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Diet, Hydration, Lifestyle and Training Practices of Elite Kenyan Endurance Runners

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Faculty of Biomedical and Life Sciences

University of Glasgow

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“Research is to see what everybody else has seen, and to think what nobody else has thought.”

-Albert Szent-Gyrgy, Nobel Prize in medicine, 1934

Abstract

Background: Since the emergence of Kenyan endurance runners on the world stage at the 1968 Mexico Olympics, where they won 8 medals ranging from 400 m relay to the 10 000 m, Kenyan success has grown year on year. The staggering success of a country that comprises just 0.5 % of the world population has triggered a number of explanations. Heavily cited explanations are genetic superiority and environmental factors. Despite a number of investigations, genetic superiority remains to be determined, what is clear though is that the environmental factors that interact with each genetic element leading to world-class performance are particularly important. **Aims and objectives:** Given the importance environmental factors may have on the process leading to world class performance, the main aims of the following research were: 1) to determine the composition of elite Kenyan endurance runners diet and assess their energy balance status prior to major competition using gold standard methods; 2) to establish lifestyle practices of elite Kenyan endurance runners prior to major competition that will allow an insight in to the preparation of some of the best athletes in the world; 3) to ascertain the hydration status of elite Kenyan endurance runners during an important training period and directly compare these results to traditional paradigms and current thinking on optimal fluid intake for superior endurance running performance; 4) to investigate the training process leading to world class performance by quantifying training load in the lead up to major competition; 5) to determine the fluid intake behaviours of the world's best marathon runners during racing. This will allow an insight into current practices of elite runners that will act as a benchmark and comparison of current fluid intake guidelines; and 6) to validate and combine existing technologies of heart rate and accelerometry for quantifying energy expenditure during free living conditions. **Methods:** Chapters 2 and 3 detail extensively the diet, hydration, lifestyle and training practices of a group of highly successful elite Kenyan endurance runners during important training periods based at a high altitude camp in Kenya. Chapter 4 explores the significance of the hydration practices reported in Chapters 2 and 3 (i.e., *ad libitum* fluid intake) have

on elite marathon running performance and the wider implications for fluid intake recommendations for elite marathon running. Chapter 5 investigates novel technology (i.e., the combined use of accelerometry and heart rate) that may further enhance our understanding of the physical activity patterns and training practices of elite Kenyan endurance runners on a day-to-day basis.

Results and discussion: Chapter 2 reported elite Kenyan endurance runners are in negative energy balance prior to major competition as assessed by the gold standard doubly labeled water method (Energy intake: 13.2 ± 1.3 MJ·d⁻¹ vs. Energy expenditure: 14.6 ± 1.0 MJ·d⁻¹; $p < 0.005$). Considering the relatively high carbohydrate content of their diet (e.g., 67.3 ± 7.8 %, 9.8 g·kg⁻¹BM·d⁻¹) it is hypothesised the caloric deficit may not have a direct impact on their training performance. In fact the performance implications of reducing body mass as a result of energy deficiency is that the athletes will be lighter for competition and may thus be at an advantage as the energy cost per unit distance increases in direct proportion to the added load expressed as a percentage of body mass. Measured physical activity patterns (i.e., Physical Activity Ratio (PAR) and accelerometry) of elite Kenyan endurance runners strongly suggest rest between running training sessions is an important lifestyle factor as it was found time spent relaxing, in light activity, slow running (8.0 - 13.6 km·hr⁻¹), moderate running (13.7 - 17.3 km·hr⁻¹), and fast running (≥ 17.4 km·hr⁻¹) as estimated using the PAR method was 82 ± 6 %, 8 ± 6 %, 3 ± 1 %, 5 ± 1 %, 2 ± 1 %, respectively. The reported time spent in light, moderate, hard and very hard activity as determined by accelerometry was 82 ± 3 %, 11 ± 2 %, 6 ± 3 %, and 1 ± 1 % respectively. A further striking finding in Chapter 2 was the relatively low daily fluid intake that consisted of primarily water (0.9 ± 0.5 L·d⁻¹) and milky tea (0.9 ± 0.3 L·d⁻¹). Chapter 3 found athletes remained hydrated day-to-day drinking *ad libitum* despite this relatively low daily fluid intake that corroborated prevailing fluid intake recommendations. This was evidenced by mean total body water and pre training body mass being maintained day-to-day throughout the recording period ($p = 0.194$ and $p = 0.302$, respectively). Furthermore, there was no significant difference between the osmolality of the morning urine sample and the evening sample ($p = 0.685$). It was also found that

athletes remained in electrolyte balance (Na^+ intake: 3245 ± 901 vs. Na^+ loss: $3254 \pm 1070 \text{ mg}\cdot\text{d}^{-1}$; $p = 0.975$) day-to-day thus negating the need for further supplementation. The training load analysis supports the contention that elite endurance athletes spend the majority of their training time at low intensity (26 % of total weekly training time spent > 80 % heart rate peak) with periods of high intensity work interspersed (e.g., twice weekly track session). Chapter 4 reported prevailing fluid intake recommendations that recommend a specific fluid intake rate (i.e., $0.4\text{-}0.8 \text{ L}\cdot\text{hr}^{-1}$) are insufficient for elite marathon running evidenced by mathematical modelling and video analysis of drinking behaviours of the winners of a major city marathon. As a direct result of these findings it is proposed the best strategy for competitive marathon running in temperate conditions is to drink *ad libitum* as long as body mass loss is kept within acceptable limits, possibly < 3 %. The *ad libitum* drinking pattern supports observations of the elite Kenyan endurance runners reported in Chapter 2 and 3. Chapter 5 is the first study to report an accelerometer that can operate up to and including $20 \text{ km}\cdot\text{hr}^{-1}$. It was also found the combined use of tri-axial accelerometry and heart rate ($R^2 = 0.80$) predict $\dot{V}\text{O}_2$ better during fast running than either predictor alone (heart rate: $R^2 = 0.59$; accelerometry: $R^2 = 0.76$) and that subjects individually calibrated data further improves $\dot{V}\text{O}_2$ estimation ($R^2 = 0.99$).

Conclusions: The main findings of the research do not point to one single explanation for the Kenyan running phenomenon. The results suggest the explanation is likely to be complex in origin and that many individual factors may well aggregate to produce world class performance. It is proposed that future studies should focus on developing combined technologies such as accelerometry and heart rate in order to better understand physical activity patterns and energy expenditure of elite Kenyan endurance runners on a day-to-day basis over an extended period of time that incorporates multiple training cycles. It is also suggested that similar studies to those presented here in Chapters 2-3 are conducted in Ethiopia due to their recent staggering success in endurance running.

Declaration

I hereby declare that this thesis has been composed by myself, and that the work of which it is a record has been done by myself, except where specifically acknowledged. I also confirm that it has not been submitted in any previous application for a higher degree and that all sources of information have been specifically acknowledged by means of references.

Some of the results contained in this thesis have been published in peer-reviewed journals as follows:

1. Fudge B.W., Westerterp K.R., Kiplamai F.K., Onywera V.O., Boit M.K., Kayser B., and Pitsiladis Y.P. (2006). Evidence of negative energy balance using doubly labeled water in elite Kenyan endurance runners prior to competition. *British Journal of Nutrition* 95(1): 59-66.
2. Fudge B.W., Easton C., Wilson J., Irwin L., Clark J., Haddow O., Kayser B., and Pitsiladis Y.P. (2007). Estimation of oxygen uptake during fast running using accelerometry and heart rate. *Medicine and Science in Sports and Exercise* 39(1): 192-198.
3. Fudge B.W., Easton C., Kingsmore D., Kiplamai F.K., Onywera V.O., Westerterp K.R., Kayser B., Noakes T.D., and Pitsiladis Y.P. (2008). Elite Kenyan endurance runners are hydrated day-to-day with *ad libitum* fluid intake. *Medicine and Science in Sports and Exercise* 40(6): 1171-1179.
4. Fudge B.W. and Pitsiladis Y.P. (Manuscript submitted). Efficacy of new fluid intake recommendations for elite marathon running. *Medicine and Science in Sports and Exercise*.

Some of the results contained in this thesis have been presented at conferences as follows:

1. Fudge B.W., Westerterp K.R., Kiplamai F.K., Onywera V.O., Boit M.K., and Pitsiladis Y.P. (2005). Evidence of negative energy balance

in elite Kenyan endurance runners during intense high altitude training. *Medicine and Science in Sports and Exercise*, 37(5): S142.

2. Fudge B.W., Easton C., Kingsmore D., Kiplamai F.K., Onywera V.O., Westerterp K.R., Kayser B., Noakes T.D., and Pitsiladis Y.P. (2006). Hydration status and drinking behaviours of elite Kenyan endurance runners during intense training prior to competition. *Medicine and Science in Sports and Exercise*, 38(5): S328.
3. Wilson J., Haddow O., Clark J., Irwin L., Easton C., Fudge B.W., Kayser B., and Pitsiladis Y.P. (2006). Tri-axial accelerometry as a simple means to estimate fast running speeds. *Medicine and Science in Sports and Exercise*, 38(5): S501.

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1. Fudge B.W., Pitsiladis Y.P., Kingsmore D., Noakes T.D., and Kayser, B. (2006). Outstanding performances despite low fluid intakes: The Kenyan running experience. In *East African Running: Toward a Cross-disciplinary Perspective* (Edited by Pitsiladis Y.P., Bale J., Sharp C., and Noakes T.D.) United Kingdom: Routledge.
2. Fudge B.W., Kayser B., Westerterp K.R., and Pitsiladis Y.P. (2006). Energy balance and body composition of elite endurance runners: A hunter-gatherer phenotype. In *East African Running: Toward a Cross-disciplinary Perspective* (Edited by Pitsiladis Y.P., Bale J., Sharp C., and Noakes T.D.) United Kingdom: Routledge.

Signed

Barry W. Fudge

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List of Abbreviations

ACTN3	Alpha Actinin 3
ACE	Angiotensin Converting Enzyme
a.s.l.	Above Sea Level
ACSM	American Collge of Sports Medicine
AD·kg ⁻¹	Surface Area to Mass Ratio
AD	Body surface area
ADMR	Average Daily Metabolic Rate
BMI	Body Mass Index
BMR	Basal Metabolicc Rate
DNA	Deoxyribonucleic Acid
EE	Energy Expenditure
EI	Energy Intake
GPS	Global Positioning System
HR _{peak}	Peak Heart Rate
IAAF	International Association of Athletics Federations
IMMDA	International Marathon Medical Directors Association
K ⁺	Pottasium
MET	Metabolic Equivilant
mtDNA	Mitochondrial Deoxyribonucleic Acid
Na ⁺	Sodium
NAAT	National Association of Athletic Trainers
PAR	Physical Activity Ratio
RH	Relative Humidity
RPE	Rating of Perceived Exertion
SD	Standard Deviation
SEE	Standard Error of the Estimate
T _a	Ambient Temperature
T _i	Intestinal Temperature
$\dot{V}O_2$	Oxygen Uptake
$\dot{V}O_{2max}$	Maximal Oxygen Uptake
$\dot{V}O_{2peak}$	Peak Oxygen Uptake
$v\dot{V}O_{2max}$	Speed at Maximal Oxygen Uptake
T _i	Intestinal Temperature

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1

General Introduction

1.1 Kenyan Running Phenomenon

After the world witnessed Lazaro Chepkwoney, the first Kenyan endurance runner to race on European soil, drop out 15 laps into the 6 mile race due to fatigue at the English Amateur Athletics Association championships in 1954, no one would have thought Kenya would go on to be a leading force in world endurance running. Fourteen years on though Kenya displayed their running prowess by winning 8 medals ranging from 400 m relay to the 10 000 m at the 1968 Mexico City Olympic Games. Leading on from then, Kenyan success has grown year on year (Table 1.1). So much so that by 2004 the majority (51 %) of top ten yearly performances from 800 m to marathon were from Kenyan athletes compared to just 1 % in 1964 (data taken from IAAF all time outdoor list). In cross-country running the pattern of winning is even more staggering for a country that comprises just 0.5 % of the total world population. Since 1986 Kenya has won a remarkable 18 straight men's IAAF world cross-country crowns; Ethiopia eventually breaking the stranglehold by winning in 2004. Individually, three Kenyans have won 12 individual crowns since the cross-country championships inception in 1973. John Ngugi won five titles between 1986 and 1992, William Sigei won twice in 1993 and 1994, and previous marathon world record holder Paul Tergat won five straight titles between 1995 and 1999. At the highest level Kenyans have also excelled. Since 1964 Kenya has won 54 medals including 16 gold, 23 silver and

1.2. EXPLANATIONS

Table 1.1: Percentage of male Kenyan athletes in IAAF top ten yearly rankings in events ranging from 800 m-marathon. *Kenyan withdrawal from international competition due to a boycott.

Year	% In top ten
2004	51
2000	49
1996	47
1992	40
1988	16
1984	7
1980	*
1976	*
1972	7
1968	9
1964	1

15 bronze in events ranging from 400m to the marathon at summer Olympic Games. At IAAF World Championships the phenomenon is underlined with Kenya winning a staggering 72 medals since the first championship in 1983 in events ranging from 400 m to the marathon that places them 3rd in the all-time medal table behind the USA and Russia. The medal haul includes 27 gold, 22 silver and 23 bronze with the largest in any one championship being the most recent (Osaka, 2007) where Kenyan athletes won 5 gold, 3 silver and 5 bronze indicating their running prowess is by no means diminishing. Historically the success of Kenya in all major competitions is almost exclusively due to male runners but as Figure 1.1 demonstrates the increase in medals at the 2007 IAAF World Championships was due to a significant increase in the number of medals won by female Kenyan runners suggesting female Kenyan runners are beginning to excel on the world stage also.

