



Original Research Article

SYSTEMATIC COMPARISON OF TREADMILL GENERATED AND FORMULA DERIVED VO₂ MAX: A PROSPECTIVE VALIDATION STUDY IN PRIMARY CARE WELLNESS GYM

Jinesh Kizhakoodan Sasidharan¹, Wadha Ahmed AlBaker¹, Sohel Salim Samnani¹, Mokhtar Ahmad Edrees¹, Neeli Vijayakumar¹, Maroua Ben Braham¹

¹Preventative Health - Wellness Programs, Primary Health Care Corporation, Qatar

Received : 28/08/2026
Received in revised form : 23/09/2026
Accepted : 06/10/2026

Corresponding Author:

Dr. Jinesh Kizhakoodan Sasidharan,
Preventative Health - Wellness
Programs, Primary Health Care
Corporation, Qatar
Email: drjineshks@gmail.com

DOI: 10.70034/ijmedph.2026.4.68

Source of Support: Nil,
Conflict of Interest: None declared

Int J Med Pub Health
2026; 16 (4); 466-473

ABSTRACT

Background: Maximal oxygen uptake (VO₂ max) is a recognized gold-standard indicator of cardiorespiratory fitness and is widely used for exercise prescription, patient monitoring, and evaluation of wellness interventions. Automated treadmill-generated VO₂ max estimations are commonly used in wellness settings; however, their validity under varying exercise conditions remains uncertain. Inaccurate VO₂ max estimation may negatively affect clinical decision-making, documentation reliability, and patient-centered care outcomes. The objective is to evaluate the accuracy of treadmill-generated VO₂ max values compared with a policy-approved formula-derived reference method.

Materials and Methods: A prospective quality improvement and validation study was conducted between February and May 2026 at a Primary Health Care Corporation wellness center in Qatar. Treadmill-generated VO₂ max values were compared with reference values calculated using the Cooper 12-minute test equation from PHCC approved policy. Validation was performed under three testing conditions: controlled fixed-speed and variable subject weight testing, controlled variable-speed with constant subject weight testing, and no control real-world testing. Patient expectations regarding documentation accuracy were additionally evaluated using a structured Patient-Centered Care survey

Results: Under controlled fixed-speed and varied body weight conditions, treadmill-generated VO₂ max values demonstrated a consistent systematic underestimation of -11.99% across all observations, independent of body weight variation. When treadmill speed was varied with constant subject weight conditions, substantial overestimation was observed, with percentage errors ranging from +82.95% to +120.19%. In real-world no control practice, error variability ranged from +7.92% to +100.41%, with a persistent trend toward overestimation. Controlled fixed-speed testing demonstrated negligible variability (SD 0.00), whereas both controlled variable-speed testing and no control real-world testing demonstrated high variability (SD 18.70 and SD 24.11, respectively).

Conclusion: Treadmill-generated VO₂ max estimations demonstrated substantial systematic inaccuracies and clinically significant variability, particularly under conditions involving treadmill speed fluctuations. The errors ranged leading that the treadmill speed fluctuation may be the primary determinant of measurement error.

Keywords: VO₂ max assessment; cardiorespiratory fitness; documentation accuracy

INTRODUCTION

Maximal oxygen uptake ($\text{VO}_2 \text{ max}$) is widely recognized as the key indicator of cardiorespiratory fitness (CRF) and reflects the integrated capacity of the cardiovascular, pulmonary, and muscular systems to transport and utilize oxygen during exercise.^[1] Higher $\text{VO}_2 \text{ max}$ values are strongly associated with improved cardiovascular health, reduced morbidity, and lower all-cause mortality rates.^[2,3] Consequently, $\text{VO}_2 \text{ max}$ assessment has become an important component of preventive medicine, rehabilitation, sports science, and wellness programs.^[4]

Cardiorespiratory fitness has been increasingly described as a “vital sign” because of its strong predictive value for cardiovascular disease, metabolic disorders, and premature mortality.^[1] Evidence suggests that even modest improvements in $\text{VO}_2 \text{ max}$ can significantly reduce long term health risks, including hypertension, diabetes mellitus, obesity, and coronary artery disease.^[4,5] Studies have also demonstrated that low CRF is independently associated with increased mortality risk irrespective of traditional risk factors.^[3]

