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Original Research Article

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Validation of marathon performance model based on physiological factors in world-class East African runners: a case series

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Abstract

Objectives: The aim of this study was to compare the measured physiological factors that limit running performance with real marathon results from world-class distance runners, evaluating the compatibility between measured data and predicted results based on the previously suggested model.
Methods: Four world-class East African marathon runners (three male, one female) underwent physiological running assessments to predict marathon performance times using a model based on $\dot{V}\,O_2$peak, percentage of $\dot{V}\,O_2$peak at the second ventilatory threshold, and running economy. Predictions were then compared to participants' best marathon times.
Results: The measured $\dot{V}\,O_2$peak of the world-class runners was 75.1 ± 2.7 mL/kg/min. The second ventilatory threshold occurred at 85 ± 3 % of the peak, with a running economy of 63.7 ± 2.4 mL/kg/min at 19.6 ± 0.9 km/h. The predicted marathon performance time was 2:06:51 ± 0:03:17 h:min:s for the males and 2:17:36 h:min:s for the female. Comparing these predictions to their personal best times, the average difference was 00:55 ± 00:51 min:s (range: 00:20-02:08).
Conclusions: This research provides laboratory data on world-class road running athletes, reinforcing the link between marathon performance and $\dot{V}\,O_2$peak, the percentage of $\dot{V}\,O_2$peak at the second ventilatory threshold, and running economy. The examined athletes had lower $\dot{V}\,O_2$peak compared to predicted values, highlighting the importance of running economy and fractional utilization of $\dot{V}\,O_2$peak in achieving such performances. Future studies should continue to advance the field by including additional bioenergetic parameters measured during race conditions and expanding the participant cohort of elite marathoners, encompassing both sexes.

Keywords: marathon performance; predictive model; peak aerobic capacity; second ventilatory threshold; running economy; marathon running

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Introduction

In recent years, long distance running events have seen a surge in world records with the current marathon record for males set in October 2023 with a time of 2:00:35 h:min:s and for females in September 2023 with a time of 2:11:53 h:min:s [1–3]. Previous research aimed to predict the absolute limits of human performance for the marathon using different methods and models. One study utilized historical data of world record progression to create a statistical model suggesting the limit of marathon performance for males to be 1:58:05 and 2:05:31 h:min:s for females [4]. Another innovative approach introduced by di Prampero et al. in 1986 explored the physiological factors that restrict endurance running performance, proposing that the speed of performance can be computed by considering $\dot{V}O_2max$, its maximal sustainable fraction, and the energy cost of running per unit distance [5]. Joyner refined this approach in 1991 with a physiological model for predicting marathon performance (Eq. (1)) [6, 7].

$$\text{Marathon Running Speed}\left(\frac{\text{km}}{\text{h}}\right) = \dot{V}O_2\ \text{max}\left(\frac{\text{mL}}{\text{kg} \bullet \text{min}}\right) \times \%\ \dot{V}O_2\ \text{max at LT} \times \text{RE}\ \frac{\text{km/h}}{\dot{V}O_2\left(\frac{\text{mL}}{\text{kg}\bullet\text{min}}\right)} \tag{1}$$

$\dot{V}O_2max$ – maximal oxygen uptake; LT – lactate threshold; RE – running economy; $\dot{V}O_2$ – oxygen uptake

In Joyner's model, three main determinants of a marathon are considered: (1) athletes' maximal oxygen update or $\dot{V}O_2max$, (2) their fractional utilization of $\dot{V}O_2max$ or the percentage of their maximum work rate that they can sustain during a running event, and (3) their running economy [5, 6]. $\dot{V}O_2max$ represents the upper limit of what this individual can aerobically metabolize [8]. Fractional utilization of $\dot{V}O_2max$, linked to blood lactate accumulation, reflects an individual's ability to maintain high intensities thereby determining the speed runners can maintain during the marathon [8]. For this, Joyner's model uses a lactate threshold related value, correlating a higher percentage of $\dot{V}O_2max$ here with better marathon performance [6, 9]. Favorable running economy, the oxygen cost of running at a given speed, minimizes energy expenditure, leading to faster race times and superior marathon performance [8, 10]. Typically expressed as oxygen uptake per distance covered in mL/kg/km, Joyner adapted this term in his equation to be able to use it as a variable to calculate marathon pace [6]. Joyner employed this model to speculate on the human limits for a marathon by optimizing values for each of these three limiting factors. With a $\dot{V}O_2max$ of 84 mL/kg/min, a lactate threshold at 85 % of $\dot{V}O_2max$, and an exceptional running economy of 71.4 mL/kg/min at 21.46 km/h, Joyner formulated a marathon limit of 1:57:58 h:min:s [6]. These predicted limits serve as motivation for world-class runners, coaches, and the sports industry, inspiring them to push boundaries and contribute valuable knowledge to the field of marathon performance using physiological models.

