Physiological Determinants of Ultramarathon Trail Running Performance

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ABSTRACT

Context: The physiological determinants of ultramarathon success have rarely been assessed, and likely differ in their contributions to performance as race distance increases. **Purpose:** The aim of this study was to examine predictors of performance in athletes who completed either a 50km, 80km, or 160km trail race over a 20km-loop course on the same day. **Methods:** Measures of running history, aerobic fitness, running economy, body mass loss, hematocrit alterations, age, and cardiovascular health were examined in relation to race-day performance. Performance was defined as the percent difference from the winning time at a given race distance, with 0% representing the fastest possible time. **Results:** In the 50km race, training volumes, cardiovascular health, aerobic fitness, and a greater loss of body mass during the race were all related to better performance (all $P < 0.05$). Using multiple linear regression, peak velocity achieved in the VO_2max test ($\beta = -11.7$, $P = 0.002$) and baseline blood pressure ($\beta = 3.1$, $P = 0.007$) were the best performance predictors for the men's 50km race ($r = 0.98$, $r^2 = 0.96$, $P < 0.001$), while peak velocity achieved in the VO_2max test ($\beta = -13.6$, $P = 0.001$) and loss of body mass ($\beta = 12.8$, $P = 0.03$) were the best predictors for women ($r = 0.94$, $r^2 = 0.87$, $P = 0.001$). In the 80km race, only peak velocity

achieved in the VO_2max test predicted performance ($\beta = -20.3$, $r = 0.88$, $r^2 = 0.78$, $P < 0.001$). In the 160km race, there were no significant performance determinants. **Conclusions:** While classic determinants of running performance including cardiovascular health, and running fitness predict 50km trail running success, performance in longer distance races appears to be less influenced by such physiological parameters.

INTRODUCTION

Predicting ultramarathon running performance is a unique challenge, as ultramarathon races can vary greatly in distance, duration, and physiological demand. Ultramarathon running races range from any race exceeding the marathon distance ($>42.2\text{km}$) to multi-day events, and commonly include diverse terrains, and environmental conditions^{1,2}. This results in vastly different physiological requirements between races, and can make comparison across races challenging. The demographic of athletes racing ultramarathons is typically older than shorter-distances, and is comprised primarily of masters and recreational participants, rather than elite athletes¹. Proposed contributors to successful ultramarathon performance include high aerobic fitness^{3,4}, an ability to mitigate injuries⁵, avoidance of gastrointestinal issues⁶, delay of fatigue², and psychological fortitude³.

The physiological determinants of running performance in standard distances from 5000m to the marathon have been highly investigated, and primarily include measures of aerobic fitness including maximal oxygen uptake (VO_2max), lactate threshold or the percentage of sustainable VO_2max , and running economy⁷. Aerobic fitness seems likely as a determinant of ultramarathon performance as well, as lactate threshold and VO_2max are related to distance covered in a 24h treadmill run⁴, and peak treadmill running velocity achieved during an incremental test is the best laboratory predictor of performance for races $\leq 90\text{km}$ ⁸. Lower body mass index (BMI) and body fat percentage are typically related to improved endurance running performance^{9,10}; however, the correlation of BMI and ultramarathon performance is equivocal^{6,9,11,12}, and performance is more strongly related to training volumes than BMI^{9,12}. Excessive dehydration has been shown to negatively alter endurance exercise performance¹³, yet faster marathon runners typically lose more weight over the course of a race than slower runners, and a loss of upwards of 3% of body mass has been demonstrated in runners who completed marathons in less than 3h¹⁴. Loss of body mass following 161km races is similar to that of marathons ($\sim 2\%$)¹⁵; however, there is only a weak relationship to faster racing times¹⁶. Furthermore, in contrast to shorter distance running, body mass loss cannot be solely attributable to dehydration in ultramarathon¹⁷, which may complicate the relationship between body mass loss and performance. Finally, while peak performance in the marathon is typically achieved around the age of 30yr, the age of the fastest 160km runners worldwide is approximately 37yr for men and 39yr for women¹⁸, with experience being a greater determinant of success than age¹⁸. This may further suggest a shift in the importance of certain physiological parameters, such as aerobic fitness, which decrease with age.

To date, a comparison of the physiological determinants of performance across increasing ultramarathon race distances, and within similar racing conditions, has not been performed. The objective of this study was to examine whether common indicators of running performance could be used to predict performance in athletes who raced either a 50km, 80km, or 160km ultramarathon, on the same day and over a common course.

