitor, Fitness tracker, Cardiorespiratory fitness, Hypoxia, Altitude

Corresponding author: Jonas K. Weber
E-mail: jonas.weber@outlook.com

How to Cite This Article: Weber JK, Müller F, Schmidt AL. Assessing VO2max and Pulse Oximetry Accuracy in Wearable Devices. Bull Pioneer Res Med Clin Sci. 2022;2(1):126-33. https://doi.org/10.51847/eWqGluHrGT

Introduction

Wearable technology has experienced rapid growth, becoming one of the most popular tools for health and fitness monitoring worldwide, topping global fitness trend surveys in seven of the past nine years and ranking in the top three for the other two years (2018 and 2021) [1–9]. Nearly a third of Americans currently use wearable devices to track exercise and health metrics, and approximately 70% report owning or planning to acquire a device in the near future [10, 11]. This widespread adoption presents a unique opportunity for physiology and public health research, as these devices can generate large volumes of continuous, individualized physiological data, offering unprecedented insight into human health patterns [12, 13]. However, the accuracy of these consumer-grade devices is not guaranteed, as they are unregulated, making independent validation essential for ensuring their reliability for both research and personal use.

Among the physiological variables wearable devices can monitor, VO2max and blood oxygen saturation (BOS) are especially relevant. VO2max represents the maximum rate at which oxygen can be delivered to and utilized by the body for energy production, serving as a key indicator of

cardiorespiratory fitness (CRF) and being strongly associated with reduced risk of cardiovascular disease and overall mortality [14–16]. VO2max is also a critical determinant of endurance performance in athletes [17–19]. Pulse oximeters estimate BOS non-invasively by measuring the oxygen bound to hemoglobin through light absorption, providing valuable information on cardiopulmonary function, which is useful for individuals with pulmonary conditions or athletes monitoring altitude acclimatization [20, 21]. Given the growing reliance on wearables for health monitoring and performance tracking, this study aimed to evaluate the accuracy of VO2max and BOS measurements obtained from the Garmin fēnix 6 in a general population cohort.

Materials and Methods

Prior to beginning the study, all procedures were approved by the University of Nevada, Las Vegas Institutional Review Board (IRB). Participants provided written informed consent and completed pre-assessment questionnaires before any testing. VO2max and pulse oximetry measurements were conducted separately, though some individuals participated in both assessments and were included in each dataset. Since the participant groups differed between VO2max and pulse oximetry testing, demographic information is reported separately for each cohort.

VO2max testing

Nineteen apparently healthy adults (self-reported as healthy at the time of testing), including both physically active and sedentary individuals, were recruited for VO2max assessment (mean age 25.50 ± 5.26 years; 11 males, 8 females; height 173.63 ± 9.08 cm; body mass 74.08 ± 14.16 kg; BMI 24.42 ± 3.21 kg/m²; fat mass 22.14 ± 6.06%; muscle mass 36.87 ± 4.58%; weekly running distance 25.07 ± 23.65 km; all mean ± SD). Data collection occurred over two sessions.

During the first session, participants completed a graded exercise test with incremental increases in speed and incline to determine VO2max. Maximal oxygen uptake was measured using the ParvoMedics TrueOne 2400 metabolic cart (ParvoMedics Inc., Salt Lake City, UT, USA). VO2max was defined as the highest averaged oxygen consumption over specific intervals, with aggregated values calculated for 4-breath, 15-s, 30-s, and 1-min averages, which served as the reference measurements for device comparison.

