Establishing the physiological, anthropometric and training characteristics, and pacing patterns of runners racing in a tropical ultra-marathon.

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Candidate declaration

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Chapter Four

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I confirm that I have been granted permission by my co-authors to include the publications.

To meet the stylistic requirements of a dissertation, the format of the published papers have been adjusted accordingly and abbreviations of units and terms standardised throughout.

Abstract

Background: The popularity of ultra-marathons has rapidly increased in recent years, especially in Southeast Asia, with more recreational runners entering the field. The physiological, anthropometric, and training characteristics of runners participating in these ultra-marathons run in high temperature and humidity, along with their pacing have not been documented. Knowing these parameters and their relationship with performance in this group of participants are important for prescribing appropriate training to maximise performance and minimise the risk of injury, especially heat injury, as well as choosing the optimal pacing strategy for races.

Aim: The first aim of the thesis was to compare and determine the differences in the physiological, anthropometric, and training characteristics of the finishers (FIN) and non-finishers (N-FIN) in a tropical ultra-marathon. The second aim was to establish and compare the pacing patterns of fast and slow FIN in the same race. Two studies were conducted to achieve these aims.

Methods: For the first study, two groups of participants of the 161-km category of the race (FIN; N=12 and N-FIN; N=14) completed a series of anthropometric and physiological measurements over two separate sessions at least three weeks prior to the race. Training sessions starting from six weeks prior to the race were recorded. Sum of 7 skinfolds, arm and calf girths, VO_{2max} and peak treadmill speed (PTS) were taken during session 1 while the lactate threshold (LT) and running economy (RE) were assessed during session 2. For the second study, FIN of the 161-km (N=47) and 101-km (N=120) categories of the race were divided into thirds (Group A-C) by merit of finishing time. Altogether, 17 and 11 split times were recorded for the 161-km and 101-km finishers, respectively, and used to calculate the mean running speed for each distance segment. Running speed for the first segment was normalised to 100, with all subsequent splits adjusted accordingly. Running speed during the last 5 km was calculated against the mean race pace to establish the existence of an “end spurt”.

Main findings: For the first study, effect size (ES) calculations showed moderate and clear differences in the lactate concentration at LT1 (ES = 0.88; P = 0.05), velocity at LT2 (ES = 0.70; P = 0.07), longest run attempted (ES = 0.73; P = 0.07) and number of cross-training hours (ES = 0.73; P = 0.06) between the FIN and N-FIN. For the second study, a reverse J-shaped pacing profile was demonstrated in all groups for both distance categories. Only 38% of the finishers executed an end spurt. In the 101-km category, in comparison to group B and C, group A maintained a significantly more even pace (P = 0.013 and 0.001, respectively) and completed the race at a significantly higher percent of initial starting speed (P = 0.001 and 0.001, respectively). Descriptive data also revealed that the top five finishers displayed a “herd-behaviour” by staying close to the lead runner in the initial portion of the race.

Conclusion: Findings from the studies conducted suggest that from a physiological perspective, the ability to finish a 161-km ultra-marathon in a hot and humid climate might be differentiated by metabolic attributes via LT measurements. For training, runners should not neglect the importance of the long runs and should incorporate cross-training to provide additional stimuli to the body while allowing the running muscles to recover from. Finally, to avoid a significant decline in running speed during the later parts of the race, recreational ultra-runners should adopt a conservative sustainable starting speed. Less competitive runners should set realistic performance goals while competitive runners with a specific time goal should consider running in packs of similar pace.

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List of Abbreviations

BF%:	Body fat percentage
BM:	Body mass
BMI:	Body mass index
BPM:	Beats per minute
CL:	Confidence limits
CP:	Checkpoint
CV:	Coefficient of variation
ES:	Effect size
FIN:	Finishers
FU:	Fractional utilization
h:	Hour
HIIT:	High intensity interval training
km:	kilometre
LSDT:	Long slow distance training
LT:	Lactate threshold
min:	minute
MS:	Multi-stage
N-FIN:	Non-finishers
O_2:	Oxygen
OBLA:	Onset of blood lactate accumulation
P:	Probability
PTS:	Peak treadmill speed
r:	Correlation co-efficient
r^2:	Co-efficient of determination
RE:	Running economy
S:	Seconds
SS:	Single-stage
SUMSF:	Sum of skinfold
ThT:	Threshold training
TT:	Time trial
US:	United States
V.LT:	Velocity at lactate threshold
V.RCT:	Velocity at respiratory compensation threshold
VS:	Versus
$V.VO_{2max}$:	Velocity at maximum oxygen uptake
VO_2:	Volume of oxygen
VO_{2max}:	Maximum oxygen uptake
W:	Watts
w/o:	without
wk:	week
X:	Times
%:	Percentage

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CHAPTER ONE

Introduction

Background and research problem

Running is a popular sports discipline that is performed over many distances. Current trends in endurance running participation now include events much longer than the standard marathon distance i.e. ultra-marathons. While there is no consensus on the definition of an ultra-marathon, it is usually regarded as a distance longer than the classic marathon distance of 42.195 km (1). There are basically two types of ultra-marathon events: single-stage (e.g. Western States 100-miles, Ultra-trail du Mont-Blanc or Comrades Marathon) and multistage (e.g. Marathon Des Sables or Four Deserts Race). Both take place on terrain varying from mostly flat road to various terrain trails.

Although physiological characteristics of endurance runners ranging from middle to marathon distance of varying participation levels has been widely reported in the scientific literature (2, 3), little is known about the physiology of the ultra-running community. The limited research on the physiological profiling of ultra-runners tend to focus on small sample groups of elite athlete and is dated decades prior to the current growth in popularity of ultra-endurance racing (4, 5) . Similarly, the predictor variables of ultra-marathon performance are also poorly identified. Until only recently, there have been no data in the literature on the potential association between physiological or training parameters and race performance in ultra-marathoners competing over distances longer than 90 km (6-9).

The limited present knowledge on the physiological characteristics of ultra-runners was derived from research largely conducted on race finishers. Unless an extensive comparison across parameters is made between both the finishers (FIN) and non-finishers (N-FIN), one cannot confidently conclude that such physiological, anthropometric and training characteristics apply to both FIN and N-FIN or FIN alone. Should both FIN and N-FIN share similar attributes, the established association between these parameters and race performance will become invalid.

Successful running performance is characterised by the ability to sustain a higher absolute speed for a given distance than other competitors. Hence, runners engage in pacing during races to delay the onset of fatigue and optimise overall performance (10). Pacing, defined as the subjective competitive strategy in which an individual manipulates speed to achieve his/her performance goal (11), is also not frequently studied in ultra-marathons. While an even pacing strategy is believed to be ideal for long duration events in a stable external (e.g. environmental and geographical) environment (12), ultra-marathons are often conducted under dynamic external conditions (e.g. varying altitudes and extreme ambient temperatures), making it difficult for ultra-runners to adopt such a profile. Although appropriate pacing allows the completion of exercise tasks prior to marked hyperthermia as documented in recent laboratory studies (13, 14), no information exists about the pacing habits of runners participating in distances greater than 100 km in a hot and humid environment.

Despite the surge in popularity of endurance running events, especially ultra-marathons in Southeast Asia in recent years, very little work has been done to document the scientific characteristics of this Southeast Asian ultra-running community. This particular geographical area presents specific problems for endurance runners due to the extreme temperature (30 - 34 °C) and humidity (80 – 95%) experienced by the runners in most races in this region, yet not much is known about the training & pacing strategies needed to manage the physiological stress and demands experienced by runners competing in this region of extreme ambient conditions. This lack of information in the scientific literature warrants further investigation.

Thesis aim and objectives

The studies which comprise this dissertation aim to further our understanding of the applied physiology of ultra-running. The objectives of each research chapter are presented below:

- Study 1 (Chapter Three) – To compare the differences in the physiological, anthropometric and training characteristics of the FIN and N-FIN in a 161-km ultra-marathon.

- Study 2 (Chapter Four) – To establish and compare the pacing patterns of fast and slow FIN in a tropical ultra-marathon.

Aligned to the objectives, the following specific questions will be answered:

1. Are there any differences in the physiological and anthropometric profiles of FIN and N-FIN in a tropical 161-km race? If yes, what are they?

2. Do the FIN train differently from the N-FIN?

3. What are the pacing profile(s) that exist among 161-km and 101-km ultra-runners competing in a tropical ultra-marathon?

4. Do faster ultra-runners pace differently from slower runners?

To date, little scientific knowledge exists on the physiological profiles and pacing trends of the Southeast Asian ultra-running community who compete in a hot and humid environment. By establishing these data, runners will better understand the demands and training required to excel in tropical ultra-marathons, hence directing their preparation in a systematic approach instead of a "trial and error" way.

Following this chapter (introduction) will be a review of the relevant literature to better understand the specific problems related to completing an ultra-endurance race under conditions of high temperature and humidity. This will be followed by two original investigations (Chapters Three and Four) which address the aims outlined above. Finally, there are several practical applications that arise from this research. These are discussed in the final chapter (Chapter Five) along with answers to the above research questions.

CHAPTER TWO

Literature review

The physiological model for predicting endurance running performance

Although participation in ultra-marathons, especially the 100-mile event, has risen exponentially since the late 1970's (15), few studies exist that examine the physiological and physical profiles, as well as training characteristics of these runners. The relationship between these variables and actual ultra-marathon performance is also unclear. This is most likely due to the difficulty to conduct research related to ultra-marathon performance, given the exceptionally broad range of distances over which the ultra-marathon is run, ranging from 50 km to 24 h events and more. While the determinants of endurance running performance across a variety of distances, ranging from 3 km to the marathon, have been widely studied (16-27), the characteristics of the ultra-marathon (e.g. excessive distance, elevation profile, technical difficulty or altitude) make it inappropriate to extrapolate current knowledge obtained in these studies over shorter distances, to the ultra-distances.

Since the early study by Hill and Lupton (28) which identified an upper limit to oxygen uptake during endurance running, a number of additional physiological variables have been identified as important predictors of endurance running performance. These determinants explain > 70% of the between-subject variance in endurance running performance (29). The most commonly cited are maximal oxygen uptake (VO_{2max}), running economy (RE), fractional utilization (FU) of VO_{2max} (%VO_{2max}), and the velocity at lactate threshold (V.LT) (30). Ultimately, the runner with the highest VO_{2max}, who is able to utilise the highest fraction of the maximal oxygen uptake at the highest velocity at LT for an extended period of time and with the lowest O_2 cost of running per kilometre, will most probably win the race.

Maximal oxygen uptake (VO_{2max})

As early as the 1930s, maximal oxygen update or VO_{2max} , expressed relative to body weight, has been identified as a marker of elite endurance running performance (31). However, a strong association between VO_{2max} and endurance running performance is evident only in heterogeneous groups (16, 32-35). Early data by Costill et al presented a strong inverse correlation (r = -0.91) between VO_{2max} and performance time in a 16-km run in subjects with a large range in VO_{2max} values (54.8 - 81.6 ml/kg/min) (16). Similar correlation coefficient values have been found subsequently in studies that utilised distances ranging from 5 km to marathon length (4, 20, 21). However, investigations of homogeneous populations have demonstrated that VO_{2max} is a weak predictor of performance within such a group (17, 24, 36, 37). With such homogenous running ability groups, Conley and Krahenbuhl for example, reported that the correlation between VO_{2max} and race performance was -0.12 in elite endurance runners evenly matched for 10-km race times (37) while Costill found only a 0.08 correlation between VO_{2max} and marathon performance with runners of similar abilities (19). Generally, while VO_{2max} is reflected by the upper limits of genetically determined running performance, it cannot differentiate the small differences between elite endurance runners.

Running economy

The relationship between running economy (RE) and performance is well documented (34, 37-42). Conley and Krahenbuhl studied 12 elite male runners with a narrow range of 10-km race times [30.5 – 33.5 minutes (min)] and demonstrated a strong relationship between the race performance and RE measured at 14, 16 and 18 km/h, respectively. The authors also attributed some 65% of the variation in race performance to differences in RE, with the more economical runners performing the best (37). Indeed, the domination of the endurance running scene by

runners of East African origin during the last 25 years (43, 44) may be partly explained by differences in RE (45). In a comparison of black South African and Caucasian distance runners evenly matched in 10-km race performance and body mass, Weston et al showed that the RE of the former was approximately 5% better than the latter, despite having a 13% lower VO_{2max} (46).

Studies in the literature that failed to establish a strong predictive power of RE for endurance running performance tend to utilise a heterogeneous group of runners and/or measured RE at an arbitrary submaximal velocity (47-49). Generally, while RE does not distinguish performance amongst groups with a wide range of running abilities, it has the potential to be the predominant physiological predictor of success in a homogeneous group (50).

Velocity at lactate threshold

Despite debate within the scientific community about the determination of the lactate threshold (LT), an overwhelming majority of the studies evaluating the relationship of the velocity at lactate threshold (V.LT) with endurance running performance reported strong linear correlations (22-24, 33, 51-59). The hallmark study by Farrell et al concluded that the V.LT to be most closely related to running performance across a range of distances (3 km to the marathon) when pitted against a battery of other physiological variables including VO_{2max} and RE (33). Sjodin and Jacobs showed that the velocity at onset of blood lactate accumulation (OBLA - 4.0 mmol/L) accounted for 92% of the variation in the marathon race pace of 18 male runners (51) and Fohrenbach et al reported that velocities at a lactate concentration of 2.5 and 3.0 mmol/L had the highest correlations with marathon race pace (60). While many of these early studies were done with only a small sample size (61) , untrained subjects (53), or in moderately-trained runners (51), findings from the past decade showed similar results when well-trained endurance runners were tested (48, 62, 63). Generally, there is a tendency for higher correlations with longer endurance running events as the average intensity sustained in these distances is closer to V.LT (64).

Fractional utilization of VO_{2max}

Success in endurance running can also be (partly) explained by one’s fractional utilization of VO_{2max} (FU), which is the ability to maintain a high proportion of one’s VO_{2max} throughout the event (4, 16, 18, 65). Studies have indicated that African distance runners race with a higher FU (46, 66). Bosch et al investigated the physiological characteristics of black African and Caucasian distance runners while they ran a simulated marathon on the treadmill. When running at the same percentage (~ 87%) of their best marathon time, the African runners ran at a higher percentage of VO_{2max} (76% VS 68%; $P < 0.05$) (66). In addition, Weston et al. reported that in a group of runners homogenous in 10-km race performance, the black African runners utilised a higher FU at race pace than the Caucasian group (92% vs 86%; $P < 0.001$) (46). On the contrary, the relationship between 3-km or 5-km running performance and FU is not well-established. Studies by Lacour et al and StØa et al utilizing elite 5-km runners demonstrated no correlation with FU and race performance (67, 68).

Generally, FU is a poor predictor of performance at shorter endurance distances (3 – 5 km) but is of gradually greater importance with increasing distances from 10 km (4, 69).

Peak treadmill speed

Peak treadmill speed (PTS) is sometimes claimed to be the single best laboratory predictor of endurance running performance (24, 25, 49, 70). This belief was first proposed by Scrimgeour et al who observed a stronger correlation between PTS (r = 0.72) than VO_{2max} (r = -0.54) in 30 runners across a range of running distances from 10 km to 90 km (70). In an extension study, Noakes et al confirmed the superior predictive power of the PTS over the other physiological variables including VO_{2max}, RE and V.LT for running performance at the same range of running distances (25). In part, this is most likely because peak speed is a function of VO_{2max}, economy and V.LT

Similar correlation coefficient values can be seen in subsequent studies that utilised shorter distances of 3 to 5km (24, 48, 49). Slattey et al highlighted PTS as the most important determinant of 3-km time trial performance in a group of experienced triathletes (49) while Stratton et al. suggested that PTS could solely explain 77.8% of the variance in the average 5-km run velocity in their subjects (24). The mechanisms regulating PTS remain unclear though it has been suggested to reflect the interaction between an individual's VO_{2max}, RE, anaerobic capacity, muscle power and neuromuscular skills (71) as mentioned above. Generally, the strongest relationships between PTS and endurance running performance are observed with shorter distance events (3 - 5km). This is because PTS more closely reflects the velocities at which these events are raced at (72).

Anthropometry – body mass, body mass index, skinfold and girth of extremities

In running, an excess of adipose tissue and body mass (BM) usually require a greater muscular effort to accelerate the legs and, in theory, the energy expenditure at the same velocity would be higher. Hence, a large volume of early research has considered the anthropometrics of athletic performance and in particular endurance running (26, 27, 73-75).

It is well-established in many studies that BM and body mass index (BMI) are inversely related to endurance running performance ((21, 43, 76-79). A lower body mass produces and stores less metabolic heat at a given submaximal running velocity, thus incurring a lesser absolute heat load (80, 81). The good RE of elite endurance runners can also be attributed to their lower BMI, with values ranging from 18 – 20 kg/m^2 in Kenyan and East African runners (43, 44, 82).

Early studies conducted with non-elite and/or heterogeneous groups of endurance runners reflect a good correlation between the sum of skinfold and running performance over a range of distances from 10km to the marathon (21, 69, 78). Bale et al concluded in his study of 60 male runners that total skinfold scores of five sites was a good predictor of success at the 10-km distance (78) while Hagan et al was able to establish a relationship between the sum of 7 skinfolds and the performance times of both male and female marathon runners (21). Recent evidence suggests gender-specific differences of skin-folds in the prediction of distance running performance. Rust et al described positive correlations between both the abdominal and calf skin-fold thicknesses and the race time in male half-marathoners (83), whereas the individual skinfold value of the pectoral, mid-axilla, subscapular, abdominal and suprailiac predicted performance in the female half-marathoners (79). Interestingly, only front thigh and medial calf skin-folds were associated with marathon race time in recreational female runners (84).

Very few studies have explored the relationship between the sum of skinfold (SUMSF) and running performance in homogeneous groups of elite endurance runners. Conley and Krahenbuhl reported no significant relationship between SUMSF and 10-km performance in an elite group of runners (37) while Kenney and Hodgson found similar outcomes in a homogeneous group of elite 3-km runners (85). A notable pilot study by Arress and Ostarize tried to determine if the SUMSF thickness and specific skinfold sites were related to elite endurance running performance (86). The authors reported high correlations between the front thigh and medial calf skinfolds to 10-km race times ($r = 0.59$ and $r = 0.57$, respectively) in male runners while marathon race time in female runners was closely related to the iliac crest and abdominal skinfolds ($r = 0.62$ and $r = 0.61$, respectively). There was no significant relationship between the SUMSF to race performance in either gender. It should be noted that it is very risky to compare skinfold values from different studies, given the variability in technique, equipment, and site location.

Studies establishing a direct connection between the girth of extremities and endurance performance race times are rare in the literature. An early study by Tanaka and Matsura conducted on Japanese young distance runners of similar performance level revealed correlations between the girths of the thigh and upper arm to 5-km and 10-km performance, respectively (87). Recently, Schmid et al reported a significant inverse relationship between the circumference of the calf and race time in recreational female marathoners (77) The superior RE of the elite East African endurance runners over their Caucasian counterparts can partly be attributed to their smaller calf girth (43). This is because increased mass at the end of the leg has a disproportionate effect on the cost of ambulation, presumably by increasing the cost of the recovery portion of the stride (88).

The training characteristics of endurance runners

Although the physiological predictors of endurance running performance are well-established, as discussed earlier in this review, debate abounds regarding how one should train to elicit the optimal improvement in these variables. Endurance runners often seek the most effective training methods to enhance performance, and is probably most evident in elite runners where the state of training adaptation and performance enhancement may have reached a plateau (89).These runners often engage a variety of training methods of different intensities to elicit specific physiological adaptations (71, 90). Generally, training characteristics of endurance runners include (i) training volume, (ii) training methodology and (iii) training intensity distribution.