With advancements in shoe technology, endurance running records have accelerated, leading to significant changes in marathon performance [3, 11]. In this dynamic context, a valuable opportunity arises to investigate physiological changes and explore how they may impact existing models. Jones et al. conducted similar research, examining the physiological demands of running at 2-h marathon race pace of 21.1 km/h in a sample of the world's best male distance runners [12]. However, the article does not further elaborate on these marathon performance predictions.

As research in world-class road running continues to advance, the field would greatly benefit from acquiring additional data from some of the world's fastest runners. Therefore, the primary aim of this study is to examine and assess the relationship between measured running physiology variables, which are considered key determinants of performance, obtained through controlled laboratory testing, and the actual marathon results achieved by world-class distance runners. Furthermore, the aim is to evaluate the compatibility and congruity between the measured data and the predicted outcomes based on Joyner's original model. The summary of this article is presented in Figure 1.

Materials and methods

Participants

Four world-class professional road racing East African runners, volunteered to participate in this retrospective study. These, three males and one female, runners (mean ± SD, age: 26.0 ± 0.8 years; weight: 56.1 ± 10.7 kg; height: 171 ± 11 cm) gave and signed written informed consent after receiving a clear explanation of the experimental procedures, potential risks, and anticipated benefits. Their impressive personal records for the marathon, achieved within one year of laboratory testing, with a mean time of 2:06:51 ± 3:17 h:min:s for the males and a time of 2:17 h:min for the female, underscore their exceptional calibre (Table 1). This experiment was submitted to the Technical University of Munich Ethics Committee who advised us that the study did not need to be approved by the whole committee (ref: 2022-417-W-SR).