The second session involved an outdoor run guided by the Garmin fēnix 6® (Garmin Ltd., Olathe, KS, USA) to estimate VO2max. The fēnix 6 is a robust multisport GPS smartwatch designed for outdoor and athletic use, integrating features of a fitness tracker, smartwatch, and navigation device. Participants returned between two and seven days after the first session (mean 5.06 ± 3.96 days). Before each trial, the watch was reset to factory settings to prevent carryover data from previous participants. A Garmin HRM-Run® heart rate monitor was worn during the run. Participants ran for 10–15 minutes at an intensity above 70% of their estimated maximal heart rate, as recommended by the manufacturer, allowing the device to calculate VO2max through linear extrapolation of heart rate and running speed [22]. Runs were conducted either on the university track (n = 5) or on flat campus terrain (n = 14). The altitude during testing was ~686 m, with an average outdoor temperature of 20.67 ± 12.62 °C. Device-recorded average run parameters were: distance 2.13 ± 0.17 km, duration 12.91 ± 1.42 min, pace 6.33 ± 1.49 min/km, and heart rate 153.50 ± 11.45 bpm. Data collection spanned approximately 14 months, with runs performed at various times of day.

Pulse oximetry testing

Twenty-two apparently healthy adults participated in pulse oximetry assessment (mean age 25.48 ± 6.02 years; 13 males, 9 females; height 173.27 ± 7.70 cm; body mass 68.88 ± 9.10 kg; BMI 22.91 ± 2.40 kg/m²; fat mass 18.55 ± 7.05%; muscle mass 38.73 ± 3.61%). Participants wore the fēnix 6 on the left wrist, with strap tension adjusted for comfort. A medical-grade fingertip pulse oximeter (Roscoe Medical, POX-ROS, Roscoe Medical Inc., Middleburg Heights, OH, USA) was placed on the right index finger.

Participants completed eight trials across four conditions (two trials per condition): normoxia with watch on posterior and anterior wrist, and hypoxia with watch on posterior and anterior wrist. For hypoxic testing, participants were exposed to simulated altitude using a Hypoxico Everest Summit II chamber (Hypoxico Inc., New York, NY, USA) set to 3657.6 m (12,000 ft). If participants experienced discomfort, the altitude was lowered, followed by a five-minute stabilization period before resuming. Participants remained seated throughout all trials, maintaining controlled breathing synchronized with the chamber's air bursts at a rate of 12.5 breaths per minute. Hypoxic exposure averaged 9.18 ± 1.05 minutes. If the fēnix 6 failed to generate a BOS reading, up to three attempts were made; if unsuccessful, no further attempts were conducted. Data from both devices were collected simultaneously and testing concluded once all values were recorded.

Data analysis

VO2max (4-breath, 15-s, 30-s, 1-min averages) and BOS measurements (anterior/posterior placement, normoxia/hypoxia) were entered into Google Sheets (Alphabet Inc., Mountain View, CA, USA). Pulse oximetry values were analyzed by condition and

combined. All calculations were performed within Google Sheets, while summary statistics, validation measures, and figures were generated in jamovi (version 2.6.19, https://www.jamovi.org/). Analyses included descriptive statistics, mean absolute percentage error (MAPE), correlation analysis (Pearson's r and Lin's concordance correlation coefficient [CCC]), equivalence testing via TOST paired samples, and Bland–Altman bias assessment. TOST equivalence bounds were set at ±0.5 Cohen's D. VO2max validation was determined by comparing fēnix 6 estimates to each laboratory-aggregated interval, with CCC > 0.7 and MAPE < 10% considered valid.

Results and Discussion

VO2max

For the 19 participants, mean VO2max was 48.9 mL/kg/min, with an average VO2max percentile of 83.37 ± 21.14% based on 30-s averaged values. Error analysis indicated that fēnix 6 VO2max estimates yielded MAPE values below 10% for the 15-s, 30-s, and 1-min intervals **(Table 1)**. Correlation analysis produced CCC values > 0.7 for both 15-s and 30-s averages **(Table 1)**. TOST equivalence testing did not indicate equivalence for any intervals, with 4-breath, 15-s, 30-s, and 1-min averages all violating equivalence criteria **(Table 1)**. Bland–Altman bias values and 95% confidence intervals are reported in **Table 1**, with corresponding plots in **Figure 1** for all timeframes.