1.2 Explanations

The staggering success of Kenya has prompted many explanations. It is however recognised that it is unlikely that one aspect alone can explain the

1.2. EXPLANATIONS

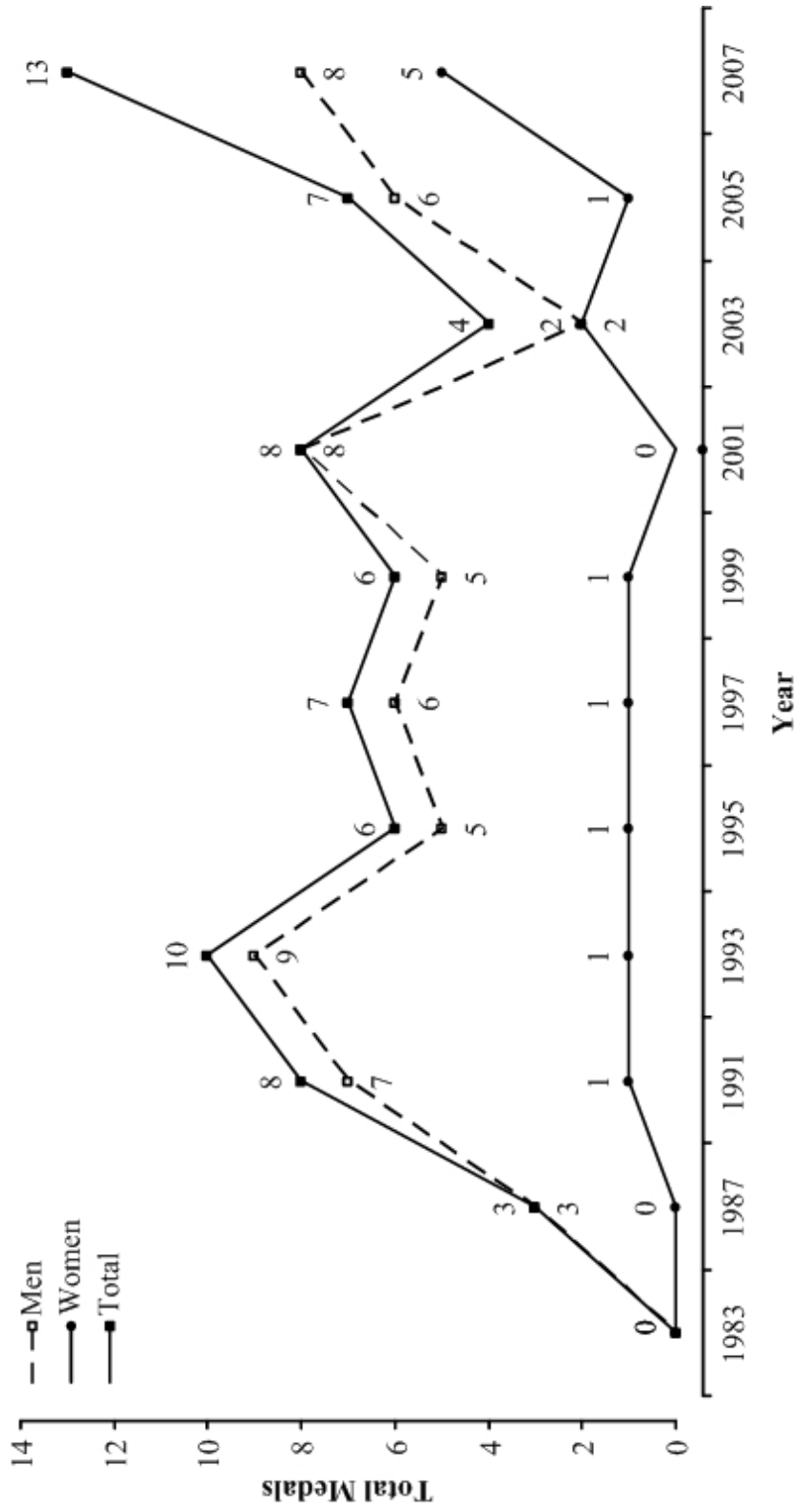


Figure 1.1: Number of medals won at IAAF World Championships by male and female Kenyan runners between 1983 and 2007.

Kenyan running phenomenon. Accordingly, Myburgh (2003) proposes that advancement in understanding of what makes elite athletes truly elite will require a multidisciplinary approach. For ease of discussion here however, explanations are broadly described as psychological, socio-cultural, physiological, genetic and environmental. The following sections address each of these areas in sequence.

1.2.1 Psychological explanations

The Kenyan running phenomenon is unequivocal; however there have been periods in history when other countries or groups of athletes have also had great success in distance running. For example Scandinavian runners such as Paavo Nurmi and Lasse Viren and British runners such as Sebastian Coe and Steve Ovett enjoyed considerable success in their own era. However, these feats by these individual athletes are exactly that, individual. That is they do not reflect a domination of endurance running like what we see today by east African runners as a whole. There are of course outstanding Kenyan athletes such as Kip Keino, Amos Biwott and more recently Paul Tergat who enjoyed a large amount of individual success but Kenyan athletes as a whole seem to do well even if not always in major competitions. To illustrate this point, in 1986 48.3 % of the top 20 performances in events ranging from 800 m to the marathon were from European athletes compared to 26.6 % by east Africans. By 2003 this changed to 11.7 % Europeans and 85.0 % east Africans, with the majority of these places filled by Kenyans (55.8 %) (data taken from IAAF all time outdoor list). It is this level of domination in endurance running that has led Hamilton (2000) to postulate that Kenya's past and present success that has resulted in a steadily growing dominance may in fact be self-perpetuating. That is, when athletes with ancestry other than east African stand on the start line next to those that do have east African ancestry they may well be psychologically primed for racing to be the first non-African runner rather than the overall race winner. This potential psychological advantage is the basis for the concept typically termed stereotype threat that is used by Baker and Horton (2003) to explain the

dominance of certain sports by certain groups. The crux of the argument is that the level of success in a certain situation/task may actually be dependant on the individual's perception of their own ability rather than their actual ability. In the context of endurance running, and indeed across a number of other sports, the perception is typically that black athletes are more athletically gifted than their white counterparts, a perception that has been augmented and driven by the media in more recent times (e.g., Entine, 2001). An example of the influence stereotype threat could have on the potential outcome of a sporting event is demonstrated in the study of Stone et al. (1999). Those authors gave black and white students the same golf task with three varying conditions. The three conditions were designed to measure the outcome when the perceived reasons for testing were natural athletic ability, sport intelligence and sport psychology. It was found that both black and white students scored equally for sport psychology, but black students outperformed white students when the test was perceived as a test of natural athletic ability, whereas when the test was perceived as a test of sport intelligence the whites outperformed the blacks. These results corroborate the stereotype threat thesis but it is still unclear what affect this trend may actually have when applied to endurance runners competing at the elite level.

1.2.2 Social-cultural explanations

Regardless of whether the continued success of Kenyan runners on the road and track racing circuits can be attributed to stereotype threat, many Kenyan athletes are capitalising from the sport and making a good living for their families and villages back home. Considering the average daily wage in Kenya is around \$1-2 the lucrative road and track racing circuits in Europe and America are very attractive. Indeed the motivation to compete for money is demonstrated by Onywera et al. (2006) who reported the main motivation for 33 % of Kenyan international athletes (n = 97) and 38 % of Kenyan national athletes (n = 307) to run was money compared to just 14 and 12 %, respectively who stated Olympic glory (Figure 1.2).

1.2. EXPLANATIONS

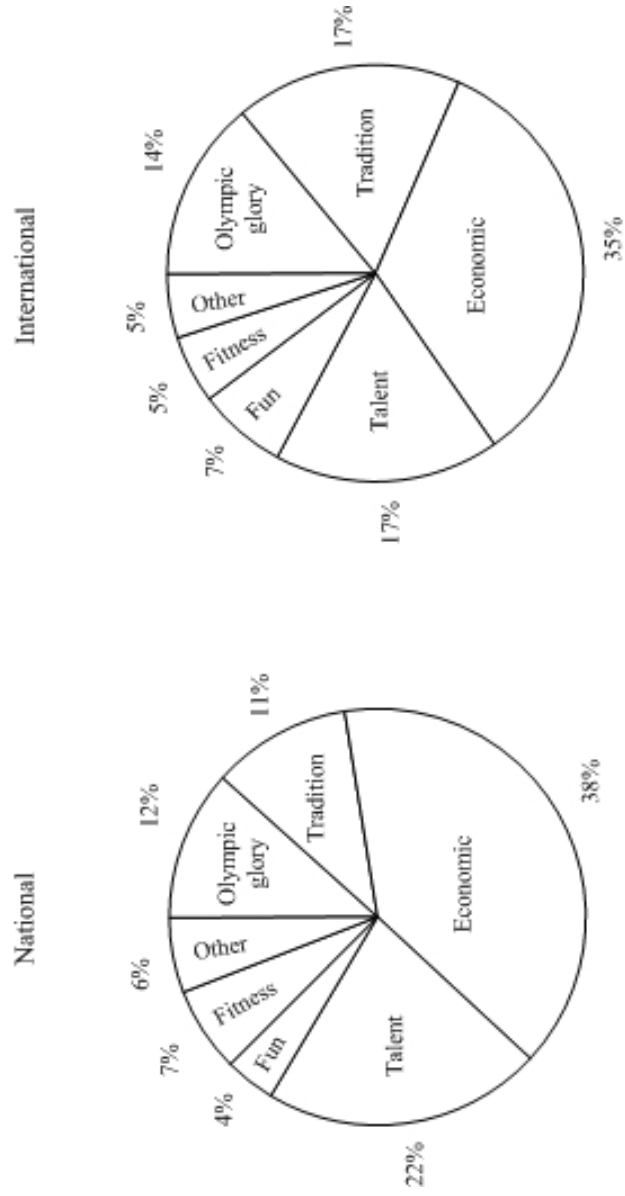


Figure 1.2: Motivation to become a competitive athlete. Both athlete groups showed similar reasons for becoming a competitive athlete ($p = 0.36$), with economic motivation most prevalent. Figure taken from Onywera et al., 2006.

1.2. EXPLANATIONS

However, although running for money may be a powerful motivator for some Kenyan athletes, it is by no means an explanation for the Kenyan running phenomenon as if it were that simple then significantly more athletes from other relatively poor countries would be cashing in also. Manners (1997) argue other aspects of Kenyan culture may have more of a connection to their running success. That author proposes that the history and customs of one ethnic group in particular, the Kalenjin, may provide important clues. The Kalenjin have a population of around 3 million (10 % of the total Kenyan population) yet have won about 75 % of the countries medals (Manners, 1997). To further highlight their extraordinary success, Manners (2006) reports that Kalenjin runners account for 50 % of the all time top 10 times in the 8 Olympic endurance running races alone. Data reported by Onywera et al. (2006) supports the performance data by demonstrating that among Kenyan national ($n = 307$) and international ($n = 97$) athletes, Kalenjin ethnicity is predominantly overrepresented (49 % and 75 %, respectively) compared to a control group made up of the general population ($n = 87$; 8 %). As a result Manners (1997) has highlighted their custom of male circumcision and cattle raiding as important factors in their success on the track and road. It follows that the ritual of public male circumcision of young boys about to enter adulthood instils courage, endurance and determination which when combined with the fierce tactics and large distances run during cattle raiding mean that a track or road race are relatively painless. These rituals are no longer practiced by the Kalenjin and opponents of this hypothesis may well argue that there has never been a cattle raider go on to be an elite runner. In addition Bale and Sang (1996) suggest that such rituals are not unique to just the Kalenjin when compared to Kenya's other diverse ethnic groups or indeed throughout the world and propose that the Kalenjin stereotype for successful endurance running has meant that this group has been particularly cultivated for talent and hence overrepresented in world endurance running. In addition, those authors stress the influence British colonisation had throughout east Africa that undoubtedly laid the foundations and instilled a competitive spirit that we see so overwhelmingly today.