In clinical and wellness environments, $\text{VO}_2 \text{ max}$ measurements are frequently used to guide individualized exercise prescription, evaluate physical performance, monitor rehabilitation progress, and assess intervention outcomes.^[1] Within structured wellness programs, small changes in $\text{VO}_2 \text{ max}$ may represent clinically meaningful physiological adaptations, consistent with the concept of the Minimal Clinically Important Difference (MCID), which denotes the smallest improvement in a measure that patients perceive as beneficial and that clinicians consider significant enough to warrant a change in management.^[6] Evidence indicates that even modest gains in $\text{VO}_2 \text{ max}$ can surpass this threshold: for instance, increases of approximately 1 MET ($\sim 3.5 \text{ mL/kg/min}$) are strongly linked to reduced all-cause mortality and cardiovascular events.^[1] Improvements of $\sim 1\text{--}2 \text{ mL/kg/min}$ have been described as clinically important in chronic respiratory disease outcomes.^[7] And each 1 MET increase ($\sim 3.5 \text{ mL/kg/min}$) has been associated with a 12% improvement in survival among men referred for exercise testing.^[3] Therefore, accuracy and consistency in $\text{VO}_2 \text{ max}$ assessment are essential to ensure appropriate patient monitoring and safe exercise recommendations.

Direct measurement of $\text{VO}_2 \text{ max}$ through cardiopulmonary exercise testing (CPET) remains the reference standard; however, its implementation is often limited by cost, technical requirements, equipment availability, and need for trained personnel.^[1] As a result, many health and wellness centers rely on indirect estimation methods incorporated into treadmill systems like Cooper 12-minute test.^[8] Although these systems provide convenient automated outputs, the predictive algorithms used may vary substantially between

manufacturers and may not always reflect validated formula calculation assessment models.^[9,10]

If the automated treadmill generated $\text{VO}_2 \text{ max}$ estimations produces clinically important inaccuracies under varying exercise conditions such as treadmill speed fluctuations, exercise intensity, user body weight may contribute to substantial overestimation or underestimation of $\text{VO}_2 \text{ max}$ values. Such inconsistencies may compromise exercise prescription, misrepresent patient progress, and reduce the effectiveness of outcome monitoring programs.^[9–11]

Standardized formula-based assessment methods, such as the Cooper 12-minute test equation approved organization’ policy or international bodies are considered more transparent and reproducible approaches for estimating aerobic capacity in clinical and field settings.^[8] These methods provide a practical framework for validation of automated treadmill outputs and allow organizations to standardize documentation practices according to institutional policies and evidence-based guidelines.

In addition to the clinical implications, accurate documentation has become increasingly important within patient centered care frameworks.^[12] Patients expect healthcare providers to maintain reliable, transparent, and precise health records.^[13] Documentation inaccuracies may negatively affect patient trust, communication, continuity of care, and confidence in healthcare services.^[14] Ensuring accuracy in fitness assessment results is therefore not only a technical requirement but also an essential component of healthcare quality and safety.

This study aimed to systematically compare treadmill generated $\text{VO}_2 \text{ max}$ values with formula derived reference values and to evaluate sources of variability affecting the accuracy in a primary care wellness setting. The project further sought to support implementation of standardized assessment practices to enhance patient monitoring, exercise prescription, and overall quality of care.

Objective: To assess the accuracy of treadmill generated $\text{VO}_2 \text{ Max}$ measurements and enhance the reliability of their documentation by systematically validating them against policy approved, formula-based reference methods in a primary care setting. Additionally, the study aims to identify sources of variability in current assessment practices and support the implementation of standardized approaches to improve clinical decision making and patient monitoring.