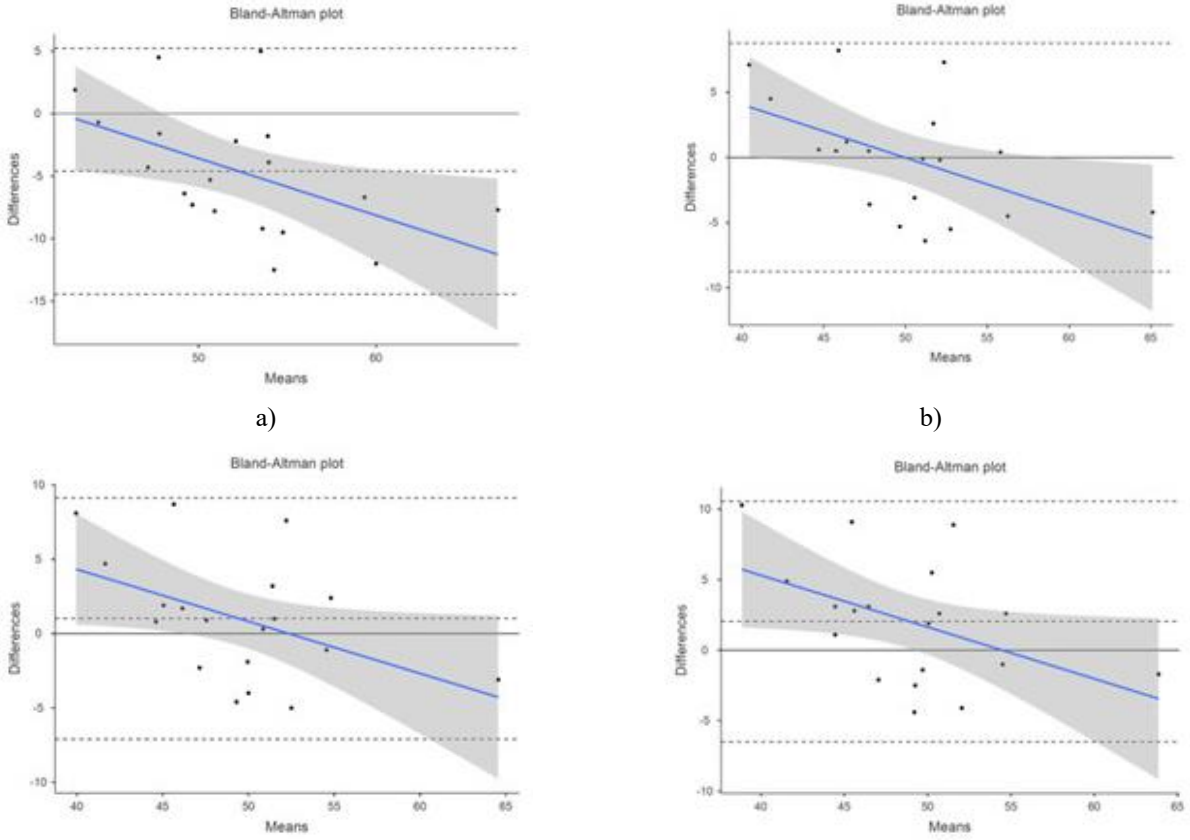

Figure 1. Bland–Altman plots comparing VO2max measurements from the Garmin fēnix 6 to laboratory reference values: 4-s average (top left), 15-s average (top right), 30-s average (bottom left), and 1-min average (bottom right). The blue line indicates the proportional bias, with shaded areas representing its 95% confidence intervals. The X-axis shows the mean of the paired measurements, and the Y-axis shows the difference between them. Dashed lines denote the mean bias (middle line) and the upper and lower limits of agreement, while the solid line represents a hypothetical mean bias of zero.

Table 1. VO2max descriptive and validation statistics results, n = 20. Notes: MAPE = mean absolute percentage error; TOST test = two one-sided t-tests. Bland–Altman bias values and 95% confidence intervals are provided. Values that met the predetermined validation criteria are bolded.