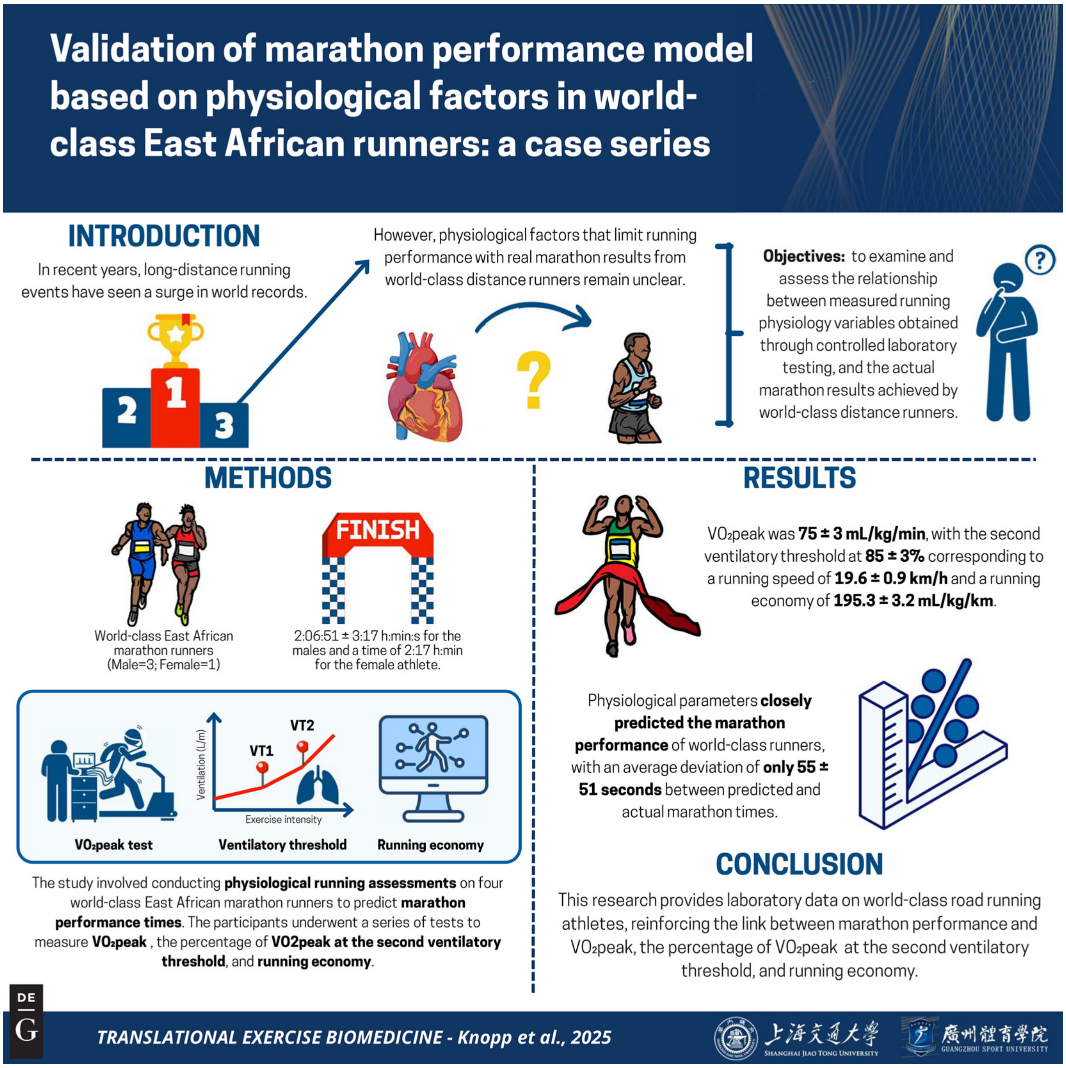

Figure 1: Graphical representation of this study. Key points: (1) the findings of this study support the validity of the predictive model developed by Joyner in 1991 as a predictor of marathon performance in world-class athletes. (2) there is causative relationship between key laboratory-derived physiological markers ($\dot{V}O_2$peak, the percentage of $\dot{V}O_2$peak at the second ventilatory threshold, and running economy) and marathon performance. (3) comparing performance predictions to their personal best times, the average difference was 00:55 ± 00:51 min:s (range: 00:20-02:08). Figure created with BioRender.

Table 1: Experimental physiological results, predicted marathon race results, and personal best marathon time for each examined subject.

Subject	$\dot{V}O_2$peak (mL/kg/min)	*v* $\dot{V}O_2$peak (km/h)	Percent of $\dot{V}O_2$peak at VT2	$\dot{V}O_2$ (mL/kg/min) at VT2	*v* at VT2, km/h	Running economy at VT2, mL/kg/km	Marathon personal best time (h:min)	Predicted marathon pace, km/h	Predicted marathon time (h:min)
Subject 1	73.9	21.4	89.7 %	66.2	20.1	197.7	2:06	20.1	2:05
Subject 2	76.0	22.1	83.0 %	63.1	19.4	195.1	2:10	19.4	2:10
Subject 3	78.4	22.2	82.8 %	64.9	20.4	190.9	2:06	20.4	2:04
Subject 4	72.2	21.3	83.9 %	60.6	18.4	197.6	2:17	18.4	2:17

$\dot{V}O_2$, oxygen uptake; VT2, second ventilatory threshold; v, velocity; $\dot{V}O_2$peak, peak oxygen uptake; v $\dot{V}O_2$peak, velocity at $\dot{V}O_2$peak.

Experimental protocol

We conducted comprehensive assessments to capture maximal physiological running data using an HP Cosmos motorized treadmill (venus 200/75, h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany) in a standardized laboratory chamber. Of note, data was collected through tests initially designed for other purposes and subsequently analyzed for this research. To familiarize the runners, we started with a 15-min warm-up session on the treadmill with progressively increasing speeds. We then fitted each athlete with a heart rate monitor and face mask connected to the MetaMax 3 B portable cardiopulmonary gas exchange measuring device (CORTEX Biophysik GmbH, Leipzig, Germany). Hereby, we collected respiratory parameters using an automated breath-by-breath method with the MetaSoft Studio measurement and evaluation software. Before each testing session, we calibrated the system according to the manufacturer's instructions. To ensure clear communication and the comfort of the athletes, their coach and manager accompanied them and assisted with the testing process.

