Physiological demands of running at 2-hour marathon race pace

Andrew M. Jones[1], Brett S. Kirby[2], Ida E. Clark[1], Hannah M. Rice[1], Elizabeth Fulkerson[2], Lee J. Wylie[1], Daryl P. Wilkerson[1], Anni Vanhatalo[1], and Brad W. Wilkins[2,3]

[1] Sport and Health Sciences, College of Life and Environmental Sciences, St. Luke's Campus, University of Exeter, Heavitree Road, Exeter, EX1 2LU, United Kingdom; [2] Nike Sport Research Lab, One SW Bowerman Dr, Beaverton 97005, USA; [3] Department of Human Physiology, Gonzaga University, Spokane WA, USA.

Address for Correspondence:
Andrew M Jones PhD
Sport and Health Sciences
University of Exeter
United Kingdom
Tel: 01392 262815
E-mail: a.m.jones@exeter.ac.uk

Abstract

The requirements of running a 2 hour marathon have been extensively debated but the actual physiological demands of running at ~21.1 km/h have never been reported. We therefore conducted laboratory-based physiological evaluations and measured running economy (O_2 cost) while running outdoors at ~21.1 km/h, in world-class distance runners as part of Nike's 'Breaking 2' marathon project. On separate days, 16 world-class male distance runners (age, 29 ± 4 years; height, 1.72 ± 0.04 m; mass, 58.9 ± 3.3 kg) completed an incremental treadmill test for the assessment of $\dot{V}O_2$peak, O_2 cost of submaximal running, lactate threshold and lactate turn-point, and a track test during which they ran continuously at 21.1 km/h. The laboratory-determined $\dot{V}O_2$peak was 71.0 ± 5.7 ml/kg/min with lactate threshold and lactate turn-point occurring at 18.9 ± 0.4 and 20.2 ± 0.6 km/h, corresponding to 83 ± 5 % and 92 ± 3 % $\dot{V}O_2$peak, respectively. Seven athletes were able to attain a steady-state $\dot{V}O_2$ when running outdoors at 21.1 km/h. The mean O_2 cost for these athletes was 191 ± 19 ml/kg/km such that running at 21.1 km/h required an absolute $\dot{V}O_2$ of ~4.0 L/min and represented 94 ± 3 % $\dot{V}O_2$peak. We report novel data on the O_2 cost of running outdoors at 21.1 km/h, which enables better modelling of possible marathon performances by elite athletes. Using the value for O_2 cost measured in this study, a sub-2 hour marathon would require a 59 kg runner to sustain a $\dot{V}O_2$ of approximately 4.0 L/min or 67 ml/kg/min.

Key words: endurance performance; aerobic fitness; running economy; performance prediction.

New and Noteworthy: We report the physiological characteristics and O2 cost of running over-ground at ~21.1 km/h in a cohort of the world's best male distance runners. We provide new information on the absolute and relative O2 uptake required to run at 2 h marathon pace.

Introduction

There is considerable scientific and public interest in the requirements of running a 26.2 mile (42.195 km) marathon in less than 2 hours (36, 37, 61), as was recently accomplished by Eliud Kipchoge of Kenya in an exhibition event in Vienna. Traditional physiological factors that have been proposed to exert an important influence in this regard include the runner's maximal oxygen (O_2) uptake ($\dot{V}O_2$max), the fraction of the $\dot{V}O_2$max that can be sustained during the marathon which is, in turn, related to the lactate threshold (LT) or critical speed (CS), and the O_2 cost of submaximal running (i.e., running economy in units of ml of O_2/kg/km), (28, 35, 37). Other important 'external' factors include the course profile, environmental conditions (altitude, ambient temperature, relative humidity and wind speed), pacing strategy, drafting, pre- and in-race nutrition, and footwear and apparel (9, 23, 24, 36).

To run a marathon in under 2 hours, an elite distance runner must be able to sustain a metabolic steady-state while running at just over 13.1 mph (i.e. ~4 minutes and 34 seconds per mile) or 21.1 km/h (i.e. ~2 minutes and 50 seconds per km). To our knowledge, the O_2 cost of running outdoors at sea level at ~21.1 km/h has never been reported. This is understandable given that there are presumably very few athletes in the world capable of running at this speed in a metabolic steady-state, which is a necessary condition for the valid assessment of running economy (48). Estimating the O_2 cost of running at 21.1 km/h by extrapolating the $\dot{V}O_2$-running speed relationship established at lower speeds (typically 15-19 km/h) in less highly-trained athletes might not be appropriate, especially given the difference in air resistance which is evident between treadmill and outdoor running at higher speeds (32, 56). Debate surrounding whether or not a sub-2 hour marathon might be possible in competitions ratified by the International Association of Athletics Federations (IAAF) would be informed by improved knowledge of the O_2 cost of running at ~21.1 km/h, and the fraction of $\dot{V}O_2$max this requires, in world-class marathon runners (36).

The purpose of this study was to investigate the O_2 cost and physiological demand (i.e., fraction of $\dot{V}O_2$max required) of running at ~21.1 km/h in a cohort of the world's best distance runners who underwent physiological evaluation as part of Nike's 'Breaking 2' marathon project.

Methods

Participants

Sixteen elite male distance runners volunteered and gave written informed consent to participate in the study after the experimental procedures, associated risks, and potential benefits of participation had been explained. All procedures were approved by the University of Exeter Research Ethics Committee. The athletes, who were predominantly of East African ethnicity, were recruited for the first phase of Nike's 'Breaking 2' project which had the purpose of identifying athletes with the physiological characteristics that might enable them to run a marathon in less than 2 hours. The athletes were evaluated at uncontrolled time points in their racing and training programs and they were, therefore, not necessarily in their best physical condition at the time of testing. The athletes had a mean personal record for the half-marathon of 59:53 ± 0:46 min:s and a mean personal record for the full marathon of 2:06:53 ± 0:02:58 h:min:s. The cohort included the current official world marathon record holder (set in 2018), the 2019 world marathon champion, and the former world half-marathon record holder (until 2019).

Testing occurred between November 2015 and September 2016 and took place either within the Department of Sport and Health Sciences at the University of Exeter and at Exeter Arena athletics track in Exeter, UK (n = 11), or within the Nike Sport Research Laboratory and at the Michael Johnson athletics track on the Nike campus in Beaverton OR, USA (n = 5). The athletes were instructed to arrive at the laboratory and track in a rested and fully hydrated state, ≥ 3 h postprandial, and to avoid strenuous exercise in the 24 h preceding each testing session. The athletes were asked to refrain from caffeine for 6 h and from alcohol for 24 h before each test.

Testing Overview

On arrival at the laboratory, measurements of the athletes' anthropometry and pulmonary function were made before they completed an incremental treadmill test to volitional exhaustion. This test was used to measure the pulmonary gas exchange, heart rate, and blood lactate responses to incremental exercise and for evaluation of the O_2 cost of submaximal running, LT, lactate turn-point (LTP), and $\dot{V}O_2$peak. Following a 30-60 min recovery period, the athletes who were tested in Exeter attended the biomechanics laboratory for the measurement of force and kinematic data while running short distances at ~21.0 km/h (n = 10). On the following day, the athletes reported to the local track where they completed a protocol designed to measure the O_2 cost of running outdoors at close to 2 hour marathon race pace. For all tests, the athletes ran in lightweight racing flats.

Laboratory Tests

Height was measured using a stadiometer and body mass was recorded using balance scales (Seca 700, Hamburg, Germany). An accredited kinanthropometrist assessed the athletes' anthropometry using skinfold measurements at four sites (biceps, triceps, subscapular and suprailiac) as an index of body composition and measurements were also made of thigh and calf girths, biepicondylar femur and bimalleolar breadths, and left and right leg Achilles tendon and shank lengths. Body fat percentage was estimated using the equation of Durnin & Womersley (16). Pulmonary function was assessed using standard spirometry procedures (Vitalograph Ltd., Buckingham, UK).

All treadmill exercise testing sessions were carried out in an air-conditioned exercise physiology laboratory at 20–22°C and performed on a motorised treadmill (Woodway PPS-55 Sport (Exeter) or Woodway Pro XL (Beaverton), Woodway, Weil am Rhein, Germany) set at a 1% gradient (32). Prior to testing, a resting blood sample was drawn from a fingertip for the assessment of baseline blood lactate concentration. The athlete was then fitted with a telemetric heart rate (HR) monitor (Polar S610, Kempele, Finland (Exeter) or Wahoo TickrX, Atlanta, GA (Beaverton)) and allowed to perform his individual warm-up regimen including 10-15 min jogging and some stretching if desired. The athlete was then fitted with a mask and a portable pulmonary gas exchange measuring device (Oxycon Mobile, Jaeger, Heidelberg, Germany (Exeter) or Cosmed K4b2, Rome, Italy (Beaverton)) for the measurement of $\dot{V}O_2$ and asked to complete a multi-stage incremental treadmill running test. Prior to testing, the gas exchange measurement systems were each calibrated according to the manufacturer's instructions; the O_2 and CO_2 analyzers using gases of known concentration and the turbine flow meters with a 3 L syringe. The principles of operation of the two systems are similar and it has been reported that they provide measurements of $\dot{V}O_2$ that are reliable and valid relative to the gold standard Douglas bag method (1, 25, 51).