	Fēnix 6 VO2max Estimate	Lab VO2max—4 Breath Avg	Lab VO2max—15 s Avg	Lab VO2max—30 s Avg	Lab VO2max—1 min Avg
Mean (mL/kg/min)	49.68	54.54	49.95	48.94	47.91
Standard Deviation	4.61	7.28	7.04	6.67	6.76

MAPE	10.70%	**7.23%**	**7.05%**	**8.53%**
Pearson Correlation	0.73	0.78	0.78	0.76
Lin's Concordance	0.49	**0.71**	**0.73**	0.68
Bland–Altman Bias	−4.87 (−7.30, −2.44)	−0.26 (−2.45, 1.92)	0.75 (−1.28, 2.78)	1.77 (−0.35, 3.89)
TOST Test (Upper)	<0.001	0.80	0.45	0.10
TOST Test (Lower)	<0.972	0.01	0.09	0.34

Pulse oximetry

Error analysis indicated that the fēnix 6 produced a mean absolute percentage error (MAPE) below 10% across all four testing conditions and the combined dataset (anterior/posterior placement, normoxia/hypoxia). However, correlation analysis revealed that Lin's concordance correlation coefficient (CCC) did not exceed 0.7 for any individual condition or the combined data. Equivalence testing using the TOST method failed for all single conditions but was satisfied when analyzing the combined dataset. Bland–Altman bias values and 95 percent confidence intervals for the combined dataset are reported in **Table 2**. Corresponding plots for the combined dataset are shown in **Figure 2**. Out of all attempts, the fēnix 6 successfully generated 52 BOS measurements, corresponding to an overall success rate of 59%, meaning that it provided a reading in just over half of the prompted measurements.

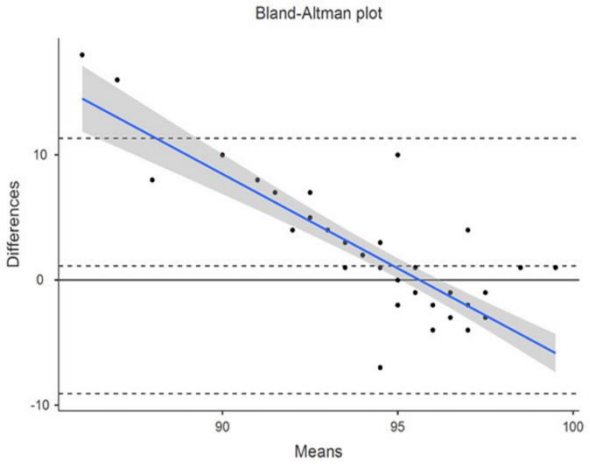

Figure 2. Bland–Altman plots of combined pulse oximetry measurements, including both normoxic and hypoxic conditions. The blue line indicates the proportional bias, with shaded areas representing its 95% confidence intervals. The X-axis shows the average of the paired measurements, while the Y-axis represents the difference between them. Dashed lines indicate the mean bias (center line) and the upper and lower limits of agreement, and the solid line represents a hypothetical mean bias of zero.

Table 2. Blood oxygen saturation measurements measured via pulse oximetry in Garmin fēnix 6 and criterion device. Descriptive and validation statistics results for n = 22 (52 distinct fēnix 6 values from all conditions and participants). Bland–Altman bias values and 95% confidence intervals are provided. Values that met the predetermined validation criteria are bolded.

	Fēnix 6 Blood Oxygen Saturation Measurement (%)	**Criterion: Blood Oxygen Saturation Measurement (%)**
Mean	95.44%	92.06%
Standard Deviation	1.60%	8.17%
MAPE		4.29%
Pearson Correlation		0.18
Lin's Concordance		0.10
Bland–Altman Bias (−0.34, 2.57)		1.12
TOST Test (Upper)		0.13
TOST Test (Lower)		0.02