1.2.3 Physiological explanations

While psychological and socio-cultural reasons, discussed above, may be important factors in shaping Kenyan runners, to compete and win at the elite level in endurance running it is undoubtedly necessary to have the correct physiology to do so. A pre-requisite for elite endurance running is certainly a high $\dot{V}O_{2max}$. Typically international male endurance runners have $\dot{V}O_{2max}$ values of 70-85 mL·kg⁻¹·min⁻¹ (Sjodin & Svedenhag, 1985) that are about 45 % higher than age and sex matched sedentary individuals (American College of Sports Medicine, 2006); females generally have values around 10 % lower due to lower haemoglobin and higher body fat levels (Davies & Thompson, 1979). $\dot{V}O_{2max}$ values of Kenyan runners reported in the scientific literature appear to support this principal (Saltin et al., 1995; Billat et al., 2003). It follows then that a high $\dot{V}O_{2max}$ is an important predictor of performance in a heterogeneous population (e.g., Sjodin & Svedenhag, 1985), it does not however appear to be so in a homogenous population such as a group of elite or sub-elite distance runners with comparatively similar $\dot{V}O_{2max}$ values (Conley & Krahenbuhl, 1980). For example, those authors (Conley & Krahenbuhl, 1980) reported the relationship between $\dot{V}O_{2max}$ and 10 km race time was $r = -0.12$ ($p = 0.35$) in 12 elite runners who had a narrow range of $\dot{V}O_{2max}$ values (66.1-73.7 mL·kg⁻¹·min⁻¹). This is in contrast to the relationship between $\dot{V}O_2$ at three submaximal running paces (241, 268, and 295 m·min⁻¹) and 10 km race time that were $r = 0.83, 0.82$ and 0.79 ($p < 0.01$), respectively. The submaximal $\dot{V}O_2$ at a given running velocity is typically termed running economy as it reflects the ratio of work done to energy expended. Runners with good running economy use less oxygen than runners with poor running economy at the same steady state speed (Saunders et al., 2004) and this can vary by as much as 30 % in runners with similar $\dot{V}O_{2max}$ values (Daniels, 1985). To illustrate the potential performance implications of good or poor running economy, Figure 1.3 depicts two international 10 km runners that have similar $\dot{V}O_{2max}$ values but significantly different running economies. Subject 1 is 1 min quicker over 10 km which is likely a result of better running economy (Saunders et al., 2004). Evidence

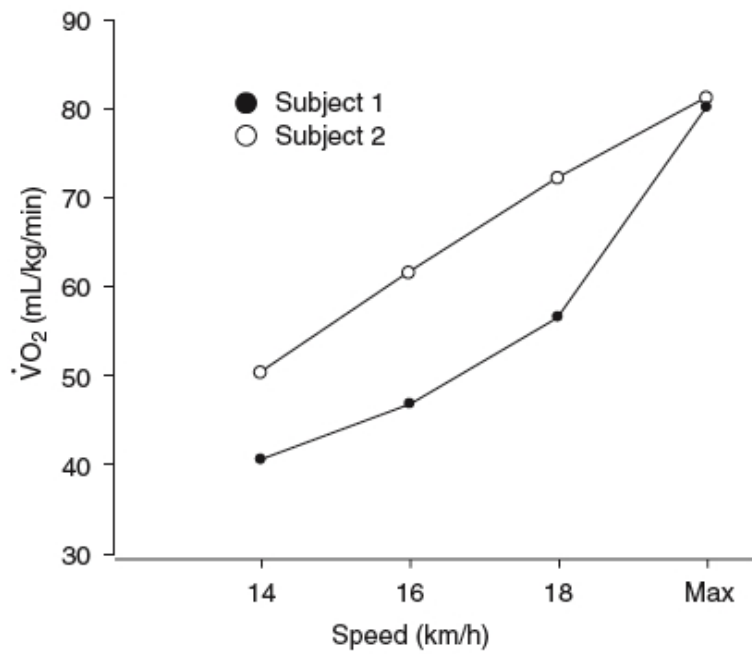


Figure 1.3: Comparison of $\dot{V}O_2$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) in two international caliber 10 km runners, one with good economy (i.e., subject 1) and the other with poor economy (i.e., subject 2). Figure taken from Saunders et al., 2004.

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favouring superior running economy in Kenyan endurance runners compared to Caucasian athletes is presented by Saltin et al. (1995). In that study, Kenyan runners exhibited better running economy compared to their Scandinavian counterparts whilst running at sub-maximal running speeds even though their absolute $\dot{V}O_{2max}$ was not different. Those authors also found the Kenyan runners had lower lactate and ammonia accumulation. Other East African runners have also been reported to have superior running economy compared to Caucasians. Lucia et al. (2006a) reported elite Eritrean runners had superior running economy compared to elite Spanish runners. This finding is further supported by Lucia et al. (2008) who reported the running economy of Eritrean Tadesse Zerisenay, IAAF World Cross Country Champion 2007, was 150 mL O₂·kg⁻¹·min⁻¹; the lowest ever published value to the present author's knowledge. Zerisenay's $\dot{V}O_{2max}$ is 83 mL·kg⁻¹·min⁻¹ and supports the principal of a high $\dot{V}O_{2max}$ for superior endurance running. However it may be that the reported values may be erroneous. Successful endurance running performance is essentially related to the interplay of three key physiological principles: $\dot{V}O_{2max}$, running economy and the fractional utilisation of the $\dot{V}O_{2max}$ (which is related to markers of blood lactate accumulation such as the lactate threshold and maximal lactate steady state) (Coyle, 1995). The interaction of $\dot{V}O_{2max}$ and running economy can be used to calculate the speed at $\dot{V}O_{2max}$ (i.e., $v\dot{V}O_{2max}$) (Morgan et al., 1989). For example, an athlete with an economy of 200 mL O₂·kg⁻¹·min⁻¹ and a $\dot{V}O_{2max}$ of 65 mL·kg⁻¹·min⁻¹ would have a $v\dot{V}O_{2max}$ of 19.5 km·hr⁻¹ (65 × 60) ÷ 200) (example taken from Jones, 2006). In the case of Zerinesay his calculated $v\dot{V}O_{2max}$ is 33.2 km·hr⁻¹. Assuming a typical fractional utilisation of $v\dot{V}O_{2max}$ of 97 % for a 5 km run, this would predict a time of 9 min 31 sec. Even considering a small error in the percentage fractional utilisation of $v\dot{V}O_{2max}$ assumed for 5 km running performance, this time is considerably quicker than the present world record set by Ethiopia's Kennisa Bekele of 12 min 37 sec and Zerinesay's own personal best of 12 min 59 sec. Nevertheless that study does convey the importance of excellent running economy for superior endurance running performance. Jones (2006) reports longitudinal laboratory physiological data of Paula Radcliffe, the current women's

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marathon world record holder, from 1992 to 2003. Over the 11 year period $\dot{V}O_{2max}$ remained relatively stable at approximately $70 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ but running economy on the other hand improved by 15 % ($205 \text{ ml O}_2\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ vs. $175 \text{ ml O}_2\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, respectively) that coincided with steady improvements in performances also. Hand in hand with an improvement in running economy was an increase in the speed at lactate threshold ($14\text{-}15 \text{ km}\cdot\text{hr}^{-1}$ vs. $17.5\text{-}18.5 \text{ km}\cdot\text{hr}^{-1}$, respectively) and the second lactate turn point ($16 \text{ km}\cdot\text{hr}^{-1}$ vs. $20 \text{ km}\cdot\text{hr}^{-1}$, respectively). This improvement in running economy over a significant number of years of training shares similarities with Lance Armstrong, seven times Tour de France Champion (Coyle, 2005b). In that study, Coyle (2005b) reported a 9 % improvement in cycling efficiency over a 7 year period. It has been suggested however that the timing of testing may have been a limitation of this study (i.e., tested 5 times over a 7 year period with only first and last test conducted in the same month of a given year) (Martin et al., 2005). Nevertheless, considering these studies (Conley & Krahenbuhl, 1980; Jones, 2006; Lucia et al., 2006a; Lucia et al., 2008) it may be concluded that a high $\dot{V}O_{2max}$ is indeed a requirement for superior endurance performance but major improvements in running economy, that may take several years of training, may be the major physiological improvement leading to world class performances in future years.

As mentioned there is evidence that Kenyan runners may pose superior running economy compared to Caucasians (Saltin et al., 1995). In his 2003 review, Larsen (2003) postulated that superior running economy of Kenyan runners may partly be explained by their small calf circumference. It follows that the minimum amount of mass around the extremities is conducive for running economy (Myers & Steudel, 1985; Jones et al., 1986). Myers and Steudel (1985) compared adding weight proximally to the centre of mass (i.e., the waist) and distally on the limbs (i.e., foot/ankle) during running and reported that the energy cost was increased by a factor of 1.5-5.5 by the latter. Similarly, Jones et al. (1986) measured the energy cost of wearing shoes of varying weight during running and walking and reported an average increment in $\dot{V}O_2$ cost of 1 % per 100 g of weight added. There is no scientific evidence of elite Kenyan endurance runners having smaller calf circumfer-

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ences just anecdotal observations. However there is emerging evidence albeit in Eritreans compared to their Spanish counterparts that east African runners do indeed have smaller calf circumferences (Lucia et al., 2006a). There is an important, often overlooked, issue to address here if generalising the results of subjects purely by skin colour though. This is discussed in the following section (section 1.2.4) but essentially the preconception that race, defined simply by skin colour, constitutes a genetically homogenous group is contrary to the finding of Yu et al. (2002) that there is more genetic variation within Africa than between Africa and Eurasia. In the athletic arena this is demonstrated by the fact that athletes of west African ancestry dominate sprint events whereas athletes of east African ancestry dominate endurance events; both populations have black skin but typically have physiologies at the opposite end of the spectrum. Therefore, the finding of smaller calf circumferences of Eritrean's compared to Caucasian Spanish runners (Lucia et al., 2006a) should be interpreted with caution. Similarly any inferences regarding running economy from that study (Lucia et al., 2006a) and others that have compared physiological parameters of black (South African) runners versus white runners (Bosch et al., 1990; Coetzer et al., 1993; Weston et al., 1999; Weston et al., 2000) should also be treated with caution. It was found that black South African runners have lower levels of lactate accumulation (Bosch et al., 1990; Coetzer et al., 1993; Weston et al., 1999), superior running economy (Weston et al., 2000), greater fatigue resistance (Coetzer et al., 1993; Weston et al., 1999) and greater fractional utilisation of $\dot{V}O_{2max}$ at race pace (Bosch et al., 1990; Coetzer et al., 1993; Weston et al., 2000) compared to white runners. Another overlooked factor with those studies is that the athletes were elite compared to the general population but they were not world class as none of the athletes studied have 10 km and 42.2 km race times that would qualify them to compete in the Olympic Games (Table 1.2). Larsen (2003) suggests that the Kenyans studied by Saltin et al. (1995) may have also been sub-elite apart from one (J. Machuka) who incidentally recorded the highest $\dot{V}O_{2max}$ ($84.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) compared to his Kenyan (mean: $79.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and Scandinavian (mean: $79.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) counterparts that is more in keeping with other elite Kenyan runners such as

Table 1.2: Top: Mean 10 km and 42.2 km race times of white and black subjects; Bottom: A-Standard qualifying time for 10 km and 42.2 km races in the Olympic Games plus the winning race times for the 2008 Beijing Olympic Games.

Study	White Runners		Black Runners	
	10 km Race Time	42.2 km Race Time	10 km Race Time	42.2 km Race Time
Coetzer et al., 1993	29 min 38 Sec		28 min 33 sec	
Weston et al., 1999	33 min 36 sec		32 min 48 sec	
Weston et al., 2000	32 min 00 sec		32 min 48 sec	
Bosch et al., 1990	2 hr 32 min 31 sec		2hr 30 min 42 sec	
<hr/>				
A-Standard Qualifying Time 2008 Beijing Olympics Winning Time				
10 km Race	27 min 50 sec		27 min 01 sec	
42.2 km Race	2 hr 15 min 00 sec		2 hr 06 min 32 sec	

Kipchoge Keino ($82.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Saltin & Astrand, 1967) and Henry Rono ($84.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (see Saltin et al., 1995). Therefore, on reflection there is very limited scientific data to conclude that Kenyan runners have unique physiological advantages over runners from other countries, particularly Caucasian runners. Rather it is clear to perform at a world-class level in endurance running a high $\dot{V}O_{2max}$, excellent running economy and an ability to run at a high percentage of $\dot{V}O_{2max}$ is desirable regardless of ethnicity. Myburgh (2003) proposes that conventional methods (i.e., physiology, biochemistry and histology) may be insufficient for assessing and distinguishing between elite and truly world-class athletes and exercise physiologist must embrace a multidisciplinary approach that also includes molecular biology and genetics.

1.2.4 Genetic explanations

Onywera et al. (2006) reported an over-representation of national (65 %) and international (82 %) runners from a distinct region in Kenya called the Rift Valley compared to controls (20 %) (Figure 1.4). Given that such a large percentage of the world's best endurance runners originate from one distinct region rather than being evenly distributed it is tempting to suggest that the Kenyan running phenomenon may in fact be genetically mediated (Entine, 2001; Larsen, 2003). Either genetic drift (in isolated populations this has the potential to cause certain alleles to increase or decrease in frequency compared to neighbouring populations) or selection for a particular phenotype such as endurance performance (if it offers an advantage in that environment) may result in individuals with a conducive genetic make up for endurance running (Scott & Pitsiladis, 2007). Evidence from unmeasured genotype approach studies that estimate the relative contribution of the genetic variation to the phenotype variance by studying twins as well as extended family data support a large genetic component in aerobic fitness parameters such as $\dot{V}O_{2max}$ (Klissouras, 1971; Bouchard et al., 1986; Fagard et al., 1991; Maes et al., 1996; Bouchard et al., 1998). In the first such study Klissouras (1971) estimated $\dot{V}O_{2max}$ heritability as high as 93

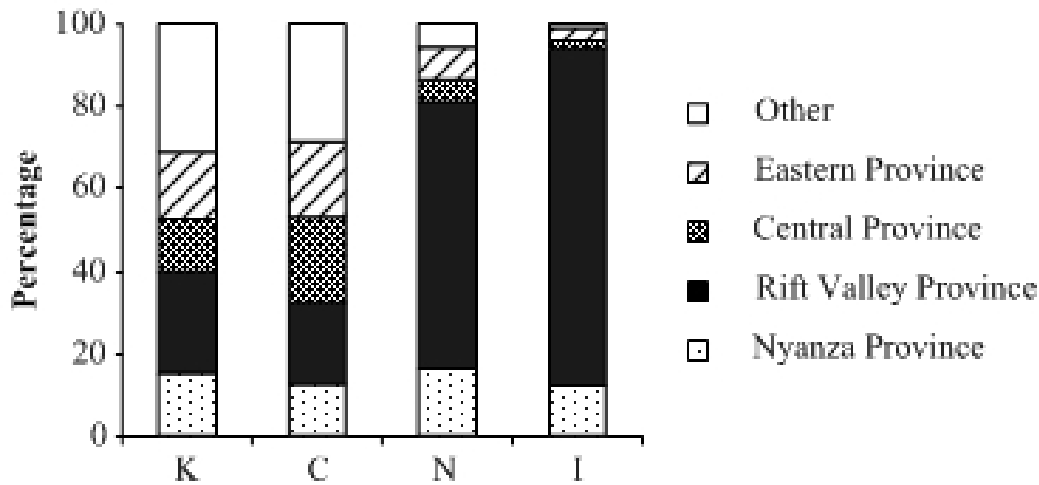


Figure 1.4: Regional distribution of subject groups and Kenyan population (K). Regional distribution of controls did not differ from the Kenyan population ($p = 0.23$), but differed from both national ($p < 0.001$) and international athletes ($p = 0.001$). National athletes also differed from international athletes ($p = 0.022$). Figure taken from Onywera et al., 2006.