METHODS

Experimental Design

Fifty-one recreational runners who were registered in the Sulphur Springs trail races (Ancaster, Canada) in the 50km, 80km, or 160km distances were recruited via email for this cross-sectional study. The race was comprised of 20km hilly trail loops ($\sim 620\text{m}$ of cumulative elevation gain per loop). Participants were all healthy

and non-smoking individuals between the ages of 18-60yr, and provided written informed consent prior to testing. In the month prior to the race (mean 12 ± 7 days prior to race day), participants underwent baseline testing including a training and racing history questionnaire, basic anthropometrics, resting blood pressure (BP), heart rate (HR), and heart rate variability (HRV), a venous blood draw to assess hematocrit, and an incremental running test to exhaustion. Participants were asked to refrain from caffeine and heavy meals for 33h , drugs and alcohol for 324h , and intense exercise for 348h prior to baseline testing. On race morning, all athletes were weighed immediately prior to racing. Immediately following the race, a post-race weight and hematocrit were collected to assess dehydration status.

The study was carried out under approval of the University of Guelph ethics board, and in accordance with the Declaration of Helsinki, and was part of a larger study on ultramarathons and cardiovascular fatigue^{19,20}.

Training and Racing History Questionnaire

In a written questionnaire, athletes were asked to report on their previous month of training, including how many hours and km per week they ran, how many hours of strength or resistance training they underwent each week, and how many additional hours were spent on cross-training. They were also asked to report the km/week completed on average in the past year. Lastly, athletes reported the number of years of past endurance run training, and how many marathons and ultramarathons they had previously completed.

Cardiovascular Health

Age, height, and body mass were recorded. Supine BP was taken in triplicate using an automated oscillometric device (BPtru, Vancouver, BC) once the participant was relaxed (~ 1 -2min following positioning). The first recording was discarded and the remaining 2 were averaged. Following a minimum of 5min of quiet rest, a 4-min recording of heart rate variability (HRV) using a SphygmoCor CPVH single-lead ECG (AtCor Medical Ltd, NSW, Australia) was collected, during spontaneous breathing. Mean resting HR, the natural log of the square root of the mean of successive differences (lnRMSSD), and lnRMSSD divided by HR were selected as the measures of interest, as they provide reliable measures of parasympathetic activity over a short time frame²¹.

Aerobic Fitness and Running Economy

Following resting measures, an incremental running test to volitional fatigue, with measures of indirect calorimetry, was performed (HP Cosmos Treadmill, Cosmed Quark metabolic cart) to determine VO_{2max} , ventilatory thresholds, and steady-state running economy. Participants completed three 3min submaximal stages at 1% grade to simulate outdoor running²². Paces were increased by 0.8kph (0.5mph) per stage from what was estimated to be a sustainable steady-pace for the individual. The initial velocity was chosen after discussing the protocol with the participant, and was often at a pace around or just below the individual's half-marathon pace (ranging from 8.0-15.3kph). This ensured that by the end of the 3rd stage, all participants had surpassed their first ventilatory threshold. Following the 3 submaximal stages, speed was increased each minute by 0.8kph or 1% incline per the participant's choice, until volitional exhaustion. The choice to increase running speed or incline at the end of the test was designed so that those athletes unfamiliar with running at faster velocities could still achieve VO_{2max} . Athletes were not instructed to stop upon reaching a plateau in oxygen consumption, and the highest VO_2 value achieved using a 30s rolling average was taken as maximal (VO_{2max}). Peak velocity was recorded as the highest velocity achieved during the maximal test if the treadmill incline was kept at 1%, or was calculated as peak velocity = max velocity + (% grade $\times$ 0.2kph)²³. Ventilatory thresholds were determined as previously described by Pallares et al²⁴.

Running economy was assessed as both oxygen cost (ml/kg) and caloric unit cost (kcal/kg) per km in the last minute of the 3-min running stage prior to the first ventilatory threshold²⁵ at a 1% treadmill grade. As such,

while the velocities of running were not the same across participants, the relative intensity of running was, and mathematically, running velocity was not included in the calculation²⁵.

Fluid Alterations and Body Mass

Body mass was assessed directly prior to the race start on a standing scale positioned on a firm platform and post-race mass was taken immediately following the races on the same scale. Brachial venipuncture was performed to collect a 10 mL sample for blood analysis in a related study¹⁹, with hematocrit assessed on site by sampling from the vacutainer and using a micro-capillary reader (Damon/IEC Division, Massachusetts, USA).

Statistical Analysis

Race performance was determined as percent difference of winning time, accounting for race distance and sex ((subject time – winning time) / (winning time)x100). Thus, the best performance would be noted as 0% different from winning time. Statistical analysis was performed using Statistical Package for the Social Sciences software (SPSS version 25; IBM). Data were assessed for normality using the Shapiro-Wilk test. Between-race group analysis and finisher to non-finisher analysis was assessed via one-way ANOVA with Bonferroni corrections for post-hoc testing. Basic correlation matrix analyses were used to compare race distance performances to all outcome variables. Finally, stepwise multivariable linear regression was performed to determine predictors of performance for finishers of each race distance. To control for collinearity, the variable with the strongest relationship to performance was chosen from co-related variables. Sex-related differences were only examined in the 50km race due to inadequate female representation in the other distances.

RESULTS

Performance

Race times and percentage of winning time are presented in Figure 1. Mean finishing time for 50km was 6.2 ± 2.3 h for men and 6.4 ± 1.5 h for women. The 80km and 160km finishing times were 11.6 ± 1.8 h, and 25.2 ± 3.6 h respectively.

Figure 1. Finishing time (A) and percentage of winning time (B) across 50km males (M), females (F), 80km mixed sex, and 160km mixed sex trail running races. * $P < 0.0001$ from 50km races, ϕ $P < 0.0001$ from 80km race, † $P < 0.0001$ from 160km race.

Subject Characteristics

All subjects were assessed post-race, therefore data from all race starters (including non-finishers) is presented in Table 1. The only between-group differences were that the 50km race finishers had completed fewer marathons and ultramarathons than the 80 and 160km finishers (all $P < 0.05$; see Table 1). Of the 51 subjects tested at baseline, 42 (82%) completed their respective race distances (see Table 1). Only 1 male and 1 female in the 50km race, and 1 male in the 80km race did not finish, whereas 6 males did not finish in the 160km race; therefore, finisher vs non-finisher data was pooled across race distances. In the month prior to testing, non-finishers completed fewer weekly training kilometers compared to finishers (51 ± 36 vs 77 ± 34 km/week, $P = 0.04$), and reported a lower weekly running distance for the previous year (36 ± 24 vs 58 ± 20 km/week, $P = 0.006$). Non-finishers also had significantly higher resting mean arterial pressure (MAP) than finishers (105 ± 18 vs 92 ± 7.8 , $P = 0.002$). No other baseline characteristics differentiated the two groups; however, non-finishers were trending towards having a post-race increase in hematocrit ($+2.3 \pm 3$ vs -0.3 ± 3.3 , $P = 0.051$). Alterations in body mass and hematocrit following the race can be seen in Figure 2. All groups lost on average -1.6 ± 1.0 kg ($P < 0.0001$), but hematocrit was unchanged ($0.13 \pm 3.4\%$, $P = 0.15$).

Table 1. Baseline Subject Characteristics, Training History, and Running Fitness of 50km, 80km, and 160km Ultramarathon Finishers, and Non-Finishers of all Distances

	50km	80km	160km	Non-Finishers (all distances)
Baseline Characteristics				
Number of Participants (sex)	21(M:10 F:11)	13(M:9, F:4)	8(M:6, F:2)	9(M:8:F:1)
Age (years)	40 $\pm$ 10	45 $\pm$ 9	45 $\pm$ 10	44 $\pm$ 11
BMI (kg/m ²)	24.1 $\pm$ 3.6	24.0 $\pm$ 3.3	24.1 $\pm$ 2.3	24.3 $\pm$ 2.7
Resting Heart Rate (bpm)	55 $\pm$ 8	56 $\pm$ 7	52 $\pm$ 8	56 $\pm$ 8
Mean Arterial Pressure (mmHg)	91 $\pm$ 9	95 $\pm$ 8	94 $\pm$ 5	105 $\pm$ 18 [‡]
RMSSD (ms)	62.6 $\pm$ 39.0	58.2 $\pm$ 39.1	53.2 $\pm$ 23.5	72.5 $\pm$ 54.9
RMSSD/HR (a.u)	1.2 $\pm$ 0.9	1.1 $\pm$ 0.9	1.1 $\pm$ 0.6	1.3 $\pm$ 1.5
Aerobic Fitness and Running Economy				
VO ₂ max (ml/kg/min)	49.8 $\pm$ 10.3	48.0 $\pm$ 3.8	53.8 $\pm$ 8.3	48.5 $\pm$ 8
Peak Velocity in GXT (kph)	14.7 $\pm$ 2.9	14.8 $\pm$ 1.0	15.6 $\pm$ 2.2	14.6 $\pm$ 1.6
Oxygen Cost (ml/kg/km)	216.5 $\pm$ 21.6	203.4 $\pm$ 11.0	206.6 $\pm$ 14.1	204.8 $\pm$ 28.6
Caloric Cost (kcal/kg/km)	1.04 $\pm$ 0.12	1.04 $\pm$ 0.16	1.04 $\pm$ 0.13	0.99 $\pm$ 0.16
Training and Racing History				
Running time in last month (hr/wk)	7.9 $\pm$ 3.4	8.2 $\pm$ 1.9	8.6 $\pm$ 1.9	6.3 $\pm$ 3.5
Running volume in last month (km/wk)	66 $\pm$ 24	87 $\pm$ 49	88 $\pm$ 14	51 $\pm$ 36 [‡]
Running volume in last year (km/wk)	54 $\pm$ 21	56 $\pm$ 17	72 $\pm$ 19	36 $\pm$ 24 [‡]
Estimated strength training (hr/wk)	1.4 $\pm$ 1.3	1.4 $\pm$ 1.1	1.3 $\pm$ 1.5	0.7 $\pm$ 1.0
Estimated total training hours (hr/wk)	11.7 $\pm$ 5.2	10.2 $\pm$ 2.6	12.6 $\pm$ 3.5	8.5 $\pm$ 3.4
Completed Marathons/Ultramarathons (n)	7 $\pm$ 5 [†]	14 $\pm$ 10 [*]	20 $\pm$ 9 [*]	17 $\pm$ 22
Years Running (yr)	6 $\pm$ 4	8 $\pm$ 9	12 $\pm$ 6	8 $\pm$ 6