This study evaluated the accuracy of VO2max estimates and blood oxygen saturation (BOS) measurements from wearable technology (WT) against established gold-standard methods. Based on pre-defined validation criteria, the Garmin fēnix 6 demonstrated acceptable accuracy for VO2max estimation (MAPE < 10%, CCC > 0.7), particularly aligning with the 15-s and 30-s averaged laboratory timeframes. In contrast, BOS measurements via the fēnix 6 failed to meet accuracy standards under any condition or in combined analyses. It is important to emphasize that these devices are consumer-grade and not designed or regulated as medical instruments, meaning their accuracy and effectiveness are not governed by the FDA or other regulatory bodies. VO2max and pulse

oximetry are clinically significant metrics, used to monitor general health, cardiorespiratory fitness (CRF), and to assess risk in individuals with cardiovascular or pulmonary conditions. While some researchers and clinicians may use WT for monitoring these metrics in clinical populations, these devices were not originally intended for such applications. Nevertheless, WT is increasingly employed by scientists, healthcare professionals, and public health authorities to collect data for research, policy development, and healthcare monitoring [23–29], underscoring the need for independent validation to assess reliability relative to gold-standard measurements. The widespread adoption and continuous monitoring capability of WT could transform public health and physiology research, making validation essential for the scientific community [12, 13].

VO2max estimation in wearable devices is possible because of the well-established linear relationship between heart rate (HR) and oxygen consumption [22]. The fēnix 6 uses HR and running speed to extrapolate VO2max to an age-predicted maximal HR. While the device can measure HR using its built-in photoplethysmography (PPG) sensor, the current study employed an accessory chest strap with ECG technology, which provides more accurate HR readings during exercise. PPG sensors are susceptible to motion artifacts and are generally less precise than ECG-based monitors during dynamic activity [30–34]. Thus, using ECG-based HR monitoring during exercise, as implemented here, enhances the reliability of VO2max estimates.

Although WT represents a convenient method for monitoring physiological metrics like VO2max, field-based maximal and submaximal VO2max tests have been in use for decades [35]. Meta-analyses comparing submaximal predictive equations with gold-standard testing report correlation coefficients ranging from r = 0.57 to 0.92 [36]. In this study, the fēnix 6 produced an r = 0.78 for both the 15-s and 30-s intervals. Previous research on the Garmin fēnix 3 has reported correlations up to 0.92 [37], comparable to the most accurate submaximal predictive equations. While correlation alone does not fully capture a device's validity, reliability, or overall accuracy, it offers a useful comparative measure.

Accurate VO2max estimation is clinically and practically valuable, as it reflects CRF—a robust independent predictor of all-cause and disease-specific mortality [14–16]. Individuals with lower VO2max values are at increased risk of mortality regardless of other health indicators. The American Heart Association emphasizes the importance of CRF measurement in clinical practice, citing extensive evidence that CRF is often a stronger predictor of mortality than traditional risk factors such as smoking, hypertension, hyperlipidemia, and diabetes mellitus. Integrating CRF into risk models can improve the precision of health risk assessments [38]. Ideally, CRF assessment involves maximal exercise testing with direct measurement of oxygen consumption and carbon dioxide production using a metabolic cart; however, this is not feasible for all individuals, particularly those with cardiovascular, musculoskeletal, or pulmonary limitations, or those unable to afford laboratory testing. Wearable devices offer an accessible alternative, estimating VO2max during light exercise or even at rest, depending on the device. Consequently, accurate VO2max estimates from wearables can inform personal fitness decisions and provide valuable population-level insights for researchers and public health policymakers.

Given the results of this study, the fēnix 6 provides reliable VO2max estimates, suggesting that recreational users and possibly researchers, healthcare providers, and public health officials can rely on the data generated by this device. Nonetheless, professionals may wish to adopt stricter validation thresholds than those applied in the present investigation to ensure higher confidence in VO2max measurements.