%. Later studies corroborate this finding but to a lesser extent, Fagard et al. (1991) reported $\dot{V}O_{2max}$ heritability ranged from 66-77 % when considering body weight, skinfold thickness and time spent training. Similarly, Maes et al. (1996) reported the genetic component for $\dot{V}O_{2max}$ variation was 87 % for females and 69 % for males. In contrast, the heritability of $\dot{V}O_{2max}$ has been found to be significantly lower at 40 % (Bouchard et al., 1998). Those authors propose a more realistic value may actually be 10 % once environmental conditions are considered. More recently though in the HERITAGE Family Study (Bouchard et al., 1998), the biggest study of its kind, heritabilities for $\dot{V}O_{2max}$ ranged from 51-59 % depending on the type of adjustment performed (i.e., age, sex, body mass). Thus taking all these studies together it is clear that there is a genetic influence on $\dot{V}O_{2max}$ in the sedentary state with the estimate varying depending on which environmental factors are considered in the analysis. Considering elite endurance running performance requires a high $\dot{V}O_{2max}$, amongst other physiological factors (see section 1.2.3), intuitively elite endurance runners as a whole must therefore have the correct genetics compared to the general population. As a result

there is growing exploration of the genome to identify particular gene variants that may be responsible for this genetic effect using the measured genotype approach. The measured genotype approach includes direct measurement of genetic variation at the protein or DNA level and seeks to estimate the impact of allelic variation on the phenotypic variation (Klissouras, 2001). The most recent yearly publication that summarises genes and gene variants that contribute to human performance includes 165 autosomal gene entries, plus 5 on the X chromosome and a further 17 mitochondrial genes (Rankinen et al., 2006). Despite a growing number of candidate genes, only two nuclear candidate genes have been investigated in elite Kenyan runners, the ACE and ACTN3 genes (Scott et al., 2005a; Yang et al., 2007).

The ACE gene has an insertion polymorphism (I) in intron 16 of the gene that is associated with lower levels of circulating and tissue ACE than the deletion (D) (Rigat et al., 1990; Danser et al., 1995). It has been reported homozygotes for the I-allele, and therefore lower circulating ACE levels, is conducive for endurance performance (Gayagay et al., 1998; Montgomery et al., 1998; Myerson et al., 1999; Scanavini et al., 2002). For example Myerson et al. (1999) reported the frequency of the I-allele increased linearly with running distance in Australian runners (i.e., < 200 m, 400-3000 m or > 5000 m). Other studies have not found the same association (Rankinen et al., 2000a; Rankinen et al., 2000b). Investigation of 221 national and 70 international Kenyan athletes (Scott et al., 2005a) corroborates those other studies (Rankinen et al., 2000a; Rankinen et al., 2000b) as no association was found between ACE genotype (frequency of I-allele) and elite endurance athlete status compared to 85 control subjects (general Kenyan population), as shown in Figure 1.5. Unlike Caucasians, Africans have another variant that is closely associated with circulating ACE levels. The polymorphism A22982G in the ACE gene is normally in linkage disequilibrium in a Caucasian population but in Africans this is typically not the case. As a result this gene was also investigated (Scott et al., 2005a), but similarly it was found not to be associated with elite endurance status and genotype frequency. Thus in this elite Kenyan cohort the absence of an association between the I/D and A229282G polymorphisms with elite endurance athlete status suggests that

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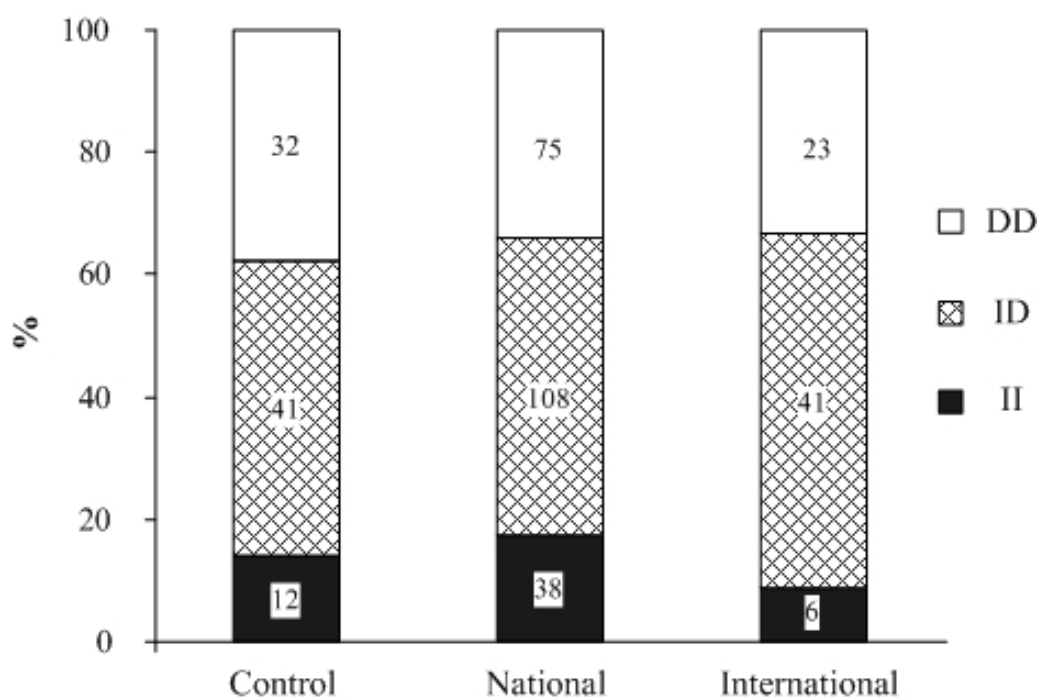


Figure 1.5: ACE I/D genotype frequencies in athletes and controls. The number of subjects for each genotype is indicated. No significant differences in genotype frequency were present between groups. Figure taken from Scott et al., 2005a.

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the ACE gene is not important or indeed partly responsible for the Kenyan running phenomenon.

Similar to the ACE gene, there are equivocal findings for the ACTN3 R577X polymorphism (Niemi & Majamaa, 2005; Lucia et al., 2006b; Paparini et al., 2007; Yang et al., 2007). The nonsense polymorphism R577X results in complete deficiency of α -actinin-3 protein in around 16 % of the global population (North et al., 1999). The α -actinin-3 deficient XX genotype has been found at low frequencies in power/strength athletes and at higher frequencies in elite female endurance runners compared to controls (Yang et al., 2007). This finding is supported in Finnish track and field athletes (Niemi & Majamaa, 2005) but not in elite Spanish endurance cyclists and runners (Lucia et al., 2006b) and elite Italian rowers (Paparini et al., 2007). In elite Kenyan endurance runners there was no association between the R577X polymorphism and elite endurance athlete status (Yang et al., 2007). In that study it was also found there was no association in elite Ethiopian endurance runners and also elite Nigerian sprinters suggesting the α -actinin-3 deficiency is not a major influence in African runners as a whole.

Investigation of mtDNA haplogroup distribution and its association with elite Kenyan endurance runners looks more promising (Scott et al., 2009). mtDNA is subject to a matrilinear pattern of inheritance and can be used to trace the ancestral origins of individuals or populations. Given the strong maternal influence of aerobic performance phenotypes such as $\dot{V}O_{2max}$ (e.g., Bouchard et al., 1998), this hints that mtDNA may in fact have some role in determination of aerobic endurance capacity. A hypothesised role of mtDNA in the determination of aerobic capacity is further supported as mtDNA encodes for a number of proteins that are vital for oxidative phosphorylation. It was found international athletes (n = 70) showed a significantly different distribution of mtDNA haplogroups relative to control subjects (general Kenyan population; n = 85) and national standard athletes (n = 221), displaying an excess of L0 haplogroups (controls: 15 %, national: 18 %, international: 30 %) and a dearth of L3* haplogroups (control: 48 %, national: 36 %, international: 26 %) (Scott et al., 2009). This may suggest that these haplogroups contain polymorphisms which may influence aerobic performance but it is

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unclear which variant(s) this could be as full genome sequencing have found greater than 40 polymorphisms (Maca-Meyer et al., 2001; Kivisild et al., 2004). In fact those authors (Scott et al., 2009) do stress that further investigation at a higher resolution is required as mutations in mtDNA have in the past been demonstrated to only subtly influence disease phenotypes (for a review see Herrnstadt & Howell, 2004). This study (Scott et al., 2009) does however represent a significant leap forward in beginning to understand the genetics of elite endurance athlete status but the significance of these results should be interpreted with care. For example Scott et al. (2005b) reported no association between mtDNA haplogroup and elite Ethiopian athlete status. The haplotype frequency differences are in fact large between the Kenyans and Ethiopians. For example, the frequency of the Eurasian haplogroup, R, is at less than 5 % frequency in Kenya but almost 30 % in Ethiopia. Such diversity in the Ethiopian's mtDNA and indeed the haplogroup frequency differences between Kenyans and Ethiopians highlights that east Africans are by no means a genetically distinct group. This supports the contention, as mentioned in the previous section (section 1.2.3), that results of investigations that have used skin colour as a surrogate for defining genetically homogenous groups (i.e., black versus white runners) should thus be interpreted with caution (Bosch et al., 1990; Coetzer et al., 1993; Weston et al., 1999, 2000; Lucia et al., 2006a). The findings from investigations of mtDNA (Scott et al., 2005b; Scott et al., 2009) and nuclear polymorphisms (Scott et al., 2005a; Yang et al., 2007) also demonstrate that the suggestion of African genetic superiority is not at present warranted. Williams and Folland (2008) recently calculated that the likelihood of a single individual in the world possessing the advantageous form of 23 polymorphisms that would lead to the ideal polygenic profile for endurance running is 0.00005 %. Given the genetic contribution to endurance performance (Klissouras, 1971; Bouchard et al., 1986; Fagard et al., 1991; Maes et al., 1996; Bouchard et al., 1998) this suggests there is significant unrealised potential in the human genome for endurance performance improvements and the prediction by Joyner (1991) of a 1 hr 58 min marathon may be plausible. However this investigation (Williams & Folland, 2008) further highlights that the success

of east African endurance runners is likely to be an interplay of complex genetic factors and their surrounding environment. Without this interaction between each genetic element and the environment, world class performance will never be achieved.

1.2.5 Environmental explanations

As mentioned in the previous section (Section 1.2.2; Figure 1.4), a major stimulus for a genetically mediated explanation for the Kenyan running phenomenon is the finding that many runners originate from a distinct region of Kenya (Onywera et al., 2006). The Rift Valley region is part of the Great Rift Valley that is approximately 6000 km in length running from northern Syria in Southwest Asia to central Mozambique in East Africa. The Rift Valley in Kenya is about 2000 m a.s.l. and it is this altitudinous location that has been speculated to be an important factor for their success. Many lowlanders sojourn to altitude as some coaches and athletes believe there may be a benefit for subsequent sea level performance. The scientific literature generally corroborates the anecdotal evidence with about a typical 1 % improvement in endurance performance reported (Levine & Stray-Gundersen, 1997; Nummela & Rusko, 2000; Hahn et al., 2001; Stray-Gundersen et al., 2001) when using the popular live high-train low model that was proposed by Levine and Stray-Gundersen (1997). As the name implies, the protocol requires sleeping at moderate altitude (1500-3000 m a.s.l.) and training at low altitude (< 1500 m a.s.l.); this allows maintenance of training intensities plus the proposed benefits of adaptations to altitude. It is unclear what the exact mechanism(s) may be for an improvement in subsequent sea level endurance performance but the primary explanations for an improvement are favourable alterations in haematological parameters and or improvements in running economy (for a review of the key arguments see Point:Counterpoint Gore & Hopkins, 2005; Levine & Stray-Gundersen, 2005). Another explanation may be a role for the brain (Noakes, 2005) but as yet this is undetermined. Regardless of the mechanism for an improvement in performance following a live high-train low regime it is difficult to extrapolate these find-

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ings to elite Kenyan endurance runners as they are indigenous high altitude natives who are born, raised and train at moderate altitude. Whether being able to train normally at moderate altitude affords them any benefit is unclear. Schmidt et al. (2002) reported, albeit it in cyclists, that endurance training and chronic altitude exposure (2600 m a.s.l.) combine synergistically to influence performance. Those authors propose that a high $\dot{V}O_{2max}$ at altitude would intuitively result in even higher values at sea level, this however is equivocal (e.g., Saltin et al., 1995; Favier et al., 1995). Thus the relative importance of chronic altitude exposure and endurance training on the Kenyan running phenomenon is unclear and therefore requires further investigation.

Another often cited explanation for the extraordinary success of Kenyan runners is that many Kenyan runners ran to school (Onywera et al., 2006). Onywera et al. (2006) reported 81 % of international athletes and 73 % of national level athletes ran to school compared to 22 % of control subjects (Figure 1.6). Those authors also reported that a higher proportion of international (51 %) and national athletes (42 %) travelled farther than 5 km to school each day than controls (25 %). In terms of the potential physiological effects of increased childhood physical activity, a previous investigation suggests that Kenyan boys who run to school have $\dot{V}O_{2max}$ levels 30 % higher than sedentary Kenyan boys (Saltin et al., 1995). Although the sample size was small (6 sedentary boys and 4 active boys), this does suggest that childhood physical activity may be important for developing aerobic capacity. Indeed this finding has since been corroborated in other studies that investigated the physiological characteristics of Nandi town boys compared to Nandi village boys (Larsen et al., 2004; Larsen et al., 2005). For example Larsen et al. (2004) found that $\dot{V}O_{2max}$ was significantly correlated to daily physical activity ($r = 0.55$, $p < 0.01$) with town boys having a mean $\dot{V}O_{2max}$ of $50 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ compared to $55 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in village boys. Hence childhood activity, particularly running, is likely to be an important factor in the development of aerobic capacity in many Kenyan runners; it is recognised however that there are many elite Kenyan runners who did not run or walk to school that have gone on to be very successful on the track and

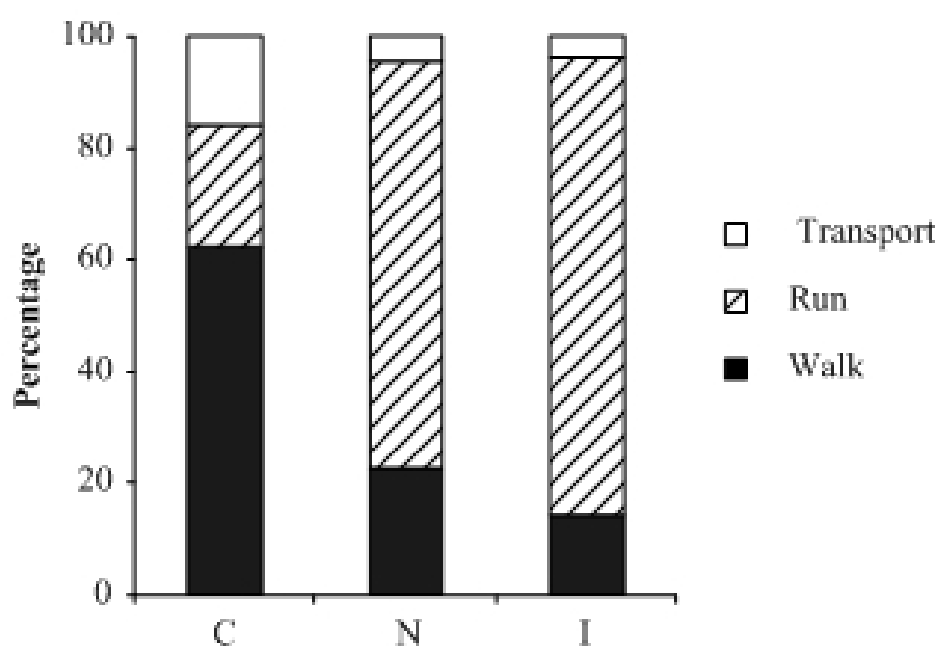


Figure 1.6: Method of travel to school. The percentage of participants using each method of travel to school is shown. Controls differed from both athlete groups (N: $p < 0.001$, I: $p < 0.001$). National and international athletes did not differ in their distribution ($p = 0.22$). Figure taken from Onywera et al., 2006.

road racing circuits (e.g., former men's marathon world record holder Paul Tergat).

Further investigation of the benefits of childhood physical activity is a growing area of investigation due to the increasing prevalence of childhood obesity in the UK and USA (Ebbeling et al., 2002). Accelerometry is a commonly used tool to assess physical activity in large epidemiology studies (Puyau et al., 2002; Reilly et al., 2004) with cut-off limits set for minimum desired physical activity per day. Recently Ojiambo et al. (2008) used accelerometry to objectively measure habitual physical activity levels in urban and rural Kenyan children from the region of Nandi. Those authors found rural children in the Nandi region of Kenya spent significantly more time doing moderate to vigorous activity (Puyau et al., 2002; Reilly et al., 2004) compared to urban children that may reflect a rural African lifestyle (e.g., cattle herding) and the necessity to travel long distances to school by walking or running (Onywera et al., 2006). The physical activity pattern of elite (adult) Kenyan endurance runners is however undetermined. Accelerometry may offer an insight, and in combination with heart rate may even offer the possibility of training quantification as it has previously been reported that combining methodologies improves the accuracy to predict physical activity and energy expenditure compared to their respective individual methods (Avons et al., 1988; Haskell et al., 1993; Moon & Butte, 1996; Luke et al., 1997; Eston et al., 1998). For example, Heskell et al. (1993) reported an R^2 value improved from 0.69 to 0.82 when arm motion, as assessed by accelerometry, was combined with heart rate monitoring during arm ergometer exercise. There is no doubt that the training process is a cornerstone of the development of world class athletes (Myburgh, 2003) and technology such as accelerometry and heart rate may allow a greater insight into this process on a larger scale due to its ease of use, viability to wear during training and its inexpensive cost. Combining methodologies thus seems promising, but it remains to be determined whether laboratory defined relationships between heart rate, accelerometer counts and $\dot{V}O_2$ will also apply in free-living situations (Strath et al., 2005).

Other factors that may have a significant impact on the effectiveness of

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training and subsequent performances of elite Kenyan endurance runners are diet and hydration practices. Indeed hydration status and muscle glycogen content are both important determinants of endurance performance. However, during the first half of the twentieth century it was typically believed and practiced by many sportsmen that consuming fluid, or indeed eating during an endurance event, was not necessary, but was in fact, a sign of weakness (Noakes, 1993). For example, Arthur Newton, an ultra-marathon runner holding several world records in events ranging from 50-130 miles in the early part of the twentieth century, commented: “Even in the warmest English weather, a twenty-six mile run ought to be manageable with no more than a single drink, or at most two” (Newton, 1948). But by the 1930 and 40s the effects of dehydration on exercise performance began to be studied (e.g., Adolph, 1938) with Pitts et al. (1944) first demonstrating that some fluid intake compared to no fluid intake improves long duration exercise. More recently there has been a vociferous debate regarding just how much fluid intake is required to maintain performance (e.g., Noakes, 2003). A recent review (Cheuvront and Haymes, 2001b) of the endurance running literature reported no effect of dehydration on core temperature for losses of body mass up to 3.1 % (mean: < 2.5 %), whereas a positive relationship was found between the level of dehydration and rise in core temperature when losses were greater than 3 % body mass. Coyle (2004) suggests that a range of 1 - 2 % may be tolerable in temperate conditions and that > 2 % may be tolerated in colder environments. A number of studies have reported no benefit of drinking enough fluid to replace sweat losses during exercise (Convertino et al., 1996) compared to *ad libitum* fluid intake during exercise. This has prompted the ACSM to recently update their Position Stand (ACSM, 2007) that now advocates drinking *ad libitum* (0.4-0.8 L·hr⁻¹) during exercise (with the lower value for slower, lighter individuals competing in cooler environments, and the higher value for faster, larger individuals competing in warmer environments) in order to prevent excessive dehydration (i.e., < 2 % body mass loss) and only aggressively ingest fluid and electrolytes before/after exercise if time does not permit consumption of normal meals and beverages to replace exercise induced fluid and electrolyte

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losses. The importance of muscle glycogen for endurance exercise capacity is also well recognised (Jeukendrup, 2004). Alterations in muscle glycogen availability have marked effects on muscle substrate utilization and exchange during exercise (Gollnick et al, 1972) with a linear relationship between pre-exercise muscle glycogen levels and its subsequent utilisation during exercise (Hargreaves, 1995). Late in a bout of continuous exercise, such as marathon running, ingested carbohydrate may become the predominant fuel source and it has been shown that carbohydrate ingestion delays fatigue during prolonged running and cycling and it also improves the power output that can be maintained (Millard-Stafford et al., 1995, 1997; Hargreaves, 1996). It is also known that depletion of muscle glycogen during exercise activates glycogen synthase and this activation is greater when muscle glycogen is lower (Zachwieja et al., 1991). More recently it has also been demonstrated that low muscle glycogen content actually results in greater transcriptional activation of a number of genes that are important for exercise adaptation (Keller et al., 2001; Febbraio et al., 2002; Pilegaard et al., 2002). Given the importance of carbohydrate, electrolyte and hydration status, such factors have been the subject of extensive investigation over the last several decades which have resulted in a plethora of recommendations for optimal nutrition for superior performance. An International Olympic Committee consensus statement on sports nutrition (Maughan et al., 2004) encapsulates the main findings of these studies and the importance of diet and hydration: “The amount, composition and timing of food intake can profoundly affect sports performance. Good nutritional practice will help athletes train hard, recover quickly and adapt more effectively with less risk of illness and injury. The right foods contribute not only to success in sport, but also to enjoyment of life.” Considering the phenomenal success of Kenyan runners and the importance of diet and hydration before, during and after exercise for optimal performance, these factors certainly warrant further investigation in elite Kenyan endurance runners.

The diet of 10 elite Kenyan endurance runners was investigated over a 7 day training period one week before the Kenyan national cross country trials (Onywera et al., 2004). Energy intake was assessed by weighed dietary

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record and was significantly lower than energy expenditure as assessed by PAR (Ainsworth et al., 2000) (EI: $12\,486 \pm 1225 \text{ kJ}\cdot\text{d}^{-1}$ vs. PAR: $15\,069 \pm 497 \text{ kJ}\cdot\text{d}^{-1}$; mean \pm SD), suggesting that the athletes were in negative energy balance prior to competition. The mean difference of $2585 \text{ kJ}\cdot\text{d}^{-1}$ between energy intake and energy expenditure accounted precisely for the loss in body mass over the 7 day period (BM: $58.9 \pm 2.7 \text{ kg}$ vs. $58.3 \pm 2.6 \text{ kg}$; where 1 kg was assumed to be 30 000 kJ; (Westerterp et al., 1995)). These results corroborated those of an earlier study that evaluated the nutrient intake of Kenyan runners (Mukeshi & Thairu, 1993). The reported energy intake in that study was low (EI: $9781 \text{ kJ}\cdot\text{d}^{-1}$) and considering the athletes were training intensely, the validity of these results were questioned by the authors of the only other study to have assessed the dietary intake of Kenyan runners (Christensen et al., 2002). Those authors studied 12 adolescent (15-20 y) male Kenyan runners during a 2 week period and found the athletes to be in energy balance (EI: $13\,186 \pm 274 \text{ kJ}\cdot\text{d}^{-1}$ vs. EE: $13\,210 \pm 283 \text{ kJ}\cdot\text{d}^{-1}$). However, those athletes were regarded as promising junior athletes competing at regional level and were studied during a period of regular training. Unfortunately none of the previous studies used the gold standard doubly labeled water method to measure energy expenditure prior to major competition and so the findings are equivocal. Hence further investigation of the diet of elite Kenyan endurance runners is required so that firm conclusions can be made regarding performance implications.

Onywera et al. (2004) found athletes did not consume fluids before or during training, and only infrequently consumed modest amounts of fluids immediately after training. This contributed to low daily fluid intake, mainly water ($1.1 \pm 0.3 \text{ L}$) and milky tea ($1.2 \pm 0.3 \text{ L}$). This fluid intake and drinking habits are substantially less than previous recommendations of the American College of Sports Medicine (Convertino et al., 1996), which were 0.4-0.6 L of fluid 2-3 hr before exercise, $0.6\text{-}1.2 \text{ L}\cdot\text{hr}^{-1}$ while exercising, aiming at total replacement of all fluid lost during exercise, or at least up to the maximal amount tolerated; a pattern and volume of fluid replacement similar to that recommended by the NAAT (Binkley et al., 2002), and the US Army (Mountain et al., 1999). The drinking behaviours (i.e., *ad libitum*) reported previ-

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ously in elite Kenyan endurance runners (Onywera et al., 2004) are consistent with empirical observations that elite athletes typically do not adhere to prevailing fluid intake recommendations (for a review see reference Cheuvront & Haymes, 2001b). Recently the ACSM has replaced their prior Position Stand (Convertino et al., 1996) with an updated version on exercise and fluid replacement (American College of Sports Medicine, 2007) that advocates drinking *ad libitum* ($0.4\text{-}0.8\text{ L}\cdot\text{hr}^{-1}$) during exercise (with the lower value for slower, lighter individuals competing in cooler environments, and the higher value for faster, larger individuals competing in warmer environments) in order to prevent excessive dehydration (i.e., $< 2\%$ body mass loss), and only aggressively ingest fluid and electrolytes before/after exercise if time does not permit consumption of normal meals and beverages to replace exercise induced fluid and electrolyte losses. These new recommendations (American College of Sports Medicine, 2007) appear to be more in keeping with previous observations of elite Kenyan endurance runners (Onywera et al., 2004) though their hydration status day-to-day during an important training period remains to be determined. Furthermore, little is known of what today's best elite athletes actually drink during racing (for a review of the marathon running literature see reference Cheuvront & Haymes, 2001b). The ACSM's new guidelines represent a compromise between preventing dehydration that may impact upon performance (i.e., $> 2\%$ body mass loss from water deficit (Wyndham & Strydom, 1969; Cheuvront & Haymes, 2001b; Coyle, 2004; Fudge et al., 2006a; American College of Sports Medicine, 2007) versus preventing excessive ingestion of fluid that may result in hyponatraemia (i.e., serum sodium concentration $< 130\text{ mmol}\cdot\text{L}^{-1}$ (Almond et al., 2005; Hew-Butler et al., 2005). The rationale for drinking *ad libitum* $0.4\text{-}0.8\text{ L}\cdot\text{hr}^{-1}$ during exercise is based on a theoretical study modelling data that reflects the general population (Montain et al., 2006). It does not take into consideration the fluid requirements of elite endurance runners in its calculations (e.g., maximum running speed calculated was $15\text{ km}\cdot\text{hr}^{-1}$ whereas the winner of a major city marathon will have to run $> 19\text{ km}\cdot\text{hr}^{-1}$). Therefore the fluid intake behaviours of the world's leading endurance runners during racing also require investigation.

1.3 Aims and Objectives

Given the staggering success of Kenyan endurance runners on the road and track and the possible role environmental factors may play in their success, the main objectives of the following research were:

1. To determine the composition of elite Kenyan endurance runners diet and assess their energy balance status prior to major competition using “gold standard” methods. The results will allow direct comparison to established guidelines on optimal nutrition and from this the performance implications may be considered.
2. To establish lifestyle practices of elite Kenyan endurance runners prior to major competition that will allow an insight in to the preparation of some of the best athletes in the world.
3. To ascertain the hydration status of elite Kenyan endurance runners during an important training period and directly compare these results to traditional paradigms and current thinking on optimal fluid intake for superior endurance running performance. From this the performance implications may be considered.
4. To investigate the training process leading to world class performance by quantifying training load in the lead up to major competition.
5. To determine the fluid intake behaviours of the world’s best marathon runners during racing. This will allow an insight into current practices of elite runners that will act as a benchmark and comparison of current fluid intake guidelines.
6. To validate and combine existing technologies of heart rate and accelerometry for quantifying energy expenditure during free living conditions. This may allow future investigations a greater insight in to the lifestyle and training practices of elite Kenyan endurance runners.

2

Energy balance and lifestyle practices of elite Kenyan endurance runners

2.1 Introduction

Male Kenyan middle- and long-distance runners have dominated athletics since the 1960s. Until recently, diet and nutrition in these athletes had not been comprehensively investigated. The diet of 10 elite Kenyan endurance runners was investigated over a 7 day training period one week before the Kenyan national cross country trials (Onywera et al., 2004). Energy intake was assessed by weighed dietary record and was significantly lower than energy expenditure as assessed by PAR (EI: $12\,486 \pm 1225 \text{ kJ}\cdot\text{d}^{-1}$ vs. PAR: $15\,069 \pm 497 \text{ kJ}\cdot\text{d}^{-1}$; mean \pm SD), suggesting that the athletes were in negative energy balance prior to competition. The mean difference of $2585 \text{ kJ}\cdot\text{d}^{-1}$ between energy intake and energy expenditure accounted precisely for the loss in body mass over the 7 day period (BM: $58.9 \pm 2.7 \text{ kg}$ vs. $58.3 \pm 2.6 \text{ kg}$; where 1 kg was assumed to be 30 000 kJ; (Westerterp et al., 1995)). These results corroborated those of an earlier study that evaluated the nutrient intake of Kenyan runners (Mukeshi & Thairu, 1993). The reported energy intake in that study was low (EI: $9781 \text{ kJ}\cdot\text{d}^{-1}$) and considering the athletes were training intensely, the validity of these results were questioned by the authors of the only other study to have assessed the dietary intake of Kenyan runners (Christensen et al., 2002). Those authors studied 12 adoles-

cent (15-20 y) male Kenyan runners during a 2 week period and found the athletes to be in energy balance (EI: $13\,186 \pm 274 \text{ kJ}\cdot\text{d}^{-1}$ vs. EE: $13\,210 \pm 283 \text{ kJ}\cdot\text{d}^{-1}$). However, those athletes were regarded as promising junior athletes competing at regional level and were studied during a period of regular training.

The dietary habits and energy balance of elite senior Kenyan endurance runners have not been comprehensively studied in the days prior to major competition. Since none of the previous studies used the doubly labeled water method to measure energy expenditure, the aim of the present study was to directly measure the energy balance status of elite Kenyan endurance runners prior to major competition using gold-standard methods. Taking previous results into consideration we hypothesized that elite Kenyan endurance runners may be in negative energy balance prior to major competition.

2.2 Methods

2.2.1 Subjects

Nine male elite Kenyan endurance runners with a mean (\pm SD) age of 21 ± 2 y and percent body fat of 7.1 ± 2.5 % were invited to participate in this study (Table 2.1). All athletes gave their written informed consent prior to participating in the study. The research protocol was in accordance with the Helsinki declaration and was approved by the local Kenyan authorities in Nairobi, Kenya. The athletes were highly trained and included World, Olympic and Junior Champions frequently competing in major national and international middle- and long-distance running events. At the time of the study the athletes were based at a high altitude training camp (Global Sports Training Camp, Kaptagat, Eldoret, Kenya) situated in the North Rift Valley (altitude: 2200 m a.s.l., daytime T_a : 8-24 °C, RH: 31-100 %). All athletes belonged to one of eight small tribes, collectively known as the Kalenjin (i.e., Nandi, Kipsigis, Tugen, Keiyo, Marakwet, Pokot, Terik and the Sabaot). The Kalenjin have a population of approximately 3 million, or about 10 % of the Kenyan population, yet have won about 75 % of all major distance

running races in Kenya (Pitsiladis et al., 2004). The athletes were in peak physical condition as the investigation was undertaken in the week before the Kenyan Olympic trials and 5 months before the Athens 2004 Olympics.

2.2.2 Experimental design

Subjects were monitored for a period of 7 training days during the course of a standard training week prior to major competition. Organised training runs were carried out mostly in groups that were influenced by athletic discipline and instructions from coach/manager. Training schedules typically incorporated up to 2 variable distance-training sessions per day (i.e., a morning run and a non-compulsory afternoon run) and 2 interval-training sessions per week (i.e., mid-morning run).

2.2.3 Experimental procedures

Food and water intake

In order to ensure a representative sample of the dietary habits, athletes were asked to follow their normal diet whilst weighing (individual digital weighing scales readable to 1 g were used) and recording all food and water consumed for 7 consecutive days using a nutritional diary. The manager of the high altitude training camp assured investigators that the 7 day dietary intake was typical of the diet during a period of intense training. Meals and snacks were served at standard times of day: breakfast (08:00), mid-morning snack (10:00), lunch (13:00), afternoon snack (16:00), and dinner (19:00); the athletes selected their portion sizes *ad libitum* from the provided food. The athletes were also required to weigh and record all food and water consumed away from the camp. Data from the nutritional diaries were used to calculate the intake of total energy, carbohydrate, fat, protein, and water using a computerised version of the National Food Composition Tables of Kenya (Sehmi, 1993). Total water intake was determined by combining the reported dietary intake of water with the estimated metabolic water. Metabolic water was determined by multiplying measured energy expenditure by the fraction

Table 2.1: Physical characteristics of elite Kenyan endurance runners.

Subject	Age	Height (cm)	Start BM (kg)	End BM (kg)	Δ BM (kg)	BMI (kg·m ⁻²)	Start %BF	End %BF	Δ BF %
1	24	173	62.5	62.0	-0.5	20.7	8.0	7.0	-1.0
2	23	175	54.8	54.6	-0.2	17.8	6.5	7.0	0.5
3	21	178	56.7	55.6	-1.1	17.5	6.0	6.0	0.0
4	25	171	54.9	54.8	-0.1	18.7	9.0	9.0	0.0
5	23	176	54.8	54.4	-0.4	17.6	5.0	5.5	0.5
6	18	171	51.0	49.3	-1.7	16.9	6.0	4.5	-1.5
7	19	179	53.8	55.0	1.2	17.2	3.5	4.5	1.0
8	20	173	55.2	55.5	0.3	18.5	8.0	8.0	0.0
9	20	172	60.1	59.8	-0.3	20.2	12.0	11.0	-1.0
Mean	21	174	56.0	55.7	-0.3	18.3	7.1	6.9	-0.1
SD	2	2.9	3.4	3.6	0.8	1.3	2.5	2.1	0.8

of energy in the diet from carbohydrate, protein, and fat (data derived from the 7 day nutritional diaries). The oxidation of carbohydrate, protein and fat yields 0.60, 0.41, and 1.07 mL water·g⁻¹, respectively (Fjeld et al., 1988). In the calculations of the doubly labeled water method we corrected for the effect on isotope abundance changes resulting from the exchange of water in the respiratory system. If on a net basis water is lost in the expired air, inspired water is partly taken up in the respiratory system thus diluting the doubly labeled water induced increases in isotope abundances. Inspired water was calculated as:

Inspiratory water intake (g·d⁻¹) = Respiratory volume × Absolute humidity ÷ 1000 (Fjeld et al., 1988)

Where respiratory volume (L·d⁻¹) was estimated using carbon dioxide production (rCO₂) derived from the measurement of energy expenditure by doubly labeled water, assuming that 3.5 % of expired air was CO₂. The reported mean absolute and relative humidity was 10.2 mg·L⁻¹ (range: 2.6-21.7 mg·L⁻¹) and 75 % (range: 31-100 %) respectively at a mean ambient temperature of 16 °C (range: 8-24 °C).

Body mass, energy expenditure and water loss

On the morning (05:30) of the first and final day of the recording week, body mass and percent body fat was measured by bio-electrical impedance (Tanita Body Fat Analyzer, Tanita Corporation of America, Inc., IL., USA). The estimates of percent body fat provided by the manufacturers software were reported (the prediction equation used by the Tanita system is not disclosed by the manufacturer so the equation used cannot be presented). Measurements were made after the subjects had voided and before any food or drinks had been consumed. Energy expenditure was measured by doubly labeled water (EE_{DLW}) (see Westerterp et al., 1986). Water loss was calculated from deuterium elimination in accordance with the doubly labeled water method. Athletes were given a weighed dose of a mixture of 99.84 atom% ²H₂O in

10.05 atom% H_2^{18}O , on the evening of day 0 in order to increase baseline levels to ≥ 300 ppm for ^2H and ≥ 2300 ppm for ^{18}O . A background urine sample was collected on the evening of day 0 and additional urine samples were collected on day 1 (from the second daily void and in the evening), the morning and evening of day 3, and the morning and evening of day 7. A correction factor for the change in isotope dilution space was applied, as calculated from the difference between initial and final study body mass of the athletes, assuming the change in body water was linear and proportional to the change of body mass. Doubly labeled water measured CO_2 production was converted to energy expenditure with an energy equivalent calculated from the macronutrient composition of the diet. BMR was estimated using the Schofield Equation (Schofield, 1985). A significant difference between energy intake and energy expenditure required the calculation of percent underreporting and undereating as follows:

$$\text{Underreporting} = [(\text{EI} - \text{EE}) \div \text{EE}] \times 100 \% \text{ (Goris \& Westerterp, 1999)}$$

$$\text{Undereating} = [(\Delta \text{BM} \times 30\,000 \text{ kJ}\cdot 7\text{d}^{-1}) \div \text{EE}] \times 100 \% \text{ (Lissner et al., 1998)}$$

Physical activity and training

The ActiGraph activity monitor (Manufacturing Technology, Inc., Florida, USA) and PAR were used to assess physical activity (Ainsworth et al., 2000). The activity monitor was secured to the right hip with a belt after being initialized according to the manufacturer's specifications. The data were analysed according to Freedson et al. (1998) and Ainsworth et al. (2000). In short, waking time was subdivided in categories of activity ranging from light to very heavy and relaxing to fast running, respectively. Subjects were also instructed to record in detail their individual activities each day (including type, intensity and duration of activity). The Compendium of Physical Activity (Ainsworth et al., 2000) was used to assign specific activities with

their respective MET. The Timex Bodylink™ system (Timex Corporation, Middlebury, CT, USA) was used to accurately determine the distance, time and speed of the training runs by utilizing GPS technology. Athletes wore the Timex Performance device during individual and group runs.

2.2.4 Data analysis

Data are expressed as the mean \pm SD or median (range) as appropriate following a test for the normality of distribution. Paired t-tests were used to compare energy intake vs. energy expenditure, total water intake vs. water loss, and starting body mass vs. final body mass. The Pearson product moment correlation coefficient (r) was used to assess the relationship between energy intake and expenditure, and also the relationship between the percent underreporting and the percent energy derived from carbohydrate, protein and fat to determine whether there was selective underreporting. Statistical power calculations (80 % power) were carried out using energy intake vs. energy expenditure data from Onywera et al. (2004). Statistical significance was set at $p < 0.05$.

2.3 Results

Values for energy intake, energy expenditure, BMR, ADMR/BMR, change in body mass, BMI, water intake, water loss, metabolic water and inspiratory water intake are shown in Table 2.2. The reported energy intake of $13\,241 \pm 1330 \text{ kJ}\cdot\text{d}^{-1}$ was significantly lower than the measured energy expenditure (EE_{DLW} : $14\,611 \pm 1043 \text{ kJ}\cdot\text{d}^{-1}$; $p = 0.046$). The value calculated for percent underreporting was 13 % (range: -24-9 %). There was no correlation between energy intake and expenditure ($r = -0.071$; $p = 0.855$) as shown in Figure 2.1; line of identity and $\pm 2SD$ are also shown.

The initial body mass of $56.0 \pm 3.4 \text{ kg}$ was not significantly different from the final body mass ($55.7 \pm 3.6 \text{ kg}$; $p = 0.285$); however the vast majority of subjects lost body mass over the 7 day recording period. Percent underreporting was calculated at 9 % (range: -54-39 %). The mean difference in

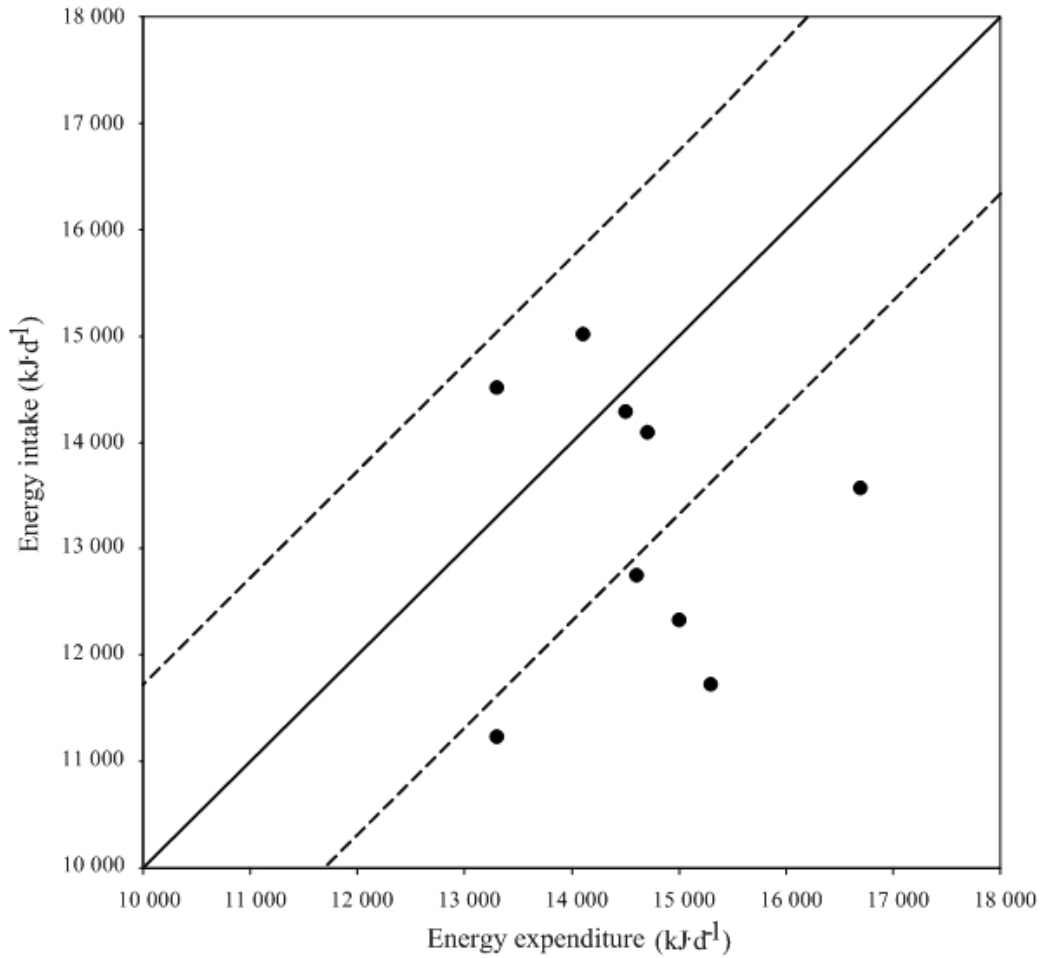


Figure 2.1: Relationship between energy intakes from weighed dietary intake and energy expenditures measured with doubly labeled water in elite Kenyan endurance runners. Solid line: line of identity, dashed lines: $\pm 2SD$.

2.3. RESULTS

Table 2.2: Energy and metabolic parameters over the 7 day recording period.

	Mean	SD
EI (kJ·d ⁻¹)	13 241	1330
EE _{DLW} (kJ·d ⁻¹)*	14 611	1043
BMR (kJ·d ⁻¹)	6408	224
ADMR/BMR	2.3	0.1
Δ BM (kg·wk ⁻¹)	-0.3	0.8
BMI (kg·m ⁻²)	18.4	1.3
Water Consumed (L·d ⁻¹)	3.5	0.6
Metabolic water (L·d ⁻¹)	0.5	0.04
Inspiratory water (L·d ⁻¹)	0.2	0.01
Total water intake (L·d ⁻¹)	4.2	0.6
Water Loss (L·d ⁻¹)	4.5	0.8

Key: *significantly different from EI, $p = 0.046$.

energy intake (EI: $13\,241 \pm 1330$ kJ·d⁻¹) and energy expenditure (EE_{DLW}: $14\,611 \pm 1043$ kJ·d⁻¹; $p = 0.046$) was 1370 ± 1738 kJ·d⁻¹; when calculated over the 7 day period this equated to approximately 9590 kJ, or alternatively, 0.3 kg (where 1 kg was assumed to be 30 000 kJ; (Westerterp et al., 1995)). Total water intake (including reported water intake, calculated metabolic water and inspiratory water) was 4.2 ± 0.6 L·d⁻¹ and was not significantly different to the measured water loss (4.5 ± 0.8 L·d⁻¹; $p = 0.496$).

Approximately 77 % of the energy consumed by the athletes was attributable to vegetable sources; the remaining 23 % coming from animal sources (Table 2.3). The diet consisted mainly of carbohydrate (67.3 ± 7.8 %, 9.8 g·kg⁻¹BM·d⁻¹) compared with protein (15.3 ± 4.0 %, 2.2 g·kg⁻¹BM·d⁻¹) and fat (17.4 ± 3.9 %, 1.1 g·kg⁻¹BM·d⁻¹). Daily variation in the macronutrient composition of the athlete's diet was observed during the 7 day experimental period. The reported percentages of energy from carbohydrate ($r = 0.085$; $p = 0.828$), protein ($r = 0.019$; $p = 0.962$) and fat ($r = 0.187$; $p = 0.629$) were not related to percent underreporting. Fluid intake was modest and consisted mainly of water (0.9 ± 0.5 L·d⁻¹) and milky tea (0.9 ± 0.3 L·d⁻¹) with a small contribution from the intake of other fluids such as soft drinks (0.4 ± 0.2 L·d⁻¹).

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Table 2.3: Food sources as percentage of daily intake of each macronutrient.

	Energy (%)	Carbohydrate (%)	Fat (%)	Protein (%)
Sugar ¹	10	15	0	0
Bread	9	10	3	8
Rice	9	12	2	6
Potatoes	3	4	0	2
Beans	2	2	0	5
Kales	2	2	0	10
Milk	12	5	35	17
Maize	1	2	1	1
Meat	11	0	28	38
Ugali	19	25	5	6
Chapatti	7	6	14	4
Other ²	15	17	12	3
Animal	23	5	63	55
Vegetable	77	95	37	45
	Energy (kJ)	Carbohydrate (g)	Fat (g)	Protein (g)
Mean	13 241	552	61	122
SD	1330	81	15	33

Key: ¹Sugar consumed in tea and porridge; ²Food sources that contribute less than 1 % to total energy intake.

Time spent in activity during waking hours estimated using accelerometry and PAR is presented in Table 2.4. The reported time spent in light, moderate, hard and very hard activity as determined by accelerometry was $82 \pm 3 \%$, $11 \pm 2 \%$, $6 \pm 3 \%$, and $1 \pm 1 \%$ respectively. Time spent relaxing, in light activity, slow running ($8\text{-}13.6 \text{ km}\cdot\text{hr}^{-1}$), moderate running ($13.7\text{-}17.3 \text{ km}\cdot\text{hr}^{-1}$), and fast running ($\geq 17.4 \text{ km}\cdot\text{hr}^{-1}$) as estimated using the PAR method (Ainsworth et al., 2000) was $82 \pm 6 \%$, $8 \pm 6 \%$, $3 \pm 1 \%$, $5 \pm 1 \%$, $2 \pm 1 \%$, respectively. The morning run (06:00) comprised a long run of $10.6 \pm 3.8 \text{ km}$ carried out at either moderate or fast running pace (average running speed: $15.1 \text{ km}\cdot\text{hr}^{-1}$, maximum: $24.0 \text{ km}\cdot\text{hr}^{-1}$) depending on instructions received from the coach/manager (distances and speed determined by the Timex Bodylink™ system). The late-morning (11:00) training session was not compulsory and included light exercise such as jogging, stretching or walking. Athletes completed at least one weekly high-intensity interval training session on a 400 m dirt track. Typical interval training sessions included 4 times 600 m at 1 min 30 sec pace and 6 times 400 m at 58 sec pace for the middle distance runners or 6 times 600 m at 1 min 33 sec pace and 6 times 400 m at 59 sec pace for the long distance runners. The late-afternoon run (17:00) was a short run ($6.2 \pm 1.3 \text{ km}$) usually run at an easier running speed (average running speed: $14.7 \text{ km}\cdot\text{hr}^{-1}$ maximum: $15.2 \text{ km}\cdot\text{hr}^{-1}$). Weekly training distance was in excess of 117 km (note this does not include the late morning training session). The remainder of the time at the training camp was spent resting, eating, and washing. Some athletes went home at the weekend and completed individual training runs as prescribed by the coach/manager.

2.4 Discussion

The average energy intake of the elite Kenyan runners investigated was lower than energy expenditure (i.e., $13\,241 \pm 1330 \text{ kJ}\cdot\text{d}^{-1}$ vs. $14\,611 \pm 1043 \text{ kJ}\cdot\text{d}^{-1}$; $p = 0.046$), suggesting that these elite runners were, as a group, in negative energy balance during the study period of intense training. These results confirm previous studies evaluating the food and macronutrient intake

Table 2.4: Percentage of time spent in activity during waking hours estimated using accelerometry and PAR.

Subject	¹ Accelerometer Data					Physical Activity (%)					² PAR Data		
	Light	Moderate	Heavy	Very heavy	Relax	Light	Light	Slow run	Moderate run	Fast run			
1	78	12	8	2	74	13	3	7	3				
2	84	10	5	1	88	4	3	3	2				
3	88	8	3	1	75	17	2	5	1				
4	80	7	13	0	84	4	5	5	2				
5	84	12	3	1	89	2	3	5	1				
6	79	15	4	2	90	3	2	4	1				
7	80	12	6	2	81	10	4	3	2				
8	83	12	4	1	75	17	3	4	1				
9	80	11	7	2	86	4	4	5	1				
Mean	82	11	6	1	82	8	3	5	2				
SD	3	2	3	1	6	6	1	1	1				

Key: ¹Light < 1952 counts·min⁻¹ (< 3.00 MET): Moderate 1952-5724 counts·min⁻¹ (3.00-5.99 MET): Heavy 5725-9498 counts·min⁻¹ (6.00-8.99 MET): Very Heavy > 9498 counts·min⁻¹ (> 8.99 MET): Freedson et al (1998); ²Rest ≤ 1.00 MET (i.e., lying at rest sleeping): Relaxing 1.01-2.10 MET (i.e., Sitting down, standing, walking, talking): Light 2.11-3.70 MET (i.e., Warm-up/cool-down exercises): Slow Run 3.71-8.00 MET: Moderate Run 8.01-14.00 MET: Fast Run 14.00-18.00 MET: Ainsworth et al (2000).

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of Kenyan runners (Mukeshi & Thairu, 1993; Onywera et al., 2004). Combined with the subsequent outstanding performances of these athletes, the observations raise the intriguing possibility that this seemingly unintentional negative energy balance during an intense training week just prior to major competition may somehow benefit their race running performance.

The reported energy intake of the elite runners in the present study (i.e., $13\,241 \pm 1330 \text{ kJ}\cdot\text{d}^{-1}$) was very similar to a previous investigation carried out at the same training camp (i.e., $12\,486 \pm 1225 \text{ kJ}\cdot\text{d}^{-1}$; (Onywera et al., 2004)) but both were at the lower end of the range of $12\,540$ - $20\,900 \text{ kJ}\cdot\text{d}^{-1}$ recommended for endurance athletes during intense training (Grandjean, 1997). As in the present study, the data in the earlier study suggested that athletes were in negative energy balance. Energy expenditure, however, was only estimated in the previous study using PAR, which may be subject to significant errors when applied to athletes of this caliber. For example, in the Compendium of Physical Activity compiled by Ainsworth et al. (2000), the fastest running speed possible is $\geq 17.4 \text{ km}\cdot\text{hr}^{-1}$ and assigned 14-18 MET. However, the Kenyan athletes participating in both these studies would frequently run at much faster running speeds in training and the MET assigned using the Compendium of Physical Activity would most likely underestimate the true metabolic cost, although this has yet to be demonstrated. Despite this limitation in the determination of energy expenditure, the mean difference of $2583 \text{ kJ}\cdot\text{d}^{-1}$ between energy intake and expenditure in the earlier study by Onywera et al. (2004) agreed precisely with the loss of body mass over the 7 day period ($58.9 \pm 2.7 \text{ kg}$ vs. $58.3 \pm 2.6 \text{ kg}$). Estimated energy expenditure in that study ($15\,069 \pm 497 \text{ kJ}\cdot\text{d}^{-1}$) was also very similar to energy expenditure measured in the present study ($14\,611 \pm 1043 \text{ kJ}\cdot\text{d}^{-1}$). The present study thus confirms and consolidates these earlier findings because of the more accurate methodology used, i.e., doubly labeled water.

The negative energy balance in the present study was not accompanied by a significant loss in body mass ($56.0 \pm 3.4 \text{ kg}$ vs. $55.7 \pm 3.6 \text{ kg}$; $p = 0.285$) as reported previously (Onywera et al., 2004). Nevertheless, the energy equivalent of the non-significant change in body mass was very similar to the significant energy deficit when calculated over the 7 day assessment

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period (9000 kJ vs. 9590 kJ respectively; where 1 kg is assumed to be 30 000 kJ; (Westerterp et al., 1995)). Failure to achieve and/or detect a significantly lower body mass over the 7 day period may be due to the slightly higher mean energy intake and lower energy expenditure in the current study. It can also be seen from Figure 2.1 that there was considerable amount of heterogeneity in the energy balance status of the athletes; five runners were clearly in negative energy balance, two were somewhat borderline, while the remaining two runners were in positive energy balance. Interestingly, both athletes in positive energy balance ran in the Kenyan National Championships (i.e., 5 km and 10 km races) on day 5 of the investigation and had actually reduced their training load in the days leading up to and after the event while appearing to maintain normal dietary habits.

Percent underreporting, which expresses a measured energy deficit in the light of any possible inaccurate dietary intake recording, was calculated at 13 % (range: -24-9 %) in the present study. However, we found that it was almost entirely accounted for by undereating which was calculated at 9 % (range: -54-39 %). It is unlikely that there was considerable underrecording in the present study since no significant difference was found between total water intake and total water loss ($4.2 \pm 0.6 \text{ L}\cdot\text{d}^{-1}$ vs. $4.5 \pm 0.8 \text{ L}\cdot\text{d}^{-1}$; $p = 0.496$), suggesting that the athletes had accurately recorded all food and water consumed. The percent underreporting of 13 % in the present study was lower than values reported in other studies on athletes (Westerterp et al., 1986; Edwards et al., 1993). For example, Edwards et al. (1993) reported that energy intake was 32 % below energy expenditure estimated by doubly labeled water in non-elite female distance runners. In another study, underreporting rose progressively over a 3 week period in professional cyclists competing in the Tour de France; one of the world's most demanding cycle races. In that study underreporting over the 3 week study period was 13 % over the first 7 days (i.e., similar to the present study), 21 % over the next 8 days, and 35 % over the last 7 days (Westerterp et al., 1986). The authors attributed the significant underreporting to athletes not recording what they had eaten (i.e., underrecording) rather than undereating as no difference in body mass (or body composition) was found over each

of the three recording periods. The elite cyclists in that study reached an ADMR of 3.4-3.9 and 4.3-5.3 times BMR based on the food record technique and the doubly labeled water technique, respectively; while in the present study the athletes reached an ADMR/BMR of 2.1 (range: 1.7-2.4) and 2.3 (range: 2.1-2.6) for the two respective techniques. It is recommended that an ADMR/BMR for sustainable lifestyles should fall within the range of 1.2-2.5 (Black et al., 1996); individuals with values > 2.5 may experience a loss of body mass (Westerterp, 1998) and may thus require supplementation of the diet with energy dense carbohydrate. The difference between values reported in the present study and those obtained in elite cyclists (Westerterp et al., 1986) is likely to be due to the length of daily exercise in the Tour, typically 4-5 hours for a flat stage and 5-6 hours for a mountain stage (Lucia et al., 2003). Nevertheless, an ADMR/BMR of 2.3 ± 0.1 estimated in the present study (Table 2.1) highlights the substantial amount of training undertaken by these athletes in the week prior to major competition for most of the athletes. Although weekly training distances in excess of 117 km were documented in the present study (note this does not include the late morning training session), the athletes spent the majority (82 %) of their waking hours resting (Table 2.3). A Previous study by Saltin et al. (1995) reported the daily training schedule of Kenyan athletes; in that study, athletes were running less than $100 \text{ km}\cdot\text{wk}^{-1}$. However, the majority of these runners were talented junior runners ($n = 16$) with only the inclusion of a small number of truly elite athletes ($n = 6$). The greater training distances in the more recent study may also reflect the current increased demands placed on the athletes as compared to almost a decade ago.

The consequences of training and competing while in negative energy balance have been well documented and current recommendations for endurance events advocate athletes refrain from training and/or competition while consuming a hypocaloric diet (American College of Sports Medicine, 2000). Informal discussion with the present group of elite Kenyan runners revealed a number of the athletes complained of reduced appetite following hard training, a phenomenon commonly referred to as “exercise-induced anorexia” (King et al., 1994; Blundell et al., 2003). For example, Blundell

et al. (2003) proposed that a depressed appetite following strenuous exercise could be due to a re-distribution of blood away from the splanchnic circulation in favour of the working muscles. On the other hand, King et al. (1994) argued for a delayed response in the matching of energy intake to acute changes in energy expenditure resulting in acute periods of negative energy balance. Whether either of these suggestions is implicated in the reported negative energy balance found in the current study is unclear. Both are in agreement with a recent review that suggested that the control of appetite was due to a complex interaction between homeostatic mechanisms and environmental and cognitive factors (Berthoud, 2004). Therefore, a great number of factors could be responsible for the negative energy balance and reduced appetite reported by many of the athletes during the 7 day recording period.

The view that reducing body mass may potentially improve endurance running performance has been discussed previously (Myers & Steudel, 1985; Jones et al., 1986; Noakes, 2000). Indeed, the simple notion of reducing mass while keeping power constant, and therefore reducing the oxygen cost of movement, seems valid and there is not a single study to date that would refute this view. Yet current recommendations discourage reducing body mass in the build-up to an important race; rather it is typically recommended that athletes follow adequate nutrition and hydration practices and remain in energy balance, or even attempt to increase energy stores in the form of glycogen, combining training and dietary manipulation (for a review see American College of Sports Medicine, 2000). Interestingly, even though anecdotic, is the recent observation that the winner of the women's 2004 London Marathon was Margaret Okayo from Kenya (previous marathon world record holder) who weighed only 39 kg at the time of the race (normal weight: 43 kg, height: 1.5 m).

Analysis of allometric relationships throughout the animal kingdom may allow an insight into additional benefits of reducing body mass. For example, Noakes (2000) proposes that the small size and high degree of running economy displayed by the Cheetah provides a physiological advantage over its prey in terms of delaying heat accumulation and therefore, the onset of fatigue. Extrapolating this notion to humans, smallness, lightness, and a

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greater running economy may benefit endurance running performance. Indeed, Marino et al. (2000; 2004) suggest that heavier runners display a greater degree of heat retention than lighter individuals and this may be a major factor limiting the performance of physically larger and heavier athletes in distance running events; this is particularly evident in hot environments. It was additionally reported that heavier runners self-selected a slower running speed than lighter runners whilst running in the heat and that this speed was inversely related to body mass (Marino et al., 2000; Marino et al., 2004). In addition, observations from human gait analysis suggest that the addition of mass will increase absolute O_2 cost (Myers & Steudel, 1985; Jones et al., 1986). For example, Myers and Steudel (1985) compared adding weight proximally to the centre of mass (i.e., the waist) and distally on the limbs (i.e., foot/ankle) during running and reported that the energy cost was increased by a factor of 1.5-5.5. Interestingly, the largest increase in energy cost was observed when weight was added distally and when running velocity was increased, thus prompting the authors to conclude that long and slender legs would confer an advantage to running economy. Similarly, Jones et al. (1986) measured the energy cost of wearing shoes of varying weight during running and walking and reported an average increment in O_2 cost of 1 % per 100 g of weight added. Consequently, reducing body mass and leg mass in particular, ought to enhance running economy and therefore running performance as a consequence of reducing the kinetic energy required to accelerate and decelerate the limbs. When considering that running economy has been consistently shown to be a good indicator of performance, it would stand to reason that a low body mass and minimal leg mass in particular, may be advantageous for endurance running performance. Evidence favouring superior running economy in Kenyan endurance runners compared to Caucasian athletes was first presented by Saltin et al. (1995). In that study, Kenyan runners exhibited better running economy compared to their Scandinavian counterparts whilst running at sub-maximal running speeds even though absolute $\dot{V}O_{2max}$ was not different. Interestingly, the BMI of the Kenyan runners was significantly lower than the Scandinavian runners. In a recent review, Larsen (2003) postulated that the superior running economy

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of Kenyan runners could partly be explained by their low BMI combined with the fact that the majority of their body mass is distributed proximally, with the mass of the extremities being kept to a minimum, especially in the calf and thigh area. More recently, Larsen et al. (2004) reported that untrained Kenyan Nandi (a Kalenjin sub-tribe) boys, are slender, have relatively long legs, and have 20-25 % lower BMI as compared to untrained children of a similar age from Nigeria, Libya, USA (i.e., blacks, whites, and Hispanics), Mexico (i.e., Mexican-Americans) and Greenland (Larsen et al., 2004). Whether these anthropometric characteristics are indeed typical of Kenyans and responsible, in part at least, for the outstanding running performances of Kenyans remains to be determined.

In the present study, the diet consisted mainly of carbohydrate sources (67.3 ± 7.8 %, $9.8 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$) compared with protein (15.3 ± 4.0 %, $2.2 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$) and fat (17.4 ± 3.9 %). The composition of the diet was consistent with previous results from this laboratory (i.e., 77 % carbohydrate, 10 % protein, 13 % fat; (Onywera et al., 2004)) and complied with current recommendations for macronutrient intake for endurance athletes, typically 55-58 % ($6-10 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$) of energy from carbohydrate, 12-15 % ($1.2-1.4 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$) of energy from protein and > 15 % of energy from fat (American College of Sports Medicine, 2000). A particular feature of the Kenyan diet is the large contribution of carbohydrate to the diet. A typical nutrient is Ugali (a carbohydrate dense combination of maize and water that is usually eaten in combination with meat-stew, vegetables, and grains). In fact, there are anecdotal reports attributing the success of Kenyan endurance athletes to the frequent inclusion of Ugali in their diets (e.g., Tanser, 1997). It is also noteworthy that Ugali continues to be part of the training diet of the Kenyan athletes when living and competing abroad (e.g., at the Global Sports Communication Camp, Nijmegen, The Netherlands). There is, however, no scientific justification for Ugali to have effects on performance; the macronutrient composition of Ugali is similar to rice (i.e., carbohydrate, protein and fat content of Ugali is 25.3, 1.3, and $0.5 \text{ g}\cdot 100\text{g}^{-1}$ and for cooked rice 31.0, 2.6, and $1.3 \text{ g}\cdot 100\text{g}^{-1}$, respectively; (Sehmi, 1993)). Nevertheless, a typical Kenyan diet, rich in carbohydrate, allows optimal storage of liver and muscle

glycogen. This is in contrast to what appears to be the case in athletes from industrialised countries where carbohydrate intake can be at the lower end of the range recommended for endurance athletes (e.g., $6.1 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$, (Moses & Manore, 1991)), especially when a typically western diet of 55-58 % carbohydrate (American College of Sports Medicine, 2000) is consumed. Endurance athletes consuming a western diet will almost certainly be limiting carbohydrate availability, especially if they are trying to be as light as possible before racing. Interestingly, the ACSM (2000) proposes that athletes training and competing while in negative/borderline energy balance are at increased risk of fatigue, illness, injury and loss of muscle mass. Indeed, it has previously been proposed that the high turnover of Kenyan runners in international athletics may be a consequence of repetitive periods of negative/borderline energy balance in the face of increased pressure to compete successfully internationally (Onywera et al., 2004).

Fluid intake in the present study was comprised primarily of water ($0.9 \text{ L}\cdot\text{d}^{-1}$) and milky tea ($0.9 \text{ L}\cdot\text{d}^{-1}$), thus confirming previous results (i.e., water: $1.1 \text{ L}\cdot\text{d}^{-1}$, tea: $0.9 \text{ L}\cdot\text{d}^{-1}$; (Onywera et al., 2004)). As in the previous study, the athletes in the present study did not consume water before or during training and sometimes consumed only small amounts of water following training. Therefore, the fluid intake reported here is substantially less than current recommendations (e.g., American College of Sports Medicine, 2000), although it has recently been suggested that such recommendations are excessive and can be detrimental to exercise performance (Noakes, 2003). The advantages and disadvantages of drinking *ad libitum* or drinking enough liquid to satisfy specific guidelines remain to be investigated in this population of elite athletes (see chapter 3).

Physical activity patterns assessed using accelerometry and PAR (Ainsworth et al., 2000) are reported in Table 2.4. The reported time spent in light, moderate, hard and very hard activity as determined by accelerometry was $82 \pm 3 \%$, $11 \pm 2 \%$, $6 \pm 3 \%$, and $1 \pm 1 \%$ respectively. Time spent relaxing, in light activity, slow running ($8.0\text{-}13.6 \text{ km}\cdot\text{hr}^{-1}$), moderate running ($13.7\text{-}17.3 \text{ km}\cdot\text{hr}^{-1}$), and fast running ($\geq 17.4 \text{ km}\cdot\text{hr}^{-1}$) as estimated using the PAR method (Ainsworth et al, 2001) was $82 \pm 6 \%$, $8 \pm 6 \%$, $3 \pm 1 \%$, 5 ± 1

%, 2 ± 1 %, respectively. To the present authors knowledge there are no comparable data in elite western endurance runners, but time spent in light activity as assessed by accelerometry and the time spent relaxing as assessed by accelerometry is high. Taking these measures together it may be suggested that rest is an additional important facet of elite Kenyan endurance runner's typical training practices.

Unfortunately the precise quantification of physical activity or energy expenditure using PAR and accelerometry can be erroneous. PAR is an indirect method and in the case of accelerometry, studies have reported that despite increased energy demands as a result of increasingly faster running speeds, output from some motion sensors plateau (Haymes & Byrnes, 1993; Nichols et al., 2000; Brage et al., 2003). Future studies should address these issues by assessing whether biomechanical and/or device limitations cause the observed levelling off of accelerometer counts during running by investigating the outputs from a number of accelerometers, uni- and tri-axial, with various sampling frequencies, band pass filtering ranges and peak acceleration amplitudes (see chapter 5).

Conclusions

This study confirms previous findings (Onywera et al., 2004) that elite Kenyan endurance runners are frequently in negative/borderline energy balance during periods of intense training and/or prior to major competition. The significance of this is unclear, however, it is suggested that a reduced body mass consequent to being in negative energy balance may potentially be advantageous to the endurance athlete as this may enhance running economy, this is especially apparent when competing in the heat. The unintentional weight loss prior to competition is most likely a gradual process taking place over a number of weeks leading up to an event rather than a rapid reduction in body mass in the week before the event. This "strategy" would have less, or even no negative impact on the quality of training especially when athletes are consuming a diet high in carbohydrate (e.g., 67.3 ± 7.8 %, $9.8 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$) and sufficient protein (e.g., 15.3 ± 4.0 %, $2.2 \text{ g}\cdot\text{kg}^{-1}\text{BM}\cdot\text{d}^{-1}$)

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as is typically the case in Kenya.

3

Hydration and electrolyte balance and training load in elite Kenyan endurance runners

3.1 Introduction

Kenya has enjoyed increasing success in international racing over the last four decades since its emergence in world athletics in the 1960s. For example, in 2004 the majority (51 %) of top ten yearly performances from 800m to marathon were from male Kenyan athletes. