



Validation of a Heart Rate-Based System for Assessing Exercise Thresholds and Aerobic Endurance

Scientific Validation of the TrueZone System

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*Submaximal heart rate analytics as a practical and accurate alternative to cardiopulmonary
exercise testing (CPET)*

The METFIT PhD study, University of Iceland

Authors

Agnar Steinarsson¹
Gréta Jakobsdóttir²
Erlingur Jóhannsson²

Affiliations

*University of Iceland, Department of Sports Science
Driftline Analytics, Reykjavik, Iceland*

Date

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Correspondence:
agnar@driftlineanalytics.com
www.driftline.io

Abstract

Aim: This study aimed to validate TrueZone, a novel heart rate-based fitness analytics system, by comparing its submaximal predictions of key physiological parameters with results from gold-standard cardiopulmonary exercise testing (CPET) and direct sprint testing.

Methods: A total of 38 recreational runners (21 men, 17 women) completed three tests: (1) a submaximal treadmill test for TrueZone analysis, (2) a 50-meter sprint test, and (3) an incremental CPET. TrueZone estimated maximum heart rate (HR_{max}), VO_{2max} , ventilatory thresholds (VT1, VT2), and maximum speed (V_{max}) based solely on heart rate and treadmill speed. Statistical comparisons included paired and independent t-tests, Pearson correlations, Bland-Altman plots, and linear regression. A priori power analysis set the required sample size at $n = 34$.

Results: TrueZone estimates showed strong agreement with CPET for VO_{2max} ($R^2 = 0.86$), HR_{max} ($R^2 = 0.86$), VT2 speed ($R^2 = 0.91$), and V_{max} ($R^2 = 0.73$). Paired t-tests revealed no significant differences between TrueZone and CPET for VO_{2max} , V_{max} , or VT2 speed ($p > 0.05$). Statistically significant differences were observed for VT1 speed and HR-based variables, likely due to limitations in CPET threshold detection. Gender comparisons showed higher endurance scores in females, while males demonstrated significantly higher VO_{2max} and V_{max} .

Conclusion: TrueZone provides accurate, physiologically valid estimates of key performance metrics using only submaximal heart rate and speed data. It offers a practical and scalable alternative to laboratory-based fitness testing, especially for endurance assessment, training guidance, and population screening.

Keywords: heart rate analytics, TrueZone, VO_{2max} , ventilatory threshold, HR_{max} , endurance, CPET, fitness testing, validation.

Introduction

Despite decades of progress, exercise physiology lacks a unifying framework for core concepts such as exercise thresholds, oxygen kinetics, and aerobic endurance. Key challenges remain: defining a universal system of exercise thresholds, constructing a continuous intensity scale, and establishing a direct, physiologically valid measure of aerobic endurance. Moreover, heart rate responses during submaximal exercise and recovery are poorly understood, and current methods cannot reliably estimate maximum heart rate or aerobic capacity. This study aims to address these gaps by validating a new heart rate-based model against gold-standard testing.

Exercise thresholds have been debated for over 50 years, with 25+ lactate threshold definitions, now broadly grouped under maximal metabolic steady state (MMSS) (Faude et al., 2009; Jones et al., 2019). Standardized ventilatory thresholds (VT1, VT2, VT3) aim to improve threshold determination (Binder et al., 2008; Westhoff et al., 2013), but CPET software often relies on subjective breakpoint detection, reducing accuracy (Vyntus CPX, 2019).

A key debate centers on critical power (CP) vs. maximal lactate steady state (MLSS). CP, derived from power-duration models, marks the transition from physiological homeostasis to metabolic instability (Jones et al., 2019), whereas MLSS defines the highest intensity where lactate remains stable. However, CP typically exceeds MLSS, leading to claims that it overestimates MMSS, while MLSS may underestimate it. Despite this, CP has been proposed as the gold standard for MMSS, though this remains contested. Although VO₂ kinetics research has introduced domains like moderate, heavy, and severe (Whipp, 1996), no unifying theory exists linking exercise thresholds.

VO₂max has long been central to endurance assessment but poorly predicts performance, as similarly fit athletes often differ markedly (Larsen & Sheel, 2015; Jones et al., 2021). Fat oxidation is a key factor, enhancing glycogen sparing and delaying fatigue (San-Millan & Brooks, 2017), with PPAR δ activation shown to improve endurance via increased fat metabolism (Wang et al., 2003, 2004; Fan et al., 2017). Alternative metrics include W', glycogen depletion time, and heart rate kinetics (Poole et al., 2016; Zakyntinaki, 2015; Emig & Peltonen, 2020). EPR (Fukuba & Whipp, 1996) and EI (Péronnet & Thibault, 1989) quantify endurance from power output decline. Power-law models like Riegel's ($V = S \cdot D^E$; $F = 1/E$) capture fatigue dynamics, with elite athletes showing $F \approx 1.03$ – 1.06 (Zinoubi et al., 2017; Blythe & Király, 2016). Recent work emphasizes durability — resistance to fatigue — as a missing dimension (Jones, 2024; Maunder et al., 2021).

Heart rate kinetics describes the time-course of heart rate during exercise. Recent models (Stirling, 2008; Zakyntinaki, 2015; Mazzoleni et al., 2016) simulate non-steady-state responses but lack physiological grounding. Cardiovascular drift during prolonged activity results from dehydration, thermoregulatory strain, muscle inefficiency, and glycogen depletion. Accurate HR_{max} measurement is

essential for training but declines with age and varies widely across individuals, rendering predictive formulas unreliable. Current methods such as CPET and maximal field tests are effort-intensive and often underestimate true HR_{max} , reinforcing the need for a valid submaximal alternative.

The traditional endurance model includes VO_{2max} , running economy (RE), and MLSS (Joyner & Coyle, 2008). VO_{2max} , while central to fitness, poorly predicts performance among elite athletes (Legaz Arrese et al., 2005; Daniels et al., 1978; Larsen & Sheel, 2015). RE improves only modestly with training and is inversely related to VO_{2max} (Barnes & Kilding, 2015). VT_2 remains the strongest predictor of endurance performance, especially for marathon pacing (Sjödin & Jacobs, 1981; Sjödin & Svedenahg, 1985). However, recent work identifies fatigue resistance as a missing variable in the endurance model (Jones et al., 2021) — a variable that could serve as a direct marker of aerobic endurance, rather than an indirect correlate.

Endurance performance hinges on mitochondrial function, capillarization, myoglobin content, and substrate preference — especially fat oxidation (San-Millan & Brooks, 2017). PPAR δ activation in mice increased type I fibers and endurance (Wang et al., 2004), while pharmacologic activation enhanced fat oxidation and resistance to weight gain (Fan et al., 2017). Despite these advances, no standardized measure of aerobic endurance exists. Previous efforts (Zakynthini, 2015; Emig & Peltonen, 2020) proposed abstract endurance indices with limited physiological basis.

The TrueZone theory, described in Supplementary Material – A1 (Steinarsson & Agnarsson, 2020) proposes a physiologically grounded heart rate model based on muscle fiber recruitment and substrate utilization across intensities. It introduces 10 aligned aerobic thresholds and models heart rate kinetics during both exercise and recovery. The model outputs a new endurance metric (E), reflecting fat oxidation capacity and fiber recruitment efficiency. It estimates fitness parameters — VO_{2max} , HR_{max} , thresholds, endurance — using only heart rate and power (e.g., speed) from a single submaximal effort. This enables precise, individualized assessment without expensive or exhaustive testing.

CPET remains the gold standard for fitness assessment but requires specialized equipment and personnel. While field tests like the Beep test are more accessible, they still require maximal effort. CPET is also prone to error in break-point detection of ventilatory thresholds and is impractical for broad use in sports, schools, or clinical settings. A reliable, submaximal method based on heart rate would be transformative — especially now that heart rate tracking is universally available in consumer wearables.

This study aimed to validate the TrueZone model by comparing its estimates of VO_{2max} , HR_{max} , VT_2 , and V_{max} with those from CPET and sprint testing. We hypothesized that there would be no significant differences between TrueZone and gold-standard methods across these key metrics.

Methods

Experiment design

The study comprised three consecutive tests: A) submaximal running, B) sprinting, and C) cardiopulmonary exercise testing (CPET). The running and CPET tests were conducted at the Sports Science Laboratory, University of Iceland.

Participants

Thirty-eight casual runners (21 men, 17 women), aged 25–55 years with BMI ranging from 18.6–39.1, were recruited via social media. All participants provided written informed consent after being briefed on potential risks. Exclusion criteria included heart disease or hypertension; no applicants were excluded. The study was approved by the Icelandic bioethics committee.

Anthropometric measurements were collected prior to testing, including height, weight, BMI, blood pressure (OMRON BP5255), and body composition (total fat, visceral fat, muscle mass) via bioelectrical impedance (OMRON HBF-514C).

Submaximal running test

Participants wore three heart rate monitors (Polar H7 chest strap, Polar Verity Sense armband, Scosche Rhythm armband). The test was performed on a Woodway treadmill (1% incline) and included a 3-minute warm-up, 2-minute rest, 20-minute run at a self-selected pace (sustainable for 40–60 minutes), and 10-minute supine recovery. Participants could stop at any time; 34 completed the full run, while four stopped early. Exertion was recorded every 5 minutes using the 20-point Borg scale. Heart rate data were continuously recorded from all devices.

Sprinting test

Conducted at least two weeks after the submaximal test on an indoor track equipped with Witty Pro infrared speed gates (0–50 m). After a standardized 20-minute warm-up (jogging, drills, sprints, stretching), participants performed up to three all-out 50-meter sprints from a standing start. A minimum 5-minute rest was allowed between attempts. All times were logged digitally and manually.

CPET

Conducted at least two weeks after the sprint test, CPET used a Woodway treadmill and Vyntus CPX system (Vyntus CPX, 2019). Participants wore the same three HR monitors and a metabolic mask. The protocol featured a fixed 1% incline and 1-minute stages with 0.5 km/h increments, tailored to reach exhaustion in 10–14 minutes. Each test began with a 5-minute jog and ended with 5-minute seated recovery.

Gas and volume calibrations were performed before each test. All equipment was sterilized and air-dried. Two certified supervisors were present, with a defibrillator on-site. Exertion was rated every 30 seconds via finger signals using the 10-point Borg scale. Heart rate and cadence (from Scosche Rhythm) were recorded.

TrueZone analysis

Heart rate and speed data from the submaximal test were loaded into the TrueZone app, which does not require anthropometric input. Analysis was conducted after all submaximal tests were completed. Treadmill speed (v_t) and incline (i) were corrected to level ground speed (v) using a modified Minetti equation:

$$v = v_t * (1 - (0.08 * (v_t - 8)/17) + 5i)$$

Heart rate data were filtered to remove noise before model fitting. The TrueZone model estimated three parameters: HR_{max} , exercise intensity (V), and endurance (E , 0–100%), by aligning heart rate curves from the exercise and recovery phases.

Statistics

Analyses were performed in Jamovi, v2.6.44 (The Jamovi project, 2022; Navarro & Foxcroft, 2022). A priori power analysis determined a required sample size of 34 ($\alpha = 0.05$, $\beta = 0.20$, $d = 0.5$). Paired-samples t-tests compared TrueZone-derived values (HR_{max} , VO_{2max} , ventilatory threshold, V_{max}) with gold-standard CPET and sprint data. Independent-samples t-tests assessed gender differences. Pearson's correlation coefficients quantified associations between predicted and reference values. Additional analyses included correlation matrices, linear regression, Bland-Altman plots, and effect size estimation using Cohen's d . Significance was set at $p < 0.05$, with both Type I and II error risks considered.

Results

The primary aim of this study was to provide scientific validation for TrueZone heart rate analytics through a comparison with gold-standard testing methods. A testable research hypothesis was designed for the study, relating to the TrueZone determination of HR_{max}, VO_{2max}, VT₂ and V_{max}.

TrueZone tests

Descriptive statistics and gender comparison.

Table 1 shows gender comparison and mean values for all the TrueZone test parameters from the submaximal running test.

Table 1

Descriptive statistics and independent sample t-tests for gender difference in the TrueZone submaximal running test. The results are sorted for gender (female (f), male (m)) and presented as mean values (M). Results from t tests include mean difference (dif.) and Cohen's d (d) with 95% confidence intervals (CI_{low}, CI_{up}).

<i>Variables</i>	<i>Units</i>	<i>M (f)</i>	<i>SD</i>	<i>M (m)</i>	<i>SD</i>	<i>Dif.</i>	<i>t</i>	<i>p</i>	<i>d</i>	<i>CI_{low}</i>	<i>CI_{up}</i>
<i>Height</i>	<i>cm</i>	163.9	7.04	182.2	5.04	-18.32	-9.72	< .001	-3.06	-4.24	-1.85
<i>Weight</i>	<i>kg</i>	63.19	8.26	87.07	11.77	-23.89	-7.31	< .001	-2.30	-3.27	-1.30
<i>BMI</i>	<i>kg/cm²</i>	23.52	2.80	26.42	3.77	-2.91	-2.73	0.009	-0.86	-1.53	-0.17
<i>Test speed</i>	<i>kph</i>	10.8	1.35	12.12	1.77	-1.32	-2.61	0.013	-0.82	-1.49	-0.14
<i>Test duration</i>	<i>min</i>	19.89	0.47	18.8	3.36	1.08	1.36	0.183	0.43	-0.21	1.05
<i>RPE</i>	<i>Borg</i>	13.53	1.99	13.63	1.99	-0.10	-0.16	0.875	-0.05	-0.68	0.58
<i>Intensity</i>	<i>T scale</i>	1.88	0.13	1.81	0.14	0.07	1.76	0.086	0.55	-0.10	1.19
<i>T1_v</i>	<i>kph</i>	8.15	1.08	9.13	1.47	-0.98	-2.37	0.023	-0.75	-1.40	-0.07
<i>T2_v</i>	<i>kph</i>	11.15	1.32	12.93	1.91	-1.78	-3.37	0.002	-1.06	-1.76	-0.34
<i>V_{max}</i>	<i>kph</i>	20.26	2.12	24.23	2.94	-3.97	-4.83	< .001	-1.52	-2.30	-0.71
<i>T1_{HR}</i>	<i>bpm</i>	129.5	8.71	127.9	6.30	1.63	0.70	0.491	0.22	-0.41	0.84
<i>T2_{HR}</i>	<i>bpm</i>	164.7	8.97	166.3	7.40	-1.59	-0.62	0.536	-0.20	-0.81	0.43
<i>Endurance</i>	<i>%</i>	72.8	0.70	65.4	0.94	7.40	2.81	0.008	0.884	0.19	1.56
<i>HR_{max}</i>	<i>bpm</i>	186.4	10.08	189.8	8.69	-3.34	-1.14	0.262	-0.36	-0.98	0.28
<i>VO_{2max}</i>	<i>ml/kg/min</i>	43.28	5.19	50.24	7.61	-6.97	-3.32	0.002	-1.05	-1.74	-0.33

Note. df = 39, H_a $\mu_1 \neq \mu_2$

No significant gender differences were observed in test duration, self-reported rating of perceived exertion (RPE), test intensity, heart rate at thresholds T1 and T2 (T1_{HR}, T2_{HR}), or maximum heart rate (HR_{max}). However, females exhibited significantly higher mean endurance scores as calculated by the TrueZone model ($p < 0.05$).

In contrast, males demonstrated significantly higher values for several anthropometric and performance variables, including height, weight, body mass index (BMI), test speed, threshold speeds ($T1_v$ and $T2_v$), maximum running speed (V_{max}), and estimated VO_{2max} ($p < 0.05$ for all comparisons).

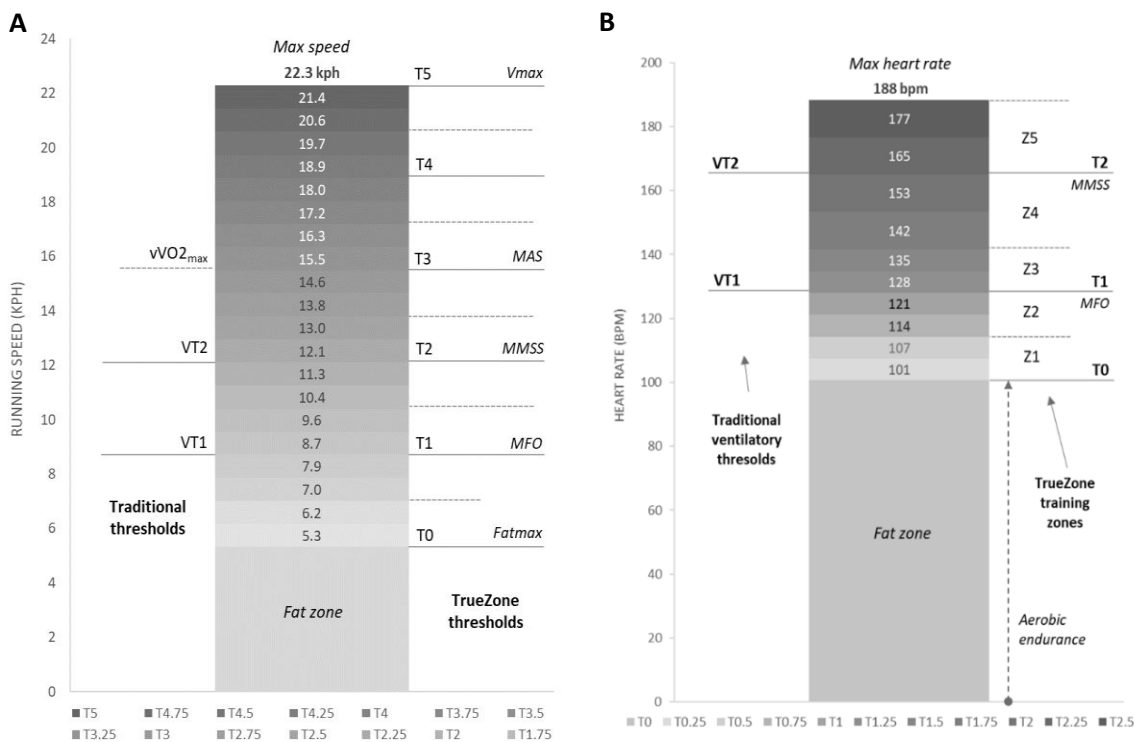
The largest gender-related differences were observed in V_{max} , VO_{2max} , and $VT2$ threshold speed ($VT2_v$), with males showing approximately 18% higher mean values compared to females.

Thresholds, zones and endurance.

The TrueZone theory introduces a novel system of multiple, evenly spaced exercise thresholds that span the entire intensity scale. It identifies five key recruitment thresholds ($T0$ – $T5$) and intermediate metabolic thresholds, including HR_{max} . The TrueZone scale (0 – $T5$) is divided into two sections: the aerobic section (0 – $T2.5$) with five heart rate zones ($Z1$ – $Z5$), and the anaerobic section ($T2.5$ – $T5$). Figure 1 shows the mean threshold values (running speed and heart rate) of the whole study group in relation to traditional threshold concepts.

Figure 1

TrueZone thresholds and zones (stacked columns) in relation to traditional threshold concepts ($VT1$, $VT2$ and vVO_{2max}). A) The mean TrueZone threshold speeds ($T0$ – $T5$) of the study group. B) The mean aerobic TrueZone threshold heart rates ($T0$ – $T2.5$) of the study group with training zones ($Z1$ – $Z5$) indicated.



The stacked column in Figure 1A shows the TrueZone intensity scale with 20 metabolic zones and five exercise thresholds (T1 – T5), presented with the mean values from the study. TrueZone thresholds T1, T2 and T3 correspond to the ventilatory thresholds VT1, VT2 and vVO2max. The mean speed values for VT1, VT2, vVO2max and Vmax can be read from the graph as 8.7, 12.1, 15.5 and 22.3 kph, respectively. The stacked column in Figure 1B shows the TrueZone aerobic scale with 10 metabolic zones and 5 heart rate zones (Z1 – Z5), presented with the mean values from the study. The mean heart rates for T0, T1, T2 and T2.5 (HRmax) can be read from the graph as 101, 128, 165 and 188 bpm, respectively. The maximum heart rate (HRmax) can be extrapolated as the highest aerobic threshold (T2.5). The maximum speed (Vmax) can be extrapolated as the highest threshold (T5).

The TrueZone concept of endurance (E) is based on the alignment of the exercise thresholds and directly reflects the relative height of the T0 threshold (fat zone). The mean endurance, Vmax and HRmax of the study subjects were 68.5%, 22.3 kph and 188 bpm, respectively. Maximum fat oxidation (MFO), maximum metabolic steady state (MMSS) and maximum aerobic speed (MAS) are associated with their respective thresholds as explained in Appendix A1.

Sprinting tests

Sprinting tests.

Table 2 summarizes the sprinting test results for all the test participants.

Table 2

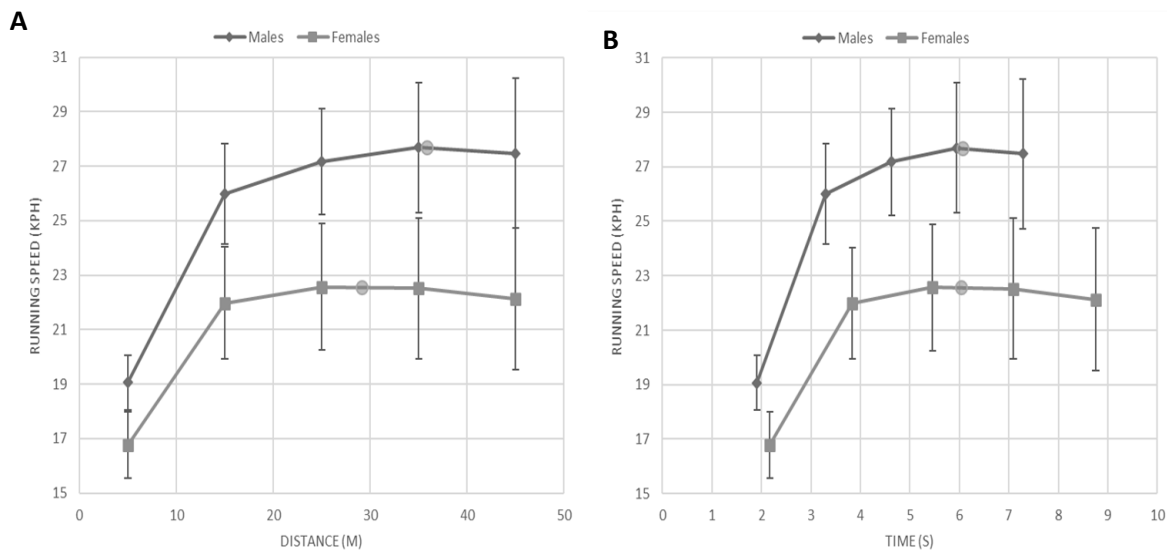
Mean total time and split times for each gender (male and female) at 10-meter intervals (10 – 50 m) in the 50-meter sprinting test.

<i>Gender</i>	<i>Parameters</i>	<i>10 m</i>	<i>SD</i>	<i>20 m</i>	<i>SD</i>	<i>30 m</i>	<i>SD</i>	<i>40 m</i>	<i>SD</i>	<i>50 m</i>	<i>SD</i>
Female	t_{split} (sec)	2.16	0.17	1.65	0.16	1.61	0.17	1.62	0.19	1.65	0.21
	t_{acc} (sec)	2.16	0.17	3.81	0.33	5.42	0.49	7.04	0.69	8.69	0.89
	Speed (kph)	16.78	1.22	21.98	2.05	22.57	2.33	22.52	2.58	22.13	2.61
Male	t_{split} (sec)	1.89	0.10	1.39	0.10	1.33	0.09	1.31	0.11	1.32	0.13
	t_{acc} (sec)	1.89	0.10	3.29	0.19	4.62	0.28	5.93	0.39	7.25	0.51
	Speed (kph)	19.06	1.01	25.99	1.85	27.17	1.95	27.69	2.38	27.48	2.74

Over all the splits, the males had significantly lower times and faster speeds than the females ($p < 0.001$) and the total time was also statistically lower ($p < 0.001$) over the 50 m distance (7.25 vs 8.69 sec, respectively). The sprinting test involved an all-out sprint from a standing start and therefore the subjects required a few seconds to reach their top speed. Figure 2 shows the mean speed reached by each gender (male and female) at each interval over the 50 m sprinting distance.

Figure 2

Mean speed (kph and standard deviation) reached by each gender (male and female) at 10-meter intervals (10 – 50 m) in the METFIT 50-meter sprinting test. A) Mean rolling speed plotted against distance covered. B) Mean rolling speed plotted against time lapsed. Approximate top speeds indicated with shaded markers.



The graph in Figure 2a shows that after only about 5 meters the subjects had on average reached about 70% of their top speed. The shaded markers show that the females and males on average reached their top speed after approximately 29 and 36 meters of sprinting, respectively. There was considerable individual variation as the slowest runners reached their top speed after only about 15 meters while the fastest runners were still accelerating at 50 meters. On average, both genders had started to slow down during the last 10-m segment. The shaded markers in in Figure 2b show that it took on average approximately 6.1 seconds for both males and females to reach top speed. The non-overlapping SD-whiskers show that there were statistically significant gender differences at every split.

Cardiopulmonary exercise testing (CPET)

Descriptive statistics and gender comparison.

The CPET protocol included three phases i.e, 5-minute warm-up, running to evolutional exhaustion and 10-min lying recovery post exercise. Table 3 shows gender comparison and mean values for all the major CPET variables.

Significant gender differences were observed across several key physiological and performance variables. Males showed significantly higher values for maximum speed (V_{max}), VO_{2max} , VT_2 speed (VT_{2v}), ventilation (VE_{max}), carbon dioxide output (VCO_2), workload (W_{max}), and cardiac output relative to oxygen consumption (Q/C_{max}), all with large effect sizes (Cohen's $d > 1.0$). The greatest differences

were found for V_{\max} and W_{\max} , where males outperformed females by approximately 18–20%. In contrast, females demonstrated significantly longer time to exhaustion (t_{50}), indicating greater endurance at submaximal intensities. Endurance scores derived from the TrueZone model were also significantly higher in females.

Table 3

Descriptive statistics and independent sample t-tests for gender difference in the cardiopulmonary exercise tests (CPET). The results are sorted for gender (female (f), male (m)) and presented as mean values (M). Results from t tests include mean difference (dif.) and Cohen's d (d) with 95% confidence intervals (CI_{low} , CI_{up}).

Parameters	Units	M (f)	SD	M (m)	SD	t	p	d	CI_{low}	CI_{up}
$VT1_v$	kph	7.74	1.19	8.70	1.52	-2.20	0.034	-0.69	-1.34	-0.02
$VT2_v$	kph	11.41	1.58	13.02	1.89	-2.91	0.006	-0.92	-1.59	-0.22
$vVO2_{max}$	kph	13.62	1.61	15.62	2.36	-3.07	0.004	-0.97	-1.65	-0.26
$VT1_{HR}$	bpm	138.5	13.8	134.8	11.6	0.82	0.420	0.30	-0.43	1.01
$VT2_{HR}$	bpm	165.9	11.0	171.2	8.0	-1.55	0.132	-0.56	-1.29	0.19
HR_{peak}	bpm	181.4	9.3	186.7	8.0	-1.73	0.094	-0.62	-1.36	0.13
$VT1_{VO2}$	ml/kg*min	24.37	3.54	28.50	5.60	-2.39	0.024	-0.86	-1.63	-0.07
$VT2_{VO2}$	ml/kg*min	37.06	5.15	43.57	6.58	-3.02	0.005	-1.09	-1.89	-0.25
$VO2_{max}$	ml/kg*min	42.64	5.16	50.45	7.55	-3.28	0.003	-1.19	-2.01	-0.33
t_{50}	sec	8.69	0.89	7.25	0.51	6.26	<.001	2.04	1.08	2.97
v_{max}	kph	22.68	2.45	27.71	2.42	-6.35	<.001	-2.07	-3.01	-1.10
$VCO2_{max}$	ml/kg*min	47.99	5.65	56.22	9.41	-2.87	0.008	-1.04	-1.83	-0.21
$VO2_{total}$	ml/min	2733	391	4281	434	-10.33	<.001	-3.73	-5.29	-2.13
$VCO2_{total}$	ml/min	3078	462	4761	499	-9.66	<.001	-3.48	-4.97	-1.97
$VO2_{rec}$	ml/min	523	69	747	86	-7.70	<.001	-2.86	-4.15	-1.53
RE	ml/kg*km	187.55	8.50	186.75	10.05	0.23	0.819	0.09	-0.65	0.81
RER_{max}	RER	1.15	0.04	1.13	0.04	0.96	0.344	0.35	-0.38	1.06
BF_{max}	breaths/min	52.66	6.66	50.98	6.73	0.70	0.493	0.25	-0.47	0.96
VE_{max}	L/min	100.8	14.7	144.7	11.7	-9.26	<.001	-3.34	-4.78	-1.87
W_{max}	W	194.6	30.6	313.3	35.3	-9.76	<.001	-3.57	-5.09	-2.02
QtC_{max}	L/min	17.85	2.41	27.74	3.27	-9.32	<.001	-3.41	-4.88	-1.91
METS	METS	12.27	1.49	14.41	2.21	-3.06	0.005	-1.12	-1.94	-0.27

Note. $df = 38$, $H_a \mu 1 \neq \mu 2$

No significant gender differences were found for test duration, RPE, test intensity, heart rate at thresholds ($VT1_{HR}$, $VT2_{HR}$), HR_{max} , running economy (RE), respiratory exchange ratio (RER), or breathing frequency (BF).

Correlation analysis.

To evaluate the internal consistency and physiological coherence of key performance variables, a Pearson correlation matrix was generated for VO_{2max} , total oxygen uptake (VO_{2total}), ventilation (VE), cardiac output relative to oxygen consumption (Q/C), metabolic equivalents (METs), maximum workload (W_{max}), and maximum speed (V_{max}). The results revealed several highly significant and physiologically plausible interrelationships, supporting the validity of the TrueZone model outputs.

Table 4

A Pearson's correlation matrix showing the correlation (r) between some of the variables measured in sprint testing and cardiopulmonary exercise testing (CPET). The table shows p-values for each correlation and statistical differences are indicated with asterisks as explained in the footnote.

Variables		VO_{2max}	VO_{2total}	VE	QtC	METs	W_{max}	V_{max}
VO_{2max}	r	—						
	p	—						
VO_{2total}	r	0.671 ***	—					
	p	<.001	—					
VE	r	0.643 ***	0.873 ***	—				
	p	<.001	<.001	—				
QtC	r	0.665 ***	0.992 ***	0.871 ***	—			
	p	<.001	<.001	<.001	—			
METs	r	0.996 ***	0.66 ***	0.635 ***	0.664 ***	—		
	p	<.001	<.001	<.001	<.001	—		
W_{max}	r	0.631 ***	0.976 ***	0.876 ***	0.976 ***	0.626 ***	—	
	p	<.001	<.001	<.001	<.001	<.001	—	
V_{max}	r	0.796 ***	0.773 ***	0.796 ***	0.766 ***	0.798 ***	0.781 ***	—
	p	<.001	<.001	<.001	<.001	<.001	<.001	—