The starting speed for the treadmill test was 17 km/h. Each stage was 3 min in duration and the belt speed was increased by 1 km/h until 19 km/h and 0.5 km/h thereafter until the athlete reached volitional exhaustion (i.e., when he could not complete a stage or declined the opportunity to start a new one). For the first stage of the test, the belt speed was increased to 17 km/h and following the command of "3-2-1-GO" the athletes commenced running, having previously stood still for 60 s with their feet astride the moving treadmill belt. A fingertip blood sample was collected as quickly as possible (within 10-20 s) at the end of each 3 min stage with the athlete interrupting exercise and standing astride the moving treadmill belt with his hand stabilized on the guard-rail. Blood [lactate] was subsequently determined in duplicate (Lactate Plus, Nova Biomedical, Waltham, USA).

The breath-by-breath pulmonary gas exchange data were collected continuously during the incremental test and averaged over consecutive 10 s periods. Running economy, as O_2 cost, was derived from measurements of $\dot{V}O_2$ during the final 50 s of each of the submaximal stages and expressed both in units of ml/kg/min and ml/kg/km. This time period was selected to allow enough time for a steady-state to be attained while also ensuring sufficient data in the collection 'window' to provide confidence in the evaluation of the mean $\dot{V}O_2$ for each speed. Where appropriate, running economy as energy cost was also calculated from $\dot{V}O_2$ and respiratory exchange ratio (RER) measurements and expressed in units of kcal/kg/km (18, 27). Blood [lactate] was plotted against running speed and LT, defined as the first increase in blood [lactate] above the baseline value of 1-2 mM, and LTP, defined as a subsequent sudden and sustained increase in blood [lactate], were identified by visual inspection. Blood [lactate]-speed plots were reviewed blind by four of the co-authors and a consensus on the running speeds at LT and LTP was reached and recorded. The $\dot{V}O_2$peak was taken as the highest 30-s rolling mean value attained prior to the termination of the test. Although the athletes exercised to volitional exhaustion, we have termed the highest $\dot{V}O_2$ recorded '$\dot{V}O_2$peak' rather than '$\dot{V}O_2$max' because we did not perform a subsequent 'verification' test on the treadmill at a higher speed (55).

The $\dot{V}O_2$ response across the single transition from standing to running at 17 km/h was modelled using a mono-exponential function to derive the phase II time constant of the $\dot{V}O_2$ kinetics (2, 31). Briefly, the breath-by-breath $\dot{V}O_2$ data from each test were initially examined to exclude errant breaths, and those values lying >4 standard deviations from the local mean were deleted. The breath-by-breath data were subsequently linearly interpolated to give 1-s values and then averaged into 10-s time bins. The baseline $\dot{V}O_2$ was defined as the mean $\dot{V}O_2$

measured during the last 60 s of standing prior to the start of running. The first 20 s of data after the onset of running (i.e. the phase I response) were not included in the analysis. An exponential model was used to describe the $\dot{V}O_2$ response, including the amplitude of the response from baseline to the steady-state and the phase II time constant, as described previously (2, 31). The parameters of the model were determined using a non-linear least squares algorithm in which minimizing the mean squared error was the criterion for convergence. The 95% confidence intervals surrounding the phase II time constant estimate were also computed.

Biomechanical Assessment

For 10 of the 11 athletes tested in Exeter, force and kinematic data were collected during over-ground running at 21.1 km/h (5.86 $m.s^{-1}$, ± 5%) using an AMTI force plate (1000 Hz, Advanced Mechanical Technology Inc., Watertown, MA, USA) and CodaMotion motion capture system (200 Hz, 3 CX1 monitors, Charnwood Dynamics Ltd., UK). Active markers were positioned on each shoe to align with the superior calcaneus of both the left and right feet. The 16.5 m runway included approximately 7 m of run-up prior to the force plate and was extended outdoors so that the athletes were not required to decelerate within the laboratory space. The athletes were encouraged to complete familiarization trials until they were comfortable running at the desired speed. Running speed was monitored using timing gates (Brower, Utah, USA) positioned 2 m apart and 1 m high. The foot that contacted the force plate was self-selected. Athletes were asked not to target the force plate during running and instead to focus on running as naturally as possible without looking at the force plate. Trials were repeated until five successful trials from the same side were recorded. A successful trial was one in which the athlete contacted the force plate fully, without adjusting their stride, and whilst running at the correct speed.

Force and kinematic data were filtered with a fourth-order Butterworth filter at 50 Hz and 12 Hz respectively. Dependent variables were calculated for each trial and a mean obtained per individual athlete. Stance was detected using a vertical force threshold of 20 N. Force variables were normalized to body weight (N). Peak vertical force was defined as the maximum force during stance. Instantaneous loading rate was defined as the first derivative of the vertical ground reaction force with respect to time, and the peak value was obtained. Stride length was defined as the distance between the step on the force plate and the following contralateral step, determined using the calcaneal markers. Vertical oscillation was defined as the maximum difference in vertical displacement of the centre of mass throughout stance, where change in centre of mass was obtained by double integration of the acceleration. Vertical effective impulse was calculated as in Nummela et al. (50).

Track Test

Following a self-selected warm-up and fitting of the HR monitor and calibrated portable gas analysis device, as described for the laboratory tests above, the athletes were instructed to complete 2 laps of a 400 m track at 17 km/h followed immediately by 6 laps at 21.1 km/h, with a final lap as fast as possible. During the first 8 laps the athletes were provided feedback every 200 m on their running speed. 400 m lap split times were recorded by two individuals and used to calculate running speed for each section of the test. The O_2 cost of running was calculated as the mean value over the last 50 s of running at 17 km/h and as the mean value over the last 2 minutes of running at 21.1 km/h. The $\dot{V}O_2$peak was taken as the highest 30-s rolling mean value attained prior to the termination of the test.

Estimation of Marathon Performance

The highest sustainable speed for the marathon was estimated by dividing the $\dot{V}O_2$ measured at LT by the O_2 cost of submaximal running (35), i.e. for an athlete with a $\dot{V}O_2$ at LT of 60 ml/kg/min, and O_2 cost of 185 ml/kg/km, then 60 x 60 / 185 = 19.46 km/h, which would predict a marathon time of 2:10:07. The same calculation was also made using the $\dot{V}O_2$ at LTP and the $\dot{V}O_2$ at 96% of LTP (34).

Statistics

Data are reported as group mean ± SD. Relationships between variables were assessed with Pearson product moment correlation coefficients. Student's t-tests were used to assess differences between treadmill and outdoor running. Statistical significance was accepted when $P<0.05$.

Results

Athlete Characteristics

The athletes were 29 ± 4 years of age, 1.72 ± 0.04 (1.63-1.80) m tall and weighed 58.9 ± 3.3 (54.7-66.3) kg. Pertinent anthropometric characteristics are shown in Table 1. The athletes' sum of 4 skinfolds was 19.8 ± 2.4 mm and their estimated percentage body fat was 7.9 ± 1.0 %. Forced vital capacity was 4.37 ± 1.05 L and forced expiratory volume in 1 s was 3.90 ± 0.88 L.

Physiological Variables: Laboratory

The group mean speed reached in the final stage of the treadmill test was 21.2 ± 0.6 km/h; 13 athletes completed a stage at 21 km/h, eight athletes completed a stage at 21.5 km/h and two athletes completed a stage at 22 km/h. The group mean $\dot{V}O_2$peak was 71.0 ± 5.7 ml/kg/min, maximal HR was 190 ± 11 b/min, maximal minute ventilation was 142 ± 20 L/min, and maximal RER was 1.05 ± 0.07. The $\dot{V}O_2$ response of a representative athlete during the incremental test is shown in Figure 1.

Over a range of speeds which could be considered to be submaximal (<LTP) for individual athletes (17.0-19.5 km/h), the mean O_2 cost of running at, was 189 ± 14 ml/kg/km (Figure 2), with a mean energy cost of 1.06 ± 0.15 kcal/kg/km. At a running speed of 21.0 km/h (n = 13) on the treadmill, O_2 cost was 188 ± 20 ml/kg/km, corresponding to an absolute $\dot{V}O_2$ of 3.98 ± 0.50 L/min, a relative $\dot{V}O_2$ of 65.8 ml/kg/min and fractional utilization of 95 ± 5 % $\dot{V}O_2$peak. For those athletes for whom 21.0 km/h was not the final completed treadmill stage (n = 8), the O_2 cost at 21 km/h was 189 ± 14 ml/kg/km, corresponding to an absolute $\dot{V}O_2$ of 3.91 ± 0.28 L/min, a relative $\dot{V}O_2$ of 66.8 ml/kg/min and fractional utilization of 94 ± 6 % $\dot{V}O_2$peak. The individual $\dot{V}O_2$-running speed profiles are presented in Figure 2A and the O_2 cost of running for the athletes across the full range of speeds is shown in Figure 2B. The mean O_2 cost of running was similar across the speeds studied but, at each speed, there was considerable inter-individual variability (with a range of ~170-220 ml/kg/km; Figure 2B).

The individual blood [lactate]-running speed relationships are presented in Figure 3A, with the response of a representative athlete highlighted in Figure 3B and the group mean ± SD LT and LTP shown in Figure 3C. The group mean LT occurred at 18.9 ± 0.4 km/h, which corresponded to 83 ± 5 % $\dot{V}O_2$peak, 166 ± 9 b/min (87 ± 5 % HR max) and a blood [lactate] of 2.2 ± 0.8 mM. The group mean LTP occurred at 20.2 ± 0.6 km/h which corresponded to 92 ± 3 % $\dot{V}O_2$peak, 181 ± 8 b/min (94 ± 2 % HR max) and a blood [lactate] of 4.6 ± 1.3 mM.