Training volume

In endurance running, the volume of training implies the total quantity of training or mileage performed per week, month or year and is the combination of duration and frequency. It is without doubt that elite endurance runners accumulate a large volume in terms of running mileage (91). Interestingly, there has been little variation in training volume over the past few decades (92-95). Pollock reported that elite male U.S. long distance runners (5-km and 10-km specialists) and marathon runners of the 1970s ran 120 km/wk and 162 km/wk, respectively (92). Similar values were subsequently noted by Sjodin and Svedenhag whose study subjects (< 2:30 marathon runners) had an average weekly mileage of 145 km (93). In a recent study conducted on U.S. Olympic Marathon qualifiers, Karp reviewed the year-round training characteristics of 37 male athletes and reported an average weekly mileage of 145 km as well

(95). Training volume increases when competition is near and can exceed 200 km/wk. Billat et al. showed that top class European male marathon runners (2:06 – 2:12) run in excess of 200 km/wk in the 12 weeks leading up to competition (3). Female elite runners tend to have a lower training volume, averaging between 105 - 120 km/wk and peaking at about 166 km/wk (3, 94, 95). On the other hand, great variability exists in the training volume of recreational endurance runners possibly due to the wide range of performance times. Generally, these non-elite runners average 30 – 35 km/wk and 30 – 60 km/wk when preparing for a half-marathon (79, 83) and marathon (77, 96, 97), respectively.

Training methodology

To improve running performance, distant runners often engage a variety of training regimens, ranging from slow long runs to intense short sprints coupled with recovery of varying duration. If training is not carefully planned, or if too strenuous a program is implemented, overtraining and injury may occur (98). Generally, the common training methods include (i) long slow distance training (LSDT), (ii) threshold training (ThT) and (iii) high intensity interval training (HIIT).

Long slow distance training

Endurance runners and their coaches have typically favoured long slow distance training (LSDT) (99, 100) which involves relatively high mileage of easy to moderately paced running. The exercise intensity tends to hover around 60 - 70% VO_{2max} or just under the first LT with a single bout of work lasting between 45 min to 120 min (101).

The physiological adaptations following a period of LSDT in sedentary to moderately-trained athletes are well-recorded in the literature. Central adaptations to LSDT result in a lower heart rate at pre-training workrates (102) coupled with an increase in blood and plasma volume (102, 103). These changes are accompanied by a greater cardiac output (102) and increases in muscle and cutaneous blood flow during exercise at the same pretraining intensity (104, 105). Combined with peripheral improvements in muscle capillary density and mitochondrial volume (106-108), one will thus experience an increase in VO_{2max} (109, 110). It has been suggested that LSDT offers limited effect on improving one's maximal aerobic capacity once a runner has reached a weekly mileage of 120 km (93) or a VO_{2max} > 60 ml/kg/min (111).

An elite runner (VO_{2max}: 70 – 80 ml/kg/min) training at 60 – 70% VO_{2max} would have about the same muscular oxidative flux as an untrained person running at or near VO_{2max}, assuming similar active muscle mass (112). Sustaining this intensity over a long duration of time will result in a large cellular energy turnover sufficient to provide an efficient stimulus of the induction of the various genes involved in mitochondrial biogenesis within type I muscle fibres (113). Coincidently, this range of intensity has also been shown to approximate the same intensity associated with maximal fat utilization in trained subjects (114). This can stimulate an increase in lipolysis, which, besides sparing muscle glycogen stores, may amplify the signal for mitochondrial biogenesis as well (115). Elite runners usually train multiple sessions a day to accumulate adequate training volume (116). Engaging in a second bout of running in a state of reduced glycogen due to an earlier bout of LSDT could promote a greater increase in the activity and content of mitochondrial enzymes such as citrate synthase and ß-hydroxyacyl-CoA deshydrogenase (117), resulting in enhanced rates of whole body fat oxidation during submaximal exercise.

Threshold training

Threshold training (ThT) refers to runs performed at or slightly above V.LT, which usually corresponds to about 80 – 90% VO_{2max} (52). Advocated and popularised in the 1980s by Daniels as one of the most productive type of training that endurance runners can do (118), a single bout of work usually last 30 – 60 min (119).

A meta-analysis by Londeree revealed that engaging in ThT resulted in significant improvements in the workload corresponding to LT in untrained to moderately-trained athletes (111). On the other hand, fewer studies documented the effects of ThT on the physiological and performance variables of elite runners. While the same meta-analysis concluded that highly-trained individuals need to train at much higher intensity (above OBLA - 4.0 mmol/L) to enhance LT, it should be noted that the author only reviewed four studies that involved well-trained subjects (111). In fact, Billat et al reported that ThT twice per week for six weeks in well-trained endurance runners led to increases in physiological adaptations such as V.LT, VO_{2max} and V.VO_{2max} (120). Improvements following ThT can be attributed to an increase in the concentration of lactate transporters, monocarboxylate transporter 1 and monocarboxylate transporter 4 (121, 122) as well as the individual's buffering capacity (123).

On theoretical grounds, this intensity has been suggested to be optimal for eliciting maximum gains in endurance performance as it is the highest intensity that can be maintained in a steady state, (124) as running at such an intensity allows the skeletal muscle cells to experience a high stimulation of oxidative metabolism which can be maintained for a prolonged period of time, as lactate production can be matched by lactate clearance (64). However, large volumes of ThT in already well-trained athletes may be inadequate to stimulate further cardiorespiratory adaptation but may contribute to fatigue, potentially via down-regulation of the sympathetic nervous system (125).

High intensity interval training

High intensity interval training (HIIT) involves repeated short to long bouts of high-intensity exercises (i.e. from maximal lactate steady state to "all-out" supramaximal exercise intensities), interspersed with recovery periods of low-intensity or complete rest (126). The progressive acceptance of this training method amongst elite athletes could be attributed to the belief that HIIT provides the most effective stimulus for enhancing VO_{2max} as it stresses the oxygen transport and utilization systems maximally (89, 127, 128). While reason to justify the need to train at such an intensity remains unclear, it can be argued that only intensities near VO_{2max} allow for both large motor unit recruitment (i.e. type II muscle fibres) (129, 130) and attainment of near-to-maximal cardiac output (131-133), which, in-turn, jointly signals for oxidative muscle fibre adaptation and myocardium enlargement.

Although it is well documented in the literature that inclusion of HIIT yields superior performance results to low/moderate intensity training of continuous nature (134-137), the mechanisms responsible for these changes with well-trained individuals are not clear. Central adaptation or an improvement in VO_{2max} is an unlikely explanation as elite athletes will have already reached the ceiling of their trainable VO_{2max} potential (138). Other physiological variables that have been shown to increase in parallel with endurance improvements include an increase in skeletal muscle buffering capacity (139), an increased ability to engage a greater volume a muscle mass (140, 141) and an increased ability to oxidise fat relative to carbohydrates (117, 142). It should be noted that additional increases in HIIT frequency ($>$ 2

X/wk) do not induce further improvements and tend to induce symptoms of overtraining (138, 143). To understand the physiological adaptations and responses of overtraining markers to different volumes of HIIT, Billat et al put eight well-trained endurance runners through two training programs varying in HIIT frequency (1 X/wk vs 3 X/wk) (138). The authors reported that engaging in HIIT thrice weekly did not further improve RE or speed at VO_{2max} following four weeks of HIIT once a week. While there was also no immediate decline in performance parameters, performing HIIT thrice weekly resulted in significant increases in subjective rates of fatigue, muscle soreness and bad sleeping quality.

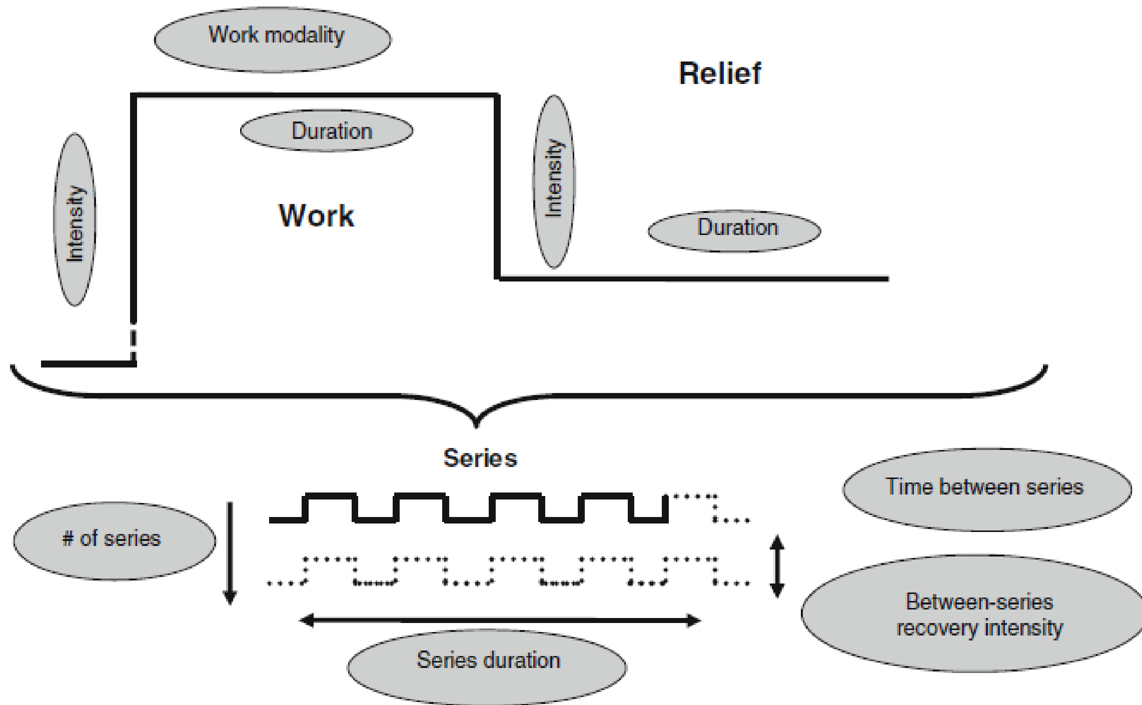

Figure 1. Schematic illustration of the nine variables defining a HIIT session. (144)

At least nine variables can be manipulated to prescribe different HIIT sessions (Figure 1). The intensity and duration of work along with relief intervals are the key influencing factors (145). Although the intensity of work can be prescribed with different methods (e.g. heart rate and rating of perceived exertion), the popular reference intensity to programme HIIT is usually $V.VO_{2max}$ (127, 146, 147). Since $V.VO_{2max}$ is theoretically the lowest speed needed to elicit VO_{2max}, it makes intuitive sense for this marker to represent a good reference for training (148, 149). Endurance runners usually include both i) long HIIT and ii) short HIIT in their training schedule.

Long HIIT

Exercise intensity does not need to be maximal during a HIIT session to elicit VO_{2max} (150). In executing long HIIT, work intensity of at least 90% $V.VO_{2max}$ can be used, since interval VO2 is likely to increase with repetitions with the development of the VO_2 slow component (150). It takes about two min from the onset of high intensity exercise to reach a state of VO_{2max} (151, 152). Hence, runners should aim to stay at least a minute or two at VO_{2max}, making each work duration three to four min.

Traditionally, active rest is recommended in long HIIT to maintain a minimal level of VO2 to reduce the time needed to reach VO_{2max} during subsequent sets (128, 146). However, current findings show that active recovery can lower muscle oxygenation (153, 154), impair phosphocreatine synthesis and trigger anaerobic system engagement during the following effort (155). It is therefore recommended that passive recovery (i.e. resting on the spot) be utilised when the relief interval is less than two to three min. Should one prefer to use an active recovery, relief intervals should be at least three to four min at submaximal intensity to avoid negating subsequent work performance (156).

Short HIIT

One should select a work intensity that ranges between 100% and 120% of $V.VO_{2max}$ when prescribing short HIIT (157, 158). As adenosine triphosphate requirements in working muscles during short intense runs [< 10 seconds (s)] are met predominantly by oxidative phosphorylation, with more than 50% of the oxygen used derived from oxymyogloblin stores (159), work duration should be > 10 s to elicit adequate cardiopulmonary responses. Longer work duration (> 30 s) should be considered for individuals with slow VO2 kinetics (160).

A relief interval duration of ≥ 20 s at an intensity of about 70% $V.VO_{2max}$ should be recommended to maximise exposure time at VO_{2max}. Such a combination has been shown to minimise the dip in VO2 levels for subsequent work effort (161, 162).

Training intensity distribution

Understanding the optimal exercise training intensity distribution to maximise adaptation and performance is important for athletes who try to gain a competitive advantage. While the ideal distribution remains debatable, it is uncommon for runners to train entirely at only one intensity (116, 163). Empirical descriptive studies in the literature suggest that well-trained and elite endurance runners perform a lot of low intensity training (significantly below V.LT) with moderate amount of HIIT (significantly above V.LT) (3, 100, 164-167).

In an early pilot study attempting to quantify training intensity distribution through the use of heart rate data, Robinson et al investigated the training characteristics of 13 national-class male New Zealand runners specializing in distances ranging from 1.5 km to the marathon (100). Over a data collection period of six to eight weeks corresponding to the preparation phase of the athletes, the authors reported that 96% of all training sessions were performed at about 77% of the heart rate at LT. In a similar investigation, Billat et al performed physiological testing and gathered the training data of elite French and Portuguese marathoners in preparation of the Olympic marathon trial (3). In the 12 weeks leading to the trial, the athletes ran 78% of their mileage below marathon race pace and 18% at 10k/3k race pace. This distribution of training intensity was identical in both high-level (< 2 h 16 min or < 2 h 38 min for males and females, respectively) and elite runners (< 2 h 11 min or < 2 h 32 min for males and females, respectively). A subsequent study on elite male and female Kenyan 5 and 10-km runners yielded similar results (164). These East Africans ran 85% of their weekly mileage below V.LT (164). While it can be criticised that training data in these studies were collected over a short time period and may not be representative of the long-term development of endurance runners, a recent study conducted on 93 U.S. Olympic Marathon qualifiers revealed that most of the training consisted of low intensity running throughout the year (95). The runners ran approximately 71.6% and 9.8% of their training volume at intensities slower than marathon race pace and faster than 10-km race pace, respectively. These studies seem to agree on a

common intensity distribution: about 80% of training sessions are done below V.LT while the remaining 20% shared between the intensities at and significantly above LT.

Despite the observation of such a distribution, it remains questionable whether the "80-20" breakdown of intensity is really a self-organised optimum for high-performance runners or a product of coaching tradition (91). In a randomised, controlled training study conducted on endurance runners to evaluate the efficacy of this distribution model (168), Esteve-Lanao et al subjected two groups (Z1 and Z2) of well-trained distance runners to a 5-month training program evenly matched in training load. Weekly running distance averaged 80 to 90 km in both groups over the study period, increasing to a maximum of 120 km in the 16th week and finally deceasing over the competition period to about 40 km per week. Z1 performed 81%, 12% and 8% of training significantly below, at and above the velocity at respiratory compensation threshold (surrogate measure of V.LT), respectively. Z2 performed more ThT, with 67%, 25% and 8% of training done in the same order as Z1. Improvement in a 10.4-km time trial conducted before and after the 5-month period revealed that Z1 had significantly greater race time improvement than Z2 (-157 s VS -121.5 s; P = 0.03).

Adopting such a distribution model might be explained by the mechanisms of molecular signalling (169). Different pathways exist to drive gene expression for mitochondrial protein proliferation (170). High volumes of low intensity training are likely to signal for adaptation through the calcium-calmodulin kinases (171) while higher intensity training appears more likely to signal for mitochondrial biogenesis through the adenosine monophosphate-activated protein kinase pathway (172). Utilizing a large quantity of high intensity training is associated with a non-linear increase in sympathetic stress. Thus, at the molecular level, such a blend of intensity distribution may elicit a stronger or more frequent promotion of the aerobic muscle phenotype through the PGC-1α mRNA transcription without disturbing autonomic balance that could lead to overtraining (125). One can also hypothesise that central circulatory adaptations might respond very fast to increase in training intensity, whereas peripheral changes in skeletal muscle mitochondrial volume, capillary density, and other skeletal muscle adaptations may take weeks or months to saturate (168). Thus, substantial volumes of low intensity training accompanied with small amount of high intensity training may provide an effective combination of stimuli for both peripheral and central adaptions.

Studies investigating the physiological, physical and training characteristics of ultra-runners

Over the past few decades, a number of studies have been conducted on ultra-runners to provide insights into their physiological, physical and training characteristics. The predictive powers of these variables to actual race performance have also been established. Some of these investigations are discussed in detail below (4, 7, 8, 25, 173-175). A summary of the findings are provided in Table 1, 2 and 3.

Davies and Thompson (4)

Davies and Thompson measured the aerobic performance and race pace fractional utilization of 13 male elite ultra-runners (4). The performance times for a 84.64-km ultra-marathon were obtained from the official records of the Road Running Club of Great Britain.

The subjects had a mean VO_{2max} of 72.5 ± 3.8 ml/kg/min and maximal minute ventilation values of 162.5 ± 19.4 L/min. They were also able to sustain 67% VO_{2max} (range: 53 – 76%) and 60 – 82% of their 5-km race pace for 84.64 km.

This is actually the first study in the literature to profile ultra-runners physiologically.
The authors reported that the VO_{2max} of their subjects are similar to those reported earlier for male marathon runners (176). Significant correlations between VO_{2max} and FU to 84.64-km race times were established ($r = -0.72$ and $r = -0.80$, respectively; $P < 0.001$). They also attributed the wide range of FU values to the differences in training volume and running experience among the subjects. The authors concluded that in a homogeneous sample, success at ultra-marathon distances is solely and crucially dependent on the utilization of a large VO_{2max}.

Noakes et al (25)

Noakes et al compared the relative predictive power of a comprehensive battery of physiological variables for running performance at distances from 10 – 90 km in two groups of subjects: specialist marathon runners and specialist ultra-marathon runners (25). The 43 subjects had their VO_{2max}, PTS, RE and the V.LT measured across two separate occasions. The best times in races of 10 – 90 km within a 3-month period prior to the laboratory tests were self-reported by the runners.

The specialist ultra-marathon runners (n=23) had a mean VO_{2max} of 64.5 ± 8.0 ml/kg/min, RE (VO_2 consumed when running at 16 km/hr) of 52.0 ± 3.1 ml/kg/min, FU (%VO_{2max} when running at 16 km/hr) of 81.6 ± 10.1%, V.LT of 15.2 ± 1.9 km/h and PTS of 20.8 ± 1.8 km/h. Their mean 90-km race time was 450.5 ± 72.3 min. Similar values were obtained from the specialist marathon runners (n=20).

Perhaps the most important finding from this study was that in a heterogeneous group of ultra-runners, the best laboratory-measured predictor of running performance in a 90-km race was the PTS ($r = -0.80$; $P < 0.005$). The other physiological variables that had significant but weaker predictive values were V.LT ($r = -0.80$), FU ($r =0.76$) and VO_{2max} ($r = -0.72$). The relationship between 90-km race performance and running economy was non-significant ($r = 0.13$). Similar predictive values were also established for the shorter race distances of 10, 21.1 and 42.2 km in both specialist groups.

The authors concluded that the physiological variables determining success at distances from 10 – 90 km are the same in marathon and ultra-marathon specialists and that the best predictor of performance in a 90-km ultra-marathon is the recent 10-km or 42.2-km race time (both $r = 0.92$).