Note. df = 38, * p < .05, ** p < .01, *** p < .001

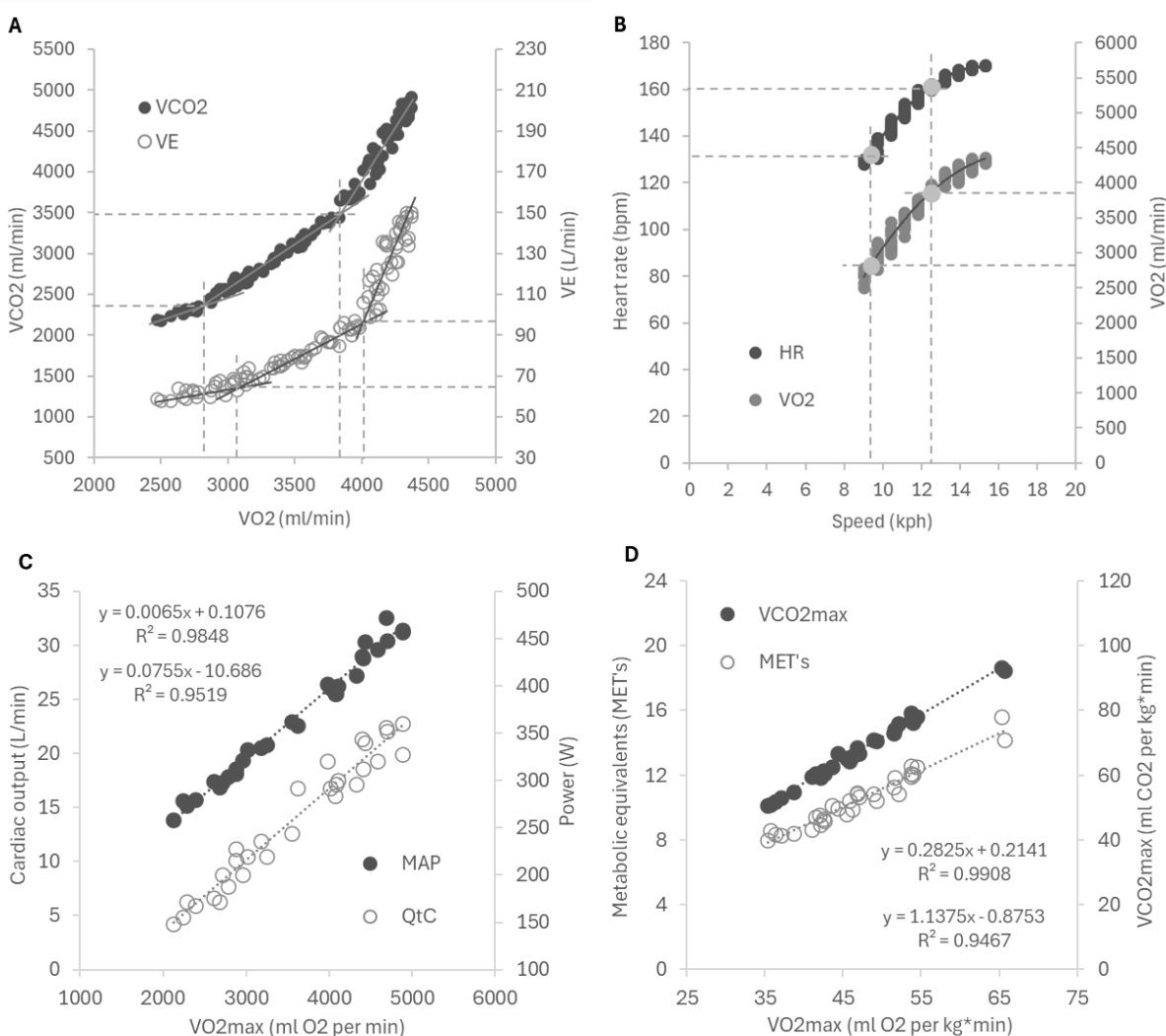
VO_{2max} was highly correlated with METs ($r = 0.996$, $p < 0.001$), confirming their direct physiological relationship. Strong correlations were observed between VO_{2total} and both VE ($r = 0.873$) and Q/C ($r = 0.992$), reflecting consistent respiratory and cardiovascular scaling. W_{max} and V_{max} showed strong correlations with nearly all other performance metrics, particularly VO_{2total} ($r = 0.976$ and $r = 0.773$, respectively), underscoring their value as global performance indicators. All variables demonstrated significant inter-correlations ($p < 0.001$), indicating a high degree of coherence across the dataset.

Figure 3 highlights the internal coherence of physiological variables measured during exercise testing. Relationships between oxygen uptake, ventilation, heart rate, power output, and metabolic

equivalents all follow expected patterns. Notably, oxygen uptake strongly correlates with both cardiac output and METs, confirming the reliability of TrueZone-based fitness estimates. Inflection points in ventilation and heart rate curves also align with known thresholds, validating the model's detection of VT2 and VO₂max.

Figure 3

Relationships among key cardiopulmonary and metabolic variables measured during cardiopulmonary exercise testing (CPET). A) VCO₂/VO₂- and VE/VO₂-plot for one participant with breakpoints indicated. B) HR/speed- and VO₂/speed-plot for one participant with breakpoints indicated. C) Cardiac output (QtC) and maximum aerobic power (MAP) versus VO₂max, all participants. D) Metabolic equivalents (METs) and VCO₂ versus VO₂max, all participants.



The visualizations in Figure 3 confirm the internal consistency of cardiopulmonary and metabolic parameters measured during maximal testing and modeled by the TrueZone system. In Panel A, both

VCO₂ and VE exhibit nonlinear increases relative to VO₂, consistent with expected ventilatory threshold dynamics. The deflection points in both curves align closely, validating the physiological detection of VT2 through gas exchange markers.

Panel B illustrates the well-established curvilinear relationship between running speed, heart rate, and VO₂. Notably, heart rate increases more steeply beyond VT2, supporting the heart rate kinetics-based threshold detection used in the TrueZone model.

Panel C demonstrates strong linear relationships between VO₂ and both cardiac output and mechanical power, with high coefficients of determination ($R^2 = 0.98$ and 0.95 , respectively). This reinforces the close coupling between oxygen uptake and cardiovascular/metabolic output and suggests that both Q_{tc} and MAP can serve as robust proxies for aerobic capacity.

In Panel D, VO₂max strongly correlates with both METs ($R^2 = 0.991$) and VCO₂max ($R^2 = 0.947$), supporting the use of METs as a simplified, yet valid, metric of aerobic performance. This also confirms that METs and VCO₂max—though distinct—reflect similar underlying physiological capacity.

Together, these findings highlight the reliability and interdependence of CPET-derived variables and support the use of heart rate-based modeling (e.g., in TrueZone) as a valid method for assessing aerobic fitness and metabolic thresholds.

TrueZone validation

The TrueZone heart rate analytics were validated through direct comparison with measured variables (CPET and sprint testing). Table 5 summarizes the results from linear regressions of measured and calculated variables and presents simple linear regression models evaluating the predictive validity of TrueZone-derived metrics against gold-standard physiological outcomes. Each model assesses the strength and significance of a single TrueZone variable in explaining variance in its corresponding reference measure.

All primary TrueZone parameters — VO₂max, V_{max}, HR_{max}, and thresholds T2.5, T2_v, and T1_v — showed highly significant associations with their respective outcomes ($p < 0.001$), with tight 95% confidence intervals and large t-values. These results indicate a strong linear relationship between TrueZone predictions and gold-standard values.

Table 5

The results from linear regressions between measured (CPET and sprinting tests) and calculated (TrueZone, TZ) variables. The table shows the model coefficients (intercept and slope) with mean values (B), standard errors (SE), 95% confidence intervals (CI_{low} and CI_{up}), t-values and p-values. The model fit shows the coefficient of determination (R^2), F-value and p-value for the model.