Conceptual Framework: The conceptual framework [Figure 1] proposes that the accuracy of treadmill-generated $\text{VO}_2 \text{ Max}$ values is primarily influenced by testing conditions, particularly treadmill speed variability. Testing variables, including speed, duration, body weight, and real-world operational conditions, affect the performance of the treadmill estimation algorithm and determine measurement accuracy. Controlled validation identified treadmill speed variation as the principal source of measurement error, whereas body weight

had minimal influence under fixed-speed conditions. Measurement accuracy directly influences the reliability of clinical documentation, which supports accurate assessment of cardiorespiratory fitness, exercise prescription, patient monitoring, and evaluation of wellness interventions. Standardized validation against a reference method improves documentation quality and strengthens evidence-based clinical decision-making. These improvements

ultimately contribute to patient-centered care by enhancing patient confidence, communication, and the overall quality and safety of healthcare. The patient survey further supports this framework, highlighting the importance patients place on accurate documentation for individualized care and clinical decision-making.

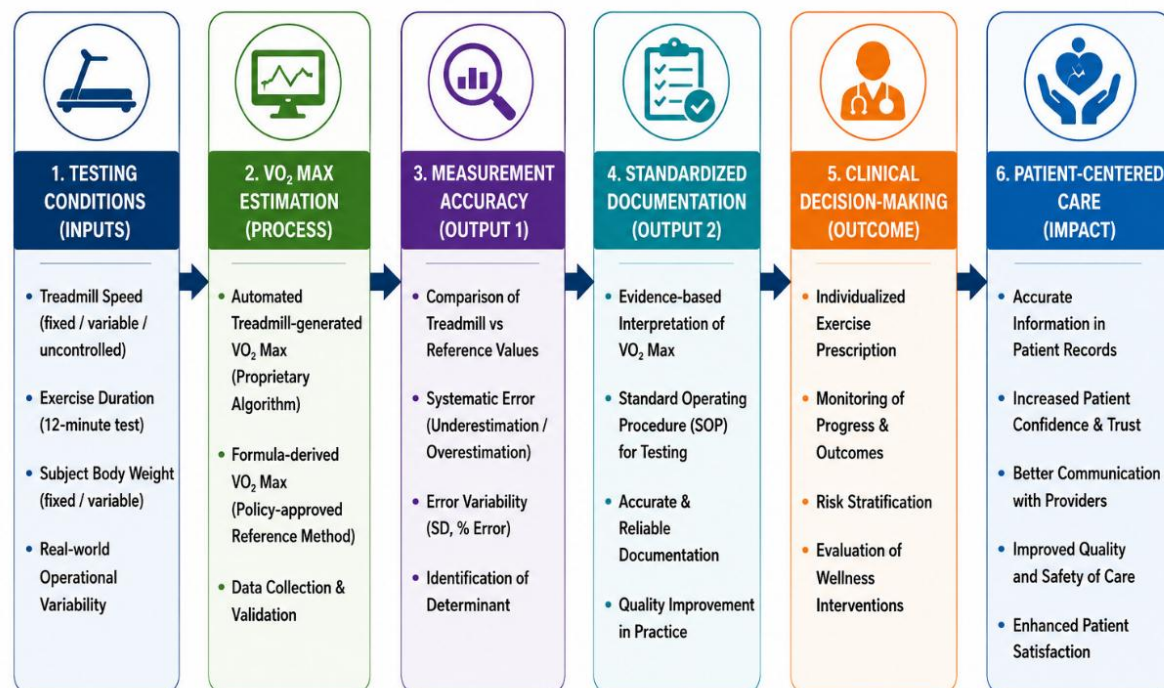


Figure 1: Conceptual framework of the study from testing conditions to patient-centered care through measurement accuracy and standardized clinical practice.

MATERIALS AND METHODS

Study Design and Setting: This study was designed as a prospective quality improvement study, using a method of comparison validation design, incorporating controlled experimental and real-world observational assessments where data were collected forward in time using predefined validation protocols for controlled experimental and real-world conditions. The study was carried out at PHCC Wellness Center, focusing on the routine practice of VO₂ Max assessment generated automatically by treadmill-based systems.

Validation Protocol: A structured validation process was implemented using three testing conditions:

Controlled Test Set 1 (Predefined Conditions): VO₂ Max assessments were performed under standardized conditions with fixed treadmill parameters (speed and duration), while varying subject weight to assess consistency.

Controlled Test Set 2 (Predefined Conditions): Assessments were conducted under predefined but varied conditions, including changes in speed while maintaining consistent duration and subject weight,

to evaluate system performance across different controlled scenarios.

No control Test Set (Real- World Practice): VO₂ Max measurements were obtained under routine clinical conditions without controls on speed fluctuations as per client comfort, but the duration is fixed reflecting real- world variability in practice.

Reference Standard: For all test conditions, treadmill-generated VO₂ Max values were compared against values calculated using a policy-approved formula-based method, which served as the reference standard:

$$VO_2 \text{ Max} = \frac{Distance (m) - 504.9}{44.73}$$

Data Analysis: Accuracy was assessed by calculating the percentage error between treadmill-generated and formula-derived VO₂ Max values. Descriptive statistics, including mean error and range of variation, were used to evaluate agreement and identify patterns of overestimation or underestimation across different test conditions.

Outcome Measures: The primary outcome of this study was the accuracy of treadmill-generated VO₂ Max values, defined by the degree of agreement with

VO₂ Max values derived from the policy- approved formula- based reference method. Accuracy was quantified using percentage error, enabling assessment of both the magnitude and direction of deviation (overestimation or underestimation). Secondary outcomes included the evaluation of variability in VO₂ Max measurements across different testing conditions and the identification of key factors contributing to observed inaccuracies. Specifically, the analysis focused on determining the influence of individual variables, such as treadmill speed changes and subject body weight, on error patterns by comparing controlled and uncontrolled test scenarios.

RESULTS

A total of three validation test sets were conducted to assess the agreement between treadmill- generated and formula- derived VO₂ Max values under controlled and real- world conditions.

In Controlled Test Set 1 (n = 9), where speed and duration were held constant and subject weight was varied in the range of 60-128 Kg, treadmill- generated VO₂ Max values consistently underestimated the reference values, with a uniform error of approximately -11.99% across all observations. This indicates a systematic underestimation that was unaffected by variations in body weight. [Table 1]

Table 1: Controlled Test Set 1, where speed and duration were held constant and subject weight was varied (n = 9)

Test (n=9)	Time (min)	Distance (m)	Speed (m/min)	Subject Weight (kg)	VO ₂ Max (Treadmill) (ml·kg ⁻¹ ·min ⁻¹)	VO ₂ Max (Reference) (ml·kg ⁻¹ ·min ⁻¹)	Error (%)
Test 1	12	1192	100	60	13.5	15.34	-11.99
Test 2	12	1192	100	60	13.5	15.34	-11.99
Test 3	12	1192	100	60	13.5	15.34	-11.99
Test 4	12	1192	100	80	13.5	15.34	-11.99
Test 5	12	1192	100	80	13.5	15.34	-11.99
Test 6	12	1192	100	80	13.5	15.34	-11.99
Test 7	12	1192	100	128	13.5	15.34	-11.99
Test 8	12	1192	100	128	13.5	15.34	-11.99
Test 9	12	1192	100	128	13.5	15.34	-11.99

In Controlled Test Set 2 (n = 3), where duration and subject weight were constant and treadmill speed was varied in the significant changes ranging 58-258 m/min, substantial overestimation was observed. The percentage error ranged from approximately +82.95% to +120.19%, demonstrating that changes

in speed significantly influenced the magnitude of deviation. These findings suggest that treadmill- generated VO₂ Max values are highly sensitive to speed variations under controlled conditions. [Table 2]

Table 2: Controlled Test, where duration and subject weight were constant and treadmill speed was varied (n = 3)

Test (n=3)	Time (min)	Distance (m)	Avg.Speed (m/min)	Subject Weight (kg)	VO ₂ Max (Treadmill) (ml·kg ⁻¹ ·min ⁻¹)	VO ₂ Max (Reference) (ml·kg ⁻¹ ·min ⁻¹)	Error (%)
Test 1	12	1675	140	60	57.6	26.16	+120.19
Test 2	12	1500	125	60	13.5	22.25	+82.95
Test 3	12	1131	95	60	13.5	14.00	+98.61

In the no control Test Set (n = 27, real- world practice), which reflected routine clinical conditions without predefined controls, considerable variability

in accuracy was observed. The error ranged from approximately +7.92% to +100.41%, with a consistent trend toward overestimation. [Table 3]

Table 3: No control Test Set (real- world practice), which reflected routine clinical conditions (n = 27)

Test (n=27)	Time (min)	Distance (m)	Avg.Speed (m/min)	Subject Weight (kg)	VO ₂ Max (Treadmill) (ml·kg ⁻¹ ·min ⁻¹)	VO ₂ Max (Reference) (ml·kg ⁻¹ ·min ⁻¹)	Error (%)
Test 1	12	1341	111.75	78	30.10	18.69	+61.03
Test 2	12	1327	110.58	67	30.10	18.38	+63.77
Test 3	12	1753	146.08	81	38.10	27.90	+36.54
Test 4	12	1145	95.42	80	27.10	14.31	+89.37
Test 5	12	1142	95.17	77	25.10	14.24	+76.22
Test 6	12	1331	110.92	94	29.40	18.47	+59.19
Test 7	12	1627	135.58	76	37.10	25.09	+47.89
Test 8	12	1037	86.42	84	23.80	11.90	+100.07
Test 9	12	1754	146.17	78	34.10	27.93	+22.11
Test 10	12	1096	91.33	90	24.10	13.21	+82.37
Test 11	12	1282	106.83	74	31.10	17.37	+79.01
Test 12	12	796	66.33	89	10.10	6.51	+55.20
Test 13	12	1141	95.08	85	28.50	14.22	+100.41
Test 14	12	1644	137.00	82	40.80	25.47	+60.21

Test 15	12	928	77.33	94	11.60	9.46	+22.63
Test 16	12	1376	114.67	88	28.50	19.47	+46.34
Test 17	12	1173	97.75	79	28.50	14.94	+90.81
Test 18	12	1290	107.50	83	30.70	17.55	+74.91
Test 19	12	1394	116.17	86	31.80	19.88	+59.98
Test 20	12	994	82.83	80	11.80	10.93	+7.92
Test 21	12	1119	93.25	82	26.80	13.73	+95.21
Test 22	12	796	66.33	79	10.60	6.51	+62.88
Test 23	12	1406	117.17	91	30.10	20.15	+49.41
Test 24	12	1159	96.58	85	24.80	14.62	+69.59
Test 25	12	1282	106.83	81	31.20	17.37	+79.59
Test 26	12	1175	97.92	79	28.20	14.98	+88.24
Test 27	12	1272	106.00	77	30.60	17.15	+78.43

Overall, the analysis demonstrated a clear pattern of systematic deviation between treadmill- generated and formula- derived VO_2 Max values, with the direction and magnitude of error varying depending on test conditions. Controlled testing identified treadmill speed changes during the test as a key factor influencing overestimation, while body weight had minimal impact under fixed conditions. In real- world settings, the interaction of multiple variables contributed to wider variability and reduced reliability of treadmill- generated values.

Patient- Centered Care (PCC) Survey Findings:

A patient survey was conducted as part of the Patient- Centered Care (PCC) framework to assess patient expectations regarding the accuracy of clinical documentation in the wellness program. A total of 65 participants responded to structured questions focusing on the role of documentation accuracy in clinical care and patient experience.

The findings indicate that majority of patients place high importance on accurate documentation practices [Figure 2]. Specifically, 83% of respondents expected healthcare staff to use appropriate assessment methodologies to ensure accuracy in documentation. Additionally, 75% of patients emphasized the importance of accurate documentation when tailoring individualized wellness or exercise plans. However, only 54% of participants expected health records to be completely free from errors, suggesting a degree of tolerance for minor inaccuracies but a strong preference for methodological correctness.