Millet et al (8)

Millet et al studied the physiological and biological factors related to a 24-h ultra-marathon in 12 male ultra-runners (8). Running performance was determined by the total distance covered in the 24-h running on a treadmill. VO_{2max}, PTS, V.LT and RE at 8 km/h were measured. 8 km/h was chosen as the speed was representative of the pace utilised in the ultra-marathon. The authors also obtained vastus lateralis muscle biopsy samples 2 h before the 24-h treadmill run to establish the muscle capillarization, fiber distribution and enzyme activity. The actual

running time was about 19 h due to the mandatory stops during the treadmill run for data to be collected for another study.

The subjects had a mean VO_{2max} of 52.4 ± 6.0 ml/kg/min, RE of 28.6 ± 1.9 ml/kg/min, V.LT of 15.2 ± 1.9 km/h and PTS of 18.3 ± 1.6 km/h. They were also able to sustain 39.4 ± 4.2% of their peak treadmill speed over the treadmill running test. The mean distance covered in the test was 149.2 ± 15.7 km.

The results demonstrated that maximal aerobic power (VO_{2max} and PTS) and a high FU during the run (inferred from the % of peak treadmill speed maintained over the run) are associated with performance in ultra-marathon lasting as long as 24 hrs. Neither the V.LT nor RE had a direct relationship with performance. These findings are in agreement with earlier studies conducted by Davies and Thompson and Noakes et al.

Histological analysis of the biopsy sample showed that the subjects had an average of about 70% type I fibres. This value is slightly lower than elite marathon runners but higher than good and slower marathon runners featured in an early study by Sjodin and Svedenhay (93). No correlation was found between the percentage of type I fibres and running performance due to an outlier effect. However, a correlation was established between these two variables after removing the outlier ($r = 0.68$; $P < 0.05$).

Contrary to an earlier study on marathon runner by Sjodin and Jacobs, no correlation was found between capillary density and running performance (51) but a significant relationship was established between the performance and the length of capillary-fiber contact ($R = 0.82$; $P < 0.01$). As the latter represents the percentage of muscle fiber perimeter in contact with the wall of the microvessel and takes into account the tortuosity of the vessel, the authors speculated that ultra-endurance training improves the blood-muscle exchange surface by increasing capillary tortuosity rather than modifying the knee extensor muscle typology.

Gatterer et al (175)

Gatterer et al compared the relative predictive power of a battery of physiological parameters for endurance running performance in two groups of participants: finishers of a 121-km and 68-km mountain ultra-marathon, respectively (175). The 18 runners participating in the study had their VO_{2max} and ventilatory thresholds measured at least two weeks prior to the race. Creatine kinase (CK) levels were determined from venous blood collected before and after the race.

The 121-km ultra-marathon runners (n=7) had a mean VO_{2max} of 59.3 ± 4.7 ml/kg/min, VO_2.VT1 (VO_2 consumed at the first ventilatory threshold) of 38.4 ± 2.2 ml/kg/min and VO_2.VT2 (VO_2 consumed at the second ventilatory threshold) of 51.3 ± 3.3 ml/kg/min. Similar values were obtained from the 68-km ultra-marathon runners. Overall finishing time was 1649 ± 203 min and 686 ± 124 min for the long and short ultra-marathon, respectively.

This is the first study in the literature to investigate the association between laboratory-measured physiological parameters and performance in a mountain ultra-marathon of over 100-km in distance. The findings revealed that VO_{2max}, VO_2.VT1 and VO_2.VT2 were only significantly correlated to the performance time for the 68-km race (r = -0.76, -0.78 and -0.73, respectively; $P < 0.05$). This caused the authors to speculate that the additional muscle damage as evidenced by the significantly higher CK values in the 121-km finishers might be a possible

reason for the disassociation between their race performance and the measured physiological parameters. They also concluded that runners looking to finish either a short or long mountain ultra-marathon should have a minimum VO_{2max} value of 50.0 ml/kg/min.

Knechtle et al (7)

Knechtle et al studied 169 finishers in the Biel 100-km race to establish the factors predicting performance (7). Before the start of the race, anthropometric measures including BM, height, skinfold thickness at eight sites (to estimate percent body fat) and girths of the thigh, calf and arm were measured. Training variables including average weekly volume (km and hours) and average training speed (km/h) were obtained from a training diary that the subjects maintained upon recruitment into the study. Race performance history was self-reported and included the number of completed marathon races and personal best times on a flat course as well as the number of 100-km races completed.

The participants had a mean BMI of 23.4 ± 2.2 kg/m^2 and body fat values of 16.1 ± 4.3%. Their mean weekly running distance and pace were 70.3 ± 27.6 km and 10.7 ± 1.5 km/h. The mean race finishing time was 11:53 ± 2:11 (hh:mm).

Knechtle and colleagues reported that personal best time in a marathon, training speed and mean weekly mileage were strong predictor variables for race time ($r = 0.65$, -0.56 and -0.43, respectively; $P < 0.0001$). These observations confirmed the similar findings established by the authors in earlier single-stage and multi-stage ultra-marathons (6, 177).

Anthropometric variables including BM, BMI, circumference of upper arm and percent body fat were also associated with finishing time ($r = 0.20$, 0.29, 0.26 and 0.45, respectively). These findings, however, could not be demonstrated consistently in other ultra-marathon studies. The same researchers found no relationship between any anthropometric measures and race performance in either a 7-day, 350-km mountain ultra-marathon (177) or a 24-hour run (178).

Hoffman et al (173)

Hoffman et al attempted to establish the body composition of participants running in the 161-km Rio Del Lago Endurance Run (173). 72 runners (17 women and 55 men) had their weight and height measured to calculate BMI while body fat percentage was determined with bioimpedance spectroscopy.

The BMI values were 24.8 ± 2.7 kg/m^2 (range 19.1–32.2) for men and 21.2 ± 2.1 kg/m^2 (range 18.1-26.7) for women. The body fat values were 17 ± 5% (range 5-35) for men and 21 ± 6% (range 10-29) for women. Only body fat percentage of men had a significant correlation ($r^2 = 0.23$; $p = 0.04$) when compared against race performance for both genders.

The authors concluded that participants in a 161-km trail ultra-marathon varied widely in body composition. The range of BMI values are also similar to those obtained in an earlier study conducted on 161-km ultra-runners (179).

O'Loughlin et al (174)

O'Loughlin et al studied 83 finishers (57 men and 26 women) in the Wellington Urban 62-km ultra-marathon to identify the variables predicting race performance. A day before the race, anthropometric measures (i.e. height and weight), training variables (i.e. weekly mileage and running speed) and race performance history (i.e. number of years running and personal best times of 5-km, 10-km, half marathon and full marathon races) were self-reported via a questionnaire that was distributed at race check in. This is the first study in the literature to examine the predictors of performance for women in an ultra-marathon that is less than 100 km in length.

The men had a BMI of 23.1 ± 0.3 kg/m^2 and a weekly milage of 70.9 ± 22.7 km that was run at 5.8 ± 0.9 min/km. The women had a BMI of 22.1 ± 0.5 kg/m^2 and a weekly mileage of 65.5 ± 20.0 km that was run at 6.1 ± 1.1 min/km.

For men, BMI, number of years running, running speed during training, and personal best time in a marathon and 5-km race were significantly correlated with race performance (r = 0.32, 0.31, 0.45, 0.50 and 0.50, respectively; $P < 0.05$). For women, weekly running mileage and personal best times in 5-km, 10-km and half-marathon races were significantly correlated with race performance (r = 0.39, 0.68, 0.66 and 0.73, respectively; $P < 0.05$).

Table 1. Studies Investigating the Physiological Profiles of Ultra-runners (mean ± SD).

Type of race	Sample Size	Performance (h)	Age (years)	VO_2max (ml/kg/min)	V.LT (km/h)	RE (ml/kg/km)	FU (%)	PTS (km/h)	Reference
SS 121-km	7	27.5 ± 3.4	41.0 ± 10.0	59.3 ± 4.7	-	-	-	-	(175)
SS 84.64-km	13	5.96 ± 0.65	33.0 ± 6.3	72.5 ± 3.8	-	-	67.1 ± 5.8 (at race pace)	-	(4)
SS 90-km	23	7.51 ± 1.21	33.3 ± 6.3	64.5 ± 8.0	15.2 ± 1.9	195.0 ± 11.6 (at 16 km/h)	81.6 ± 10.1 (at 16km/h)	20.8 ± 1.8	(25)
SS 75-km	26	12.0 ± 2.03	41.7 ± 9.5	-	-	-	-	16.9 ± 1.4	(180)
SS 68-km	11	11.4 ± 2.1	42.0 ± 9.0	57.0 ± 6.4	-	-	-		(175)
SS 65-km	23	11.8 ± 1.6	40.2 ± 7.3	57.4 ± 6.3	-	-	-	-	(181)
SS 65-km	15	-	44.9 ± 5.7	48.8 ± 3.4	-	180.6 ± 24.8 (at 60% PTS)	-	16.2 ± 1.0	(182)
MS 93-km	11	8.25 ± 1.6	40.5 ± 8.4	55.2 ± 6.7	-	190.0 ±8.0 (at 10 km/h)	-	17.8 ± 1.6	(183)
MS 90-km	10	9.43 ± 2.25	38.2 ± 12.4	54.1 ± 6.8	-	-	-	16.3 ± 1.4	(184)
SS 24-h	12	149.2 ± 15.7 (km)	-	52.4 ± 6.0	15.2 ± 1.9	214.5 ± 14.3 (at 8 km/h)	-	18.3 ± 1.6	(8)

Note. All measurements were assessed through direct measurements via treadmill running. SS = single stage; MS = multistage.

Table 2. Studies Investigating the Anthropometric Profiles of Ultra-runners (mean ± SD).

Type of race	Sample Size	Age (years)	Body mass (kg)	BMI (kg/m^2)	Body-fat (%)	Sum of skinfold (mm)	Arm girth (cm)	Calf girth (cm)	Reference
SS 217-km	10	42.8 ± 3.5	72.3 ± 3.1	24.5 ± 0.7	13.2 ± 1.8	-	29.9 ± 1.2	-	(185)
SS 161-km									(179)
Male	310	-	72.0 ± 8.4	23.1 ± 2.2	-	-	-	-	
Female	82	-	54.76 ± 6.1	20.6 ± 1.5	-	-	-	-	
SS 161-km									(173)
Male	55	-	-	24.8 ± 2.7	17.0 ± 5.0	-	-	-	
Female	17	-	-	21.2 ± 2.1	21.0 ± 6.0	-	-	-	
SS 100-km	169	46.5 ± 10.2	74.1 ± 3.4	23.4 ± 2.2	16.1 ± 4.3	-	29.2 ± 3.0	38.4 ± 2.4	(7)
SS 75-km	26	41.7 ± 9.5	72.3 ± 5.5	23.1 ± 1.3	-	-	-	-	(180)
SS 65-km	23	40.2 ± 7.3	69.2 ± 11.8	22.9 ± 2.5	15.6 ± 4.2	-	-	-	(181)
SS 65-km	15	44.9 ± 5.7	78.4 ± 8.4	24.6 ± 2.2	-	-	-	-	(182)
SS 65-km	212	40.8 ± 10.3	70.1 ± 9.6	22.6 ± 2.1	15.7 ± 5.9	-	-	-	(186)
SS 62-km									(174)
Male	57	40.6 ± 1.3	74.4 ± 1.2	23.5 ± 0.3	-	-	-	-	
Female	26	39.1 ± 2.0	61.1 ± 1.2	22.1 ± 0.5	-	-	-	-	
SS 24-h	14	41.1 ± 8.9	73.6 ± 8.2	23.5 ± 1.9	17.7 ± 4.3	35.0 ± 3.8 (4 sites)	-	-	(8)
SS 24-h	22	45.9 ± 6.6	72.3 ± 8.0	23.0 ± 1.7	14.8 ± 3.5	76.8 ± 23.4 (8 sites)			(187)
SS 24-h	63	46.9 ± 10.3	73.3 ± 7.6	23.1 ± 1.8	16.1 ± 4.1	89.9 ± 31.1 (9 sites)	-	-	(178)
MS 93-km	11	40.5 ± 8.4	68.6 ± 8.2	23.3 ± 1.9	17.6 ± 4.4	-	-	-	(183)
MS 90-km	10	38.2 ± 12.4	74.5 ± 7.3	24.1 ± 1.6	16.1 ± 4.8	-	-	-	(184)
MS 350-km	25	44.5 ± 7.0	73.0 ± 7.8	22.9 ± 1.8	13.1 ± 3.2	59.2 ± 20.8 (7 sites)	-	-	(188)
MS 1200-km	19	46.2 ± 9.6	71.8 ± 5.2	22.5 ± 19	13.1 ± 3.3	65.7 ± 3.5 (8 sites)	27.3 ± 1.6	38.1 ± 2.0	(189)
MS 1200-km	10								(190)
MS 340-km	17	41.2 ± 6.6	71.0 ± 5.1	22.4 ± 1.2	12.9 ± 1.5	65.4 ± 2.0 (8 sites)	28.6 ± 2.3	39.3 ± 2.3	(191)

SS = single stage; MS = multistage.

Table 3. Studies Investigating the Training Characteristics of Ultra-runners (mean ± SD).

Type of race	Sample Size	Weekly training (h)	Weekly training (km)	Running speed during training (km/h)	Reference
MS 1200-km	10	12.4 ± 5.0	115.0 ± 46.0	-	(190)
MS 350-km	25	8.5 ± 5.9	80.0 ± 59.7	10.0 ± 1.0	(188)
MS 93-km	11	-	75.8 ± 16.8	-	(183)
SS 217-km	10	-	118.0 ± 20.0	-	(185)
SS 100-km	169	7.6 ± 6.3	70.3 ± 27.6	10.7 ± 1.5	(7)
SS 65-km	23	7.0 ± 3.0	55 ± 31	-	(181)
SS 65-km	15	-	75 ± 19.3	-	(182)
SS 65-km	212	7.6 ± 5.1	64.5 ± 30.0	-	(186)
SS 62-km					(174)
Male	57	-	70.9 ± 22.7	5.8 ± 0.9 (min/km)	
Female	26	-	65.5 ± 22.0	6.1 ± 1.1 (min/km)	
SS 24-h	15	10.6 ± 3.5	98.8 ± 31.8	-	(192)
SS 24-h	63	9.2 ± 5.3	85.7 ± 35.8	10.3 ± 1.5	(178)
SS 24-h	12	-	80.5 ± 11.7	-	(8)

MS = multistage; SS = single stage.

Mechanism regulating pacing

Fatigue or the acute impairment of exercise performance, leading to an inability to maintain a desired velocity (193), is a major challenge for runners competing in an endurance race. Thus, well-trained athletes utilise specific pacing strategies to delay the onset of fatigue and optimise overall performance. Pacing, defined as the distribution of work, or pattern of energy expenditure, is well documented during athletic competitions (194). Pacing is optimised when substrates are used efficiently during exercise, so that all energy stores are used before finishing a race, but not so far from the end of a race that a significant slowdown can occur (195).

It is believed that a 'teleoanticipatory system' regulates pacing during long duration exercise (196, 197), in which the brain anticipates the endpoint of exercise and changes the exercise intensity accordingly to minimise the disturbance of physiological homeostasis (198, 199). Based on prior knowledge of previous or similar events performed by the athlete (200), current environmental conditions, health status and metabolic fuel reserves (201), the teleoanticipatory system would initiate a particular pacing strategy at the start of the event. Typically, this is characterised by a fast velocity or high power output initially in endurance events. Throughout the race, afferent input supplying information from metaboreceptors, nociceptors, thermoreceptors, cardiovascular pressure receptors and mechanoreceptors would update the brain about motion, force output, muscle metabolic rate and core temperature changes associated with the chosen exercise intensity (201-204). Pacing tends to decline and remains stable at a lower intensity during the middle portion of the race, before increasing significantly towards the end of the exercise bout, resulting in the so-called "end spurt" (13, 205). This contemporary concept challenges the classic models of fatigue which advocate the failure of homeostasis due to substrate depletion, attaining a critical level of hyperthermia, or a reduction in cardiac output during exercise (206).

In support of a central regulation of pacing, numerous studies have reported changes in exercise intensity in respond to the manipulation of physiological and/or non-physiological variables (201, 207-209). For example, Tucker et al showed that during a self-paced 20-km cycling TT in hot conditions (35 °C), power output and muscle activation (measured via iEMG) were reduced before significant changes in core temperature occurred (13). In fact, while the core temperature had increased to 39.2 °C, the subjects were still able to increase both skeletal muscle activation and power-output in the final km of the trial, confirming the existence of a system which adjusts exercise performance by altering efferent motor command during exercise. These findings are similar to those of Abbiss et al who reported comparable outcomes after comparing a 100-km cycling TT in 10 °C against that in 34 °C (14).

Since the "teleoanticipatory" model of pace regulation requires knowledge of the endpoint and associated duration of the event, the inaccurate feedback of such information should result in differences in the intensity sustained throughout the work bout. While early endurance studies that tested this hypothesis failed to reflect variations in pacing during the exercise bouts, it is feasible that the mismatch created by the misinformation was too small to be consciously detected by the subjects (205, 210) in those studies.

With respect to this, a recent study by Faulkner et al had 13 men complete four self-paced 6-km treadmill TT with either accurate, inaccurate or no distance feedback (211). While there were no differences in the pacing strategies at any stage in the accurate and inaccurate trials (fast start/stable mid-portion/endspurt), subjects paced conservatively when no distance

feedback was given (slow start/progressive increase in velocity/no endspurt), resulting in a significant slower completion time.

In summary, the overall pacing strategy during endurance exercises is mediated by an anticipatory mechanism which gathers afferent feedback from the various physiological systems and past experience to prevent premature fatigue caused by the upset of physiological homeostasis.

Pacing profiles associated with ultra-marathons

Although a range of pacing profiles have been observed during different exercise tasks and under different exercise conditions (10, 212), few studies have addressed the pacing of runners during ultra-marathons. This could be attributed to the variety of mechanisms identified as contributors to fatigue as running distances increase (206), making a systematic experimental approach difficult. From the limited evidence in the literature, three pacing profiles associated with ultra-running have been suggested and will be discussed in the next section under the following headings: (i) even pacing, (ii) positive pacing and (iii) parabolic-shaped pacing. Negative pacing (speed gradually increases throughout the duration of the event) will not be addressed since it is largely observed in marathons (213) but never in ultra-marathons.

Even pacing

An even pacing profile is the maintaining of constant submaximal exercise intensity throughout the event (Figure 2). While such a strategy tends to manifest in the race characteristics of highly-trained endurance athletes (214, 215), it remains as a theoretical "optimal" pace for ultra-runners competing under stable external conditions (e.g. environmental and geographic). The theoretical support for such a strategy is primarily based on mathematical laws of motion, which indicate that velocity is dictated by the maximal constant force an athlete can exert along with the resistive forces experienced (216-218). Mathematical modelling revealed that performance will be compromised should variability of pace drop below an athlete's physiological limit (i.e. fatigue threshold) at any point during an endurance event even if the athlete attempts to make up for lost time with an increase in speed at later parts of the event (219).