To assess their maximal aerobic capacity, athletes completed a $\dot{V}O_2$peak ramp test using an incremental speed protocol with a continuous 1 % incline starting at 10 km/h for 2 min and increasing progressively 1 km/h/min until volitional exhaustion [13]. During this test, we verbally motivated all athletes to ensure a maximal output was reached. Upon completion of these tests, two experienced exercise physiologists analyzed and agreed upon the physiological thresholds, explained below in more detail. For all collected cardiorespiratory data, we cleaned the breath-by-breath raw data by removing outlying data points that were outside two standard deviations away from the mean of a seven-breath window, before taking a moving seven-breath average. The peak oxygen uptake value was recorded as the highest cleaned and smoothed value measured during the test. Since we did not repeat a verification assessment to authenticate these values, the highest recorded $\dot{V}O_2$ value will be defined as a '$\dot{V}O_2$peak' [14].

Given discrepancies in understanding and nomenclature of physiological thresholds, for the lactate threshold term in his model, Joyner included the percentage values of $\dot{V}O_2$max based on the understanding of what speeds elite runners are able to run in a marathon [6]. The ventilatory thresholds here were determined using the equivalent ventilatory method where the first ventilatory threshold was identified based on the criteria of an increase in ventilatory equivalent of oxygen ($\dot{V}E/\dot{V}O_2$) without a simultaneous increase in ventilatory equivalent of carbon dioxide ($\dot{V}E/\dot{V}CO_2$) [15]. The second ventilatory threshold was identified based on the specific criteria, involving an increase in both $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ with a decrease in partial pressure of end-tidal carbon dioxide ($PETCO_2$), during progressive exercise tests [15]. This transition occurs when exceeding the lactate threshold leads to the buffering of lactic acid by bicarbonate [HCO_3^-], resulting in an increase in $\dot{V}CO_2$ as a function of $\dot{V}O_2$ [16]. This relationship change is fundamental to all anaerobic threshold detection methods using gas exchange [17, 18]. Therefore, for further analysis we employed the second ventilatory threshold, which corresponds to the anaerobic threshold, as a proxy for the fractional utilization of $\dot{V}O_2$max, based on previous studies [17]. This was further confirmed by recent research conducted on a cohort of the world's fastest runners that suggests that elite athletes run marathons at a mean speed that resides in the heavy-intensity domain above their lactate threshold, defined as the first increase in blood lactate above the baseline value [12].

Marathon performance model analysis

The data we obtained from the experimental testing was used to populate Eq. (1) in our analysis. This involved incorporating the measured $\dot{V}O_2$peak, expressed in mL/kg/min, as the first term of the equation. To maintain a non-invasive approach, we did not collect blood samples for lactate testing and instead, as discussed above, employed the second ventilatory threshold as a proxy for the fractional utilization of maximum term [17]. Consequently, this value was then taken as the percentage of $\dot{V}O_2$peak for the equation. Subsequently, the running economy term was established by calculating the ratio of velocity (v) measured at the second ventilatory threshold to the corresponding oxygen uptake, matching the term needed for Joyner's model. Eq. (2) illustrates how we incorporated the collected experimental data into the original model. The output of this equation was the marathon running speed, which we subsequently converted into a predicted marathon performance time in h:min:s. Finally, we compared this predicted performance time with the personal best marathon performance, achieved within one year of the laboratory testing.

$$\begin{matrix}\text{Marathon}\\ \text{Running Speed}\end{matrix}\left(\frac{\text{km}}{\text{h}}\right) = \dot{V}O_2$$

$$\text{peak}\left(\frac{\text{mL}}{\text{kg}\bullet\text{min}}\right)\times\%\,\dot{V}O_2\text{peak at VT2}\left(\frac{\dot{V}O_2\text{ at VT2}\left(\frac{\text{mL}}{\text{kg}\bullet\text{min}}\right)}{\dot{V}O_2\text{peak}\left(\frac{\text{mL}}{\text{kg}\bullet\text{min}}\right)}\right)\times\text{RE}\left(\frac{v\text{ at VT2 (km/h\textbackslash)}}{\dot{V}O_2\text{ at VT2}\left(\frac{\text{mL}}{\text{kg}\bullet\text{min}}\right)}\right) \quad (2)$$

$\dot{V}O_2$ peak – peak oxygen uptake; VT2 – second ventilatory threshold; $\dot{V}O_2$ – oxygen uptake; RE – running economy; v – velocity

Results

Maximal testing

During the maximal testing, we obtained comprehensive data on the physiological performance of these world-class runners. $\dot{V}O_2$peak was measured at 75.1 ± 2.7 mL/kg/min, heart rate at this peak was 183 ± 15 beats per minute, and the respiratory exchange ratio was 1.1 ± 0.1. The second ventilatory threshold, occurred at 85 ± 3 % of the peak measured values. At this threshold, the $\dot{V}O_2$ was 63.7 ± 2.4 mL/kg/min, corresponding to a running speed of 19.6 ± 0.9 km/h. By converting the speed to km/min and dividing the oxygen uptake at this threshold by that speed, we calculated the running economy to be 195.3 ± 3.2 mL/kg/km. Individual data can be found in Table 1.

Marathon performance model analysis

Using these collected values and the established physiological model for marathon performance, we determined the expected marathon race pace for the male runners to be 20.0 ± 0.5 km/h, and 18.4 km/h for the female runner. Translating these paces into performance times over the 42.195 km distance, we anticipated a marathon finishing time of 2:06:51 ± 0:03:17 h:min:s for the male runners, and 2:17:36 h:min:s for the female runner. To evaluate the accuracy of these predictions, we compared them to the personal best marathon times of the individuals, finding an average deviation of only 00:55 ± 00:51 min:s, ranging from 00:20 to 02:08 min:s. Again, subject specific data for these predictions can be found in Table 1.

Discussion

This study aimed to assess the relationship between laboratory measured running physiology variables and actual marathon performance in world-class distance runners. By integrating relevant physiological parameters from maximal testing with the athletes' marathon race performances, our findings demonstrate a remarkable level of accuracy in predicting marathon race performance. In particular, the results presented here, albeit in a small number of truly elite marathoners, provide compelling support for a causative relationship between marathon performance and key physiological variables: $\dot{V}O_2$peak, percentage of $\dot{V}O_2$peak at the second ventilatory threshold, and running economy, specifically in the context of these world-class marathoners.

Initially proposed to determine the limits of human marathon performance, the model estimated a marathon time of 1:57:58 h:min:s based on the ideal high $\dot{V}O_2$max of 84 mL/kg/min [6]. Although higher $\dot{V}O_2$max levels typically correlate with faster marathon times, this relationship weakens among elite athletes who have a narrow range of $\dot{V}O_2$max values [5, 19, 20]. This suggests that while a high $\dot{V}O_2$max is fundamental for reaching such high levels of performance, other factors also play a significant role in determining marathon times [21, 22]. The maximal measured value in the examined athlete cohort was 78.4 mL/kg/min, with an average of 75.1 mL/kg/min, considerably below the presented optimal $\dot{V}O_2$max of the ideal marathoner reaching the predicted marathon limit. However, our measured results align with comparable research conducted on similar athletes, including a recent evaluation on a cohort of world-class male marathon runners, which reported a $\dot{V}O_2$peak of 71.0 ± 5.7 mL/kg/min [12, 21, 23–25]. In the experience of the present authors, elite East African athletes may struggle to achieve a true $\dot{V}O_2$max in laboratory settings due to their unfamiliarity with near maximal performance in controlled environments. This observation is consistence with findings from other studies, where authors have suggested that their lack of experience in such settings might hinder them from reaching their true maximum [26, 27].

Furthermore, the percentage of $\dot{V}O_2$peak at the second ventilatory threshold is a critical determinant of marathon performance. Numerous studies have demonstrated a strong correlation between fractional utilization of maximum or lactate threshold and performance in distance running events [5, 9, 22]. For the hypothetical optimal runner to achieve the human performance limit for a marathon, their lactate threshold was determined to be 85 % of $\dot{V}O_2$peak. Our included cohort averaged 84.8 %, in line with this optimal subject and consistent with a recent evaluation of world-class marathon runners, reporting a lactate threshold at 83 ± 5 % of $\dot{V}O_2$peak [6, 12]. However, in that study, when athletes' possible best marathon times were calculated to match their personal record times, the highest sustainable $\dot{V}O_2$ occurred at 88 % of $\dot{V}O_2$peak, considerably greater than the other values presented here [12].

Running economy is also a crucial factor influencing race performance, showing a significant correlation with marathon performance, particularly among relatively homogeneous groups of runners [6, 20]. Running economy is a difficult term to compare across research studies given differences in protocols, mainly running speed. By relating the oxygen uptake at the second ventilatory threshold (mL/kg/min) to the speed at this threshold in km/min, we calculate the running economy value proportional to distance covered (mL/kg/km), commonly referred to as the oxygen cost of transport [10]. This approach facilitates a fair comparison of individuals running at different speeds. In this study, the examined runners had an average running economy of 195.3 ± 3.2 mL/kg/km at 18.4–20.4 km/h, less than the hypothetical optimal runner who had a value of 199.6 mL/kg/km at 21.46 km/h [6]. However, this value exceeds that the mean oxygen cost of running of 189 ± 14 mL/kg/km recorded in a recent evaluation of world-class runners at submaximal speeds of 17.0–19.5 km/h [12]. These comparisons must be taken with caution given the oxygen uptake values correspond to different measured speeds across these studies.

These variables are valuable predictors of marathon performance in world-class athletes. Given this is a case series including only four subjects, further interpretation into the relative importance of these three variables in marathon performance should be made with caution. Nevertheless, of the two fastest marathon runners in this cohort (subjects one and 3), both of whom have a personal best time of 2:06 h:min, subject three had a $\dot{V}O_2$peak 4.6 mL/kg/min higher but a percentage of $\dot{V}O_2$peak at the second ventilatory threshold 6.9 % lower, and a running economy 6.8 mL/kg/km lower than subject 1. Whereas subject 2, with a personal best time of 2:10 h:min, had $\dot{V}O_2$peak, percentage of $\dot{V}O_2$peak at the second ventilatory threshold, and running economy values between those of subject one and 3. Finally, subject 4 with a marathon personal best time of 2:17 h:min, had the lowest $\dot{V}O_2$peak value, but had a percentage of $\dot{V}O_2$peak at the second ventilatory threshold, and running economy values within the range of the others. This suggests that no single factor outweighs the others in relevance for marathon performance; rather, it is the combination of all three. Further individual research in world-class athletes would provide deeper insights and enable more informed interpretations.

While the current model demonstrates impressive predictive capabilities, refining and enhancing it requires integrating new variables and a more diverse cohort of athletes, to improve its predictive accuracy. Previous studies have explored additional variables that could be used as predictors impacting marathon race performance, such as fatigue resistance, training variables, and velocity at $\dot{V}O_2$max [12, 22, 28, 29]. External factors, including racecourse, temperature, wind, and environmental conditions, also ultimately impact marathon outcomes [30]. Additionally, considering sex differences and including both male and female athletes are crucial for a more comprehensive understanding of marathon race results. Incorporating innovative technology, like sensors measuring core and skin temperature, foot kinematics and kinetics, sweat rate, and body composition changes during races, can further illuminate physiological factors affecting running performance [3]. Moreover, advancing towards the limits of human performance in marathons involves considering various factors, including advancements in footwear technology, pacing strategies, race course optimization, increased prize money, and extended athlete careers [3, 31–34].

Limitations

There are several limitations we must consider in this study. Firstly, the study only reports data on four subjects. However, this is common for studies in "extreme" populations such as world-class athletes, astronauts or centenarians [35, 36]. Additionally, there was limited representation of female athletes, with one female participant only. Unfortunately, we were limited by the athletes' schedules, otherwise more time could have improved reliability by repeating test measures and ensuring subjects were familiarized with testing procedures before collecting data [37]. Finally, while previous research has suggested the relation between the lactate threshold and a measured ventilatory threshold, since we were limited to non-invasive methods, we were unable to include the variable of lactate threshold into the model as originally intended [17]. To address these limitations, further research should expand the dataset, including more data from the cohort in a race setting for a more comprehensive exploration of potential indicators of marathon performance [38].

Conclusions

The findings of this study support the validity of the model developed by Joyner in 1991 as a predictor of marathon performance, particularly in a population of world-class athletes. Our results, albeit in a small number of truly elite marathoners, provide compelling support for a causative relationship between marathon performance and key laboratory-derived physiological markers, including peak aerobic capacity, the percentage of peak aerobic capacity at the second ventilatory threshold, and running economy at the second ventilatory threshold. Comparing the model's optimal values for the estimated 1:57:58 h:min:s limit of marathon performance with the measured values in this analysis, some similarities and differences are observed. The high $\dot{V}O_2max$ measure of 84 mL/kg/min used in the model exceeds the measured peak values in this study. However, the lactate threshold, determined to be 85 % of maximum for the optimal runner in the model, aligns well with the subjects analyzed here. Similarly, the running economy measure is comparable within the examined population and the model's optimal subject. While these laboratory-measured variables can serve as primary predictors of marathon performance in world-class athletes, further optimization of ideal marathon performance will be necessary in a larger cohort of elite marathoners and considering additional bioenergetic parameters.