Abbreviations: a.u. arbitrary units; BMI, body mass index; RMSSD, square root of the mean of successive difference; GXT, graded exercise test; HR, heart rate; M, male; F, female. Data as Mean $\pm$ SD. * $P < 0.05$ from 50km group. [†] $P < 0.05$ from 160km. [‡] $P < 0.05$ from finishers.

Figure 2. Changes to body mass and hematocrit following 50, 80, or 160km trail running races. *** $P < 0.0001$, Main effect of time. Baseline hematocrit was assessed during pretesting in the month prior to the race, whereas baseline body mass was assessed on race morning.

Training History and Performance

Amongst finishers in the 50km race, running distance (km/week) in the month preceding competition ($r = -0.66$, $P = 0.001$) and average km/week in the year preceding competition ($r = -0.50$, $P = 0.02$) were associated with performance (percent difference from winning time) when pooling across sex. For 50km men, km/week in the last month ($r = -0.67$, $P = 0.04$), km/week in the last year ($r = -0.72$, $P = 0.02$), and years of run training ($r = -0.77$, $P = 0.009$) were related to performance. For the 50km women, total training hours/week ($r = -0.78$, $P = 0.007$), and km/week in the previous month ($r = -0.84$, $P = 0.002$) were related to performance. No training variables were correlated to 80km or 160km performance, although km/week in the last year was trending in the 80km race ($r = -0.57$, $P = 0.06$).

Cardiovascular Indices and Performance

In the 50km race with both sexes pooled, all baseline health measures were correlated with performance (see Table 2). When separated by sex, BMI and MAP were no longer significantly related to performance for women. No cardiovascular indices were related to performance in the 80km and 160km races.

Table 2. Relationships between baseline cardiovascular measures and ultramarathon performance as determined by percentage difference from winning time in the 50, 80, and 160km trail races.

	50km (r value)	50km Men (r value)	50km Women (r value)	80km (r value)	160km (r value)
HR	0.72**	0.68*	0.82*	-0.18	0.22
lnRMSSD	-0.63*	-0.76*	-0.69*	0.09	0.15
lnRMSSD/HR	-0.67*	-0.78*	-0.73*	0.08	0.07
Age	0.60*	0.82*	0.67*	0.42	0.33
MAP	0.54*	0.87**	-0.31	0.21	0.33
BMI	0.67**	0.75*	0.40	0.50	0.18

Abbreviations: HR, heart rate; lnRMSSD, heart rate variability expressed as the natural log of the square root of the mean of successive differences; MAP, mean arterial pressure; BMI, body mass index (kg/m^2). * $P < 0.05$, ** $P < 0.001$.

Aerobic Fitness and Performance

With both sexes pooled, peak running velocity achieved in the incremental test ($r=-0.65$, $P=0.001$), and VO_2max ($r=-0.58$, $P=0.006$) were related to 50km performance, while the caloric cost of running ($r=0.26$, $P=0.25$) and oxygen cost ($r=-0.33$, $P=0.15$) per kilometre were not. When controlling for sex, the relationships became stronger for peak velocity (men: $r=-0.93$, $P<0.0001$; women: $r=-0.87$, $P=0.001$) and VO_2max (men: $r=-0.82$, $P=0.004$; women: $r=-0.75$, $P=0.007$). In the 80km group, race performance was related to peak velocity achieved in the incremental exercise test ($r=-0.88$, $P<0.0001$), but no other variable. In the 160km race, no correlations with aerobic fitness or running economy were linked to performance.

Body Mass, Hematocrit, and Performance

In the 50km race, a decrease in body mass was related to better performance across both sexes ($r=0.60$, $P=0.004$), while changes in hematocrit were not ($r=-0.13$, $P=0.6$). For men independently, this relationship with body mass loss was even stronger (men $r=0.70$, $P=0.02$; women $r=0.61$, $P=0.047$). In the 80km and 160km races, there were no relationships between body mass loss or hematocrit alterations with performance.

Performance Regression Models

Due to sex differences in bivariate correlations, and more participants in the 50km race compared to the other distances, models were performed for 50km male and female racers separately, but with pooled sexes for 80km and 160km races. Full models are presented in Table 3. Due to collinearity in variables, only km/week in the last month, age, BMI, MAP, HR, peak velocity achieved in the incremental test, and body mass loss, were included as predictors. Individual predictors and their relationships to performance across each race distance are presented in Figure 3.

Table 3. Multivariate models comparing performance predictor variables of training history, cardiovascular health, running fitness, and in-race dehydration to percentage difference from winning time in 50, 80 and 160km trail races.

Group	Variables	β (SE)	Standardized β (a)	R	R^2 (adjusted R^2)
50km Men	Peak Velocity	-11.7 (2.2)	-0.60(0.002)	0.98	0.96 (0.95)
	MAP	3.1 (0.8)	0.46(0.007)		
50km Women	Peak Velocity	-13.6 (2.7)	-0.73(0.001)	0.94	0.87 (0.84)
	Δ Body Mass	12.8 (4.9)	0.38(0.03)		
80km	Peak Velocity	-20.3 (3.3)	-0.88(<0.0001)	0.88	0.78 (0.76)
160km	-	-	-	-	-

Figure 3. Relationships between performance expressed as the percentage difference from winning time and training volume (A), body mass index (B), mean arterial pressure (C), resting heart rate (D), peak velocity in the maximal-oxygen-uptake test (E), and body mass changes (F) in 50, 80, and 160km ultramarathon races. Bpm indicates beats per minute.

DISCUSSION

The aim of this investigation was to examine the strength of association between ultramarathon performance of increasing distance and a comprehensive battery of physiological predictors. It was found that 50km trail racing performance is associated with physiological determinants similar to that of the marathon⁸, with the primary influence being peak velocity in an incremental test and VO_2max , followed by measures of cardiovascular health (MAP) in men, and body mass loss throughout the race¹⁴ for women. In the 80km race, only peak velocity in the incremental test was predictive of performance, and in the 160km race, no variables were associated with performance suggesting that typical physiological variables become less important as the race length increases. Notably, training volume (km/week), and baseline BP separated finishers from non-finishers, and this occurred primarily in the 160km race.

Running Fitness

To date, VO_2max , lactate threshold, and running economy have been considered the main predictors of long-distance running performance⁷. Noakes et al. previously reported that peak velocity achieved in a maximal treadmill test was the best laboratory-test predictor of performance up to 90km, followed by running velocity at the lactate turnpoint, VO_2max at 16kph, and VO_2max itself⁸. Furthermore, Millet et al. found that 24h treadmill running performance (~149km) was related to VO_2max and velocity at VO_2max ⁴. However, it is also understood that ultramarathon racers use a smaller percentage of their VO_2max with increasing race duration²⁶, and that the association between VO_2max and performance is attenuated progressively as event distances are extended from 5km races to 85km races²⁷. In this investigation, we support the finding that peak running velocity achieved during the maximal test was predictive of performance up to the 80km distance^{8,27}, but this relationship was not maintained for the 160km race. This is a similar finding to a recent study, which demonstrated laboratory fitness tests predicted performance in a 68km, but not a 121km, mountain ultramarathon²⁸. It is likely that the low-intensity effort required to complete double 80km distances, combined with all of the other physiological and behavioural determinants of outdoor ultramarathon success, make running fitness of lesser importance in the longest duration events.