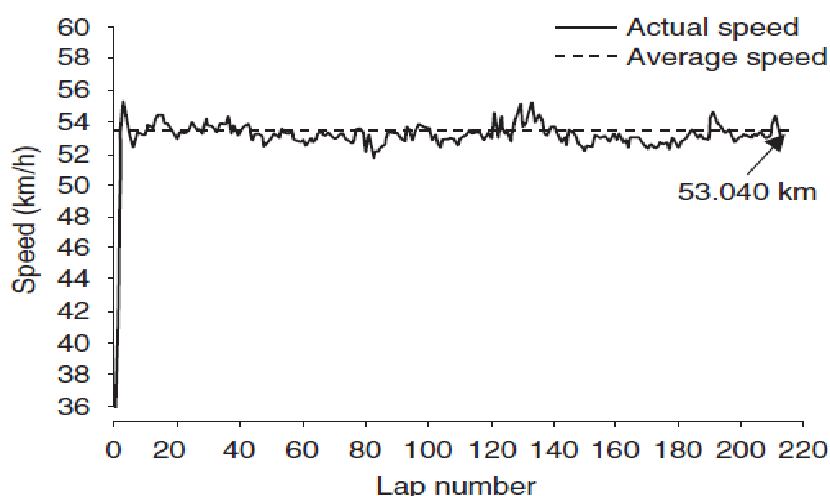

Figure 2. Average speed of a cyclist during the 1h track cycling world record. The actual speed had minimal deviation from the average speed, indicating the use of an even pacing strategy. (215)

Positive pacing

A positive pacing profile is one whereby a runner's speed gradually declines throughout the duration of the event (Figure 3). It has been shown that the adoption of a positive pacing strategy results in an increased VO_2 (220), greater accumulation of fatigue-related metabolites (220, 221) and an increase in RPE (220) during the early stages of exercise. These changes might provide the necessary cues to reduce the exercise intensity and adopt a positive pacing profile so as to prevent a catastrophic failure of the physiological systems (198, 222). Evidence suggests that self-selected exercise intensity during an ultra-endurance event tends to progressively decrease (11, 223). Laursen et al studied the heart rate response of 21 highly-trained triathletes to observe changes in race intensity during an Ironman triathlon (223). The authors reported that heart rate declined gradually during the running phase from an average of 150 BPM to about 130 BPM, reflecting a positive pacing profile.

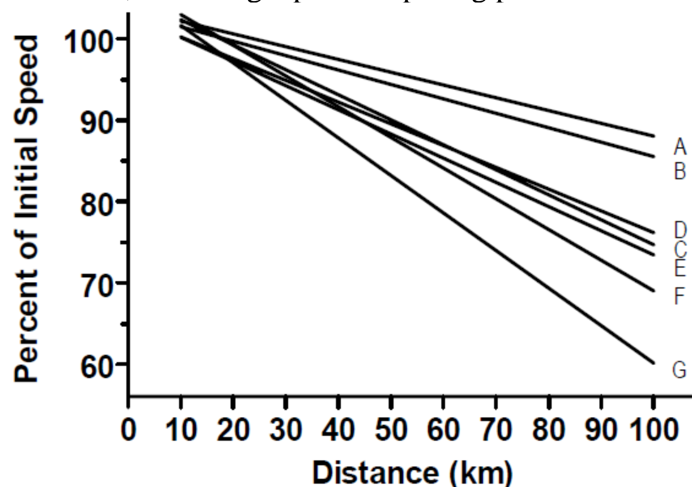

Figure 3. Normalised running speed vs distance of 7 groups (A-G) of elite ultra-runners in a 100km ultra-marathon. A gradual decline in speed occurs over time, indicating a positive pacing profile. (11)

Parabolic-shaped pacing

Traditionally, basic pacing profiles (i.e. even and positive pacing) have been derived from research examining differences in performance (based on split times) during the first and second halves of a race (12). This approach, however, is a relatively simple or gross analysis of a participant's overall pacing strategy and does not provide deeper insight into the distribution of energy expenditure throughout the event. Contemporary studies have shown that runners may progressively reduce speed during an endurance race but tend to increase speed towards the end of the race (224-226). This will result in parabolic-shaped pacing – U, J or reversed J-shaped profile (Figure 4). While such a pacing profile is commonly seen in rowing studies (227-229), little research is available to demonstrate these strategies in ultra-marathon studies.

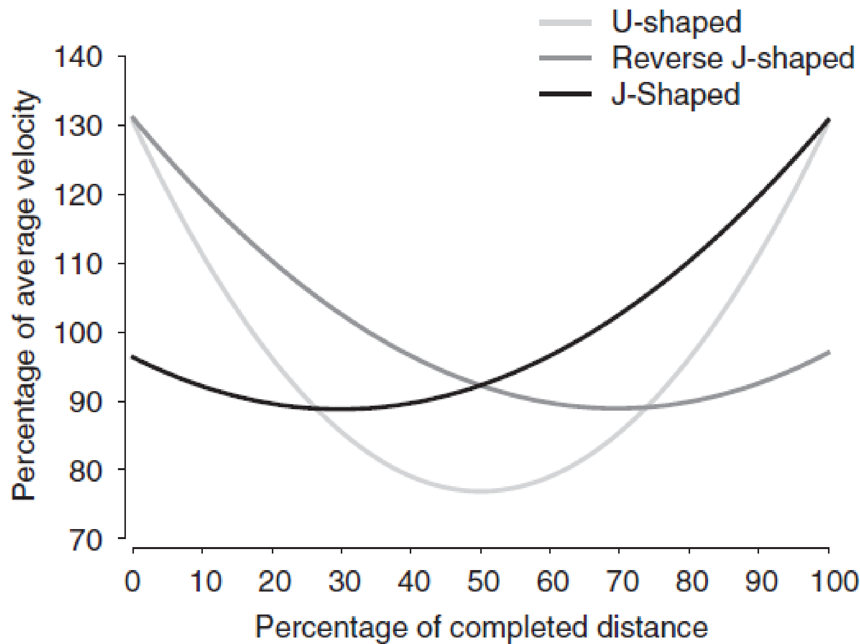

Figure 4. Examples of U-shaped, reverse J-shaped and J-shaped pacing profiles. (12)

Studies investigating the pacing strategies of ultra-runners

In the past two decades, studies have been conducted on ultra-runners to better understand their pacing strategies in ultra-marathons of various lengths, ranging from 24 h to 100 miles (230, 231). These studies offer good insights into the pacing profiles of ultra-runners with different fitness capacities, including elite athletes and recreational athletes with a wide spectrum of performance level. Some of these investigations are discussed in detail blow (11, 225, 230, 232).

Lambert et al (11)
Lambert et al studied the race times of elite ultra-runners participating in a 100-km race to determine the variations in speed turnovers between faster and slower runners (11). 10-km split times of 67 male runners who competed in the 1995 100km IAU World Challenge were obtained. They were then divided into seven groups of 10 runners by merit of finishing time (the last group had seven runners). Mean running speed (m/s) for each 10-km segment was calculated using each individual's 10-km split times. All splits were also normalised by assigning the first 10 km running speed to 100%.

The mean race time of the runners was 7:52.05 ± 1:00.58 (h:mm.ss). The fastest time recorded was 6:18.09 and the slowest time was 11:12.36 (h:mm.ss). It was found that the top three groups started at a faster and at very similar running speed (4.3 ± 0.2 m/s) compared to the next 3 (4.0 ± 0.3 m/s). The fastest and slowest groups completed the entire race at running speeds within 15% and 40% of their initial starting speed, respectively (calculated from the differences between the normalised speed of the 0 – 10-km and 90 – 100-km segments). The first four groups were also able to maintain a more even speed compared to the other three.

The authors concluded that faster ultra-runners ran with less variation in running speed and were able to sustain their initial pace for longer distances than slower runners. While the design of the study did not allow the investigators to explain the mechanisms regulating the change in running speeds, they speculated that such could be due to physiological factors such as

differences in RE and glycogen depletion and/or neuromuscular changes caused by repetitive eccentric muscle actions. Other possible explanations include training habits or insufficient practice of pacing strategies over a long distance. It should be noted that an endspurt might be present at the end of the 100-km race, but this was not detected because split times were available for 10-km intervals only.

Parise and Hoffman (225)
Parise and Hoffman examined the differences in how runners of various abilities pace themselves in a trail 100-mile race over different ambient temperatures (225). Two consecutive years when the Western States Endurance Run occurred under very different environmental temperature conditions were identified and only runners (n=50) who completed both years were studied. During the hot year, temperature and humidity ranged from 7.2 °C to 38 °C and 46% to 56%, respectively. In fact, all runners were exposed to temperatures above 35 °C by the midpoint of the course, and temperatures remained above 30 °C until it was dark. In contrast, the temperature and humidity in the cooler year varied between 2.2 °C to 30.6 °C and 38% to 43%, respectively, with temperatures hovering above 30 °C for only a brief period. 14 split-times were calculated from the arrival times at 13 checkpoints and the finish. The runners were also stratified into three groups (< 22, 22-24 and > 24h) based on their finish time in the cooler year.

The mean finish time of all the runners was significantly slower in the hot year than the cooler year (25 h VS 23 h; P = 0.000). Similar trends were observed in the average race pace across all three groups (49, 47 and 27 s slower, respectively; P < 0.003). All the runners also started the race at a faster speed during the cooler year.

A reverse J-shaped pacing profile was demonstrated in all three groups for both ambient conditions. The authors attributed the slower starting pace in the hot year to the runners setting their initial intensity at a level they thought is sustainable for the whole event after considering the afferent physiological feedback and other factors such as previous race experience. It should be noted that exact temperature data were not available at each checkpoint. Due to the remoteness of the race course, hourly temperature data could only be obtained from the weather stations near the race start, up to the 48-km checkpoint and the finish.

Bossi et al (230)
Bossi et al investigated the overall pacing strategy in a 24-h ultra-marathon and its interaction with the runners' level of performance (230). Hourly split times of 501 runners who competed in any of the five editions (2008 to 2012) of the Ultra-marathon Rio 24h were obtained. They were then divided into four equal groups by merit of total distance covered (group 2 had 126 runners). The mean running speed from each hour was percentage-normalised to the mean running speed of the 24h.

The mean distance covered by the runners in all five editions was 135.6 ± 33.0 km, with an effective-running time of 22.4 ± 1.3 h. The longest mean distance recorded was 150.5 ± 27.0 km in 2008 while the shortest distance was 129.0 ± 32.1 km in 2011.

This is the first study in the literature to capture the pacing profile of participants in a 24-h ultra-marathon. A reverse J-shaped pacing profile with a decrease in speed in the last hour was demonstrated in all four groups. The fastest runners adopted a more even pacing strategy compared to slower competitors by utilizing a conservative initial speed in the first three hours, slowing down less as the race progressed. In contrast, slower runners were unable to maintain

their initial speed as much as the fastest runners, reducing their speed more quickly, as well as displaying the greatest speed fluctuations throughout the race. The authors attributed the slowdown in these runners to the presence of a "herd behaviour" where the slower runners chose to follow the fastest runners at the first three hours, even after being overlapped (the race was held on a 400-m track), might have increased speed beyond their sustainable intensity for the race duration. Consequently, premature fatigue set in and speed was drastically reduced across the three slower groups.

These findings, however, could not be demonstrated consistently in other ultra-marathon studies. The same researchers found no improvement to race performance in a 6-h ultra-marathon when a slow-start strategy was used (233), while others reported that the fastest elite Japanese runners who covered 238.4 ± 11.4 km in a 24-h ultra-marathon found much success with the same strategy (234). The use of a slow-start strategy among the fastest ultra-runners across different age groups can also be observed in a single-stage 100-km race (235).

Balducci et al (232)

Balducci et al attempted to establish the pacing strategy used in mountain ultra-marathons by examining pacing among the first 30 male finishers of the 2016 Interlacs Trail (232). The course was 75 km long with a total positive elevation of 3930 m and a total negative elevation of 3700 m. The temperature ranged from 4 °C to 20 °C. Split times of seven (19.7, 8.5, 12.8, 7.2, 9.5, 8.8 and 8.7 km) distance segments were obtained. An index of pacing was calculated by dividing the average speed of the entire route by the average speed of the first distance segment.

The mean race time of the runners was 600 ± 60 min. The fastest and slowest times recorded were 491 and 677 min, respectively. Mean coefficient of variation (CV) in speed was 13.8 ± 2.1%.

Generally, the runners in this study adopted a conservative pacing strategy which minimised the loss of speed throughout the race. This is evidenced by them running the last 2 segments (17.5 km in total) of the race at running speeds that surpassed those of earlier segments. The authors noted that faster runners displayed lesser fluctuations throughout the race as demonstrated by the strong correlation between the CV in speed for the seven race segments and finish time ($r = -0.66$; $P < 0.001$). These runners also ran the early part of the race at a low intensity relative to their mean race pace. In fact, the winner of the race had the best index of pacing.

These findings, however, could not be demonstrated consistently in mountain ultra-marathons of much longer distances. While similar results were found in a pacing study conducted on the Western States 100-mile race (231), observations from both a 106 (236) and 173-km (237) mountain race reported no significant relationship between the variability of running speed and performance level.

Summary

Although the physiological and anthropometric determinants of performance in endurance runners are well-established in the literature, limited work has been extended to that of ultra-runners, especially across the full spectrum of runners and not just the fastest. Moreover, most of the studies were conducted only on FIN and it remains unclear if N-FIN share similar physiological and anthropometric attributes with the former. Should both groups of runners

have similar attributes, their established predictive powers to performance will thus become invalid.

While a series of recent studies provide some insights into the training characteristics of ultra-runners racing in single-stage ultra-marathons (7, 178, 192), the methodology remains questionable. It is vague whether the period for data collection was standardised for all subjects in these studies. Moreover, it is widely understood that exercise intensity not prescribed according to one's fitness level may produce large differences in internal cardiovascular and metabolic stress between individuals. Yet the authors defined the training intensity of ultra-runners in absolute terms. Such figures are of limited value in practice to runners who differ in physiological and functional capacity.

The precise pacing strategies to ensure the best possible athletic performance in ultra-marathons of different lengths are not clear. This might be attributed to the numerous dynamic external factors (i.e. extreme ambient conditions) that invoke different afferent physiological feedbacks, resulting in the various pacing profiles observed. The mechanisms regulating these profiles are similar. The brain functions as the main controller, receiving afferent signals from the various physiological systems and non-physiological cues such as past experience and ambient conditions, altering exercise intensity concurrently.

While three pacing profiles have been identified in ultra-marathon events (even, positive and parabolic-shaped), there is little information in the literature concerning this field of investigations for ultra-marathons in a tropical climate. Moreover, many of the pacing studies conducted on ultra-marathons so far used a homogenous group of elite to well-trained athletes. Thus the findings may not be representative of a more heterogeneous population of ultra-marathon FIN of lower performance level.

Taken collectively, the gaps in the current literature include:

1. Are there any differences in the physiological and anthropometric profiles of FIN and N-FIN in a tropical 161-km race? If yes, what are they?

2. Do the above FIN train differently from the N-FIN?

3. What sort of pacing profile(s) exist among 161-km and 101-km ultra-runners competing in a tropical ultra-marathon?

4. Do faster ultra-runners pace differently from slower runners?

These questions will be addressed in the experimental sections (Chapter Three and Four) that follow. Each study will have an introduction, methods section, results and discussion. The findings from these studies will then be consolidated in the final chapter (Chapter Five).

CHAPTER THREE

Assessment of differences in the anthropometric, physiological and training characteristics of finishers and non-finishers in a tropical 161-km ultra-marathon

Introduction

Running is a popular sports discipline that can be performed over many distances. Current trends in endurance running participation now include much longer athletic events or ultra-marathons. While there is no consensus on the definition of an ultra-marathon, it is usually regarded as a distance longer than the classic marathon distance of 42.195 km (1). There are two types of ultra-marathon events: single-stage (e.g. Western States 100 miles or Comrades Marathon) and multi-stage (e.g. Marathon Des Sables or Four Deserts Race). Both can occur on a mostly flat road or over various terrain trails.

Although physiological, anthropometric and training characteristics of endurance runners ranging from middle to marathon distance of varying participation levels have been widely reported in the scientific literature (2, 3), limited work has been done to capture the data of ultra-runners, especially across the full spectrum of the ultra-running community and not just the fastest. The limited research on the physiological profiling of ultra-runners tends to focus on small sample groups of elite athletes and is dated decades prior to the current growth in popularity of ultra-endurance racing (4, 25). Similarly, the relationship between these variables and actual ultra-marathon performance is also unclear. Until recently, there have been no data in the literature on the potential association between physiological or training parameters and race performance in ultra-runners competing in distances longer than 90 km (7, 8).

In endurance running, an excess of adipose tissue and body weight usually require a greater muscular effort to accelerate the legs, and in theory, the energy expenditure at the same velocity would be greater. For example, recent studies have shown that anthropometric variables such as body mass (BM), body mass index (BMI) and girth of the upper arm were indirectly associated with finishing time in a 100-km ultra-marathon (7), while in another study body fat percentage (BF%) was shown to have a significant negative correlation to 161-km race performance (173). No physiological reasoning was provided by the authors for these relationships, however.

Although it is accepted that maximal oxygen uptake (VO_{2max}), velocity at lactate threshold (vLT), running economy (RE) and fractional utilization (FU) of VO_{2max} are crucial factors determining endurance performance (30, 51, 93), only three studies have been dedicated to the characterization of these physiological parameters on ultra-running performance. These studies concluded that success at ultra-marathon distances ranging from 84 km to 150 km is dependent on VO_{2max}, a high FU during the run and peak treadmill speed (PTS) (4, 8, 25).

Besides accumulating a large training volume, endurance runners competing in distances ranging from 3000 m to the marathon also often engage a variety of training methods of different intensities to elicit specific physiological adaptations (71). Such information is currently unavailable in the ultra-marathon literature. Although a series of studies conducted by Knechtle and colleagues (7, 178, 192) found that participants racing in single-stage ultra-marathons tend to have a weekly running distance of 70 – 98 km with a training speed of 10.3 – 10.7 km/h, it is widely understood that exercise intensity prescribed according to an absolute external workload may produce large differences in internal cardiovascular and metabolic stress between individuals. Hence, the definition of training intensities in absolute terms are of limited value in practice to runners who differ in physiological and functional capacity.

In attempting to understand the physiology underpinning performance in ultra-distance running, a complicating factor is that all except three studies (173, 188, 190), have been conducted only on the event finishers. Unless an extensive comparison across parameters is

made between the finishers and non-finishers, one cannot confidently conclude that such physiological, anthropometric and training characteristics are exclusive to the former. Should both finishers and non-finishers share similar attributes, their established predictive powers to race performance will thus become invalid. Although the reasons for not completing a 161-km race can stretch beyond that of physiological and/or training parameters to include issues like nausea during the run to blisters on feet (238), these dynamic factors can vary from race to race affecting both fast and slow runners and are beyond the scope and context of applied physiology. Therefore, the aim of this study was to compare and determine if there are any differences in the physiological, anthropometric and training characteristics of the finishers and non-finishers in a 161-km race.

Methods

Participants

To increase the sample size, data were collected from two consecutive years of the same 161-km ultra-marathon. All entrants of the event in the year 2012 to 2013 were invited via a personal electronic newsletter from the organiser to participate in the study. An observational cohort was studied whereby 23 men and 3 women participated in this study. They were subsequently grouped according to their race results as either finishers (FIN; N=12; 2 women) or non-finishers (N-FIN; N=14; 1 woman). None of the runners had previously participated in a single-stage 161-km race. A personal follow up 48 h post-race was made with all participants in the N-FIN group. All the N-FIN did not complete the race due to fatigue. Specifically, none failed to complete due to injury problems, blisters or other sources of discomfort. Prior to participation in the study, all participants provided written informed consent. The study conformed to the standards set by the Declaration of Helsinki and the procedures were approved by the local Institutional Ethics Committee.

Protocol

All the laboratory measurements were conducted over two separate sessions (48 – 72 h apart) at least three weeks prior to the race. The participants' training status were recorded with logbooks and physiological profiles established with a lactate threshold (LT), PTS, VO2max and RE tests on a motorised treadmill (Venus; HP-Cosmos, Nussduoff-Traunstein, Germany). Heart rate was continuously recorded throughout all running tests. All participants were also verbally encouraged to perform maximally during the testing sessions.