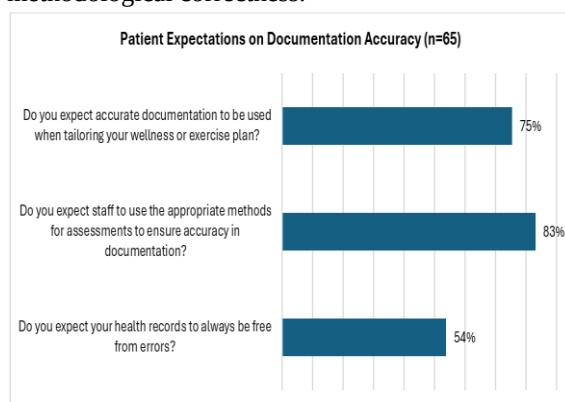


Figure 2: Patient expectations on documentation accuracy

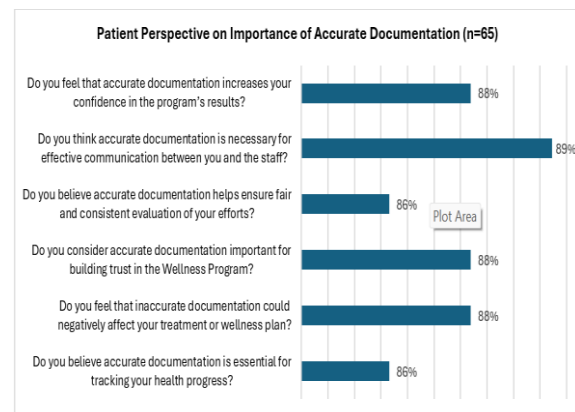


Figure 3: Patient perspective on accurate documentation

A substantial majority of participants (86%–89%) recognized accurate documentation as essential for key aspects of healthcare delivery [Figure 3]. Specifically, 89% of respondents indicated that accurate documentation is necessary for effective communication between patients and healthcare providers, while 88% reported that documentation accuracy enhances confidence in the program and supports overall care quality. Additionally, 86% of participants agreed that accurate documentation contributes to fair and consistent evaluation of their health progress. Furthermore, 88% of respondents believed that inaccurate documentation could negatively impact their treatment or wellness plans, highlighting potential risks associated with measurement errors.

DISCUSSION

A total of three validation test sets were conducted to assess the agreement between treadmill- generated and formula- derived VO_2 Max values under controlled and real- world conditions.

In Controlled Test Set 1, where speed and duration were held constant and subject weight was varied ($n = 9$), treadmill- generated VO_2 Max values consistently underestimated the reference values, with a uniform error of approximately -11.99% across all observations [Figure 4]. This indicates a systematic underestimation that was unaffected by variations in body weight.

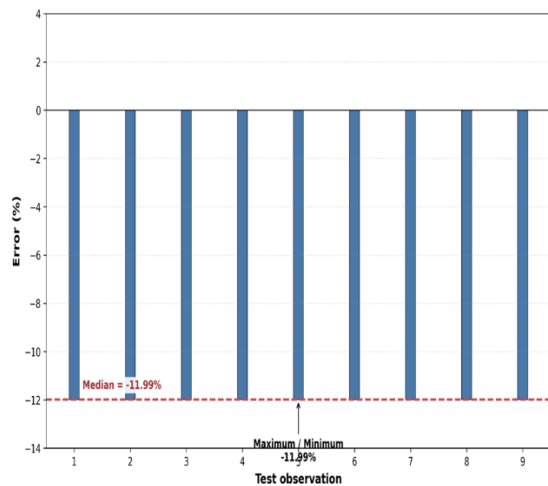


Figure 4: Error range in Controlled Test Set 1, where speed and duration were held constant and subject weight was varied (n = 9)

In Controlled Test Set 2, where duration and subject weight were constant and treadmill speed was varied (n = 3), substantial overestimation was observed [Figure 5]. The percentage error ranged from approximately +82.95% to +120.19%, demonstrating that changes in speed significantly influenced the magnitude of deviation. These findings suggest that treadmill-generated VO₂ Max values are highly sensitive to speed variations under controlled conditions.