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Research ethics: This experiment was submitted to the Technical University of Munich Ethics Committee who advised us that the study did not need to be approved by the whole committee.
Informed consent: All participants gave written informed consent to being a part of this study and using their data in this manuscript after they were informed of and understood the experimental procedures, potential injury risks, and possible benefits.
Author contributions: The idea of this analysis emerged from YP in discussion with MK and further refined by BM-P and FG. MK, and DR performed and supported the data collection with the help of additional colleagues. MK, DR, BM-P, HW, MS, FG and YP analyzed the data. MK and FG conducted additional predictive and statistical analysis. MK, MJ, DR, BM-P, HW, MS and YP interpreted the results of the experiment. MK drafted the manuscript. FG, MJ, DR, BM-P, HW, MS, and YP edited and revised the manuscript.
Use of Large Language Models, AI and Machine Learning Tools: The present work did not use any form of artificial intelligence.
Conflict of interest: MK, and DR are both employees of adidas AG. YP is the founding member of the Sub2 marathon project (www.sub2hrs.com). MJ, BM-P, FG, HW, and MS have no conflicts of interest relevant to the content of this article.
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Data availability: Given the nature of this research, the study participants did not consent to publicly disclose any further information beyond what has already been presented in the article.

References

1. World Athletics. Records by event: marathon. Men outdoor: road running 2024. [Internet] [cited 2024 Jun 20]. Available from: https://www.worldathletics.org/records/by-discipline/road-running/marathon/outdoor/men.
2. World Athletics. Records by event: marathon. Women outdoor: road running 2024. [Internet] [cited 2024 Jun 20]. Available from: https://www.worldathletics.org/records/by-discipline/road-running/marathon/outdoor/women.
3. Muñiz-Pardos B, Sutehall S, Angeloudis K, Guppy FM, Bosch A, Pitsiladis Y. Recent improvements in marathon run times are likely technological, not physiological. Sports Med 2021;51:371–8.
4. Angus SD. Did recent world record marathon runners employ optimal pacing strategies? J Sports Sci 2014;32:31–45.
5. di Prampero PE, Atchou G, Brückner JC, Moia C. The energetics of endurance running. Eur J Appl Physiol Occup Physiol 1986;55:259–66.
6. Joyner MJ. Modeling: optimal marathon performance on the basis of physiological factors. J Appl Physiol (1985)1991;70:683–7.
7. Joyner MJ. Genetic approaches for sports performance: how far away are we? Sports Med 2019;49:199–204.
8. Joyner MJ, Hunter SK, Lucia A, Jones AM. Physiology and fast marathons. J Appl Physiol (1985)2020;128:1065–8.
9. Costill DL. Metabolic responses during distance running. J Appl Physiol 1970;28:251–5.
10. Barnes KR, Kilding AE. Running economy: measurement, norms, and determining factors. Sports Med Open 2015;1:8.
11. Goss CS, Greenshields JT, Noble TJ, Chapman RF. A narrative analysis of the progression in the top 100 marathon, half-marathon, and 10-km road race times from 2001 to 2019. Med Sci Sports Exerc 2022;54:345–52.
12. Jones AM, Kirby BS, Clark IE, Rice HM, Fulkerson E, Wylie LJ, et al. Physiological demands of running at 2-hour marathon race pace. J Appl Physiol (1985)2021;130:369–79.
13. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci 1996;14:321–7.
14. Poole DC, Jones AM. Measurement of the maximum oxygen uptake $\dot{V}o2max$: $\dot{V}o2peak$ is no longer acceptable. J Appl Physiol 2017;122: 997–1002.