All participants completed the PTS and VO_{2max} tests during session 1. The test started at an initial velocity of 8 km/h (gradient = 1% throughout the test) with the speed increased by 0.5 km/h every 30 s until volitional exhaustion. Respiratory gas was analysed throughout the test using an open circuit spirometry system (TrueOne 2400MMS; Parvomedics, East Sandy, Utah, USA) and averaged every 30 s, and VO_{2max} determined based on highest 60-s average (e.g. average of two highest consecutive 30-s epochs). A test was considered maximal when three of the following criteria were fulfilled: (i) VO_2 plateau at peak exercise, (ii) respiratory exchange ratio of ≥ 1.10, (iii) peak HR ≥ 90 % of the theoretic maximal HR (220-age), and (iv) indication of maximal exhaustion by the athlete (239). PTS was determined as the last stage completed. Anthropometric measurements including the sum of 7 skinfolds (240), arm and calf girths were taken before the PTS test. BF% was calculated using the Durnin and Womersley equations which had been validated in the Singapore population (241).

All participants completed the LT and RE tests during session 2. Both tests were performed concurrently at an initial velocity of 5 km/h (gradient = 1% throughout the test). The speed

was increased by 1 km/h every 4 min, which was followed by 30-s of rest for the collection of blood samples from the finger tip. This was repeated until volitional exhaustion. Lactate concentration was determined from the blood sample by means of a portable lactate analyser (Lactate Pro; Arkray, Kyoto, Japan). From this protocol, a velocity-blood lactate profile was obtained for each participant. The velocities associated with LT1 (vLT1) and LT2 (vLT2) were established as the intensities at which the blood lactate concentration increased by 1 $mmol.L^{-1}$ above resting value and at the LT calculated via the modified D_{max} method, respectively (242, 243). Respiratory gas was collected throughout the session and RE was calculated as the average value of the oxygen consumption during the last minute of each velocity below LT2 (244).

All participants were provided with logbooks to record their training sessions starting from six weeks prior to the race. The information consisted of the number of weekly running sessions, kilometres and pace of each run, weekly kilometres run, weekly hours run and cross-training duration (if any). Training-intensity distributions were calculated by establishing the percentage of the total training time at velocities under vLT2, at vLT2 and above vLT2. In addition, all participants had to report their running experience, number and personal best time of marathons completed on a flat course in the past two years as well as number of ultra-marathons completed in the past two years.

The Craze Ultra-marathon in Singapore generally takes place during the third weekend in September on a relatively flat road course. Runners are allowed 32 h to complete the race. Eight aid stations offering a variety of food and beverages were positioned along the 80.5-km loop making up the route. In both years, the general weather conditions were similar, with the temperature at the start being 26 to 28 °C, night lows of 24 to 26 °C, and daily highs of 34 to 35 °C. Humidity ranged from 65% to 98% with no rain or wind.

Statistical analysis

The data were analysed using version 20 of the SPSS software package (SPSS Inc., Chicago, Illinois, USA). Normality of data and equality of variances were assessed using Shapiro-Wilk test and Levene's test, respectively. Independent *t* tests were performed on data that were normally distributed while data which were not normally distributed were analysed using Mann-Whitney U test. The level of significance was set at $P \leq 0.05$ and all data are presented as mean ± SD. Cohen's effect sizes (ES) were also calculated to quantify the magnitude of the differences between groups, with modified descriptor values of <0.2, 0.2-0.6, >0.6-1.2, >1.2-2.0, and >2.0 considered trivial, small, moderate, large and very large, respectively (245). Effect sizes with 90% confidence limits (CLs) not overlapping and overlapping zero were defined as *clear* and *unclear*, respectively. A comparison of data on selected parameters between the current study and that of Millet et al. (8) was also done using the same statistical procedures as above. This was possible as the data of each individual runner were reported in the study by Millet and colleagues.

Results

The mean race time for the 161-km FIN was 27:36 ± 4:34 (hh:mm), with an average race pace of 6.0 ± 1.1 km/h. The fastest and slowest time recorded were 19:24 (hh:mm) and 31:55 (hh:mm), respectively. The mean race distance covered by the N-FIN was 90.3 ± 22.5 km in 16:52 ± 4:37 (hh:mm), with an average race pace of 5.4 ± 0.4 km/h. The longest and shortest race distance completed was 139 km and 65 km, respectively. The general and anthropometric

characteristics of the 26 runners, 12 in FIN and 14 in N-FIN, are shown in Table 4. There were no significant differences between the groups.

Table 4. General Characteristics of the Participants (mean ± SD).

	FIN (n = 12)	CL (90%)	N-FIN (n = 14)	CL (90%)
Age (y)	37 ± 6	34 – 40	37 ± 8	34 – 41
Height (cm)	172 ± 8	168 – 176	173 ± 7	170 – 177
Weight (kg)	64.0 ± 5.1	61.4 – 66.7	67.8 ± 11.3	62.4 – 73.1
Body mass index (kg/m^2)	21.7 ± 1.6	20.9 – 22.6	22.5 ± 2.7	21.2 – 23.8
Sum of skinfolds (mm)	56.3 ± 20.4	45.7 – 66.9	72.3 ± 31.1	57.5 – 87.0
Upper arm girth (cm)	29.5 ± 1.9	28.5 – 30.5	31.0 ± 4.7	28.8 – 33.3
Body fat (%)	16 ± 7	13 – 20	18 ± 7	15 – 21
Calf girth (cm)	39.3 ± 2.4	38.1 – 40.5	38.3 ± 3.3	36.8 – 39.9

FIN = finishers; N-FIN = non-finishers; CL = confidence limits.

Physiological characteristics of both FIN and N-FIN are presented in Table 5. Of all the physiological measures, only the lactate concentration and RER at LT1 were statistically significant ($P = 0.05$), with effect sizes falling into the category of "clear, moderate" (ES = 0.88 and 1.15, respectively). vLT2 had an effect size of 0.7 (moderate), with the confidence limits value of 0.67 describing this as "clear".

Table 5. Physiological Characteristics of the Participants (mean ± SD).†

	FIN (n = 12)	N-FIN (n = 14)	ES; ±90% CL	Clear / Unclear
FU during race (%)	39.4 ± 12.4	35.8 ± 7.0	0.37; ±0.69	Unclear
$\dot{V}O_2max$ (mL/kg/min)	50.9 ± 5.9	49.0 ± 6.0	0.21; ±0.65	Unclear
PTS (km/h)	15.9 ± 1.6	15.5 ± 1.4	0.16; ±0.65	Unclear
vLT1 (km/h)	10.2 ± 1.3	9.6 ± 1.0	0.45; ±0.66	Unclear
Lac.Con.LT1 (mmol/L)	1.8 ± 0.5*	2.4 ± 0.8	0.88; ±0.68	Clear
RER at LT1	0.93 ± 0.03*	0.96 ± 0.01	1.15; ± 1.10	Clear
vLT2 (km/h)	12.3 ± 1.3	11.5 ± 1.0	0.70; ±0.67	Clear
Lac.Con.LT2 (mmol/L)	3.9 ± 0.8	4.6 ± 1.3	0.88; ±0.89	Unclear

†Magnitudes of ES: < 0.2 = trivial, 0.2–0.6 = small, >0.6–1.2 = moderate, >1.2–2.0 = large, and >2.0 = very large. * $P \leq 0.05$. FIN = finishers; N-FIN = non-finishers; CL = confidence limits; ES = effect size; FU = fractional utilization; VO_2max = maximal oxygen uptake; PTS = peak treadmill speed; vLT = velocity at lactate threshold; Lac.Con.LT = lactate concentration at lactate threshold; RER = respiratory exchange ratio.

RE (VO_2) at speeds lower than vLT2 are presented in Figure 5. While some participants had their vLT2 above 11 km/h, these data were not used for comparison due to inadequate sample sizes for both FIN and N-FIN groups from this point on. No statistical differences existed in the RE of both groups across speeds 6 – 11 km/h. Unclear small effect sizes (ES = 0.39, 0.33, 0.24, 0.26 and 0.23) were obtained for RE at speeds 6, 7, 8, 9 and 11 km/h, respectively.

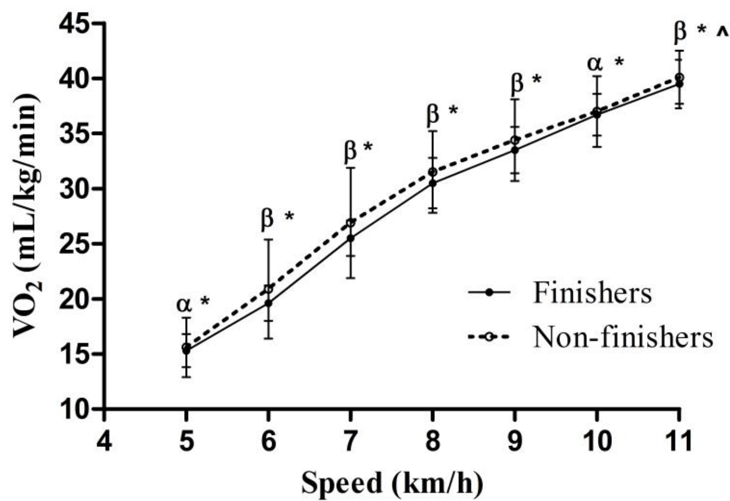

Figure 5. Running economy of the finisher and non-finisher group for speeds below the LT2 (α = trivial effect, β = small effect, * = unclear, ^ = 10 finishers and 11 non-finishers). Values are presented as mean ± SD. VO_2 = rate of oxygen (mL/kg/min) consumed.

Training variables and prerace experiences of both FIN and N-FIN are presented in Table 6. All the participants did their training runs on a relatively flat terrain. Despite having only near-statistical differences in the longest run attempted (P = 0.07) and hours spent in cross-training (P = 0.06) in both groups, the effect sizes of both variables indicated that these differences were moderate (ES = 0.73) and clear. From a descriptive point of view, Table 7 shows the performance, number of cross-training hours and types of cross-training done by the participants. Out of the 18 participants who engaged in cross-training, 12 (7 FIN and 5 N-FIN) utilised aerobic exercises while 6 (3 FIN and 3 N-FIN) opted for resistance training.

Table 6. Training Variables and Prerace Experience of the Participants (mean ±SD).†

	FIN (n = 12)	N-FIN (n = 14)	ES; ±90% CL	Clear /Unclear
Running experience (y)	5.6 ± 2.9	6.5 ± 8.1	0.12; ±0.65	Unclear
Finished marathons in past 2 years	4 ± 3	5 ± 4	0.28; ±0.65	Unclear
Personal best time in marathon (min)	229 ± 82	237 ± 72	0.10; ±0.65	Unclear
Number of finished ultra-marathons	5 ± 4	3 ± 3	0.57; ±0.66	Unclear
Distance ran per week (km)	58.6 ± 25.4	48.8 ± 38.4	0.30; ±0.65	Unclear
Longest run completed (km)	55.8 ± 30.1	38 ± 16.8	0.73; ±0.67	Clear
Cross-training (h)	19.3 ± 27.9	4.6 ± 5.3	0.73; ±0.67	Clear

†Magnitudes of ES: < 0.2 = trivial, 0.2–0.6 = small, >0.6–1.2 = moderate, >1.2–2.0 = large, and >2.0 = very large. FIN = finishers; N-FIN = non-finishers; CL = confidence limits; ES = effect size.

Table 7. Performance and Cross-training Background of the Participants over 6 weeks.

Runner	Race Time (hh:mm)	Distance Completed (km)	Cross-training (h)	Types of cross-training
FIN 1	19:24	-	30.9	Boxing
FIN 2	22:33	-	0	-
FIN 3	22:36	-	97.9	Kayaking; Team Sports*
FIN 4	23:13	-	35	Swimming; Cycling
FIN 5	26:20	-	28.9	Swimming; Cycling
FIN 6	28:20	-	16	Kayaking
FIN 7	31:14	-	1	Resistance Training
FIN 8	31:20	-	11.5	Swimming; Cycling
FIN 9	31:23	-	0	-
FIN 10	31:27	-	2.2	Swimming
FIN 11	31:29	-	0.4	Resistance Training
FIN 12	31:54	-	8	Resistance Training
N-FIN 1	-	139	0	-
N-FIN 2	-	121.5	15.8	Swimming; Cycling
N-FIN 3	-	121.5	0	-
N-FIN 4	-	95.5	0	-
N-FIN 5	-	95.5	1.5	Cycling
N-FIN 6	-	90.5	9	Tennis
N-FIN 7	-	80.5	12	Resistance Training
N-FIN 8	-	80.5	2	Resistance Training
N-FIN 9	-	80.5	0	-
N-FIN 10	-	80.5	0	-
N-FIN 11	-	78	14.7	Resistance Training
N-FIN 12	-	70	8	Swimming
N-FIN 13	-	65	0	-
N-FIN 14	-	65	0.8	Swimming

FIN = finisher; N-FIN = non-finisher; *Includes badminton, basketball and soccer.

The training intensities distributions of both groups are shown in Figure 6. In the FIN group, 94.7 ± 6.8%, 1.6 ± 2.9% and 3.8 ± 6.0% of the total training time were performed at velocities below vLT2, at vLT2 and above vLT2, respectively. In the N-FIN group, 83.5 ± 24.9%, 11.3 ± 25.1% and 5.3 ± 6.3% of the total training time were performed at velocities below vLT2, at vLT2 and above vLT2, respectively. Although there were no statistical differences in the training intensities distributions between both groups, the effect sizes indicated that there were moderate (ES = 0.62) and small (ES = 0.54) differences at the percentage of training time utilizing velocities below vLT2 and at vLT2. However, these effects were unclear.

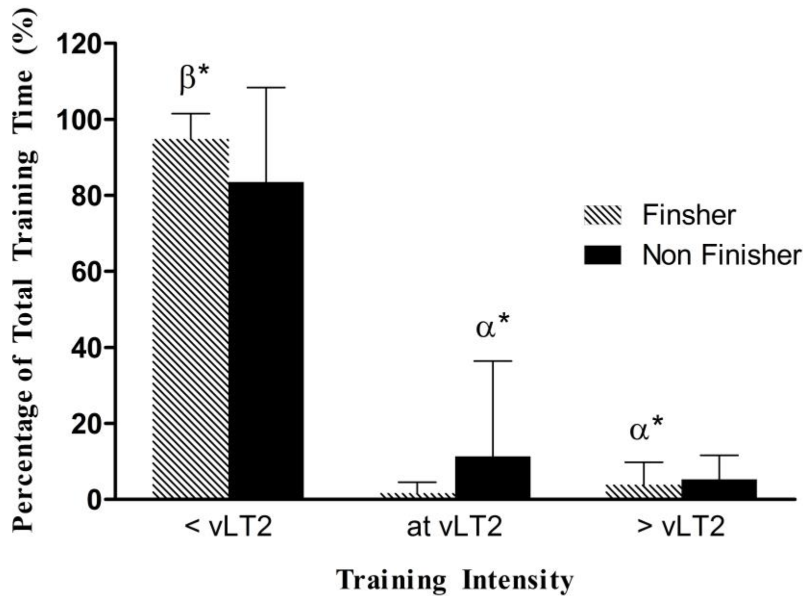

Figure 6. Training intensity distribution calculated relative to the velocity at the LT2 (α = small effect, β = moderate effect, * = unclear,). Values are presented as mean ± SD. vLT2 = velocity at the second lactate threshold.

Discussion

This is the first study to conduct such an extensive comparison of parameters between FIN and N-FIN in a 161-km race. The main findings of the study were that (i) FIN had a substantially lower lactate concentration at LT1 and faster vLT2 than N-FIN and (ii) FIN ran farther for their longest training run and cross-trained more than N-FIN. The results suggest that from a physiological perspective the ability to finish a 161-km race might be differentiated by lactate measurement and that training should extend to beyond just endurance running-specific activities.

The FIN had a mean finishing time of 27:36 (hh:mm) which is slower than previous studies where participants ran similar distances of 149 – 160 km in 24 – 26 h (ambient temperature ranged from 12.2°C to 37.6°C; mean temperature of 24.3°C) (8, 173). The N-FIN completed approximately 90.3 km in 16:52 (hh:mm). These values are still slower than previous field studies where subjects completed 84.6 – 100 km in 6 – 12 h (ambient temperature ranged from 8°C to 28°C; mean temperature unavailable) (4, 7, 25). The slow timings of the participants in the current study are likely due to the fact that they were novice athletes who aimed to simply finish the event, as well as adverse conditions of high temperature and humidity.

Many anthropometric variables have been shown to be related to ultra-running performance, such as BMI (179), body fat percentage (173) and circumference of the upper arm (189). These findings, however, could not be demonstrated consistently in ultra-marathon research, with only three studies having a N-FIN group for comparison (173, 188, 190). The participants of the current study were found to vary widely in body composition and girth values. For instance, BMI values, BF%, arm girth and calf girth ranged from 19.3 – 28.7 kg · m^{-2}, 7.5 – 31.7 %, 25.3 – 43.5 cm and 27.5 – 44.2 cm, respectively. These values are comparable to those from other investigations conducted at 161-km races and single/multi-stage ultra-marathons (7, 173, 179, 189, 190). Similar to the works of Knechtle and colleagues (188, 190), there were no anthropometric differences between the FIN and N-FIN (Table 4). Interestingly, Hoffman et al

(173) showed lower percentage body fat values in both male and female FIN than N-FIN in a 161-km race. These findings likely differ from the results of the current study due to the larger sample sizes (45 FIN vs 27 N-FIN) of Hoffman and colleagues.

Despite the suggestion by Noakes et al (25) that "there may be no unique physiological characteristics that distinguish long distance runners, marathon runners and ultra-marathon runners as is usually believed", the FIN had a significantly lower lactate concentration at LT1 (ES = 0.88; P = 0.05) and were moderately faster at vLT2 (ES = 0.88; P > 0.05) than the N-FIN. While an overwhelming number of studies exist to show the strong correlations between vLT2 and endurance running performance (64), the relationship between lactate concentration at the LTs and endurance performance is not widely explored. From the substrate utilization perspective, since lactate is a by-product of carbohydrate oxidation, a higher lactate accumulation at a given exercise intensity may indicate increased carbohydrate metabolism (246). As carbohydrates are stored as glycogen in the liver and muscle in finite quantities, a greater dependency on these substrates would accelerate the depletion of endogenous stores and ultimately lead to fatigue, along with the reduction in running speed. Hence, the lower lactate concentration of the FIN at LT1 might indicate superior lipid metabolism (thus sparing glycogen and delaying the onset of fatigue) at the lower range of submaximal speeds which coincide with their paces during the race. This explanation can also be supported by the significantly lower RER values of the FIN, which indicate a greater reliance on lipid as a fuel. These findings suggest that a combination of lactate concentration at LT1 and vLT2 might differentiate a FIN from a N-FIN among ultra-marathon participants.

Possessing a high maximal aerobic capacity has long been accepted as a marker of elite endurance running performance. Theoretically, this is also beneficial to ultra-marathon performance since the metabolic profile of the runner (e.g. substrate utilization, muscle metabolism by-products) is determined by the relative intensity of the exercise, i.e. the % VO_{2max}. Hence, the higher the aerobic power, the easier to run at a given submaximal speed (8). Success in endurance running can also be explained by FU at race pace. In this respect, studies conducted on both homogeneous and heterogeneous samples demonstrated positive relationships between FU and ultra-marathon performance. For example, Davies and Thompon (4) reported that the elite ultra-runners tested in their study were able to sustain approximately 67% VO_{2max} over 84 km while Millet et al. (8) concluded that trained runners can maintain at about 34% VO_{2max} for a 24-h race. The three studies dedicated to the characterization of physiological attributes of ultra-runners unanimously identified a strong correlation between maximal aerobic capacity (expressed as either VO_{2max} or PTS) and FU with success in ultra-marathons (4, 8, 25). In contrast to these findings, the current study showed non-significant differences with small and unclear effect sizes in the VO_{2max}, PTS and FU between FIN and N-FIN. A comparison of available data revealed no statistical or magnitude differences in the VO_{2max} between the runners of Millet et al (8) and the runners participating in the current study (the work of Millet and colleagues was selected on the basis of similar event distance). This clearly demonstrates that a good maximal aerobic capacity and high FU are insufficient to allow one to finish an ultra-marathon lasting up to 160 km, let alone predict ultra-running performance.

Theoretically, a strong RE benefits ultra-marathon performance beyond the obvious substrate conservation (a better RE would result in lower energy expenditure, which in turn reflect a lower fat and carbohydrate metabolism in absolute quantity). A lower metabolic rate reduces thermogenesis, thus allowing less heat exchange and sweating while channelling more blood to the working muscles at a given cardiac output (247). Moreover, lower oxygen consumption

might generate fewer reactive oxygen species and lessen oxidative stress. This in turn can reduce neuromuscular fatigue and muscle damage while maintaining mitochondrial efficiency (248). As suggested by Figure 5, the RE across a range of submaximal speeds (5 – 11 km/h) were similar for both groups. This further strengthens the observations of previous investigations which showed no direct relationship between ultra-marathon performance and RE.

Studies examining the relationship between training indices and ultra-marathon performance remain equivocal. The FIN and N-FIN in the current study had a mean weekly running distance of 58.6 km and 48.8 km, respectively. There were no statistical nor clear ES differences in the weekly running distance between the two groups. These values are much lesser than the 70 – 86 km and 80 – 115 km documented in the literature for participants attempting single stage and multi-stage ultra-marathons, respectively (7, 178, 188, 190). While the recent writings of Knechtle and colleagues (7, 178) showed that weekly training volume was a strong predictor of ultra-marathon performance, their earlier findings from multi-stage ultra-marathons revealed no differences in the weekly distance ran between the FIN and N-FIN (188, 190).

Evidence supporting a high-low-intensity volume training, combined with a substantial high intensity training (> vLT2) has emerged in recent years (101). Such distribution of work away from the LT intensity region is called polarised training. It is noteworthy that although a true polarization of training intensity was not found since the percentage of total training time spent above vLT2 were very low, a moderate yet unclear effect size (ES = 0.61; $P > 0.05$) was observed when the training load below vLT2 was compared between groups (Figure 6). Perhaps a longer monitoring period is required to accurately reflect the training practices of the runners.

Among the training indices, the FIN completed a longer run (ES = 0.73; $P = 0.07$) and cross-trained more (ES = 0.73; $P = 0.06$) than the N-FIN. Cross-training, defined as combining an alternative training mode with task-specific training, is usually engaged with the intent to derive a physiological and performance benefit similar or better than exclusive sport-specific training (249). Since there were no significant differences in the weekly running distance between groups, a simplistic explanation would be that a higher number of cross-training hours resulted in a greater amount of training stimuli experienced by the FIN. This in turn might lead to better physiological adaptations not measured in this study (e.g. at neuromuscular level) and improved performance, in line with the "dose-response" principle (249). Another viable reason is that the high cross-training hours (3 - 4 h per week) contributed to the FIN's resilience to neuromuscular fatigue, which has been shown in recent research to affect ultra-marathon performance (250). It is well documented that the mechanical stress of ultra-running can cause significant muscle and cartilage damage after just 50 km of running (251, 252). Utilizing dissimilar modes (same energy system but different muscle groups) of cross-training might have strengthened the overall strength and integrity of the locomotor muscles, tendons and joints of the FIN, allowing peripheral fatigue (decline in knee extensor and plantar flexor forces) to be reduced and neuromuscular fatigue to be delayed. Indeed, most of the FIN engaged in aerobic activities like kayaking, cycling and swimming in addition to their running routine (Table 7). While some of the N-FIN also engaged in cross-training, the exercise duration might have been too short (< 2 h per week) to induce any tangible fitness benefits. Furthermore, two of the three N-FIN who cross-trained more than 2 h per week engaged in resistance training, which, although has never been shown to have a negative influence on distance running performance, might not provide a stimulus intense enough to challenge the aerobic system of the runners (253).

In summary, unlike previous studies which showed VO_{2max}, a high FU during the run and PTS to be predictors of ultra-marathon performance, no differences were demonstrated in these physiological parameters between FIN and N-FIN in the current study. The findings suggest that from a physiological perspective, the ability to finish a 161-km race might be differentiated by metabolic events reflected by differences in LT measurements. Training data of the FIN also revealed that runners whose aim is to finish a 161-km ultra-marathon should not neglect the importance of the long run during training and should run at least 35% (56 km) of the race distance based on the findings from the longest run (mean value) attempted by the FIN. Runners should also engage in 3 – 4 h of cross-training weekly to provide additional training stimuli to the body while allowing the running muscles to recover from fatigue.

A limitation of the study was the relatively short monitoring period (six weeks) to establish the training-intensity distribution. Extending the duration to 10 – 12 weeks could provide clearer findings as to whether ultra-runners polarise their training intensity in a manner similar to endurance runners. Reporting of training indices in future ultra-marathon research should include the type and quantity of cross-training. Another potential yet often overlooked area of research is the psychological aspect of ultra-running. Existing studies have primarily examined the motivations of ultra-runners (254) and changes in mood states during the race (255), offering limited practical applications. The long duration of an ultra-marathon would inevitably lead to soreness and pain in the lower limbs. Therefore, ultra-runners would need a certain level of mental toughness and resilience towards pain to complete the race. The latter characteristic was documented in a recent study where 11 finishers of the 4487-km TransEurope FootRace demonstrated low pain perception (256). Future comparisons between FIN and N-FIN should include establishing the mental toughness and pain tolerance level of these participants.

CHAPTER FOUR

Similarities and differences in pacing patterns in a 161-km and 101-km ultra-distance road race

Introduction

Fatigue or the acute impairment of exercise performance, leading to an inability to maintain desired velocity (193), is a major challenge for runners competing in an endurance race. Well-trained athletes utilise specific pacing strategies in an attempt to delay the onset of fatigue and optimise overall performance (10).

Pacing can be defined as the distribution of work or pattern of energy expenditure of an individual to achieve his/her performance goal (194). From a physiological perspective, it is believed that a 'teleoanticipatory system' regulates pacing during long-duration exercise (196, 197), in which the brain anticipates the endpoint of exercise and changes the exercise intensity accordingly to prevent or minimise the disturbance of physiological homeostasis (198, 199).

Traditionally, three basic pacing profiles (positive, negative and even pacing) have been observed during different exercise tasks and conditions (10). A positive pacing profile is one whereby a runner's speed gradually declines throughout the duration of the event (12). It has been shown that the adoption of a positive pacing strategy results in an increased oxygen consumption (VO_2) (220) and greater accumulation of fatigue-related metabolites (221) during the early stages of exercise. These changes might have provided the necessary cues to reduce the exercise intensity and adopt a positive pacing profile so as to maintain physiological homeostasis (222). Conversely, a negative pacing profile occurs when there is an increase in speed over the duration of the event (12). Engagement of this pacing strategy improves endurance exercise performance by reducing the rate of carbohydrate utilization (257) and lowering VO_2 (258) early on in the exercise task. Finally, an even pacing profile is the maintaining of a constant submaximal exercise intensity throughout the event (12) and tends to manifest in the race characteristics of highly-trained endurance athletes (214). The theoretical support for such a strategy is primarily based on mathematical laws of motion, which indicate that frequent variations in pace can result in a greater percentage of the power generated to overcome fluid (i.e. air or water) resistance rather than producing forward motion (219).

These three profiles have been derived from research examining differences in performance (based on split times) during the first and second halves of a race (12). Such an approach is a relatively simple analysis and provides limited insight of one's overall pacing strategy. Contemporary studies have shown that runners naturally choose a start speed that is substantially greater than the mean speed of the race. They then progressively reduce speed during the race until approximately 90% of the entire distance has been completed before increasing the intensity to produce a so-called end spurt (224-226). This results in a parabolic-shaped pacing – U-, J- or reversed J-shaped profile (12).

Pacing is well documented during athletic competitions ranging from 800-m race to the marathon (226, 259) but not frequently studied in ultra-marathons. This could be attributed to the variety of mechanisms identified as contributors to fatigue as running distances increase, making a systematic experimental approach difficult (206).

Lambert et al (11) attempted to better understand pacing strategies by studying the race times of elite ultra-runners participating in the 100-km IAU World Challenge to determine the variations in speed changes between faster and slower runners. The authors concluded that the faster ultra-runners ran with less variation in running speed, sustaining their initial pace for longer distances into the race than slower runners. A decade later, Knechtle et al (260)

presented similar findings of top 100-km runners finishing the ultra-marathon at a high percent of their initial pace. Similarly, Parise and Hoffman (225) examined the differences in how runners of various abilities pace themselves over different ambient temperatures in the 100-mile Western States Endurance Run. They captured a reverse J-shaped pacing profile in all their subjects racing regardless of finishing time or ambient conditions. Hoffman (231) went on to examine pacing of the top five runners in 24 editions of the same race and concluded that the fastest times are achieved when speed fluctuations are limited.

The optimal pacing strategy for performance in ultra-marathons of different lengths remains unclear. Theoretically, an even-pacing strategy is believed to be ideal for long duration events in a stable environment. However, ultra-marathons are often conducted under dynamic external conditions (i.e. varying altitudes, ambient temperatures) (214, 215). Moreover, the handful of pacing studies conducted on ultra-marathons so far, utilised a homogenous group of elite to well-trained athletes. Thus, the findings may not be representative of a more heterogeneous population of ultra-marathons finishers of lower performance levels. In light of the rising popularity of ultra-marathons, the purpose of this study was to establish and compare the pacing patterns of fast and slow finishers in a tropical ultra-marathon.

Methods

This descriptive field study occurred at the Craze Ultra-marathon held in Singapore on the third weekend of September in 2012 and 2013 on a relatively flat road course. Runners from the 161-km and 101-km categories are allowed 32 h to complete the race. Eight checkpoints (CP) offering a variety of food and beverages are positioned along a relatively flat 80.5-km loop making up the route. Runners attempting the 161-km would turn back at CP8 (80.5-km mark) while those in the 101-km category would turn back at CP5 (50.5-km mark). Distance markers are available at every 5-km intervals except for the first and last 10 km of the race. In both years, the course was identical and the general weather conditions were similar, with the temperature at the start being 26 to 28 °C, night lows of 24 to 26 °C, and daily highs of 34 to 35 °C. Humidity ranged from 65% to 98% with no rain or wind. Generally, all runners were exposed to temperature above 30 °C between 9am to 7pm while humidity remained above 90% through the night from 11pm to 7am, making the race progressively more challenging as the duration increases. By analysing the split times of all the finishers and the changes in race positions of the top five runners, the current study aimed to provide important insight into the similarities and differences in pacing patterns between fast and slow recreational ultra-runners as well as the practices of the top few finishers.

Participants

To increase the sample size, data were collected from two consecutive years (2012 and 2013) of an ultra-marathon. A total of 47 runners (out of 128) and 120 runners (out of 150) completed the 161-km and 101-km race in both years, respectively. The data of 22 runners were excluded from the analysis due to missing split times. In order to assess the influence of absolute performance level on pacing strategy displayed, runners were further divided into three groups (A-C) by merit of finishing time: fastest one-third (A), middle one-third (B) and slowest one-third (C). The study was approved by the Research and Ethics Committee for the Faculty of Health Sciences, University of Cape Town and subjects were informed of the benefits and risks of the investigation prior to providing informed consent through electronic means.

Protocol
A total of 17 (12, 21.5, 30, 39, 50.5, 65, 70, 80.5, 91, 96, 110.5, 122, 131, 139.5, 149, 156 and 161 km) and 11 (12, 21.5, 30, 39, 50.5, 62, 71, 79.5, 89, 96 and 101 km) distance segments were available for the 161-km and 101-km categories, respectively. A CP was located at every segment except the last. Split times for all CPs were recorded with chronometry (System Stopwatch S149-4A00, Seiko, Tokyo, Japan). Two assistants were stationed at each CP and 5 km from the finish line to record the arrival and departure times of each runner. The last 5 km was chosen on the basis of research identifying that an end spurt occurs when a task is 95% complete, irrespective of length of task (261, 262). The finish times were subsequently obtained from the event organiser. The time taken between CPs was calculated from the point of departure from the previous CP to the point of arrival of the present CP.

Analysis of running speed
Mean running pace (km/h) for each distance segment was then calculated using each runner's segment split times. The mean absolute race pace (km/h) was calculated using each runner's finish time. Due to the possible accumulation of long bouts of rest at the CPs, thus negatively affecting the race pace, a separate mean pace "without (w/o) rest" (km/h) was calculated by dividing the race distance with only each runner's time taken to run all the distance segments. Coefficient of variation (CV) for the race pace w/o rest was also calculated.

To establish an end spurt for each individual, running speed during the last 5 km was calculated against the mean race pace w/o rest according to the following equation (224):
Percentage off mean race pace
= [(Mean speed for 5 km – Mean race pace w/o rest) / (Mean race pace w/o rest)] x 100
where a positive value represents an end spurt. A group is deemed to have achieved an end spurt when the overall mean speed of the last 5-km split is significantly faster than the overall mean race pace.

'Normalised' running speed for each runner's distance segment was calculated by assigning the first segment running speed to 100%. All the subsequent splits were adjusted accordingly. Subsequently, the mean normalised speed was derived for each group at each distance splits, and the line of best fit between distance and normalised speed was determined for them.

Statistical Analysis
The data were analysed using version 20 of the SPSS software package (SPSS Inc., Chicago, Illinois, USA). One way ANOVA and Tukey post hoc follow-up tests were used to identify differences across groups while an independent *t* test and a one-sample *t* test were used to assess the differences in average race paces and speed over the last 5 km against the overall average speed within each group, respectively. For binary data, a Chi-square analysis with a post hoc conversion of the residual to a Z-score was used to detect differences across groups. The level of significance was set at $P \leq 0.05$ (Z-score > 1.96) and data are presented as mean ± SD. No statistical analysis was done for the data of the top five finishers of both distance categories due to limited sample size.

Results

The mean race time for all the 161-km finishers was 29:01 ± 3:14 (hh:mm), with an average race pace of 5.6 ± 0.8 km/h. The fastest time recorded was 19:24 (hh:mm) and the slowest time was 31:55 (hh:mm). The performance characteristics of each group (A to C) are shown in Table 8. Tukey-post hoc tests indicated that runners in group A finished the 161-km race significantly

faster than those in group B (p = 0.001) and group C (p = 0.001). The mean race paces w/o rest of groups B and C were also significantly faster than their overall mean absolute race pace (p = 0.001 and 0.001, respectively). There were no differences between the three groups with respect to age, CV or number of runners with an end spurt.

Table 8. Performance Characteristics of the 161-km Finishers (mean ± SD).

	Group		
	A (n = 16, 2 women)	**B (n = 16, 4 women)**	**C (n = 15, 2 women)**
Age (y)	40.3 ± 6.4	41.9 ± 7.0	41.0 ± 8.0
Finish Time (hh:mm)	25:20 ± 2:56 ^{B,C}	30:20 ± 00:45	31:34 ± 00:14
Pace with rest ($km \cdot h^{-1}$)	6.4 ± 0.8 ^{B,C}	5.3 ± 0.1	5.1 ± 0.1
Pace without rest ($km \cdot h^{-1}$)	6.9 ± 0.8 ^{B,C}	5.8 ± 0.2*	5.6 ± 0.2*
Overall CV (%)	19 ± 5.3	20.4 ± 6.0	21.1 ± 4.0
Normalised Slope	-0.26 ± 0.07	-0.28 ± 0.10	-0.29 ± 0.07
Runners with end spurt	7	5	5

* and capital superscript letters denote $P \leq 0.05$ within and between groups, respectively. CV = coefficient of variation.

The mean race time for all the 101-km finishers was 21:18 ± 3:35 (hh:mm), with an average race pace of 4.9 ± 0.4 km/h. The fastest time recorded was 14:01 (hh:mm) and the slowest time was 29:04 (hh:mm). The performance characteristics of each group (A to C) are shown in Table 9. The mean race paces w/o rest of all the groups were also significantly faster than their overall mean absolute race pace (p = 0.003, 0.001 and 0.001, respectively). Tukey post hoc tests indicated that runners in group A finished the 101-km race significantly faster and ran with a significantly lower CV than those in group B (p = 0.001 and 0.013, respectively) and group C (p = 0.001 and 0.001, respectively). Runners in group B also finished the race significantly faster and and ran with a significantly lower CV than those in group C (p = 0.001 and 0.018, respectively). Group C, however, had a significantly greater number of runners with an end spurt than group A or B (Z-score = 3.00). The mean race paces w/o rest of all the groups were also significantly faster than their overall mean absolute race pace (p = 0.003, 0.001 and 0.001, respectively). There were no differences between the three groups with respect to age.

Table 9. Performance Characteristics of the 101-km Finishers (mean ± SD).

	Group		
	A (n = 33, 4 women)	**B (n = 34, 8 women)**	**C (n = 31, 5 women)**
Age (y)	39.4 ± 7.8	41.7 ± 9.0	39.0 ± 9.4
Finish Time (hh:mm)	17:25 ± 01:41^{B,C}	21:22 ± 00:45^{C}	25:22 ± 02:01
Pace with rest (km/h)	5.9 ± 0.6^{B,C}	4.7 ± 0.2^{C}	4.0 ± 0.3
Pace without rest (km/h)	6.3 ± 0.6^{*,B,C}	5.3 ± 0.3^{*,C}	4.5 ± 0.4*
Overall CV (%)	17.1 ± 5.7^{B,C}	21.0 ± 4.3^{C}	24.7 ± 6.2
Normalised Slope	-0.34 ± 0.18^{B,C}	-0.46 ± 0.14	-0.50 ± 0.22
Runners with end spurt	13	5	18^{A,B}

* and capital superscript letters denote $P \leq 0.05$ within and between groups, respectively. CV = coefficient of variation.

Figure 7 illustrates mean running speed across 17 distance segments of the 161-km course and 11 distance segments of the 101-km course for groups A-C, respectively. Pacing demonstrated a reverse J-shaped profile in all the groups for both distance categories. Overall in the 161-km category (left column), runners in group A ran faster than group B and C in 13 and 15 of the 17 segments, respectively. Runners in group B were faster than group C in only 1 of the 17 segments. Overall in the 101-km category (right column), runners in group A ran faster than group B and C in 9 and 11 of the 11 segments, respectively. Runners in group B were also faster than group C in 9 of the 11 segments. No end spurt was detected for both distances when the analysis was done at group level.