Running economy, which is often considered a better predictor of long-distance running performance than VO_2max ²⁶, was not found to predict performance across any race distance in the present investigation. This is perhaps understandable as treadmill running form is not representative of trail running form on an undulating course, and the lower intensities sustained for ultramarathon running may reduce the importance of running economy on performance³. Millet et al. have argued that factors that decrease running economy including increased leg mass, stride frequency, shoe mass, and flexibility, may in fact improve ultramarathon performance through mitigation of fatigue and injury³. As such, laboratory based running economy is an inadequate predictor of trail and ultramarathon running performance, despite its utility in road and track running. Training volumes and previous experience appear to play a large role in ultramarathon performance. It has been demonstrated that training volume is more important than training pace for predicting 100km performance⁹, but that this relationship is reversed for marathon success⁹. Furthermore, those athletes that performed longer training runs prior to a 24h race completed the most distance in the race¹², and in a survey of 500 participants in the Western States and Vermont 100 Endurance races, faster finishing times were associated with greater training volumes⁶. Finally, the fastest ultramarathon runners in the world demonstrated improvements in their race times year-to-year, despite older age (~37-39y), suggesting that experience may play a role in subsequent ultramarathon performance¹⁸. As such, it was hypothesized that in the longer duration events (80km and 160km), racing experience and training history would have a greater association with performance than other physiological variables. Unexpectedly, we found that training volumes were related only to performance in the

50km race, and more experience was not correlated to performance across any racing distance. However, when comparing finishers to non-finishers, the non-finishers ran fewer km/week. While we cannot conclude that training volumes and previous experience aided 80km or 160km performance, insufficient mileage prior to the race certainly played a role in participant withdrawal.

Health and Anthropometry

While it is understood that ultramarathon runners are typically older and less-aerobically fit than shorter distance runners²⁹, previous investigations have rarely examined baseline cardiovascular health correlates to performance. In a high-elevation trail marathon, lower resting HR and BMI, but not HRV, were correlated to performance³⁰. HRV was found to be inversely correlated with finishing time in an 118km mountain ultramarathon, and the authors suggested greater baseline parasympathetic modulation allowed for greater autonomic resources during the race³¹. In the present investigation, it was found that all baseline health measures were independently predictive of performance in only the 50km race. This may relate to the larger sample size and heterogeneity in the 50km race, but could also suggest that the higher intensity sustained during 50km, as compared to 80km or 160km races, required a greater cardiovascular and autonomic reserve.

Finally, while a lower percent body fat and BMI is generally predictive of performance in ≤ 42.2 km running¹⁰, the relationship between BMI and ultramarathon running performance is equivocal. Unlike shorter distance running, it is possible that greater fat stores may aid in ultramarathon performance³², and greater leg muscle mass may have advantages in terms of strength and resistance to muscle damage³. BMI and percent body fat were not correlated with performance in a 24-hour race¹² or a 7-day ultramarathon¹¹, but were weakly correlated to 100km⁹ and 161km performance⁶. As greater amounts of exercise usually lead to a reduction in body mass and percent body fat, the weak associations between low BMI and performance may be largely driven by training volumes¹². In accordance with the literature, our results suggest BMI is only correlated with 50km performance in men, and did not appreciably improve predictive models using multivariate analysis.

Body Mass Loss

It has been established that faster marathon runners typically lose more body mass than slower runners while racing¹⁴; however, it is also understood that excessive dehydration will impact performance through loss of thermoregulatory capacity and stroke volume¹³. As such, in shorter distance races such as the marathon and up to the 50km ultramarathon, a moderate loss of body mass (~2-3%) may be ergogenic due to a reduction in body mass to be propelled, with gains in body mass being unequivocally detrimental to performance^{14,16}. In longer distance races, the relationship between loss of body mass and improved performance is less robust, with only a weak ($r=0.092$) correlation between loss of body mass and improved performance following observation of 887 ultramarathon (161km) performances¹⁶. Furthermore, while dehydration is one cause of body mass loss, in events over 1h a given change in body mass does not equate to an equal change in body water due to body mass alterations from substrate use and metabolism¹⁷. As such, any loss in mass unrelated to a loss in body water would likely have a net-positive effect on performance¹⁷. In the current investigation, similar to the marathon, one of the primary determinants of performance in the 50km women's race was a decrease in body mass, and this was not a significant finding in the other race distances. Interestingly, it can be seen that while the 80km racers lost body mass, there was also a reduction in hematocrit suggestive of increased plasma volume or decreased blood constituents. It is likely that hemolysis and/or plasma volume expansion occurred in this group³³, although why this occurred primarily in the 80km distance is unknown. Further, non-finishers were trending toward a significant increase in hematocrit compared to finishers, possibly indicating severe dehydration, although other blood markers of dehydration were not assessed in order to confirm these findings. As pre-race hematocrit was taken during baseline testing in the month prior to the race under controlled

conditions, and post-race hematocrit was taken directly after the race, strong conclusions cannot be made regarding this variable. As it stands, a moderate (2-3%) but not excessive loss of body mass is likely beneficial to performance, as is consistent with previous findings¹⁷.