We took the opportunity to evaluate $\dot{V}O_2$ kinetics during the first stage of the incremental test (i.e. step test from standing at rest to running at 17 km/h; see Figure 1). The group mean phase II time constant was 12.1 ± 2.6 s (95% confidence interval: 2.5 ± 1.0 s) while the amplitude of the $\dot{V}O_2$ response, from resting baseline to steady-state at 17 km/h, was 2.63 ± 0.37 L/min.

Physiological Variables: Track

In the first part of the track test, the athletes chose to run at 18.4 ± 1.0 km/h. At this speed, the group mean $\dot{V}O_2$ was 3.28 ± 0.33 L/min, O_2 cost was 179 ± 16 ml/kg/km and energy cost was 1.10 ± 0.12 kcal/kg/km. In the second part of the test, as instructed, the athletes maintained a speed of 21.0 ± 0.2 km/h. At this speed, the group mean $\dot{V}O_2$ was 4.11 ± 0.37 L/min (70 ± 6 ml/kg/min; 95 ± 3 % $\dot{V}O_2$peak) and the group mean O_2 cost was 191 ± 19 ml/kg/min ($P<0.01$ compared to the lower speed). Nine athletes were able to accelerate in the final lap to achieve a speed of 22.5 ± 0.8 km/h, $\dot{V}O_2$peak of 4.20 ± 0.28 L/min (71.9 ± 6.1 ml/kg/min) and HR max of 185 ± 10 b/min.

It was notable that not all athletes were able to achieve a $\dot{V}O_2$ steady-state when running over-ground at ~21 km/h. The $\dot{V}O_2$ profiles of a representative athlete from the group that was able to achieve a steady-state (n = 7) and a representative athlete from the group that was not able to achieve a steady-state (n = 9) are shown in Figure 4A and 4B, respectively. In the former group, a delayed $\dot{V}O_2$ steady-state was evident and the athletes could further elevate $\dot{V}O_2$ when they accelerated for the final 400 m lap. In the latter group, however, a more pronounced $\dot{V}O_2$ 'slow component' was evident such that $\dot{V}O_2$ increased progressively with time and $\dot{V}O_2$ could not be increased further even with a final lap acceleration. While there was no difference in the mean O_2 cost of running at 21 km/h between the two groups (i.e. 191 ml/kg/km), this O_2 cost represented a slightly smaller fraction of $\dot{V}O_2$peak in the group that was able to reach a steady-state (94 ± 3 %) compared to the group that could not reach a steady-state (97 ± 9 %).

Relationships between Laboratory and Field Testing

The O_2 cost was not different between treadmill and track either during submaximal running (lab: 189 ± 14 vs. track: 179 ± 16 ml/kg/km at ~18.4 km/h; $P = 0.17$) or when running at 21.0 km/h (lab: 188 ± 20 vs. track: 191 ± 19 ml/kg/km; $P = 0.75$). There was no significant difference between $\dot{V}O_2$peak measured on the treadmill or the track (71.0 vs. 71.9 ml/kg/min; *P* =0.97). $\dot{V}O_2$peak was significantly correlated with the O_2 cost of submaximal running both for treadmill running (*r* = 0.86, *P*<0.0001) and for over-ground running (*r* = 0.87, *P*<0.0001).

Biomechanical Assessment

Group mean biomechanical characteristics are presented in Table 2. Four of the ten runners presented ground reaction force-time histories that displayed an impact peak typical of a rearfoot strike, whereas six presented time histories representative of a non-rearfoot strike (41). There was a significant inverse correlation between ground contact time and O_2 cost of running on the treadmill (*r* = -0.69; *P* = 0.03); i.e. better running economy was associated with shorter ground contact time. There were no other statistically significant correlations between the O_2 cost of submaximal running and biomechanical or anthropometric variables.

Estimation of Marathon Performance

The individual and group mean values for $\dot{V}O_2$peak, the fractional utilization of $\dot{V}O_2$peak (which is presumed to be associated with the accumulation of lactate in the blood) and the O_2 cost of running are shown in Figure 5. The highest sustainable speed for the marathon, estimated by dividing the $\dot{V}O_2$ measured at LT by the O_2 cost of over-ground running, was 18.7 ± 1.0 (range: 16.6-19.7) km/h. This would predict a mean marathon time for the group of 2:15:24 (range: 2:08:32-2:23:03). When the $\dot{V}O_2$ measured at LTP was used instead, the estimated highest sustainable speed for the marathon was 20.6 ± 1.0 (range: 18.9-22.0) km/h, which would predict a mean marathon time for the group of 2:02:55 (1:57:13-2:09:11). However, when the sustainable $\dot{V}O_2$ was assumed to be 96% LTP, as has been proposed previously (34), the predicted marathon time was more realistic for the cohort (2:08:31 ± 3:48; range: 2:00:01-2:19:58) and not different from the athletes' best marathon performances at the time of testing (2:08:40 ± 6:45). There were no significant correlations between the athletes' best marathon time and $\dot{V}O_2$peak (r = -0.14), O_2 cost of running (r = -0.12), LT (r = 0.10) or LTP (r = 0.05); however, marathon performance was significantly correlated with the $\dot{V}O_2$ phase II time constant (r = 0.76; P = 0.002).

Discussion

In this study, we present the physiological test data of some of the world's best male distance runners which were collected as part of Nike's 'Breaking 2' marathon project. This study makes several novel contributions to our understanding of the physiology of elite-level marathon running. To our knowledge, the O_2 cost of running over-ground at ~21.0 km/h, corresponding to 2 hour marathon race pace, has never been measured directly. We report that the O_2 cost of over-ground running at 21.0 km/h was 191 ± 19 ml/kg/km. For a 59 kg athlete, an O_2 cost of 191 ml/kg/km equates to a $\dot{V}O_2$ of approximately 4.0 L/min or 67 ml/kg/min when running at 21.0 km/h. It was notable, however, that only 7 athletes from the cohort were able to attain a $\dot{V}O_2$ steady-state when running over-ground at 21.0 km/h.

It is instructive to consider the implications of this mean O_2 cost value (i.e., 191 ml/kg/km) for the other physiological variables that are known to influence elite-level marathon performance. For example, a 59 kg athlete with a $\dot{V}O_2$peak of 4.5 L/min (or 76 ml/kg/min) and O_2 cost of submaximal running of 191 ml/kg/km, would need to sustain 88% $\dot{V}O_2$peak to run a 2 hour marathon. But, with the same O_2 cost of 191 ml/kg/km and a higher $\dot{V}O_2$peak of 80 ml/kg/min, a 2 hour marathon would require 84% $\dot{V}O_2$peak. Alternatively, for an athlete with a $\dot{V}O_2$peak of 76 ml/kg/min but a lower O_2 cost of 180 ml/kg/km and therefore a $\dot{V}O_2$ of running at 21.1 km/h of 3.8 L/min, a 2 hour marathon would require 83% $\dot{V}O_2$peak. The assumptions underpinning these predictions are discussed later (see 'Other Considerations'). However, it is pertinent to note that there are several possible and realistic combinations of $\dot{V}O_2$peak, submaximal O_2 cost and fractional utilization of $\dot{V}O_2$peak that could permit the achievement of a sub-2 hour marathon. The importance of the combination of these variables is emphasized by the fact that, when considered in isolation, $\dot{V}O_2$peak, O_2 cost of running, and lactate-related metrics were not significantly correlated with marathon performance; but when $\dot{V}O_2$peak, O_2 cost of running and LTP were considered together, the predicted marathon time was not different from the best performances recorded by the athletes at the time of testing.

Physiological Variables Measured in the Laboratory

The mean $\dot{V}O_2$peak of the athletes was ~71-72 ml/kg/min with a wide range of 62 to 84 ml/kg/min (Figure 5). These values are similar to previously reported $\dot{V}O_2$max values for highly-trained distance runners (53, 54) suggesting that improved race performances in recent decades cannot be attributed to higher $\dot{V}O_2$max values *per se*. In the present study, $\dot{V}O_2$peak was measured at the end of a multi-stage treadmill protocol with the treadmill grade set at 1%. It is possible that the reported $\dot{V}O_2$peak under-estimated the maximal value for $\dot{V}O_2$ that might have been attained if a protocol involving a progressive increase in treadmill gradient had been employed. However, any such difference is likely to have been small (~3%; Jones, unpublished observations) and the $\dot{V}O_2$peak reported here would more accurately represent the highest value for $\dot{V}O_2$ that could be attained during competition on a flat surface. Consistent with this, $\dot{V}O_2$peak was not different between the laboratory and the track indicating that the athletes were able to provide a consistent and apparently maximal effort in both environments.