Beyond its relevance for personal health, VO2max is a critical performance indicator for endurance athletes, often regarded as one of the most important—or even the single most important—determinants of endurance event success [17–19]. Knowledge of an athlete's VO2max allows coaches and athletes to design training programs tailored to individual fitness levels, optimizing performance outcomes. However, gold-standard VO2max testing is costly and time-intensive, making it impractical for many recreational athletes or sports teams. Wearable technology offers a cost-effective alternative, enabling both individuals and teams to estimate aerobic capacity during routine training sessions without the need for dedicated testing days. Moreover, continuous monitoring through these devices allows training adjustments to be made in response to small changes in aerobic fitness, enhancing training efficiency and personalization.

Pulse oximetry, a well-established clinical method for assessing blood oxygen saturation (BOS), has recently been incorporated into wearable devices such as smartwatches. These devices use photoplethysmography (PPG) sensors to detect changes in blood oxygen levels by emitting light pulses and measuring the reflected signals. This technology has potential clinical and athletic applications, including monitoring pulmonary health in conditions such as asthma, emphysema, and chronic obstructive pulmonary disease (COPD). For athletes traveling to higher altitudes, wearable pulse oximetry could assist in tracking acclimatization [39]. However, as demonstrated in the present study, the fēnix 6 performed poorly under both normoxic and hypoxic conditions. Future research could explore whether continuous BOS monitoring throughout the day, rather than on-demand

measurements, improves accuracy. Nevertheless, motion artifacts inherent to PPG sensors remain a significant limitation, with studies showing that oxygen desaturation readings can drop below 50% during movement [40]. Given these limitations, this device is currently unsuitable for precise BOS monitoring during altitude acclimatization.

In the current study, commonly accepted thresholds of MAPE < 10% and CCC > 0.7 were used to define validity. While no universal consensus exists regarding validation thresholds or analytical methods, these criteria were considered appropriate for a general population sample. However, applications in elite athletics, public health research, or clinical settings may require more conservative thresholds to ensure higher accuracy. A tiered threshold system could be developed in the future to guide appropriate use cases for wearable devices. Although MAPE and CCC were the primary metrics for validity in this study, additional analyses including Bland–Altman bias assessment and TOST equivalence testing were also performed. While these approaches are recommended in validation literature [13, 41, 42], they are not commonly used, and standardized thresholds for these tests have not yet been established. Their inclusion provides readers with a more comprehensive evaluation of device performance, even though they were not incorporated into the strict validity criteria.

Limitations

This study included both active and sedentary participants from the general population, so caution is warranted when generalizing these findings to other groups. Although the validation thresholds applied (MAPE < 10% and CCC > 0.7) have been used in prior research, they may be too lenient for contexts that demand high precision, such as elite sports, public health studies, or clinical applications. As only acute hypoxia was assessed, further research is needed to evaluate the device's accuracy and utility in monitoring blood oxygen saturation over time. Additionally, VO2max measurements were conducted outdoors, where temperature variations could influence heart rate during exercise and act as a confounding factor; however, the collection of data over approximately 14 months enhances the external validity and generalizability of the findings.

Conclusion

This study assessed the accuracy of the Garmin fēnix 6 in estimating VO2max and measuring blood oxygen saturation via pulse oximetry, comparing results to laboratory gold-standard methods. The fēnix 6 demonstrated acceptable accuracy for VO2max, particularly when using 15-second and 30-second aggregated data. Conversely, it did not provide reliable blood oxygen measurements under any condition or in combined analyses. Therefore, while the fēnix 6 can offer reasonably accurate VO2max estimates when laboratory testing is unavailable, it cannot be relied upon to accurately measure blood oxygen levels, regardless of normoxic or hypoxic conditions or watch placement on the wrist.

Acknowledgments: None

Conflict of interest: None

Financial support: None

Ethics statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of the University of Nevada, Las Vegas (protocol code: 1525606-11; date of approval: 15 February 2023).
Informed consent was obtained from all subjects involved in the study.