15. Cerezuela-Espejo V, Courel-Ibanez J, Moran-Navarro R, Martinez-Cava A, Pallares JG. The relationship between lactate and ventilatory thresholds in runners: validity and reliability of exercise test performance parameters. Front Physiol 2018;9:1320.
16. Vasquez Bonilla AA, González-Custodio A, Timón R, Camacho-Cardenosa A, Camacho-Cardenosa M, Olcina G. Training zones through muscle oxygen saturation during a graded exercise test in cyclists and triathletes. Biol Sport 2023;40:439–48.
17. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol (1985)1986;60: 2020–7.
18. Binder RK, Wonisch M, Corra U, Cohen-Solal A, Vanhees L, Saner H, et al. Methodological approach to the first and second lactate threshold in incremental cardiopulmonary exercise testing. Eur J Cardiovasc Prev Rehabil 2008;15:726–34.
19. Billat VL, Demarle A, Slawinski J, Paiva M, Koralsztein JP. Physical and training characteristics of top-class marathon runners. Med Sci Sports Exerc 2001;33:2089–97.
20. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 1980;12: 357–60.
21. Lucia A, Esteve-Lanao J, Olivan J, Gomez-Gallego F, San Juan AF, Santiago C, et al. Physiological characteristics of the best Eritrean runners-exceptional running economy. Appl Physiol Nutr Metabol 2006;31:530–40.
22. Venturini E, Giallauria F. Factors influencing running performance during a marathon: breaking the 2-h barrier. Front Cardiovasc Med 2022;9:856875.
23. Billat V, Lepretre PM, Heugas AM, Laurence MH, Salim D, Koralsztein JP. Training and bioenergetic characteristics in elite male and female Kenyan runners. Med Sci Sports Exerc 2003;35:297–304; discussion 305-6.
24. Saltin B, Larsen H, Terrados N, Bangsbo J, Bak T, Kim CK, et al. Aerobic exercise capacity at sea level and at altitude in Kenyan boys, junior and senior runners compared with Scandinavian runners. Scand J Med Sci Sports 1995;5:209–21.
25. Tam E, Rossi H, Moia C, Berardelli C, Rosa G, Capelli C, et al. Energetics of running in top-level marathon runners from Kenya. Eur J Appl Physiol 2012;112:3797–806.
26. Weston AR, Mbambo Z, Myburgh KH. Running economy of African and Caucasian distance runners. Med Sci Sports Exerc 2000;32:1130–4.
27. Bosch AN, Goslin BR, Noakes TD, Dennis SC. Physiological differences between black and white runners during a treadmill marathon. Eur J Appl Physiol Occup Physiol 1990;61:68–72.
28. Casado A, Hanley B, Santos-Concejero J, Ruiz-Pérez LM. World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs. J Strength Condit Res 2021;35:2525–31.
29. Alvero-Cruz JR, Carnero EA, Garcia MAG, Alacid F, Correas-Gomez L, Rosemann T, et al. Predictive performance models in long-distance runners: a narrative review. Int J Environ Res Publ Health 2020;17. https://doi.org/10.3390/ijerph17218289.
30. El Helou N, Tafflet M, Berthelot G, Tolaini J, Marc A, Guillaume M, et al. Impact of environmental parameters on marathon running performance. PLoS One 2012;7:e37407.
31. Knopp M, Muñiz-Pardos B, Wackerhage H, Schönfelder M, Guppy F, Pitsiladis Y, et al. Variability in running economy of Kenyan world-class and European amateur male runners with advanced footwear running technology: experimental and meta-analysis results. Sports Med 2023; 53:1255–71.
32. Hoogkamer W, Kipp S, Frank JH, Farina EM, Luo G, Kram R. A comparison of the energetic cost of running in marathon racing shoes. Sports Med 2018;48:1009–19.
33. Rodrigo-Carranza V, González-Mohíno F, Santos del Cerro J, Santos-Concejero J, González-Ravé JM. Influence of advanced shoe technology on the top 100 annual performances in men's marathon from 2015 to 2019. Sci Rep 2021;11:22458.
34. Hoogkamer W, Kram R, Arellano CJ. How biomechanical improvements in running economy could break the 2-hour marathon barrier. Sports Med 2017;47:1739–50.
35. Gilbar PJ, Mutsando H, Richmond JP, Middleton RB. Cancer treatment in the extreme elderly: case study of a 100-year-old lymphoma patient. Int J Hematol Oncol 2016;5:59–62.
36. Kaneko M, Miyatsuji K, Tanabe S. Energy expenditure while performing gymnastic-like motion in spacelab during spaceflight: case study. Appl Physiol Nutr Metabol 2006;31:631–4.
37. Poole DC, Wilkerson DP, Jones AM. Validity of criteria for establishing maximal O2 uptake during ramp exercise tests. Eur J Appl Physiol 2008; 102:403–10.
38. Muñiz-Pardos B, Angeloudis K, Guppy FM, Keramitsoglou I, Sutehall S, Bosch A, et al. Wearable and telemedicine innovations for Olympic events and elite sport. J Sports Med Phys Fit 2021;61:1061–72.