We measured the blood lactate response to progressively increasing speeds on the treadmill and identified the LT (18.9 ± 0.4 km/h; range of 18.0-19.5 km/h) and LTP (20.2 ± 0.6 km/h; range of 19.5-21.0 km/h) through visual inspection of individual blood [lactate]-running speed profiles. While numerous, more objective, methods exist for the interpretation of blood lactate responses to exercise (26, 29), these are often arbitrary and/or fail to reflect the relevant underpinning physiology (29). It is notable that the LT and LTP occurred at high fractions of the athletes' $\dot{V}O_2$peak (83 ± 5 % and 92 ± 3 %, respectively). It is also notable that the speed required to run a 2 hour marathon (21.1 km/h) exceeded the group mean LTP speed, clearly indicating that not all of the elite athletes evaluated were capable of sustaining the necessary speed without experiencing a progressive accumulation of lactate over time. The LTP approximates the CS (60) and therefore delineates the heavy-intensity exercise domain, within which steady-state physiological responses can be achieved, from the severe-intensity exercise domain (60). In the severe-intensity domain, a metabolic steady-state cannot be achieved, fatigue develops more rapidly and exercise tolerance is limited to less than approximately 30 minutes (60, 63). It appears that elite athletes run marathons at a mean speed that resides in the heavy-intensity domain, that is, above LT but below CS (33, 34). Indeed, it has been calculated that elite distance runners are able to sustain a marathon race speed at approximately 96 % of CS when the latter is estimated using personal best performance times established over shorter race distances (5, 34). Therefore, for a 2 hour marathon to be achievable, it is necessary for CS to occur at a minimum of 22 km/h. Because CS occurs at approximately 90% $\dot{V}O_2$peak in elite endurance athletes (3, 4, personal observations), this would indicate that these athletes might sustain a high fraction of $\dot{V}O_2$peak (~86-90%) during a 2 hour marathon race. This coheres with estimates derived from measurements made at altitude in elite Kenyan runners (62) and also with a recent report that marathon race speed required 91% $\dot{V}O_2$peak in a masters' world marathon record holder (40). Consistent with our previous analysis (34), when we calculated possible best marathon times for the athletes in the present study, the most realistic estimate (i.e., the one closest to the athletes' personal record times) was derived when the highest sustainable $\dot{V}O_2$ was assumed to occur at 96% of LTP (or approximately 88% $\dot{V}O_2$peak).

The type of training required to elicit a high CS and to enable a high fraction of $\dot{V}O_2$peak to be sustained during a marathon is not entirely clear (30). However, it is known that critical power (CP, which is analogous to CS) in cycling is related to a high proportion of highly-oxidative, fatigue resistant type I muscle fibers (63) and to muscle capillarity (44). Elite marathon runners complete a relatively high volume of training (170-230 km per week) but with 2-3 sessions per week at higher (peri-CS) intensity, such as continuous tempo runs at marathon race pace or extensive intervals (for example, 25-30 x 400 m, 10-15 x 1000 m, or 6-8 x 1 mile) at 10K race pace (10; personal observations of the authors).

The first stage of the treadmill exercise protocol, which was completed at a ‘moderate’ speed of 17 km/h, was deliberately designed as a ‘step’ test with the athletes dropping onto the revolving treadmill belt from a standing position. This permitted us to characterise $\dot{V}O_2$ kinetics, i.e. the integrated adaptation of the O_2 transport and utilization systems to meet the abruptly elevated metabolic demand. The phase II time constant of the pulmonary $\dot{V}O_2$ kinetics, which reflects skeletal muscle $\dot{V}O_2$ kinetics (19), was 12.1 ± 2.6 s, with 4 athletes having a time constant of <10 s. In the present study, the athletes only completed a single transition from rest to moderate-intensity running; however, the amplitude of the $\dot{V}O_2$ response was relatively large (2.63 L/min, on average), such that the 95% confidence interval surrounding the estimate of the phase II time constant was small (± 2.5 s). While fast $\dot{V}O_2$ kinetics have been reported in endurance athletes previously (2, 38), it should be noted that a time constant of ~12 s is exceedingly short and indicates that these athletes would attain a complete steady-state within 50 s of the start of running within the moderate (<LT) domain. Fast $\dot{V}O_2$ kinetics, *per se*, might not be considered to be especially relevant to marathon performance because the duration for which the athlete will be in an initial O_2 deficit is very small relative to the event duration. However, it has been reported the phase II time constant is significantly correlated with CP during cycle exercise (49), suggesting that the two

variables might be related through some common physiological mechanism such as skeletal muscle oxidative capacity (64). In this light, it is intriguing that we observed a significant correlation between the athletes' phase II time constant and their best marathon performance ($r = 0.76$, $P = 0.002$).

Running Economy: Laboratory and Field

The O_2 cost of submaximal treadmill running was ~189 ml/kg/km, with substantial inter-individual variability. These values are similar to those reported in other studies of trained endurance runners (8, 12, 13, 14, 42). At a running speed of 21 km/h on the treadmill, the $\dot{V}O_2$ and O_2 cost values we measured were similar to those reported previously by Lucia et al for elite Eritrean runners (42) and to predictions derived from the limited data presented by Joyner (see Figure 1 in ref. 35).

Direct measurement of the O_2 cost of running outdoors at ~21 km/h, as was achieved for the first time in the present study, is important in improving physiological models of endurance performance (35, 36). The measured O_2 cost was ~179 and ~191 ml/kg/km at the lower and higher track speeds, respectively. It was striking, however, that only 7/16 athletes in this world-class cohort were able to achieve a $\dot{V}O_2$ steady-state at 21 km/h. This underlines the significant challenge of running a sub-2 hour marathon. In the majority of the athletes tested, a $\dot{V}O_2$ 'slow component' was evident while running at 21 km/h, indicating that this speed was above their CS (Figure 4B). The inexorable loss of efficiency, represented by the $\dot{V}O_2$ slow component, leads to the rapid attainment of $\dot{V}O_2$peak and expedites fatigue development such that 21 km/h would prove unsustainable for the marathon distance (33, 34, 63). Even for the minority of athletes who could achieve a steady-state $\dot{V}O_2$ at 21 km/h, this speed represented a high fraction of $\dot{V}O_2$peak (~94%). As outlined earlier, this value for fractional utilization could be reduced either by enhancing $\dot{V}O_2$peak (through training) or by lowering the O_2 cost of running (through training or technological innovation).

At the group level, there was no significant difference in the O_2 cost of running at similar speeds on the treadmill compared to the track. In the laboratory, the O_2 cost of running was not different between the lower and higher speeds whereas, on the track, the O_2 cost was significantly greater at the higher speed. The explanation for this difference is not clear but might be related to changes in air resistance experienced at higher speeds when running outdoors compared to running on a treadmill (32, 56). In the present study, the treadmill gradient was set at 1% for the laboratory-based physiological assessments as an expedient to help compensate for the lack of air resistance experienced in the laboratory compared to the field (32). This previous investigation (32) was conducted in moderately-trained runners such that the range of speeds investigated was restricted to 10-18 km/h. The results of the present study suggest that adjustment of the treadmill gradient may also be appropriate up to a running speed of 21 km/h if the goal is to reflect the O_2 cost of outdoor running.

$\dot{V}O_2$peak was significantly correlated with the O_2 cost of submaximal running both for treadmill running ($r = 0.86$) and for over-ground running ($r = 0.87$); that is, athletes with a lower O_2 cost of running at submaximal speeds tended to have lower $\dot{V}O_2$peak values, and *vice versa*. This is consistent with previous reports and may be related to differences in factors such as leg muscle mass and substrate utilization (17, 47, 52, 59) although it has also been suggested that this relationship may be non-causal or even spurious (6, 17). This finding is important because it indicates that while impressive values for $\dot{V}O_2$peak and the O_2 cost of submaximal running (for example, >75 ml/kg/min and <185 ml/kg/km, respectively), *per se,* are not unusual in elite runners (Figure 5), the simultaneous possession of both a high $\dot{V}O_2$peak and a low O_2 cost may be much less common. Naturally, athletes possessing values for sustainable oxidative metabolic rate (a function of $\dot{V}O_2$peak and its fractional utilization) and O_2 cost that, in combination, permit a speed of ≥ 21.1 km/h to be sustained for the marathon distance are even more rare.

Biomechanical Variables

There has been increasing interest in running with an anterior (non-rearfoot) foot strike in recent years, despite minimal evidence to support the proposed benefits over running with a rearfoot strike (20). The present study supports data from the 2017 IAAF World Championships (21), which showed that on average 60% of men's marathon runners displayed a rearfoot strike, including the top four finishers.

The mean ground contact time of 0.16 s, measured in the present study, is similar to values previously reported in elite runners at running speeds of 19.5 km/h (39) and 20 km/h (58). The mean ground contact time tends to be shorter in elite compared to sub-elite runners. For example, a ground contact time of 0.18 s was reported in national-level athletes running at 20.9 km/h (50). In the present study, we found that shorter ground contact time was associated with a lower O_2 cost of submaximal running (r = -0.69), consistent with previous findings (46, 50, 57). A shorter ground contact time is indicative of a reduced braking phase during stance (50) which results in less deceleration of the forward motion of the body (39) and may explain the lower O_2 cost. Moreover, vertical effective impulse was 18% lower in the present study than has been measured previously in national-level athletes (50). Low vertical impulse values have been suggested to be associated with more economical running (22).

The anthropometric characteristics of the athletes in the present study, including stature, body mass, body mass index, body composition, and the lengths and girths of the thigh and calf, were similar to values reported previously in similar cohorts (see 45 for review). It has been proposed that some of these characteristics may be related to running economy and running performance (18, 42, 45). While there were no significant correlations between anthropometric variables and running economy in the present study, it is important to note that the athletes were relatively homogenous in their physical and physiological characteristics and, therefore, the lack of correlation should not be interpreted to imply that those variables are not important determinants of running economy.