Practical Applications

Previous studies examining ultramarathon performance have been restricted to single distance races, or comparisons between different races performed on separate days and on different courses. The nature of this investigation, whereby athletes ran on the same course and experienced similar environmental exposures, make between-distance performance predictors easier to discern. From this, we can conclude that 50km racing should be treated in similar fashion to a marathon in terms of preparation, with emphasis on running and cardiovascular fitness. Further, the 80km race is dictated by running fitness, but performance is not easily predicted by other physiological determinants. Lastly, the 160km race requires a certain amount of training for completion, but performance isn't predicted by typical physiological variables.

Limitations

Despite efforts, we were unable to reliably assess food, drink, or anti-inflammatory intake during the races, and as such, we cannot determine the influence of these factors on performance. Furthermore, there were many more physiological, as well as psychological, determinants that could have been assessed. We did not assess participant motivation to ensure all subjects raced to the best of their abilities; however, there was no indication that any participant had entered the event without the intention to race it. Finally, due to the nature of this work, we had relatively small sample sizes of finishers in some race distances, which may make the current findings hard to generalize to other races or cohorts. Statistically, the low number of finishers and homogeneity in participant characteristics in the 160km race may have resulted in null-findings in the regression analysis; however, the significant findings in finisher vs non-finisher data is mainly attributable to the 160km race.

Conclusions

Ultramarathon trail running performance is dictated by different physiological determinants depending on the race distance. Performance at the 50km distance is largely determined by running fitness. As the distances are increased, there are fewer physiological determinants, with only running velocity achieved in the incremental running test predicting 80km performance, and no physiological variables predicting 160km performance. Future work should assess other potential determinants not examined here, including muscular/neuromuscular and psychological fatigue resistance, in order to better predict ultramarathon performance.

Contributions

Contributed to conception and design: AMC, JAB, JFB

Contributed to acquisition of data: AMC, JAB, TJK, JFB

Contributed to analysis and interpretation of data: AMC, JAB, JFB

Drafted and/or revised the article: AMC, JAB, JFB

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1. Knechtle B. Ultramarathon runners: Nature or nurture? *Int J Sports Physiol Perform*. 2012;7(4):310-312. doi:10.1123/ijsp.7.4.310
2. Millet GY. Can neuromuscular fatigue explain running strategies and performance in ultra-marathons? *Sport Med*. 2011;41(6):489-506.
3. Millet GY, Hoffman MD, Morin JB. Sacrificing economy to improve running performance - A reality in the ultramarathon? *J Appl Physiol*. 2012;113(3):507-509. doi:10.1152/japplphysiol.00016.2012
4. Millet GY, Banfi JC, Kerhervé H, et al. Physiological and biological factors associated with a 24 h treadmill ultra-marathon performance. *Scand J Med Sci Sport*. 2011;21(1):54-61. doi:10.1111/j.1600-0838.2009.01001.x
5. Hoffman MD. Injuries and health considerations in ultramarathon runners. *Phys Med Rehabil Clin N Am*. 2016;27(1):203-216. doi:10.1016/j.pmr.2015.08.004
6. Hoffman MD, Fogard K. Factors related to successful completion of a 161-km ultramarathon. *Int J Sports Physiol Perform*. 2011;6(1):25-37. doi:10.1123/ijsp.6.1.25
7. Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: Can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sport Med*. 2007;37(10):857-880. doi:10.2165/00007256-200737100-00003
8. Noakes TD, Myburgh KH, Schall R. Peak treadmill running velocity during the vo2 max test predicts running performance. *J Sports Sci*. 1990;8(1):35-45. doi:10.1080/02640419008732129
9. Knechtle B, Tanda G. Effects of training and anthropometric factors on marathon and 100 km ultramarathon race performance. *Open Access J Sport Med*. 2015:129. doi:10.2147/oajsm.s80637
10. Bale P, Bradbury D, Colley E. Anthropometric and training variables related to 10km running performance. *Br J Sports Med*. 1986;20(4):170-173.
11. Knechtle B, Knechtle P, Rosemann T. Race performance in male mountain ultra-marathoners: Anthropometry or training? *Percept Mot Skills*. 2010;110(3):721-735. doi:10.2466/pms.110.3.721-735
12. Knechtle B, Knechtle P, Rosemann T, Lepers R. Personal best marathon time and longest training run, not anthropometry, predict performance in recreational 24-hour ultrarunners. *J Strength Cond Res*. 2011;0(0):1-7.
13. Coyle EF. Physiological determinants of endurance exercise performance. *J Sci Med Sport*. 1999;2(3):181-189. doi:10.1016/S1440-2440(99)80172-8
14. Zouhal H, Groussard C, Minter G, et al. Inverse relationship between percentage body weight change and finishing time in 643 forty-two-kilometre marathon runners. *Br J Sports Med*. 2011;45(14):1101-1105. doi:10.1136/bjism.2010.074641
15. Hoffman MD, Stuempfle KJ. Hydration strategies, weight change and performance in a 161 km ultramarathon. *Res Sport Med*. 2014;22(3):213-225. doi:10.1080/15438627.2014.915838
16. Hoffman MD, Hew-Butler T, Stuempfle KJ. Exercise-associated hyponatremia and hydration status in 161-km ultramarathoners. *Med Sci Sports Exerc*. 2013;45(4):784-791. doi:10.1249/MSS.0b013e31827985a8
17. Hoffman MD, Goulet EDB, Maughan RJ. Considerations in the use of body mass change to estimate change in hydration status during a 161-kilometer ultramarathon running competition. *Sport Med*. 2018;48(2):243-250. doi:10.1007/s40279-017-0782-3
18. Rüst CA, Knechtle B, Rosemann T, Lepers R. Analysis of performance and age of the fastest 100-mile ultramarathoners worldwide. *Clinics*. 2013;68(5):605-611. doi:10.6061/clinics/2013(05)05
19. King TJ, Coates AM, Tremblay JC, et al. Vascular function is differentially altered by distance following prolonged running. *Med Sci Sport Exerc*. 2020;In press(August). doi:10.1249/MSS.0000000000002493
20. Coates AM, King TJ, Currie KD, et al. Alterations in cardiac function following endurance exercise are not