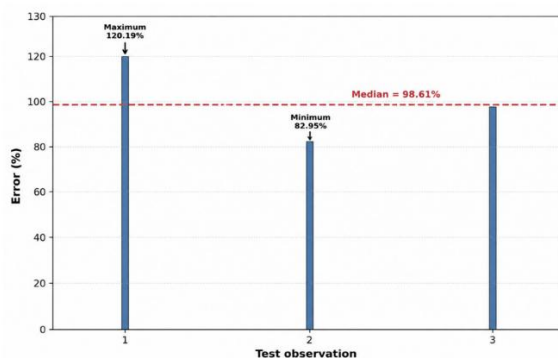


Figure 5: Error range in Controlled Test, where duration and subject weight were constant and treadmill speed was varied (n = 3)

In the no control test set (real- world practice), which reflected routine clinical conditions (n = 27), considerable variability in accuracy was observed, where only the duration had maintained constant and the body weight and speed was not predefined [Figure 6]. The error ranged from approximately +7.92% to +100.41%, with a consistent trend toward overestimation. This variability indicates the combined influence of multiple factors, including speed fluctuations and subject weight during testing. The findings of this study strongly indicate that variation in treadmill speed during assessment is a primary determinant of error in VO₂ Max estimation [Table 4]. Under controlled conditions where speed and duration were fixed, the observed error remained consistent (-11.9%), irrespective of changes in subject weight, suggesting that weight does not significantly influence the discrepancy. In contrast, when speed was systematically varied while maintaining other parameters constant, a marked increase in error magnitude was observed (+82.95% to +120.19%), demonstrating a strong sensitivity of treadmill generated VO₂ Max values to speed alterations.

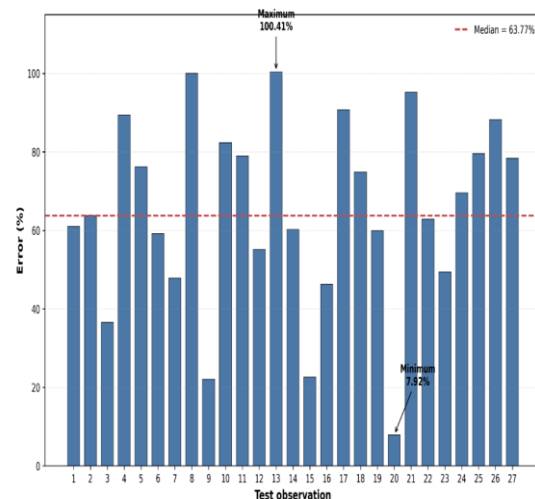


Figure 6: Error range in No Control Test Set (real- world practice), which reflected routine clinical conditions (n = 27)

Table 4: Summary of error distribution and influencing factors in vo₂ max estimation across test conditions.

Test Group	Consistent Variables	Changing Variables	Number of tests (n)	Error Range (%)	Variability (SD)	Interpretation
Controlled Test Set 1	Speed, Duration	Subject weight	n=9	-11.9 to -11.9	0.00	Consistent systematic underestimation with negligible variability, indicating stable measurement bias independent of subject weight
Controlled Test Set 2	Subject weight, Duration	Speed	n=3	+82.95 to +120.19	18.70	Marked overestimation with large variability; change in speed during identified as dominant factor influencing error magnitude
Real-World Practice	Duration	Subject weight Speed	n=27	+7.92 to +100.41	24.11	High variability with consistent overestimation, reflecting the combined influence of multiple uncontrolled factors, including variations in speed

This pattern was further reinforced in real world testing conditions, where variability in speed during routine assessments corresponded with wide error ranges (+7.92% to +100.41%) and consistent overestimation. The convergence of findings across controlled and uncontrolled scenarios suggests that speed dependent algorithms within the treadmill system may disproportionately influence VO₂ Max calculations, leading to significant inflation of results when speed increases.

Collectively, these observations provide strong analytical evidence that fluctuations in speed during testing are a critical source of measurement bias and likely represent the dominant factor contributing to inaccuracy in treadmill generated VO₂ Max values along.

Strengths: This study has several important strengths. The prospective validation design allowed for systematic evaluation of treadmill-generated VO₂ Max values under both controlled and real-world conditions. The inclusion of separate testing scenarios in which treadmill speed and body weight were independently examined enabled clear identification of speed variation as the principal factor contributing to measurement error. The combination of controlled experimental assessments with routine clinical practice data enhanced the practical applicability of the findings and provided insight into real-world performance. In addition, the incorporation of a patient-centered care survey broadened the scope of the study by linking measurement accuracy to patient expectations, confidence, communication, and quality of care.