Variables	Model coefficients							Model fit		
	Predictor	B	SE	CI_{low}	CI_{up}	t	p	R^2	F	p
VO _{2max} (CPET)	Intercept	5.063	3.227	-1.54	11.66	1.57	0.127	0.856	173	<.001
	VO _{2max} (TZ)	0.890	0.068	0.75	1.03	13.15	<.001			
v50 (sprint)	Intercept	7.542	1.678	4.14	10.95	4.49	0.012	0.770	88.3	<.001
	V _{max} (TZ)	0.694	0.074	0.54	0.84	9.40	<.001			
HR _{max} (CPET)	Intercept	2.021	13.90	-26.4	30.4	0.15	0.885	0.856	172	<.001
	HR _{max} (TZ)	0.977	0.074	0.83	1.13	13.13	<.001			
vVO _{2max} (CPET)	Intercept	0.869	0.811	-0.77	2.51	1.07	0.291	0.886	148	<.001
	T2.5 (TZ)	0.963	0.056	0.85	1.08	17.30	<.001			
VT2 _v (CPET)	Intercept	0.443	0.597	-0.77	1.65	0.74	0.463	0.912	404	<.001
	T2 _v (TZ)	0.977	0.049	0.88	1.08	20.10	<.001			
VT1 _v (CPET)	Intercept	0.278	0.697	-1.13	1.69	0.40	0.692	0.776	135	<.001
	T1 _v (TZ)	0.919	0.079	0.76	1.08	11.63	<.001			
VT2 _{HR} (CPET)	Intercept	-4.74	23.22	-52.2	42.8	-0.20	0.84	0.659	56	<.001
	T2 _{HR} (TZ)	1.060	0.141	0.77	1.35	7.48	<.001			
VT1 _{HR} (CPET)	Intercept	63.31	40.18	-18.9	145.5	1.58	0.126	0.103	3.32	.079
	T1 _{HR} (TZ)	0.573	0.314	-0.07	1.22	1.82	0.079			

The regression coefficients (B) for VO_{2max} (0.890), HR_{max} (0.977), and T2_v (0.977) approach 1.0, suggesting near-perfect one-to-one agreement with traditional testing. Similarly, T1_v and V_{max} also showed strong predictive power (B = 0.919 and 0.694, respectively), validating the TrueZone model's capacity to estimate speed and threshold-related outcomes with high fidelity.

In contrast, the intercept-only models and a few secondary predictors (e.g., T2, intercepts for V_{max} and Q/C_{max}) were not statistically significant, indicating that the predictive power lies primarily in the TrueZone metrics themselves.

Overall, these findings provide robust statistical support for the use of TrueZone analytics as a valid and accurate substitute for conventional laboratory testing.

Figure 4 presents direct comparisons between TrueZone estimates and corresponding gold-standard test results across four key performance variables: threshold speed, maximum speed, VO_{2max}, and HR_{max}. All four regressions demonstrate strong linear agreement, validating the accuracy of the TrueZone system.

Figure 4

Linear regressions between some measured (CPET and sprint tests) and calculated (TrueZone, TZ) variables. A) Ventilatory speed thresholds (VT1 and VT2). B) Maximum heart rate (HR_{max}). C) Maximum oxygen uptake (VO_{2max}). D) Maximum speed (V_{max}).

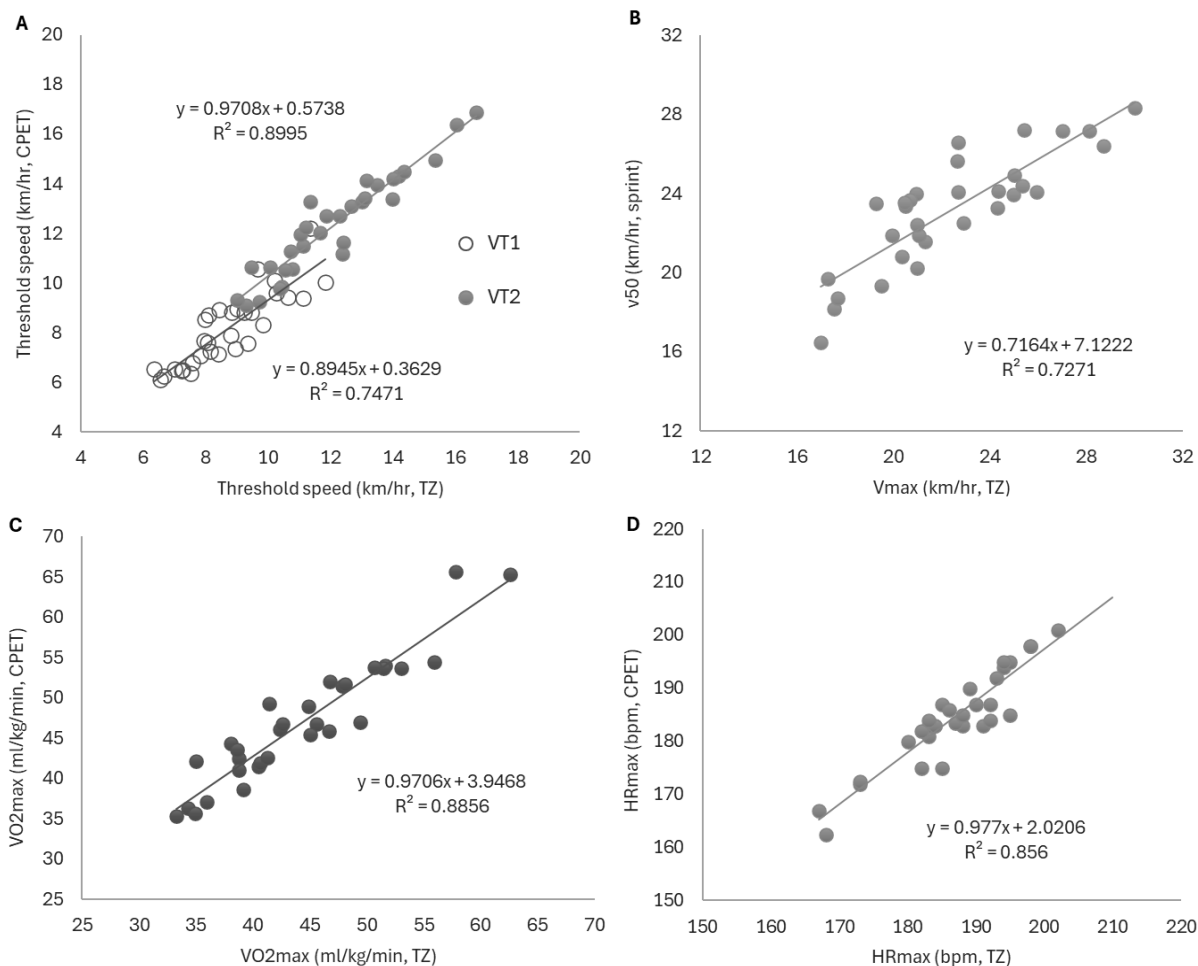


Figure 4 presents direct comparisons between TrueZone estimates and corresponding gold-standard test results across four key performance variables: threshold speed, maximum speed, VO_{2max} , and HR_{max} . All four regressions demonstrate strong linear agreement, validating the accuracy of the TrueZone system.

Panel A shows tight correlations between TrueZone and CPET threshold speeds for both VT1 ($R^2 = 0.75$) and VT2 ($R^2 = 0.90$). The regression slopes approach 1.0, indicating near-equivalence in the speed estimates for both thresholds.