References

1. Newsome A, Reed R, Sansone J, Batrakoulis A, McAvoy C, Parrott MW, et al. 2024 ACSM worldwide fitness trends: Future directions of the health and fitness industry. ACSM's Health Fit J. 2024;28(1):14–26.
2. Thompson WR. Worldwide survey of fitness trends for 2023. ACSM's Health Fit J. 2023;27(1):9–18.
3. Thompson WR. Worldwide survey of fitness trends for 2022. ACSM's Health Fit J. 2022;26(1):11–20.
4. Thompson WR. Worldwide survey of fitness trends for 2021. ACSM's Health Fit J. 2021;25(1):10–19.
5. Thompson WR. Worldwide survey of fitness trends for 2020. ACSM's Health Fit J. 2019;23(1):10–18.
6. Thompson WR. Worldwide survey of fitness trends for 2019. ACSM's Health Fit J. 2018;22(1):10–17.
7. Thompson WR. Worldwide survey of fitness trends for 2018: The CREP edition. ACSM's Health Fit J. 2017;21(1):10–19.
8. Thompson WR. Worldwide survey of fitness trends for 2017. ACSM's Health Fit J. 2016;20(1):8–17.
9. Thompson WR. Worldwide survey of fitness trends for 2016. ACSM's Health Fit J. 2015;19(1):9–18.
10. Clark E. Is your fitness tracker helping or hurting your health? [Internet]. 2024 [cited 2024 Aug 3]. Available from: https://themanifest.com/app-development/fitness-tracker-helping-hurting-health
11. Dhingra LS, Aminorroaya A, Oikonomou EK, Nargesi AA, Wilson FP, Krumholz HM, et al. Use of wearable devices in individuals with or at risk for cardiovascular disease in the US, 2019 to 2020. JAMA Netw Open. 2023;6(6):e2316634.