Other Considerations

There are, of course, many other factors that can influence marathon performance in addition to athlete anthropometry and physiology. These include the psychological characteristics of the athlete and sound biomechanics although this latter aspect may be captured, to a large extent, in measurements of running economy (18, 23). Due to the high absolute metabolic rate that must be sustained and the related heat production, thermoregulation is another important consideration and environmental factors such as ambient temperature, relative humidity, radiant heat and wind speed can therefore significantly influence marathon performance (43). It is also necessary to recognise that physiological variables, such as $\dot{V}O_2$peak, running economy and LT, measured during a ~30 minute treadmill test are unlikely to remain static over the course of a 2 hour marathon run. Indeed, a 'fourth variable' might be added to the three proposed by Joyner (35) – that of the extent of the deterioration of the three over time (i.e., fatigue resistance). Clark et al. (11) reported that the parameters of the power-duration relationship, the CP and curvature constant (W′), decreased by 9% and 23%, respectively, over the course of 2 hours of heavy-intensity cycle exercise. These effects were related, in part, to a progressive loss of efficiency (i.e. greater O_2 cost for the same external power output). Similarly, it is known that the O_2 cost of running increases during fatiguing, long-duration exercise (7), consequent to changes in both biomechanics and metabolic substrate utilization. To this end, events to date targeting the 2 hour marathon have made great efforts both to minimize O_2 cost and to protect against its deterioration over time. This has included strategies designed to: maintain the rate of carbohydrate oxidation and therefore keep RER high and $\dot{V}O_2$ low via regular carbohydrate ingestion (9, 11); minimize air resistance and therefore O_2 cost by drafting behind a rotating shield of human pacemakers (56); enable a relatively even pace with minimal changes of course direction or elevation and therefore energy demand (15); and minimize athlete energy loss to the ground via running shoe innovations (24). In this light, it is important to recognise that numerous factors, over and above extraordinary athlete physiology, must conflate to enable the achievement of a sub-2 hour marathon.

Limitations

Several limitations to this study should be acknowledged. The athletes were in different stages of training for, or recovery from, other competitions and were not necessarily in their best physical condition at the time of testing. The values reported are therefore very likely to underestimate the values that might be measured when the athletes are in their best condition prior to a major marathon competition. Due to the athletes' schedules, opportunities for familiarizing them with the treadmill and the gas exchange measurement system were limited. Some athletes had not previously experienced running on a treadmill and it is possible that this impacted on the $\dot{V}O_2$ measurements made in the laboratory, although this was not reflected in differences between treadmill and track measurements. Moreover, a lack of complete habituation to the facemask which was used for gas exchange measurement, along with some anxiety on the part of the athletes, resulted in mild hyperventilation in some cases which elevated RER and limited our ability to calculate running economy in units of energy cost. Physiological evaluation of the athletes took place in two locations (n=11 in Exeter UK and n=5 in Beaverton USA) using different treadmills and gas analysis systems. While there is evidence that the gas analysis systems are valid and reliable and likely to produce similar results (1, 25, 51), and the $\dot{V}O_2$ peak and O_2 cost measurements were similar in the cohorts of athletes tested in the two locations, it would have been preferable for all athletes to be evaluated in the same location with the same equipment.

Conclusions

For the first time, we report that the O_2 cost of over-ground running at ~21 km/h approximates 191 ml/kg/km and therefore an absolute metabolic rate of about 4.0 L/min (67 ml/kg/min) for an elite runner weighing 59 kg. Here it may be noted that while the absolute $\dot{V}O_2$ at this speed would vary according to body mass, the relative $\dot{V}O_2$ (i.e. 67 ml/kg/min) would not. To be sustainable for the requisite time, it is necessary for this metabolic rate to be lower than the 'critical metabolic rate' associated with CS. Moreover, the higher the $\dot{V}O_2$peak, the smaller the fraction of $\dot{V}O_2$peak that 4.0 L/min represents: for example, a $\dot{V}O_2$peak of ~80 ml/kg/min in a 59 kg runner gives a fractional utilisation of 85% which seems physiologically reasonable. It is essential to recognise that the traditional physiological variables we measured in this study should be considered in combination rather than in isolation (35). The absolute $\dot{V}O_2$ that is sustainable for 2 hours is the critical metabolic factor, with the O_2 cost of running at race pace, and its resilience to fatigue development over time (7, 11), being instrumental in translating the metabolic output into speed over the ground. Given that these factors are likely to have been optimized by genetic predisposition and long-term training in today's elite athletes, it would appear that scientific innovations and/or strategies which enable a higher mean oxidative metabolic rate to be sustained and/or enhance running economy will play a significant role in future improvements in marathon performance.

References

1. Akkermans MA, Sillen MJ, Wouters EF, Spruit MA. Validation of the oxycon mobile metabolic system in healthy subjects. *J Sports Sci Med*. 11(1):182-3, 2012.

2. Berger NJ, Jones AM. Pulmonary O_2 uptake on-kinetics in sprint- and endurance-trained athletes. *Appl Physiol Nutr Metab*. 32(3):383-93, 2007.

3. Billat V, Binsse V, Petit B, Koralsztein JP. High level runners are able to maintain a VO2 steady-state below VO2max in an all-out run over their critical velocity. *Arch Physiol Biochem*. 106(1):38-45, 1998.

4. Billat V, Renoux JC, Pinoteau J, Petit B, Koralsztein JP. Times to exhaustion at 90, 100 and 105% of velocity at VO2 max (maximal aerobic speed) and critical speed in elite long-distance runners. *Arch Physiol Biochem*. 103(2):129-35, 1995.

5. Billat V, Vitiello D, Palacin F, Correa M, Pycke JR. Race Analysis of the World's Best Female and Male Marathon Runners. *Int J Environ Res Public Health*. 17(4):1177, 2020.

6. Borgen NT. Running Performance, VO(2max), and Running Economy: The Widespread Issue of Endogenous Selection Bias. *Sports Med*. 48(5):1049-1058, 2018.

7. Brueckner JC, Atchou G, Capelli C, et al. The energy cost of running increases with the distance covered. *Eur J Appl Physiol Occup Physiol*. 62:385-9, 1991.

8. Bunc V, Heller J. Energy cost of running in similarly trained men and women. *Eur J Appl Physiol Occup Physiol*. 59:178-183, 1989.

9. Burke LM, Jeukendrup AE, Jones AM, Mooses M. Contemporary Nutrition Strategies to Optimize Performance in Distance Runners and Race Walkers. *Int J Sport Nutr Exerc Metab*. 29(2):117-129, 2019.

10. Casado A, Hanley B, Ruiz-Pérez LM. Deliberate practice in training differentiates the best Kenyan and Spanish long-distance runners. *Eur J Sport Sci*. 21:1-9, 2019.

11. Clark IE, Vanhatalo A, Thompson C, et al. Dynamics of the power-duration relationship during prolonged endurance exercise and influence of carbohydrate ingestion. *J Appl Physiol.* 127(3):726-36, 2019.

12. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc.* 12(5):357-60, 1980.

13. Daniels J, Daniels N. Running economy of elite male and elite female runners. *Med Sci Sports Exerc*. 24(4):483-9, 1992.

14. Davies CT, and Thompson MW. Aerobic performance of female marathon and male ultramarathon athletes. *Eur J Appl Physiol Occup Physiol*. 41:233-245, 1979.

15. Díaz JJ, Fernández-Ozcorta EJ, Santos-Concejero J. The influence of pacing strategy on marathon world records. *Eur J Sport Sci.* 18(6):781-6, 2018.

16. Durnin JV, Womersley J. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr*. 32(1):77-97, 1974.

17. Fletcher JR, Esau SP, Macintosh BR. Economy of running: beyond the measurement of oxygen uptake. *J Appl Physiol*. 107(6):1918-22, 2009.

18. Folland JP, Allen SJ, Black MI, Handsaker JC, Forrester SE. Running Technique is an Important Component of Running Economy and Performance. *Med Sci Sports Exerc*. 49(7):1412-1423, 2017.

19. Grassi B, Poole DC, Richardson RS, Knight DR, Erickson BK, Wagner PD. Muscle O2 uptake kinetics in humans: implications for metabolic control. *J Appl Physiol* (1985). 80(3):988-98, 1996.

20. Hamill J, Gruber AH. Is changing footstrike pattern beneficial to runners? *J Sport Health Sci*. 6(2):146-153, 2017.

21. Hanley B, Bissas A, Merlino S, Gruber AH. Most marathon runners at the 2017 IAAF World Championships were rearfoot strikers, and most did not change footstrike pattern. *J Biomech.* 92:54-60, 2019.

22. Heise GD, Martin PE. Are variations in running economy in humans associated with ground reaction force characteristics? *Eur J Appl Physiol*. 84(5):438-42, 2001.

23. Hoogkamer W, Kipp S, Kram R. The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. *Sports Med*. 49(1):133-143, 2019.

24. Hoogkamer W, Kram R, Arellano CJ. How Biomechanical Improvements in Running Economy Could Break the 2-hour Marathon Barrier. *Sports Med*. 47(9):1739-1750, 2017.

25. Howe CC, Matzko RO, Piaser F, Pitsiladis YP, Easton C. Stability of the K4b^2 portable metabolic analyser during rest, walking and running. *J Sports Sci*. 32(2):157-63, 2014.

26. Jamnick NA, Botella J, Pyne DB, Bishop DJ. Manipulating graded exercise test variables affects the validity of the lactate threshold and [Formula: see text]. *PLoS One*. 13(7):e0199794, 2018.

27. Jeukendrup AE, Wallis GA. Measurement of substrate oxidation during exercise by means of gas exchange measurements. *Int J Sports Med*. Suppl 1:S28-37, 2005.

28. Jones AM. The physiology of the world record holder for the women's marathon. *Int J Sports Sci Coaching*. 1:101-116, 2006.

29. Jones AM, Burnley M, Vanhatalo, A. Aerobic exercise performance. In: Eston, R. and Norton, K. (Eds). Exercise and Laboratory Test Manual (Fourth Edition). *Routledge*, pp. 318-352, 2018.

30. Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. *Sports Med*. 29(6):373-86, 2000.