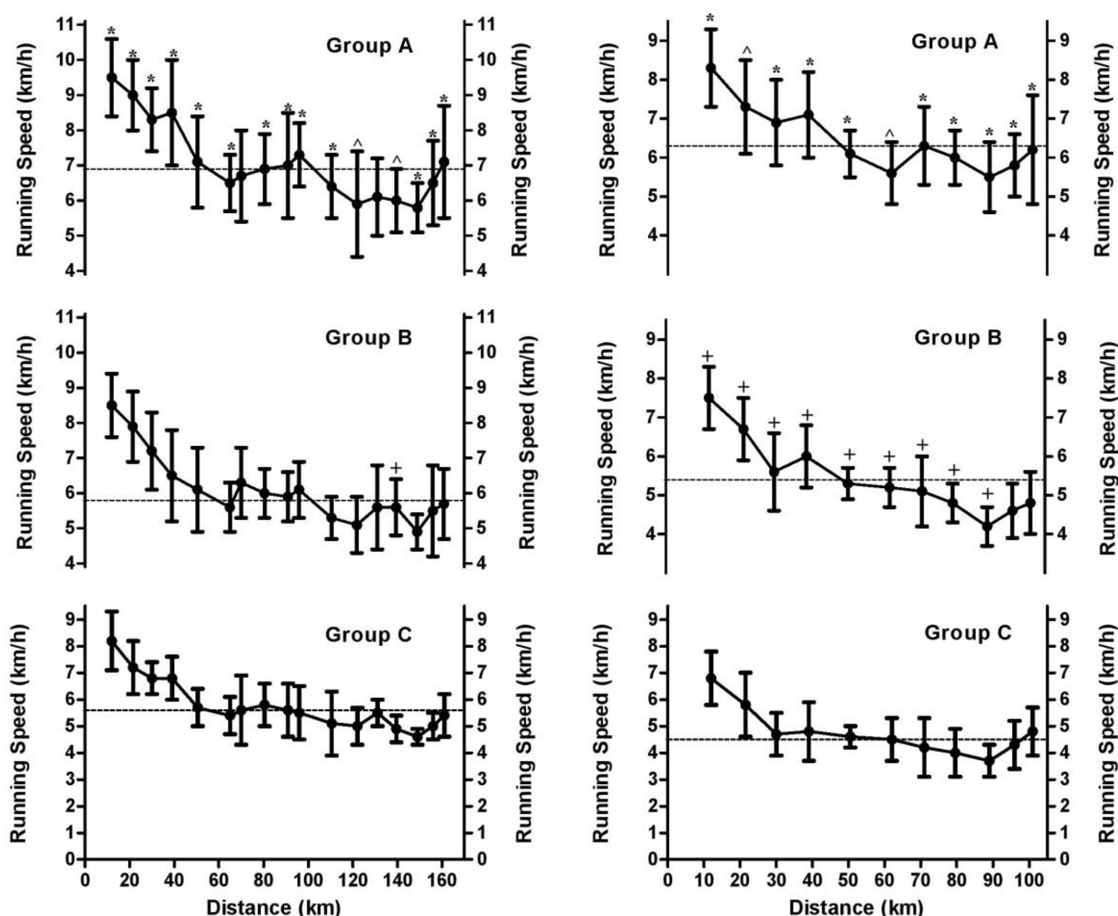

Figure 7. Mean pace across each segment of the 161-km (left column) and 101-km (right column) courses for each cohort. *, ^ and + indicate a statistically significant difference ($P \leq .05$) for Group A vs. Group B and C, Group A vs. Group C, and Group B vs. Group C, respectively. Dotted line represents overall mean race pace of the group.

In the 161-km category, runners who finished in group A, B and C, completed the entire race at running speeds within 40, 42 and 44% of their initial starting speed, respectively (Figure 8 -- left column). The slopes of the normalised running speeds ranged from -0.26 ± 0.07 to -0.29 ± 0.07 (groups A to C) (Table 8). There were no significant differences between the three slopes, suggesting that all the groups were slowing down evenly. In the 101-km category, runners who finished in group A, B and C, completed the entire race at running speeds within 34, 42 and 45% of their initial starting speed, respectively (Figure 8 – right column). The slopes of the normalised running speeds ranged from -0.34 ± 0.18 to -0.50 ± 0.22 (groups A to C) (Table 9). The slope of group A was significantly lesser than the slopes of group B and C (P = 0.001 and 0.001, respectively), indicating that runners in group A ran at a more even pace compared to groups B and C. Figure 9 shows the combined graphs of groups A-C for both 161-km and 101-km finishers. From a descriptive point of view, Figure 10 and Figure 11 show mean of speeds and positions of all editions for the top five runners at each CP for both 161-km and 101-km categories.

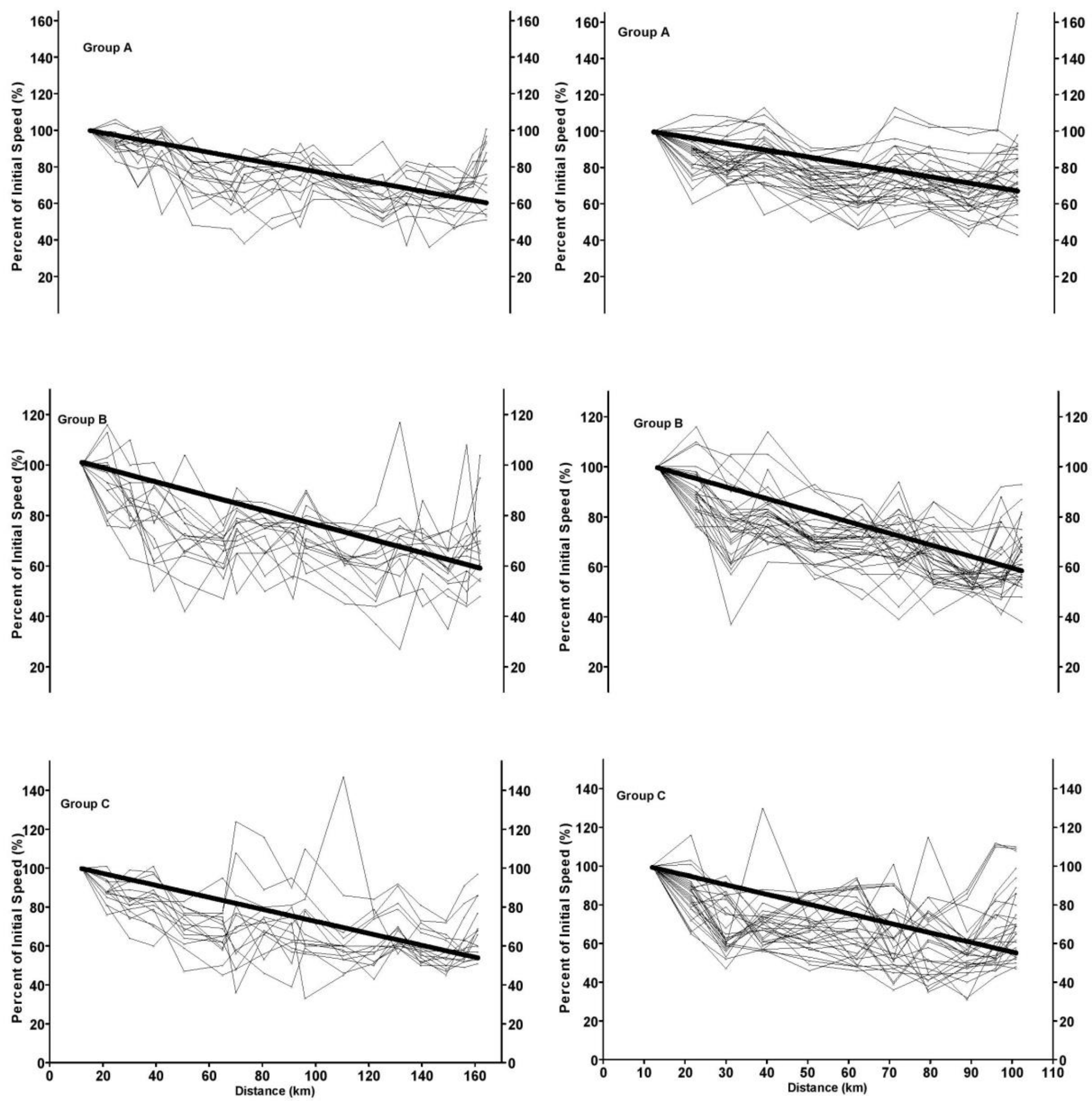

Figure 8. Normalised running speed of runners from the 161-km (left column) and 101-km (right column) courses for each cohort. The line of best fit for each group mean is shown in bold.

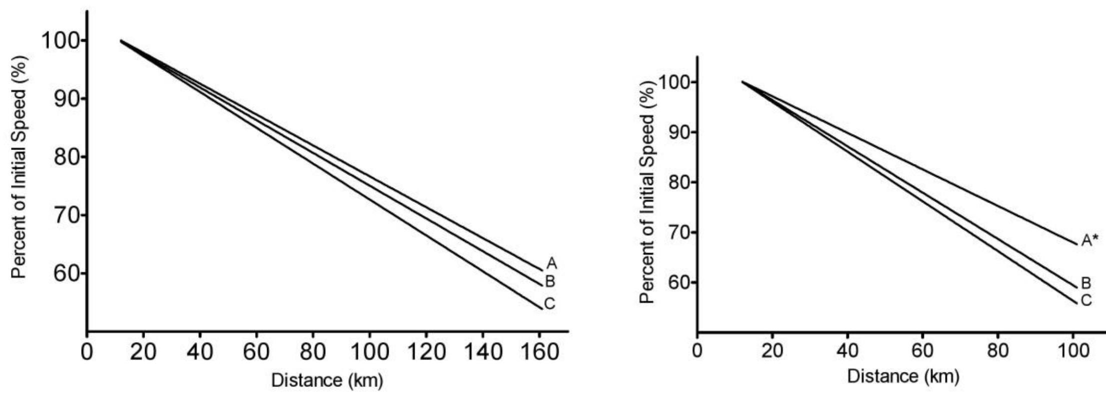

Figure 9. (L-R) Lines of best fit for 161-km and 101-km categories of normalised running speed vs. distance. * indicates a statistically significant difference (P $\leq$ 0.05) for Group A vs. Group B and C.

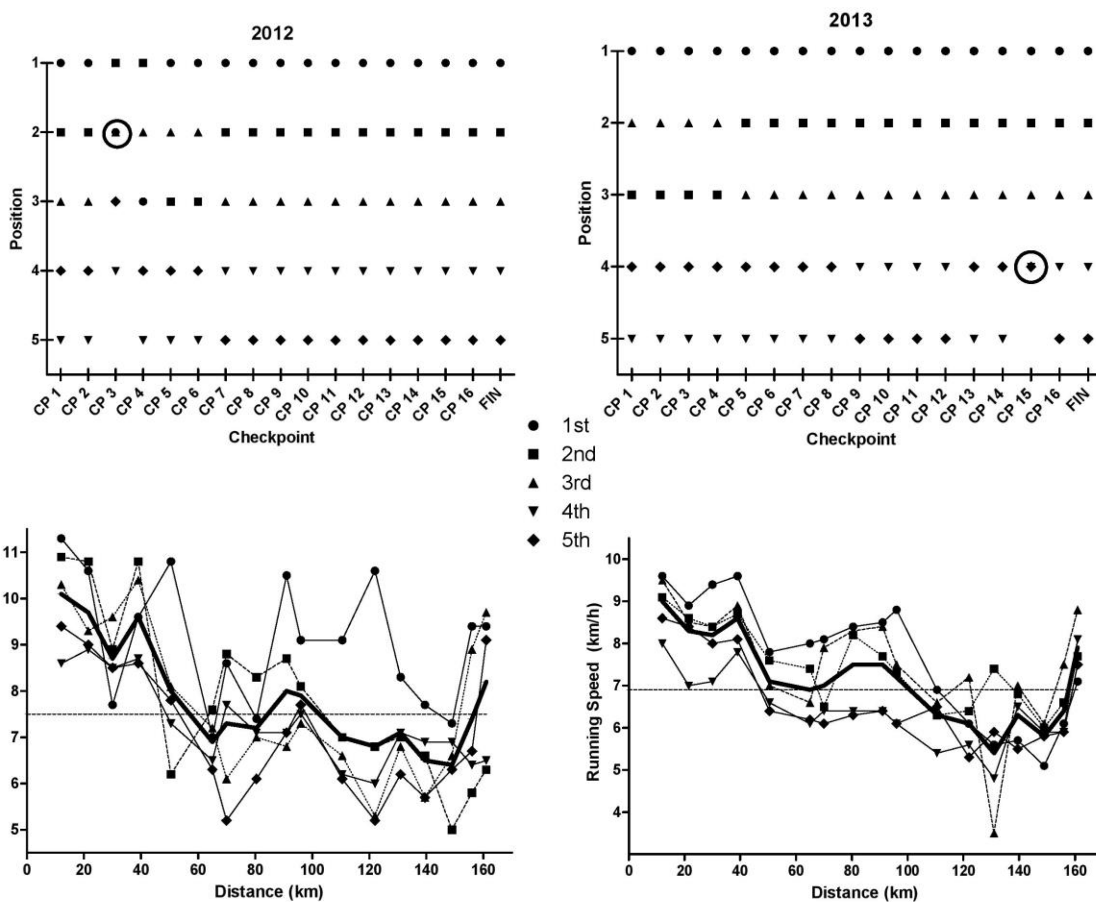

Figure 10. Global pacing comparisons among the top five finishers of the 161-km race. Top: Race positions based on checkpoint. Bold circle represents same arrival time at the checkpoint by two runners. Bottom: Speed comparisons among the top five finishers. Thick bold line represents mean pace across each segment of the 161-km courses (standard deviation bars removed for clarity). Dotted line represents overall mean race pace of the five runners. Legend reflects overall race position. All data are from 2012 – 2013 editions. CP = Checkpoint.

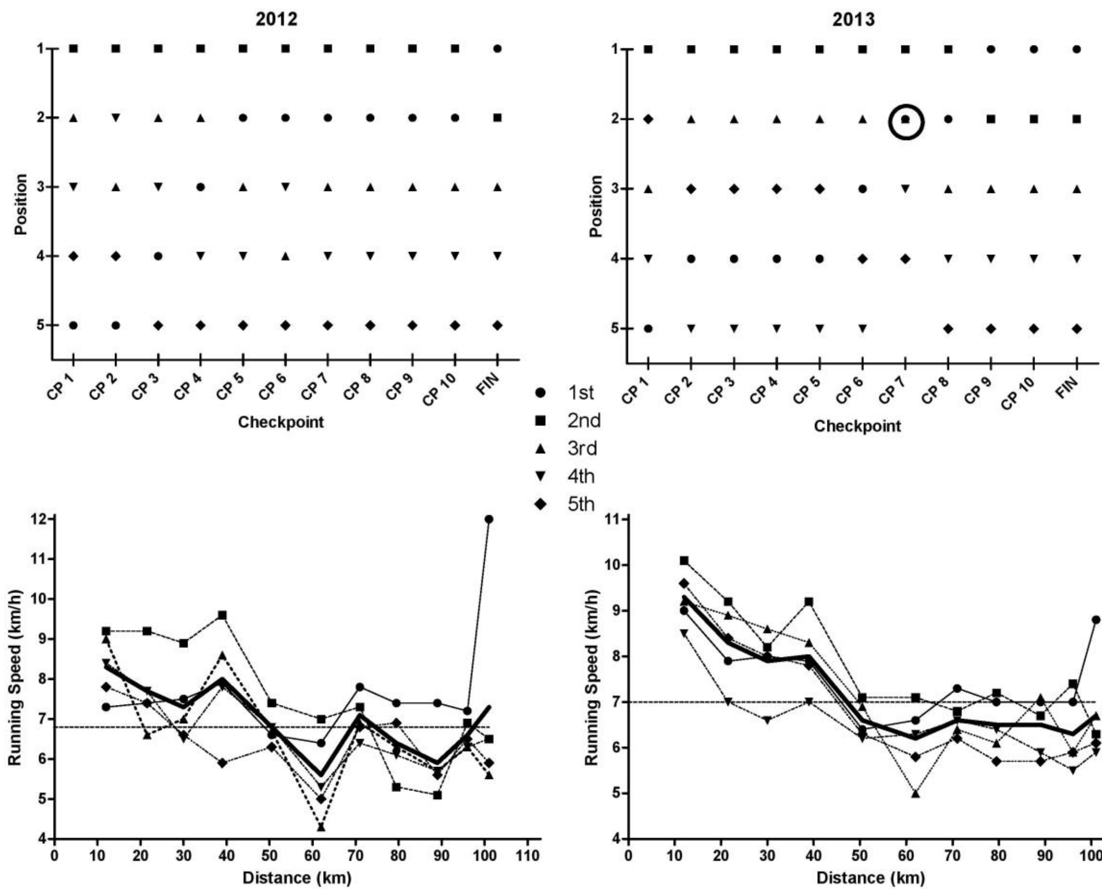

Figure 11. Global pacing comparisons among the top five finishers of the 101-km race. Top: Race positions based on checkpoint. Bold circle represents same arrival time at the checkpoint by two runners. Bottom: Speed comparisons among the top five finishers. Thick bold line represents mean pace across each segment of the 101-km courses (standard deviation bars removed for clarity). Dotted line represents overall mean race pace of the five runners. Legend reflects overall race position. All data are from 2012 – 2013 editions. CP = Checkpoint.

Discussion

The main findings of the study were that (i) pacing patterns during a 161-km and 101-km ultra-marathon remained consistent across different performance categories (ii) in the early portion of the race, top finishers tend to follow the leading runner while slower competitive finishers tend to form small packs with runners of similar pace (iii) faster finishers ran with fewer changes in speed than the slower finishers in the 101-km category and (iv) finishers remained conservative in their pacing over the last segment of the race when proximity to the end point is not known due to the absence of distance markers

In the 161-km category, finish times ranged from 25 h to 31.5 h across the three groups. This is a lot slower than the pacing study of Parise and Hoffman (225), whose participants in the fastest and middle one-thirds of the cohort ran a 100-mile race over a tougher mountainous terrain in under 22 h and 24 h, respectively. In the 101-km category, the finish times ranged from 17.5 h to 25 h across the groups. This is also slower than the timings established in the ultra-marathon literature where elite ultra-runners are able to complete the 100-km distance in 6.5 – 10 h (11) while well-trained athletes can do so in about 12 h (7). Although the high thermal load (temperature and humidity) experienced in both years of data collection would

adversely affect the race performance and pacing (263), it is clear that the bulk of the participants were merely moderately-trained athletes who aimed to simply finish the event. This is affirmed by the absence of differences between the finish times of groups B and C in the 161-km category which bordered on the event's cut-off duration of 32 h.

According to the current data, there are general trends toward a reduced-speed, positive-pacing (fast – slow) pattern, resulting in a reverse J-shaped pacing profile regardless of performance or race distances. Most runners completed the first quarter of the race relatively quickly and slowed progressively until the last CP, before picking up speed again (Figure 7). This pacing profile was also demonstrated in earlier ultra-marathon studies, with distance ranging from 100 km (264) to 161 km (225). A fast start in the less competitive / experienced runners [Figure 7 (L-R) – Group C] might simply reflect performance goals that are unrealistic and too ambitious while the top few might be chasing after the leader. For the remaining competitive participants [Figure 7 (L-R) – Groups A and B], their rate of perceived exertion (RPE) might be lower than anticipated during the start due to race excitement or the absence of fatigue, causing them to adopt a fast pace (265). After which, these runners might go on to form packs with those they find are running at similar pace during the course of the race and attempt to sustain that intensity for as long as possible. Indeed, Hanley (266) confirmed that most athletes running in packs during the IAAF World Half Marathon Championships were not actually in the lead group. A closer inspection of the data (results not shown) revealed that in the 161-km and 101-km categories, the participants were racing in packs of 5 and 10, respectively.

Although no physiological parameters were measured during the event, the rapid decline in speed after the first quarter of the race could be a result of cardiovascular strain due to the high thermal load (temperature and humidity approximately 32°C and 65%, respectively) imposed on the runners. Indeed, Périard et al (267) showed that self-paced exercise in climatic conditions similar to this study led to the utilization of a progressively greater percentage of peak aerobic capacity during the development of thermal and cardiovascular strain for a given workload. Thus, exercise intensity in the heat was reduced in order to allow one to continue exercising at the physiological limit.