12. Wright S, Brown T, Collier S, Sandberg K. How consumer physical activity monitors could transform human physiology research. Am J Physiol Regul Integr Comp Physiol. 2017;312:R358–67.
13. Carrier B, Barrios B, Jolley BD, Navalta JW. Validity and reliability of physiological data in applied settings measured by wearable technology: A rapid systematic review. Technologies. 2020;8(3):70.
14. Qiu S, Cai X, Sun Z, Wu T, Schumann U. Is estimated cardiorespiratory fitness an effective predictor for cardiovascular and all-cause mortality? A meta-analysis. Atherosclerosis. 2021;330:22–8.
15. Lee D, Sui X, Artero EG, Lee I, Church TS, McAuley PA, et al. Long-term effects of changes in cardiorespiratory fitness and body mass index on all-cause and cardiovascular disease mortality in men: The Aerobics Center Longitudinal Study. Circulation. 2011;124(23):2483–90.
16. Harber MP, Kaminsky LA, Arena R, Blair SN, Franklin BA, Myers J, et al. Impact of cardiorespiratory fitness on all-cause and disease-specific mortality: Advances since 2009. Prog Cardiovasc Dis. 2017;60(11):11–20.
17. Joyner MJ, Coyle EF. Endurance exercise performance: The physiology of champions. J Physiol. 2008;586(1):35–44.
18. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc. 2000;32(1):70–84.
19. Kenney WL, Wilmore JH, Costill DL. Physiology of Sport and Exercise. Champaign, IL: Human Kinetics; 2021.
20. Dünnwald T, Kienast R, Niederseer D, Burtscher M. The use of pulse oximetry in the assessment of acclimatization to high altitude. Sensors. 2021;21(4):1263.
21. Sinex JA, Chapman RF. Hypoxic training methods for improving endurance exercise performance. J Sport Health Sci. 2015;4(4):325–32.
22. Anonymous. Aerobic fitness level (VO2max) estimation—Firstbeat white paper. [Internet]. 2022 [cited 2022 Jul 14]. Available from: https://www.firstbeat.com/en/aerobic-fitness-level-vo%e2%82%82max-estimation-firstbeat-white-paper-2/
23. Iqbal MH, Aydin A, Brunckhorst O, Dasgupta P, Ahmed K. A review of wearable technology in medicine. J R Soc Med. 2016;109(10):372–80.
24. Park S, Jayaraman S. Enhancing the quality of life through wearable technology. IEEE Eng Med Biol Mag. 2003;22(3):41–8.
25. Greiwe J, Nyenhuis SM. Wearable technology and how this can be implemented into clinical practice. Curr Allergy Asthma Rep. 2020;20(1):1–10.
26. Burnham JP, Lu C, Yaeger LH, Bailey TC, Kollef MH. Using wearable technology to predict health outcomes: A literature review. J Am Med Inform Assoc. 2018;25(9):1221–7.
27. Qaddoori SL, Fathi I, Hammoudy MA, Ali QI. Advancing public health monitoring through secure and efficient wearable technology. Int J Saf Secur Eng. 2023;13(6):1001–14.
28. Phillips SM, Cadmus-Bertram L, Rosenberg D, Buman MP, Lynch BM. Wearable technology and physical activity in chronic disease: Opportunities and challenges. Am J Prev Med. 2018;54(2):144–50.
29. Ming DK, Sangkaew S, Chanh HQ, Nhat PT, Yacoub S, Georgiou P, et al. Continuous physiological monitoring using wearable technology to inform individual management of infectious diseases, public health and outbreak responses. Int J Infect Dis. 2020;96:648–54.
30. Estepp JR, Blackford EB, Meier CM. Recovering pulse rate during motion artifact with a multi-imager array for non-contact imaging photoplethysmography. In: Proceedings of the 2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC); 2014 Oct 5–8; San Diego, CA, USA. p. 1462–9.
31. Lu G, Yang F. Limitations of oximetry to measure heart rate variability measures. Cardiovasc Eng. 2009;9(3):119–25.
32. Carrier B, Salatto RW, Davis DW, Sertic JVL, Barrios B, Cater P, et al. Assessing the validity of several heart rate monitors in wearable technology while mountain biking. Int J Exerc Sci Conf Proc. 2021;14:18.
33. Chow H, Yang C. Accuracy of optical heart rate sensing technology in wearable fitness trackers for young and older adults: Validation and comparison study. JMIR mHealth uHealth. 2020;8(4):e14707.
34. Terbizan DJ, Dolezal BA, Albano C. Validity of seven commercially available heart rate monitors. Meas Phys Educ Exerc Sci. 2002;6(4):243–7.
35. Zwiren LD, Freedson PS, Ward A, Wilke S, Rippe JM. Estimation of VO2max: A comparative analysis of five exercise tests. Res Q Exerc Sport. 1991;62(1):73–8.
36. Evans HJ, Ferrar KE, Smith AE, Parfitt G, Eston RG. A systematic review of methods to predict maximal oxygen uptake from submaximal, open circuit spirometry in healthy adults. J Sci Med Sport. 2015;18(2):183–8.
37. Carrier B, Creer A, Williams LR, Holmes TM, Jolley BD, Dahl S, et al. Validation of Garmin Fenix 3 HR

fitness tracker biomechanics and metabolics (VO2max). J Meas Phys Behav. 2020;3(4):331–7.
38. Ross R, Blair SN, Arena R, Church TS, Després J, Franklin BA, et al. Importance of assessing cardiorespiratory fitness in clinical practice: A case for fitness as a clinical vital sign: A scientific statement from the American Heart Association. Circulation. 2016;134(24):e653–99.
39. Luks AM, Swenson ER. Pulse oximetry at high altitude. High Alt Med Biol. 2011;12(2):109–19.
40. Chan ED, Chan MM, Chan MM. Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations. Respir Med. 2013;107(6):789–99.
41. Welk GJ, Bai Y, Lee J, Godino J, Saint-Maurice PF, Carr L. Standardizing analytic methods and reporting in activity monitor validation studies. Med Sci Sports Exerc. 2019;51(8):1767–78.
42. van Lier HG, Pieterse ME, Garde A, Postel MG, de Haan HA, Vollenbroek-Hutten M, et al. A standardized validity assessment protocol for physiological signals from wearable technology: Methodological underpinnings and an application to the E4 biosensor. Behav Res Methods. 2020;52(2):607–29.