duration dependent. *Front Physiol.* 2020;11(581797).

21. Plews DJ, Laursen PB, Stanley J, Kilding AE, Buchheit M. Training adaptation and heart rate variability in elite endurance athletes: Opening the door to effective monitoring. *Sport Med.* 2013;43(9):773-781. doi:10.1007/s40279-013-0071-8
22. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci.* 1996;14(4):321-327. doi:10.1080/02640419608727717
23. Padulo J, Annino G, Smith L, et al. Uphill running at iso-efficiency speed. *Int J Sports Med.* 2012;33(10):819-823. doi:10.1055/s-0032-1311588
24. Pallarés JG, Morán-Navarro R, Ortega JF, Fernández-Elías VE, Mora-Rodriguez R. Validity and reliability of ventilatory and blood lactate thresholds in well-trained cyclists. *PLoS One.* 2016;11(9):1-16. doi:10.1371/journal.pone.0163389
25. Fletcher JR, Esau SP, MacIntosh BR. Economy of running: beyond the measurement of oxygen uptake. *J Appl Physiol.* 2009;107(6):1918-1922. doi:10.1152/jappphysiol.00307.2009
26. Scrimgeour AG, Noakes TD, Adams B, Myburgh K. The influence of weekly training distance on fractional utilization of maximum aerobic capacity in marathon and ultramarathon runners. *Eur J Appl Physiol Occup Physiol.* 1986;55(2):202-209. doi:10.1007/BF00715006
27. Davies CTM, Thompson MW. Aerobic performance of female marathon and male ultramarathon athletes. *Eur J Appl Physiol Occup Physiol.* 1979;41(4):233-245. doi:10.1007/BF00429740
28. Gatterer H, Gatterer H, Rauch S, et al. Performance determinants in short (68 km) and long (121 km) mountain ultra-marathon races. *Sportverletzung-Sportschaden.* 2020;34(2):79-83. doi:10.1055/a-1028-8644
29. Knechtle B, Nikolaidis PT. Physiology and pathophysiology in ultra-marathon running. *Front Physiol.* 2018;9(June):634. doi:10.3389/fphys.2018.00634
30. Mertová M, Botek M, Krejčí J, McKune AJ. Heart rate variability recovery after a skyrunning marathon and correlates of performance. *Acta Gymnica.* 2017;47(4):161-170. doi:10.5507/ag.2017.021
31. Martínez-navarro I, Sánchez-gómez JM, Panizo N, Hernando C, Collado-boira EJ. Cardiac damage biomarkers and heart rate variability following a 118-km mountain race: Relationship with performance and recovery. 2019;18:615-622.
32. Peter L, Rüst CA, Knechtle B, Rosemann T, Lepers R. Sex differences in 24-hour ultra-marathon performance - A retrospective data analysis from 1977 to 2012. *Clinics.* 2014;69(1):38-46. doi:10.6061/clinics/2014(01)06
33. Robach P, Boisson RC, Vincent L, et al. Hemolysis induced by an extreme mountain ultra-marathon is not associated with a decrease in total red blood cell volume. *Scand J Med Sci Sport.* 2014;24(1):18-27. doi:10.1111/j.1600-0838.2012.01481.x