31. Jones AM, DiMenna F, Lothian F, Taylor E, Garland SW, Hayes PR, Thompson KG. 'Priming' exercise and O2 uptake kinetics during treadmill running. *Respir Physiol Neurobiol*. 161(2):182-8, 2008.

32. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci*. 14(4):321-7, 1996.

33. Jones AM, Poole DC. Physiological demands of endurance exercise. In: Maughan, R.J. (Ed). Olympic Textbook of Science in Sport, IOC, Blackwell, 2008. p. 43-55.

34. Jones AM, Vanhatalo A. The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Med*. 47(Suppl 1):65-78, 2017.

35. Joyner MJ. Modeling: optimal marathon performance on the basis of physiological factors. *J Appl Physiol*. 70:683-687, 1991.

36. Joyner MJ, Hunter SK, Lucia A, Jones AM. Physiology and fast marathons. *J Appl Physiol*. 128:1065-1068, 2020.

37. Joyner MJ, Ruiz JR, Lucia A. The two-hour marathon: who and when? *J Appl Physiol.* 110:275-277; 2011.

38. Kilding AE, Winter EM, Fysh M. A comparison of pulmonary oxygen uptake kinetics in middle- and long-distance runners. *Int J Sports Med*. 27(5):419-26, 2006.

39. Kong PW, de Heer H. Anthropometric, Gait and Strength Characteristics of Kenyan Distance Runners. *J Sports Sci Med*. 7:499–504, 2008.

40. Lepers R, Bontemps B, Louis J. Physiological Profile of a 59-Year-Old Male World Record Holder Marathoner. *Med Sci Sports Exerc*. 52(3):623-626, 2020.

41. Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'Andrea S, Davis IS, Mang'Eni, RO, Pitsiladis Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*(7280), 531–535, 2010..

42. Lucia A, Esteve-Lanao J, Olivan J, et al. Physiological characteristics of the best Eritrean runners-exceptional running economy. *Appl Physiol Nutr Metab*. 31:530-540, 2006.

43. Maughan RJ. Distance running in hot environments: a thermal challenge to the elite runner. *Scand J Med Sci Sports*. 20 Suppl 3:95-102, 2010.

44. Mitchell EA, Martin NRW, Bailey SJ, Ferguson RA. Critical power is positively related to skeletal muscle capillarity and type I muscle fibers in endurance-trained individuals. *J Appl Physiol* (1985). 125(3):737-745, 2018.

45. Mooses M, Hackney AC. Anthropometrics and Body Composition in East African Runners: Potential Impact on Performance. *Int J Sports Physiol Perform*. 12(4):422-430, 2017.

46. Mooses M, Haile DW, Ojiambo R, Sang M, Mooses K, Lane AR, Hackney AC. Shorter Ground Contact Time and Better Running Economy: Evidence From Female Kenyan Runners. *J Strength Cond Res*. 2018, doi: 10.1519/JSC.0000000000002669

47. Morgan DW, Daniels JT. Relationship between $\dot{V}O_2$max and the aerobic demand of running in elite distance runners. *Int J Sports Med*. 15(7):426-9, 1994.

48. Morgan DW, Martin PE, Krahenbuhl GS. Factors affecting running economy. *Sports Med.* 7(5):310-30, 1989.

49. Murgatroyd SR, Ferguson C, Ward SA, Whipp BJ, Rossiter HB. Pulmonary O2 uptake kinetics as a determinant of high-intensity exercise tolerance in humans. *J Appl Physiol* (1985). 110(6):1598-606, 2011.

50. Nummela A, Keränen T, Mikkelsson LO. Factors related to top running speed and economy. *Int J Sports Med*. 28(8):655-61, 2007.

51. Overstreet BS, Bassett DR Jr, Crouter SE, Rider BC, Parr BB. Portable open-circuit spirometry systems. *J Sports Med Phys Fitness*. 57(3):227-237, 2017.

52. Pate RR, Macera CA, Bailey SP, Bartoli WP, Powell KE. Physiological, anthropometric, and training correlates of running economy. *Med Sci Sports Exerc*. 24(10):1128-33, 1992.

53. Pate RR, Sparling PB, Wilson GE, Cureton KJ, Miller BJ. Cardiorespiratory and metabolic responses to submaximal and maximal exercise in elite women distance runners. *Int J Sports Med*. Suppl 2:91-95, 1987.

54. Pollock ML. Submaximal and maximal working capacity of elite distance runners. Part I: Cardiorespiratory aspects. *Ann N Y Acad Sci*. 301:310-322, 1977.

55. Poole DC, Jones AM. Measurement of the maximum oxygen uptake $\dot{V}$o(2max): $\dot{V}$o(2peak) is no longer acceptable. *J Appl Physiol* (1985). 122(4):997-1002, 2017.

56. Pugh LG. Oxygen intake in track and treadmill running with observations on the effect of air resistance. *J Physiol.* 207:823-835, 1970.

57. Santos-Concejero J, Granados C, Irazusta J, Bidaurrazaga-Letona I, Zabala-Lili J, Tam N, Gil SM. Differences in ground contact time explain the less efficient running economy in north African runners. *Biol Sport*. 30:181-7, 2013.

58. Santos-Concejero J, Tam N, Coetzee DR, Oliván J, Noakes TD, Tucker R. Are gait characteristics and ground reaction forces related to energy cost of running in elite Kenyan runners? *J Sports Sci*. 35:531-8, 2017.

59. Shaw AJ, Ingham SA, Atkinson G, Folland JP. The correlation between running economy and maximal oxygen uptake: cross-sectional and longitudinal relationships in highly trained distance runners. *PLoS One*. 10(4):e0123101, 2015.

60. Smith CG, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *Eur J Appl Physiol*. 85(1-2):19-26, 2001.

61. Sousa CV, Sales MM, Nikolaidis PT, Rosemann T, Knechtle B. How much further for the sub-2-hour marathon? *Open Access J Sports Med*. 9:139-145, 2018.

62. Tam E, Rossi H, Moia C, Berardelli C, Rosa G, Capelli C, Ferretti G. Energetics of running in top-level marathon runners from Kenya. *Eur J Appl Physiol*. 112(11):3797-806, 2012.

63. Vanhatalo A, Black MI, DiMenna FJ, et al. The mechanistic bases of the power-time relationship: muscle metabolic responses and relationships to muscle fibre type. *J Physiol.* 594(15):4407-23, 2016.

64. Whipp BJ, Mahler M. Dynamics of pulmonary gas exchange during exercise. In: West JB, editor. Pulmonary Gas Exchange. Organism and Environment.vol. II. New York: Academic Press, 1980. p. 33–96.

Figure Legends

Figure 1: The $\dot{V}O_2$ response to the incremental treadmill test in a representative athlete. The treadmill test started with an abrupt transition to running at 17 km/h for the evaluation of $\dot{V}O_2$ kinetics. Thereafter, the running speed was increased by 1 km/h every 3 minutes (until 19 km/h) and by 0.5 km/h every 3 minutes thereafter until the athlete reached volitional exhaustion. Pulmonary gas exchange and heart rate were measured continuously and a blood sample for [lactate] determination was taken during short breaks between stages. $\dot{V}O_2$ data are presented in 10-s bins.

Figure 2: The $\dot{V}O_2$ response to the incremental treadmill test in all athletes. Panel A shows the absolute $\dot{V}O_2$-running speed relationship in the athletes along with the mean ± SD $\dot{V}O_2$peak attained prior to test termination. Panel B shows the data expressed as O_2 cost per kg per km (i.e. running economy) for the athletes along with the group mean (solid red line). For both panels, note the substantial inter-individual variability.

Figure 3: The blood [lactate]-running speed relationship in the incremental treadmill test. Panel A shows the individual athlete blood [lactate] profiles along with the mean response (in bold). Panel B highlights the response of a representative athlete and indicates the selected values for lactate threshold (LT) and lactate turn-point (LTP). Panel C shows the mean ± SD running speed and blood [lactate] at which LT and LTP were identified.

Figure 4: The $\dot{V}O_2$ profiles for two representative athletes while performing the track test. The athletes were asked to run 800 m at a submaximal speed, then 2400 m at ~21.0 km/h and then a final 400 m as quickly as possible. Panel A shows the $\dot{V}O_2$ profile of a representative athlete from the group who were able to achieve a delayed $\dot{V}O_2$ steady-state at 21 km/h (n =7). Notice the stable $\dot{V}O_2$ over the last ~4 minutes of the middle stage and the ability to increase $\dot{V}O_2$ further during the final stage. Panel B shows the $\dot{V}O_2$ profile of a representative

athlete from the group who were not able to achieve a steady-state at 21 km/h (n = 9). Notice the continuous increase in $\dot{V}O_2$ over time in the middle section and the inability to increase $\dot{V}O_2$ despite an increased speed in the final stage. Please note that the lower O_2 cost values in the final 'supramaximal' stage of the test are artefactual in the sense that they represent an inability of the athletes to increase $\dot{V}O_2$ to match the increased running speed. The dashed vertical lines represent changes in running speed and the dashed horizontal line represents the $\dot{V}O_2$peak measured prior to the termination of the test. $\dot{V}O_2$ data are presented in 10 s bins.

Figure 5: Individual (white circles) and group mean (red line) values for the three principal physiological determinants of marathon running performance according to Joyner and colleagues (18, 19, 20) measured in the laboratory and track tests: $\dot{V}O_2$peak (Panel A), sustainable fraction of $\dot{V}O_2$peak ((over-)estimated here from the $\dot{V}O_2$ at LTP; Panel B), and O_2 cost of submaximal running (Panel C). Note the wide range of individual values for all three variables.