Limitation: This study has several limitations. The sample size in certain test conditions was small, which may limit the generalizability of findings. The study was conducted in a single setting using one treadmill system, and the use of a formula-based method as a reference, rather than direct VO₂ Max measurement, may introduce estimation bias. Future research should include larger sample sizes, multi center settings, and different treadmill systems to enhance generalizability. Incorporating advanced statistical analysis and direct measurement methods (e.g., cardiopulmonary exercise testing) would further strengthen validation.

CONCLUSION

This study demonstrates significant discrepancies between treadmill-generated and formula-derived VO₂ Max values in a primary care wellness setting, with both the magnitude and direction of error varying across testing conditions. Under standardized conditions, treadmill-generated values showed consistent underestimation, whereas substantial overestimation was observed when treadmill speed was varied and in real-world practice.

The findings indicate that treadmill speed variation is likely a major contributor to measurement error in

automated VO₂ Max estimation. While a small and consistent systematic bias was observed under fixed-speed conditions, substantial increases in both error magnitude and variability occurred when speed was altered during testing. These results suggest that speed-dependent treadmill algorithms may significantly influence estimated VO₂ Max values and emphasize the need for standardized assessment protocols and routine validation against reference methods to ensure accurate documentation, informed clinical decision-making, and optimal patient care.

The considerable variability observed in routine practice highlights the limitations of relying solely on automated outputs for clinical decision-making. Inaccurate VO₂ Max estimation can lead to misinterpretation of patient fitness status, inappropriate exercise prescription, and reduced effectiveness of program monitoring.

Importantly, this study underscores the critical role of systematic validation of clinical practices in enhancing the accuracy and reliability of assessment methods. Regular validation against standardized reference methods enables early identification of measurement errors, supports protocol standardization, and improves clinical efficiency in functional assessments. In turn, this facilitates more precise documentation, better-informed clinical decisions, and optimized patient outcomes.

Furthermore, patient-centered care findings reinforce that accuracy in documentation is essential for maintaining trust, ensuring effective communication, and supporting high-quality care delivery.

Overall, integrating routine validation processes into clinical workflows is essential to ensure maximum accuracy in VO₂ Max assessment and documentation, thereby strengthening both the quality and safety of care in primary health settings.

Acknowledgment:

The authors sincerely thank their mentors for their valuable guidance and continuous support throughout this study. We extend our special appreciation to Ms. Rita El Ghazal, Senior Quality Improvement Coordinator, for her guidance and support throughout the quality improvement process. We acknowledge our colleagues and peers for their constructive feedback and insightful discussions that enriched this work. Special appreciation is extended to Rawdat Al Khail Health Center leadership, the Quality Improvement Team, and Primary Health Care Corporation, Qatar, for their institutional support and commitment to quality improvement, research, and workforce wellness initiatives. The support and contributions of all involved were instrumental in the successful completion of this study.

Author Contributions

Dr. Jinesh Kizhakoodan Sasidharan: Supervision, conceptualization, framework development, study implementation, data analysis, interpretation of findings, and manuscript writing.

Dr.Wadha Ahmed AlBaker: Supervision, Critical review, conceptualization, framework development, and manuscript writing.

Sohel Salim Samnani: Conceptualization, Data collection, data management, data analysis, study implementation and manuscript writing.

Mokhtar Ahmad Edrees: Data collection, data management, study implementation and manuscript writing.

Neeli Vijayakumar: Data collection, data management, study implementation and manuscript writing.

Maroua Ben Braham: Data collection, data management, study implementation and manuscript writing.

All authors reviewed and approved the final version of the manuscript and agreed to its submission for publication.

Conflict of interest

The authors declare that there are no conflicts of interest related to this study. The research was conducted independently, without any financial or personal relationships that could have influenced the outcomes.

Funding Declaration

This study received no specific grant, financial support, or funding from any public, commercial, or not-for-profit organization.

Study classification and Ethical Considerations

This study was conducted as part of an Institutional Quality Improvement (QI) project under the Quality Improvement framework of the Primary Health Care Corporation (PHCC), Qatar.

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