Generally, faster ultra-runners tend to display lesser variations in running speed (reflected via their mean CVs) than slower runners in distances ranging from 100 km to 161 km (11, 231). Such behaviour can be seen in the 101-km finishers, with the faster groups having a significantly lower CV ($P = 0.013$ and 0.001, respectively) than their slower opponents (Table 9). 101-km finishers in group A also slowed down significantly lesser ($P = 0.001$) than groups B and C (Figure 3). This is in line with the findings of Lambert et al (11) although their best 100-km runners ended the race within 15% of their starting speed while the fastest finishers in this study could only achieve it within 34%. Interestingly, no differences exist in the CVs or decline in speed among the 161-km groups (Table 8 and Figure 9, respectively) despite group A finishing the race significantly faster than the rest ($P = 0.001$).

It is interesting to note that all three groups in both categories increased their running speeds relative to the previous segment upon departure from the last CP [Figure 8 (L-R) – segment 15 and segment 9]. A similar trend was observed by Knechtle et al (260) in their analysis of pacing strategy in male elite 100 km ultra-runners where most of the runners achieved a negative (slow – fast) pacing over the last segment (23.3 km) of the race. Despite this increase in speed, only 38% of the large sample of ultra-runners in this study could execute an end spurt in the last 5-km split, with the majority ($N = 18$) in Group C of the 101-km category (Table 9). This is also significantly larger (Z-score = 3.00) than the number of runners with an end spurt in groups A

and B of the same distance category, respectively. Tucker (268) proposed that during the regulation of exercise intensity, a conscious RPE (the verbal manifestation of the integrated physiological and psychological cues) is continually matched to a subconscious "template" RPE. The ignorance of one's proximity to the end point could potentially prevent the correct interpretation of afferent feedback from numerous physiological systems, resulting in a mismatch between the template and conscious RPE, with the latter to be un-interpreted. The overall effect will be to reduce or maintain the work rate. However, should the athlete be informed that the end of exercise is approaching, it is expected that the work rate, in this case running speed, will increase. Thus, the accurate knowledge of the distance between the last CP and the end point (12 km) would cause an increase in speed for the next distance segment. However, the absence of distance markers for the last 10 km would void the runners of subsequent information of their progress and proximity to the end. Overtime, this lack of feedback could restore the uncertainty in the runners and render them unwilling to increase speed further, hence the low number of end spurts.

A reverse J-shaped pacing profile was observed for all the top five finishers in both distance categories (Figures 10 and 11 - bottom). This result is surprising given that top finishers of 100-km ultra-marathons were able to display more even pacing than less successful competitors (260, 264). A much slower start is required to achieve an even-pacing profile, which has been suggested to be the best for prolonged activity. Indeed, general performance benefits such as reduced rates of glycogen depletion, lower excessive oxygen consumption and ultimately a superior race time are associated with a slow starting speed (12). The "herd-principle" of following the leading runner at the beginning of the race might shed light on the actions of the top five runners in both categories (269). This model of herd behaviour suggests that when faced with a range of possible decisions (e.g. whether to follow the fastest runner or stick to own pace) individuals will pick the option that would result in the most positive affective response. To achieve this, an accurate assessment of both benefit and risk incurred by the potential actions has to be made and this is usually done via a rational or experiential approach (270). However, when decisions making is complex, using an overall affective impression (experiential) is easier and more efficient than performing a rational analysis of the various options available (271). Hence, runners are likely to select muscular work rates based on behaviour of rivals while giving less weighting afferent information pertaining to their personal physiological status. While the top five runners (both categories) did not run closely as a pack in the initial portion of the race, the lead runner was within sight for most of them. This can be demonstrated by the narrow differences in the spectrum of speeds maintained within the group in the early part of the race (Figures 10 and 11 - bottom). In fact, the second and third runners were usually just five to eight min behind the lead runner while the rest attempted to close the distance gap. This lasted for 21.5 km (CP 2) before the time gap between the lead and second runner widened considerably to about 20 - 30 min. It should be noted that the first split time was only available from the 12-km mark (CP 1) while subsequent splits were captured at every 9 to 15-km intervals. Future research should incorporate higher resolution data (i.e., 5-km splits for the first half of the race) to capture any potential pack running behaviour among the top ultra-runners.

A recent study by Hoffman (231) revealed that winners from 24 editions of a 161-km ultra-marathon did not always lead the race throughout, but remained relatively close behind the leading runners at the beginning of the race before taking the lead in the middle half, and then avoided slowing down as much as the other top runners in the later stages of the race. However, such a pattern was not consistently observed in the top five finishers of both distance categories in 2012 and 2013. Winners of the 161-km race took the lead early or immediately from the

start of the race (Figures 10 and 11 - top) while those in the 101-km event adopted a conservative strategy and only overtook the second finisher very late into the race (Figure 11 - top). The aggressive pacing strategy of the 161-km victors might be attributed to their confidence in the ability and fitness to maintain a fast pace, which could be reflected in their reasonably good finish times of 19.4 h and 22.4 h, respectively. However, two editions of the race might be insufficient to generalise adequate meaningful practices of the top finishers and that more years of data should be included.

It is noteworthy that the 2012 winner of the 101-km event displayed atypical pacing characteristics compared to the other top finishers in both distance categories. This participant was able to maintain an even pacing profile for 8 of the 11 distance segments (total 73 km), with speed kept at a narrow range of 7.2 km/h to 7.9 km/h before speeding up considerably for the last 5 km of the race. The decline in speed at segment 5 and 6 (Figure 11 – bottom left) coincided with running along an unshaded path during the hottest period of the day. This is not surprising since it is well-documented that increased ambient temperature can disrupt the even pacing patterns of faster runners. A study of marathon finishers on a flat course indicated that the fastest runners maintained an even pace under cool conditions but slowed down in the second half of the race under hot conditions (262). The mean CV of 6.3% across the first 10 distance segments (Segment 11 was excluded in the calculation as the end spurt would inflate the mean overall CV severely) was comparable to the mean CV (5.4%) displayed by the top 10 elite ultra-runners in the 100 km IAU World Challenge (11). This figure is also much lower than the mean CV (16.3%) measured over the same segments of the remaining top 10% 101-km finishers in both years. These findings concur with earlier studies that faster athletes display more even pacing than less successful competitors in distances ranging from 100-km ultra-marathon (264) to marathon running (272), suggesting that similar mechanisms pertaining to regulation of intensity influence the strategy utilised in endurance activities of varying durations. The absence of the 'herd principle', as evidenced by the runner's adoption of a low starting speed instead of keeping up with the faster runners (7.3 km/h vs 8.6 km/h of the other top 4 101-km finishers in 2012), combined with an unusually large end spurt of 62% above his mean race pace, is possibly the result of an overly conservative race strategy. His reluctance to increase his pace could be attributed to a high and low perception of risk and benefits, respectively (265). As periods of uncertainty during closed-loop exercise decrease with proximity to the end point (212), it might have been deemed safe to finally run faster, thus explaining the large end spurt of the runner. In fact, he only overtook the lead runner somewhere along the last 5 km of the race.

In summary, findings presented in this study agree with previous research that sub-elite ultra-runners of varying performance levels tend to adopt a reverse J-shaped pacing profile. This might be attributed to unrealistic performance goals or running in packs of similar (yet unsustainable) pace in the initial portion of the race. Faster 101-km finishers also displayed fewer variations in their running speeds and slowed down lesser than their weaker competitors. A herd behaviour of following the leader was present in the top finishers and that the eventual winner need not be the leading runner at all times.

CHAPTER FIVE

Summary and practical applications

Summary

The aim of this research is to further our understanding of the applied physiology of ultra-running, especially in the Southeast Asian ultra-running community. This particular geographical area presents specific problems for endurance runners due to the extreme temperature (30 - 34 °C) and humidity (80 – 95%) experienced by the runners in most races in this region, yet very little is known about the physiological characteristics of runners competing in ultra-distance events in this region, the training and pacing strategies needed to manage the physiological stress and demands experienced by runners competing in this region of extreme ambient conditions. Limited work has also been extended to the full spectrum of ultra-runners and not just the fastest. Moreover, most of the studies were conducted only on FIN. Unless an extensive comparison across parameters is made between FIN and N-FIN, one cannot confidently conclude that such physiological, anthropometric and training characteristics are exclusive to the former. Should both FIN an N-FIN share similar attributes, their established predictive powers to race performance will thus become invalid.

The precise pacing strategies to ensure the best outcome in ultra-marathons of different distances remain unknown. This might be due to the numerous dynamic external factors (i.e. extreme ambient conditions) that demand different afferent physiological feedbacks, resulting in the various pacing profiles observed. While three pacing profiles have been identified in ultra-marathon events (even, positive and parabolic-shaped), little information exists in the literature concerning this field of research for ultra-marathons in a tropical climate. Moreover, many of these studies used a homogenous group of elite to well-trained ultra-runners. Thus, the findings may not be representative of a more heterogeneous population of ultra-marathon FIN of lower performance level.

With this in mind, this dissertation focused on a heterogenous group of recreational ultra-runners. The findings of the two studies conducted addressed the two objectives outlined in Chapter One while four specific questions were discussed in Chapters Three and Four. The objectives and questions are listed below with succinct answers, practical applications, and suggestions for future research associated with each study.

Chapter Three – Study 1

The aim of this study was to compare the differences in the physiological, anthropometric and training characteristics of the FIN and N-FIN in a 161-km ultra-marathon. This comparison is answered in greater details through the two questions asked below.

Question #1

Are there any differences in the physiological and anthropometric profiles of FIN and N-FIN in a tropical 161-km race? If yes, what are they?

Answer #1

Similar to the works of Knechtle and colleagues (188, 190), no anthropometric differences were found between the FIN and N-Fin. In fact, the participants of the current study were found to vary widely in body composition and girth values. For instance, BMI values, BF%, arm girth and calf girth ranged from 19.3 – 28.7 kg · m^{-2}, 7.5 – 31.7 %, 25.3 – 43.5 cm and 27.5 – 44.2

cm, respectively. These values are comparable to those from other investigations conducted at 161-km races (173, 179).

From a physiological perspective the ability to finish a tropical 161-km race might be differentiated only by lactate measurement. The FIN had a significantly lower lactate concentration at LT1 (1.8 ± 0.5 mmol/L VS 2.4 ± 0.8 mmol/L) and were moderately faster at vLT2 (12.3 ± 1.3 km/h VS 11.5 ± 1.0 km/h) than the N-FIN. From the substrate utilization perspective, since lactate is a by-product of carbohydrate oxidation, a higher lactate accumulation at a given exercise intensity may indicate increased carbohydrate metabolism (246). As carbohydrates are stored as glycogen in the liver and muscle in finite quantities, a greater dependency on these substrates would accelerate the depletion of endogenous stores and ultimately lead to fatigue, along with the reduction in running speed. Hence, the lower lactate concentration of the FIN at LT1 might indicate superior lipid metabolism (thus sparing glycogen and delaying the onset of fatigue) at the lower range of submaximal speeds which coincide with their paces during the race.

Question #2

How do the above FIN train differently from the N-FIN?

Answer #2

The FIN and N-FIN had a mean weekly running distance of 58.6 km and 48.8 km, respectively. There were no statistical nor clear ES differences in the weekly running distance between the two groups. These values are much lesser than the 70 – 86 km documented in the literature for participants attempting single stage ultra-marathons (179, 189).

Although the polarization of training intensity is common among runners competing in endurance races of shorter distances (101), this practice was not found in both the FIN and N-FIN since the percentage of total training time spent above vLT2 were very low. Interestingly, a moderate yet unclear effect size (ES = 0.61; $P > 0.05$) was observed when the training load below vLT2 was compared between groups.

Among the training indices recorded over six weeks, the FIN covered more distance for their longest run (55.8 ± 30.1 km VS 38 ± 16.8 km) and cross-trained more (19.3 ± 27.9 h VS 4.6 ± 5.3 h) than the N-FIN. Since there were no significant differences in the weekly running distance between groups, a simplistic explanation would be that a higher number of cross-training hours resulted in a greater amount of training stimuli experienced by the FIN. This in turn might lead to better physiological adaptations not measured in this study (e.g. at neuromuscular level) and improved performance, in line with the “dose-response” principle (249). Another possible reason is that the high cross-training hours (3 - 4 h per week) contributed to the FIN’s resilience to neuromuscular fatigue, which has been shown in recent research to affect ultra-marathon performance (250). Utilizing dissimilar modes (same energy system but different muscle groups) of cross-training might have strengthened the overall strength and integrity of the locomotor muscles, tendons and joints of the FIN, allowing peripheral fatigue (decline in knee extensor and plantar flexor forces) to be reduced and neuromuscular fatigue to be delayed. Indeed, among the 10 FIN who cross-trained, 7 engaged in aerobic activities like kayaking, cycling and swimming in addition to their running routine.

Practical applications

- Training data of the FIN revealed that runners whose aim is to finish a 161-km ultra-marathon should not neglect the importance of the long run during training and should run at least 35% (56 km) of the race distance based on the findings from the longest run (mean value) completed by the FIN.
- Runners should also engage in 3 – 4 h of cross-training weekly to provide additional training stimuli to the body while allowing the running muscles to recover from fatigue.

Future research

- Future research profiling the characteristics of ultra-runners should include N-FIN across the variety of distances which the ultra-marathon is run.
- Extending the monitoring period to a minimum duration of 10 – 12 weeks could provide clearer findings as to whether ultra-runners polarise their training intensity in a manner similar to runners competing in endurance races of shorter distances.
- Future reporting of training indices should include the type and quantity of cross-training.
- Future comparisons between FIN and N-FIN should include establishing the mental toughness and pain tolerance level of these participants through psychological questionnaires. The long duration of an ultra-marathon would inevitably lead to soreness and pain in the lower limbs. Therefore, ultra-runners would need a certain level of mental toughness and resilience towards pain to complete the race.

Chapter Four – Study 2

The aim of this study was to establish and compare the pacing patterns of fast and slow FIN in a tropical ultra-marathon. This comparison is answered in greater details through the two questions asked below.

Question #3

What sort of pacing profile(s) exist among 161-km and 101-km ultra-runners competing in a tropical ultra-marathon?

Answer #3

The pacing patterns during a 161-km and 101-km ultra-marathon remained consistent across different performance categories. There were general trends toward a reduced-speed, positive-pacing (fast – slow) pattern, resulting in a reverse J-shaped pacing profile in both 161-km and 101-km ultra-runners regardless of performance. Most runners completed the first quarter of the race relatively quickly and slowed progressively until the last checkpoint, before picking up speed again. This pacing profile was also demonstrated in earlier ultra-marathon studies, with distance ranging from 100 km to 161 km (225). A fast start might be attributed to several reasons such as performance goals that are unrealistic and too ambitious, race excitement or the absence of fatigue (265).

Meanwhile, the rapid decline in speed after the first quarter of the race could be a result of cardiovascular strain due to the high thermal load (temperature and humidity approximately 32°C and 65%, respectively) imposed on the runners. Indeed, Périard et al (267) showed that self-paced exercise in climatic conditions similar to this study led to the utilization of a progressively greater percentage of peak aerobic capacity during the development of thermal and cardiovascular strain for a given workload. Thus, exercise intensity in the heat was reduced in order to allow one to continue exercising at the physiological limit.

It is interesting to note that all three groups in both categories increased their running speeds relative to the previous segment upon departure from the last CP. A similar trend was observed by Knechtle et al (260) in their analysis of pacing strategy in male elite 100 km ultra-runners where most of the runners achieved a negative (slow – fast) pacing over the last segment (23.3 km) of the race. Despite this increase in speed, only 38% of the ultra-runners in this study could execute an end spurt in the last 5-km split. Generally, should the athlete be informed that the end of exercise is approaching, it is expected that the work rate, in this case running speed, will increase (268). Thus, the accurate knowledge of the distance between the last CP and the end point (12 km) would cause an increase in speed for the next distance segment. However, the absence of distance markers for the last 10 km would void the runners of subsequent information of their progress and proximity to the end. Overtime, this lack of feedback could increase the sense of uncertainty in the runners and render them unwilling to increase speed further, hence the low number of end spurts.

Question #4

Do faster ultra-runners pace differently from slower runners?

Answer #4

Generally, faster ultra-runners tend to display lesser variations in running speed (reflected via their mean CVs) than slower runners in distances ranging from 100 km to 161 km (11, 231). Interestingly, among the 161-km participants, faster runners did not pace differently from slower ones. All three groups slowed down evenly, completing the entire race at running speeds within 40, 42 and 44% of their initial starting speed despite group A (the fastest group) finishing the race significantly faster than the rest (P = 0.001).

Among the 101-km participants, group A slowed down the least, completing the entire race within 34% of the initial starting speed, while group B and C could only finish within 42 and 45% of their initial starting speed, respectively. Group A also ran at a more even pace and displayed fewer variations in speed than the other two slower groups. This is in line with the findings of Lambert et al (11) although their best 100-km runners ended the race within 15% of their starting speed.

Finally, the top five finishers in both distance categories displayed a "herd-behaviour" by staying close to the lead runner in the initial portion of the race. This practice suggests that when faced with a range of possible decisions (e.g. whether to follow the fastest runner or stick to own pace) individuals will pick the option that would result in the most positive affective response. To achieve this, an accurate assessment of both benefit and risk incurred by the potential actions has to be made and this is usually done via a rational or experiential approach (270). Although the top five runners (both categories) did not run closely as a pack in the initial

portion of the race, the lead runner was within sight for most of them. This can be demonstrated by the narrow differences in the spectrum of speeds maintained within the group in the early part of the race.

Practical applications

- Results from this descriptive field study of pacing involving ultra-runners of varying fitness levels seems to suggest that adopting a conservative sustainable starting speed is recommended.

- Less competitive / experienced runners aiming to just finish the ultra-marathon can benefit from having realistic performance goals while competitive runners with a specific time goal in mind can consider running in packs of similar pace. The latter group is also strongly discouraged from switching pace under the external influence of others early in the race.

- Judging from the severe decline in pace during the hottest period of the race, athletes competing in ultra-marathons held in hot and humid conditions are recommended to practice adequate heat acclimatization before the event.

Future research

- The relationship between pacing and performance might be better understood if runners were interviewed before the race about their expected race time. This would give researchers more insight about pacing strategy.

- Future research should examine the influence of gender on pacing strategy. A question to consider is whether women pace themselves more evenly than men during ultra-marathons like they do during marathons.

Conclusion

In conclusion, unlike previous studies which showed VO_{2max}, a high FU during the run and PTS to be predictors of ultra-marathon performance, no differences were demonstrated in these physiological parameters between FIN and N-FIN. Novel findings from this thesis suggest that from a physiological perspective, the ability to finish a 161-km ultra-marathon in a hot and humid climate might be differentiated by metabolic attributes via LT measurements. Training data of the FIN also revealed that runners should not neglect the importance of the long runs and should incorporate 3 – 4 h of cross-training weekly to provide additional training stimuli to the body while allowing the running muscles to recover from fatigue. Finally, sub-elite ultra-runners of varying performance levels tend to adopt a reverse J-shaped pacing profile. This might be attributed to unrealistic performance goals or running in packs of similar (yet unsustainable) pace in the initial portion of the race. Hence, to avoid a significant decline in running speed during the later parts of the race, recreational ultra-runners should adopt a conservative sustainable starting speed, with less competitive runners setting realistic performance goals while competitive runners with a specific time goal to consider running in packs of similar pace.

CHAPTER SIX

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