Table 1: Mean ± SD anthropometric variables of lower limbs

	Mean ± SD
Thigh girth (cm)	46.5 ± 2.0
Calf girth (cm)	33.4 ± 1.6
Biepicondylar femur breadth (cm)	9.8 ± 0.4
Bimalleolar breadth (cm)	7.5 ± 0.4
Leg length (cm)	87.9 ± 3.7
Shank length (cm)	41.0 ± 1.8
Achilles tendon length (cm)	25.9 ± 2.0

Table 2: Mean ± SD force and temporospatial characteristics during over-ground running at 21 km/h

	Mean ± SD
Ground contact time (s)	0.16 ± 0.01
Peak vertical force (BW)	2.92 ± 0.26
Peak instantaneous loading rate (BW/s)	135 ± 47
Vertical oscillation (m)	0.04 ± 0.006
Vertical effective impulse (BW.s)	0.13 ± 0.02
Stride length (m)	1.74 ± 0.06
Relative stride length (% height)	100.4 ± 3.6

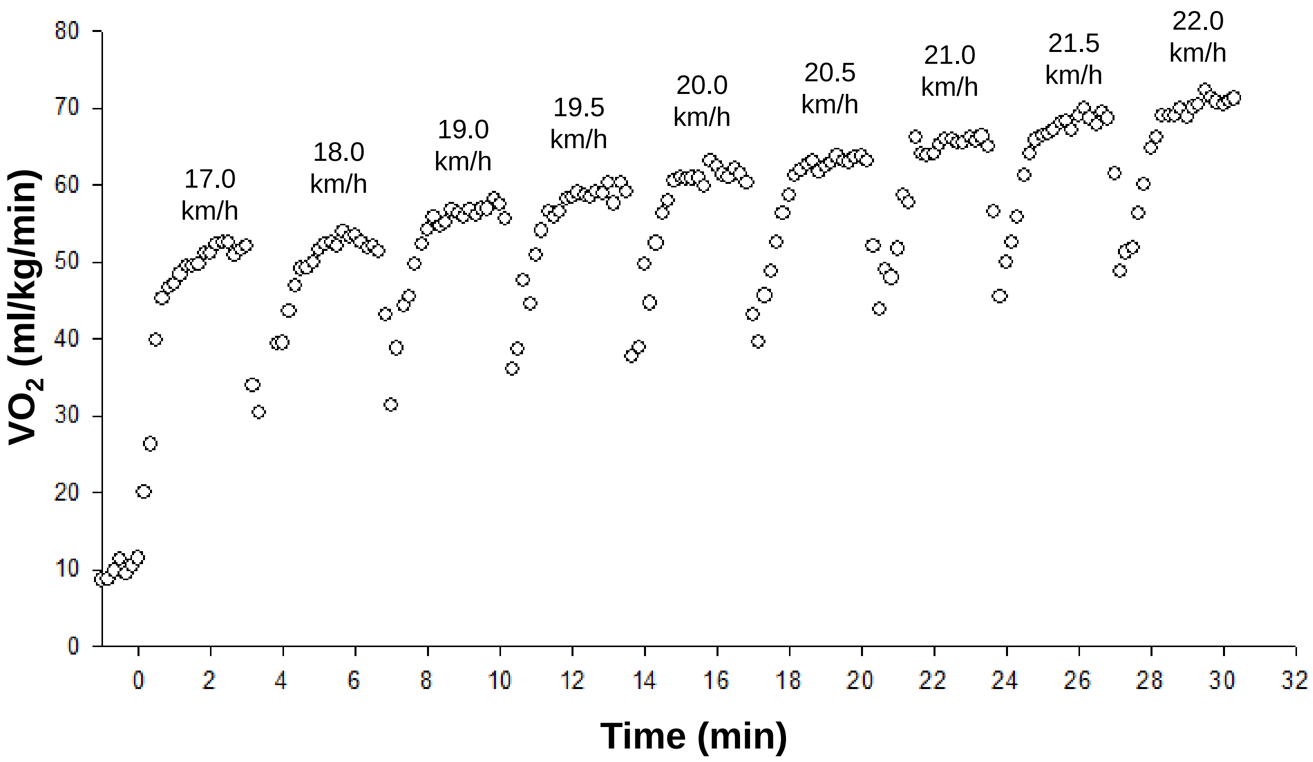
17.0 km/h
18.0 km/h
19.0 km/h
19.5 km/h
20.0 km/h
20.5 km/h
21.0 km/h
21.5 km/h
22.0 km/h
VO2 (ml/kg/min)
0
10
20
30
40
50
60
70
80
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Time (min)

Figure 1

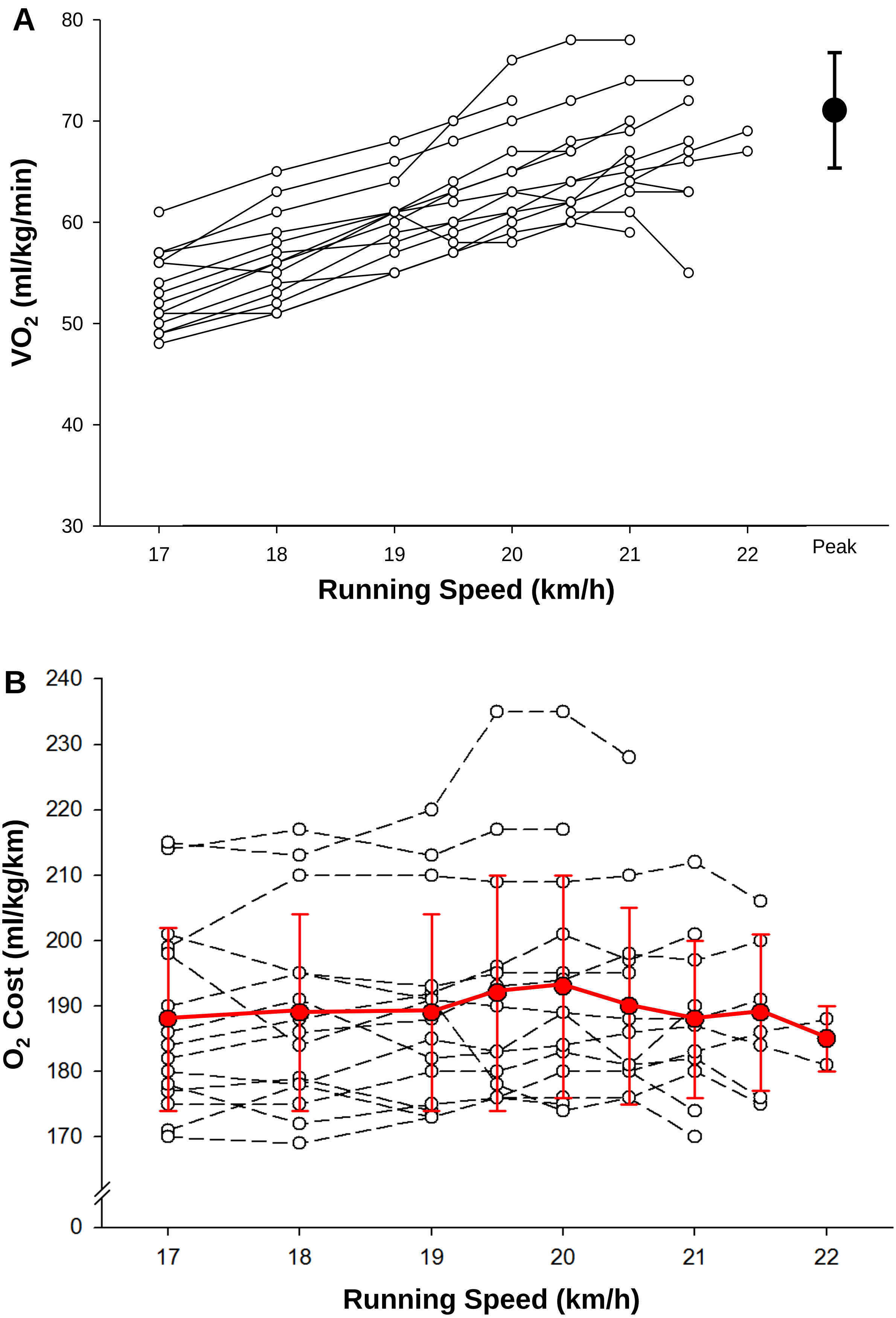
A
80
70
60
50
40
30
VO2 (ml/kg/min)
17
18
19
20
21
22
Peak
Running Speed (km/h)
B
240
230
220
210
200
190
180
170
0
O2 Cost (ml/kg/km)
17
18
19
20
21
22
Running Speed (km/h)