Panel B compares TrueZone-derived V_{max} with sprint-derived 60-meter speed. Although this comparison involves different test modalities, the correlation remains strong ($R^2 = 0.73$), confirming that TrueZone V_{max} meaningfully reflects real-world sprint capacity.

Panel C shows excellent agreement between VO_{2max} values from TrueZone and CPET ($R^2 = 0.89$, slope = 0.98), suggesting that the submaximal model captures aerobic capacity with high precision.

Panel D illustrates a similarly strong relationship between TrueZone-derived and CPET-derived HR_{max} ($R^2 = 0.86$), reinforcing the model's ability to estimate peak heart rate accurately without maximal exertion testing.

Overall, these results demonstrate that the TrueZone system provides accurate and reliable estimates of physiological thresholds and maximal capacities, comparable to gold-standard laboratory testing.

Table 6 compares measured outcomes from cardiopulmonary exercise testing (CPET) with corresponding values calculated by the TrueZone system. The goal was to evaluate the agreement between the two methods across a range of physiological performance metrics, including maximum speed (V_{max}), ventilatory thresholds (VT1 and VT2), and heart rate values.

Table 6

Comparison of mean values of some measured (CPET and sprint tests) and calculated (TrueZone, TZ) variables. Paired sample t-test results include t-values, p-values and effect size (d) with 95% confidence intervals (CI_{low} , CI_{up}).

Variable			Measured		Calculated		Cohen's effect size				
Measured	TrueZone	Units	Mean	SD	Mean (TZ)	SD	t	p	d	CI_{low}	CI_{up}
VO_{2max}	VO_{2max}	kph	46.92	7.6	47.04	7.9	-0.22	0.831	-0.039	-0.39	0.31
v_{50}	V_{max}	kph	23.14	2.8	22.48	3.4	2.29	0.058	0.371	0.04	0.70
VT_{2v}	T_{2v}	kph	12.31	1.9	12.15	1.9	1.86	0.071	0.290	-0.02	0.60
VT_{1v}	T_{1v}	kph	8.28	1.5	8.70	1.4	-3.90	<.001	-0.609	-0.94	-0.27
HR_{peak}	HR_{max}	bpm	184.3	8.9	186.6	8.4	-3.74	<.001	-0.672	-1.06	-0.28
VT_{1HR}	T_{1HR}	bpm	136.5	12.6	127.7	7.0	3.98	<.001	0.715	0.31	1.11
VT_{2HR}	T_{2HR}	bpm	168.8	9.7	164.2	7.5	4.55	<.001	0.817	0.40	1.22

Note. $df = 40$, $H_0: \mu_{\text{Measure 1}} - \mu_{\text{Measure 2}} = 0$

Among the six performance variables compared, three showed no statistically significant difference between TrueZone and CPET: VO_{2max} speed, maximum speed (V_{max}), and VT_2 speed (T_{2v}). These results support the validity of the TrueZone model for estimating core performance parameters, especially those related to speed at ventilatory threshold and maximal effort. The non-significant differences and small effect sizes (Cohen's $d < 0.1$ for VO_{2max} and T_{2v}) indicate a high degree of alignment between methods.

In contrast, significant differences were found for VT_1 speed (T_{1v}), maximum heart rate (HR_{max}), and VT_2 heart rate (T_{2HR}). While TrueZone provided strong predictions overall, the differences in heart rate values — particularly for VT_2 (mean difference ~ 9 bpm) and HR_{max} (~ 2.3 bpm) — may reflect

systematic discrepancies caused by automated threshold detection in CPET, which can vary based on mask fit, effort variability, or breath-by-breath resolution.

Interestingly, although HR_{max} differed statistically, the practical difference was small and the direction was consistent, with TrueZone slightly overestimating HR_{max}. This suggests a systematic bias rather than random error, which could be addressed in future model calibration. Similarly, the underestimation of T1_v by TrueZone may result from individual variability in early-exercise response dynamics, which are harder to detect from heart rate alone.

In summary, TrueZone demonstrated excellent agreement with CPET for VO₂max speed, maximum speed, and VT2 speed, and acceptable accuracy for heart rate-based thresholds, despite minor systematic deviations. These findings support TrueZone as a valid, scalable alternative to laboratory testing — especially in contexts where speed thresholds are more relevant than exact heart rate values.

Discussion

The present study aimed to validate the TrueZone heart rate analytics system as a practical, low-tech alternative to laboratory-based fitness testing. The primary hypothesis — that TrueZone would yield fitness parameters not significantly different from CPET and sprint test results — was partially supported. The results demonstrated strong agreement between TrueZone and reference methods for VO₂max, maximum speed, and VT2 speed, with minimal mean differences and tight confidence intervals. These outcomes confirm the reliability of TrueZone's submaximal estimates for aerobic performance.

Validation Outcome

Linear regression analyses showed near one-to-one correspondence for VO₂max ($B = 0.89$), HR_{max} ($B = 0.98$), VT2 speed ($B = 0.98$), and V_{max} ($B = 0.69$), all with $p < 0.001$. Paired t -tests confirmed that three key parameters — VO₂max, V_{max} , and VT2 speed — did not differ significantly between TrueZone and CPET, supporting the primary hypothesis. These findings validate the TrueZone model's accuracy in predicting threshold and maximal performance measures from a submaximal effort.

Exploratory Findings and Limitations

TrueZone showed statistically significant deviations from CPET for VT1 speed, HR_{max}, and VT2 heart rate. However, these differences were modest in magnitude and likely reflect inherent variability in CPET threshold detection, which depends on breath-by-breath data and visual break-point estimation. TrueZone's model, based on heart rate kinetics and intensity scaling, may offer more consistent results in field applications. Notably, TrueZone slightly overestimated HR_{max}, but the mean difference was under 3 bpm, and the error was systematic—suggesting future calibration could improve accuracy further.

Gender Differences

As expected, males had significantly higher VO_2max and V_{max} , while females showed greater endurance scores and longer time-to-exhaustion (t_{50}), consistent with prior research. Interestingly, there were no gender differences in HR_{max} , threshold HR, or perceived exertion, indicating comparable cardiovascular strain at relative intensities.

Strengths and Limitations

The study's strength lies in its comprehensive protocol, which included a standardized submaximal test, sprint testing, and CPET. However, limitations include a relatively small sample size for subgroup analyses, potential threshold estimation errors in CPET, and a lack of randomization. Moreover, while TrueZone performance was robust across speed-derived parameters, heart rate-based comparisons showed slightly more variability—highlighting areas for refinement.

Implications and Future Research

TrueZone's ability to extract threshold data, VO_2max , and HR_{max} from submaximal heart rate kinetics makes it ideal for population screening, training zone prescription, and longitudinal monitoring. Its potential for detecting blunted heart rate responses also opens new avenues for metabolic health assessment and early detection of cardiometabolic disorders. Future studies should include clinical populations, real-world sport settings, and cross-validation with additional wearables.

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