Figure 2

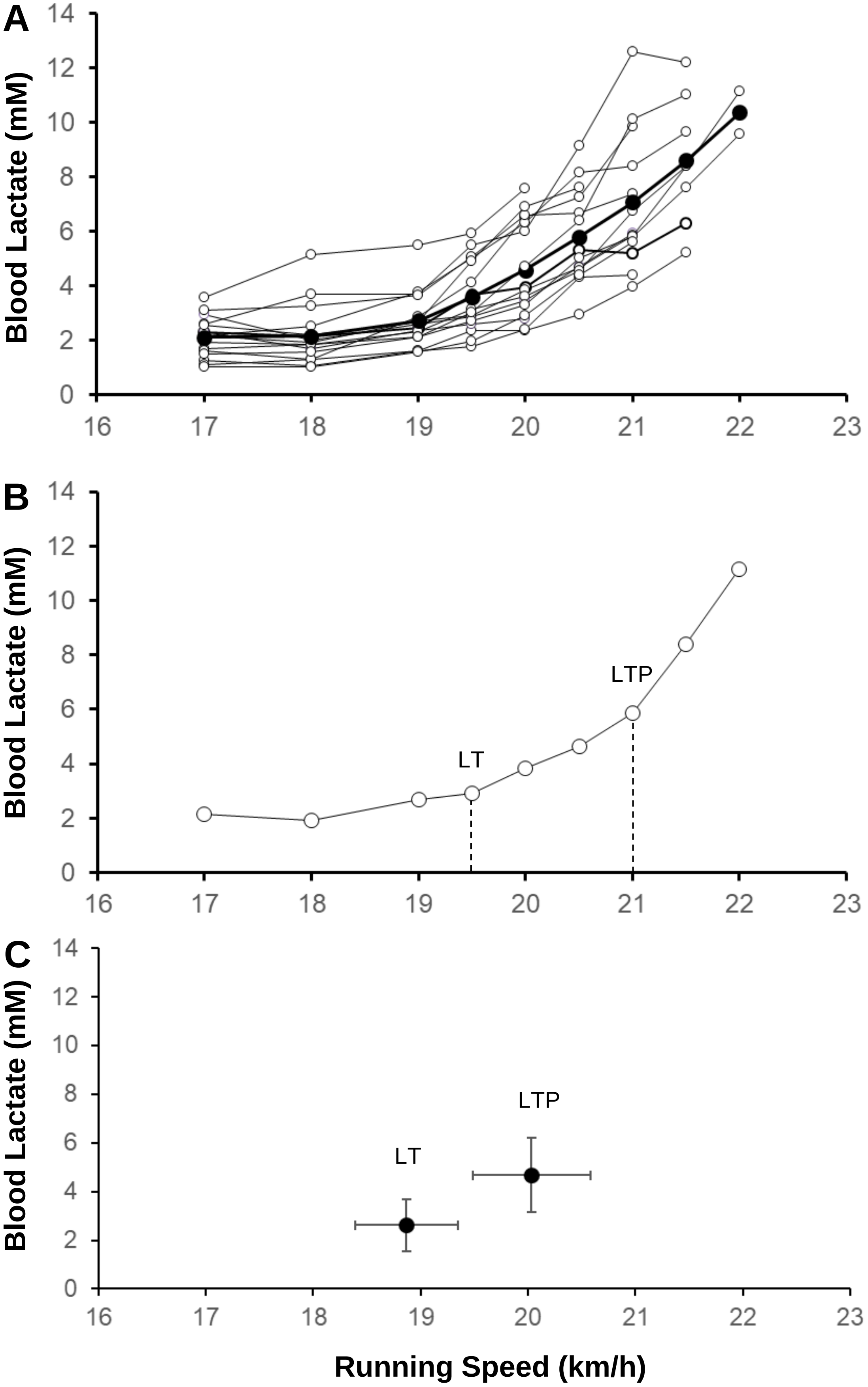
A
B
C
Blood Lactate (mM)
0
2
4
6
8
10
12
14
16
17
18
19
20
21
22
23
LT
LTP
Running Speed (km/h)

Figure 3

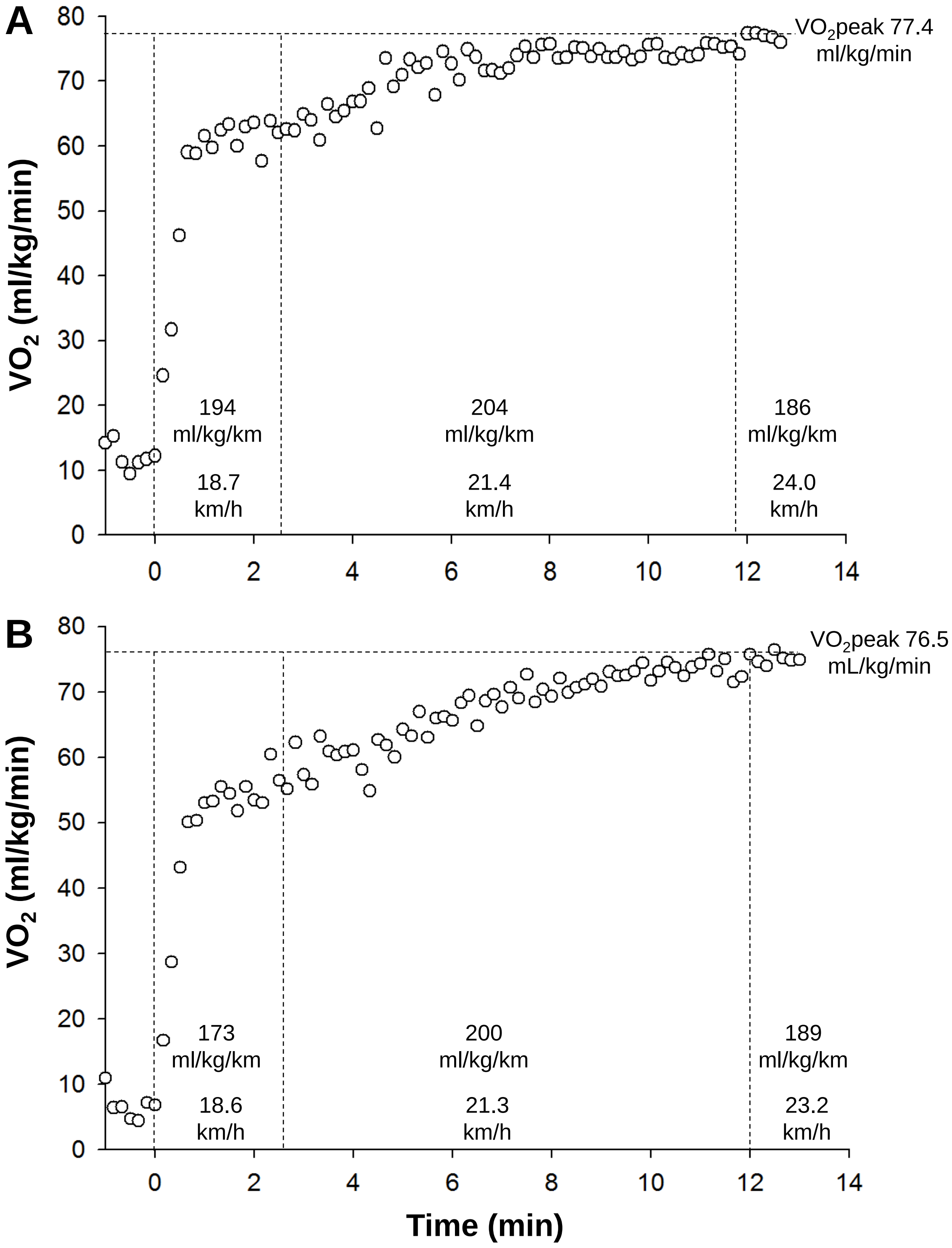
A
VO$_2$peak 77.4
ml/kg/min
194
ml/kg/km
18.7
km/h
204
ml/kg/km
21.4
km/h
186
ml/kg/km
24.0
km/h
B
VO$_2$peak 76.5
mL/kg/min
173
ml/kg/km
18.6
km/h
200
ml/kg/km
21.3
km/h
189
ml/kg/km
23.2
km/h
VO$_2$ (ml/kg/min)
Time (min)
0
10
20
30
40
50
60
70
80
0
2
4
6
8
10
12
14

Figure 4

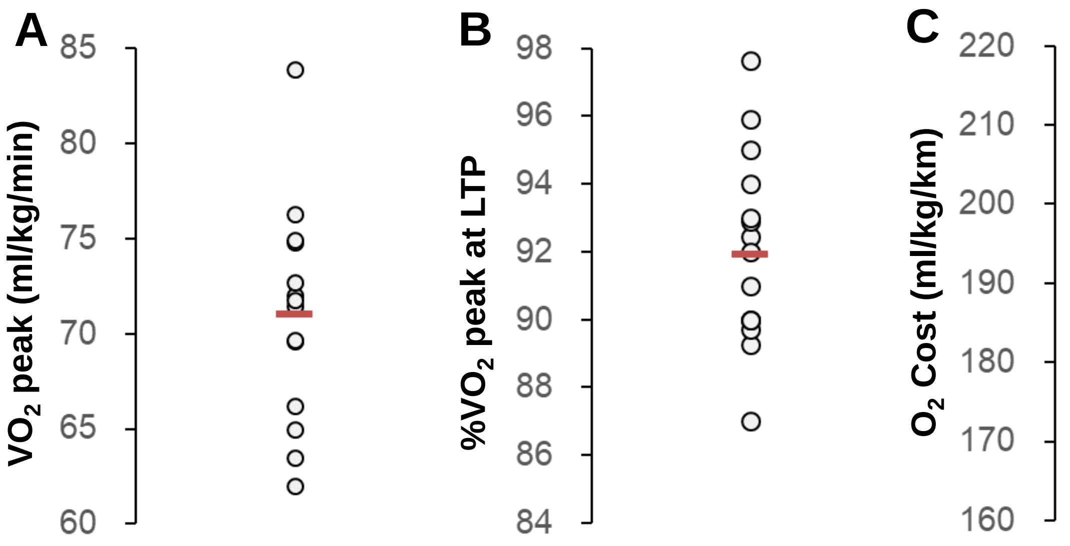
A
B
C
VO$_2$ peak (ml/kg/min)
85
80
75
70
65
60
%VO$_2$ peak at LTP
98
96
94
92
90
88
86
84
O$_2$ Cost (ml/kg/km)
220
210
200
190
180
170
160

Figure 5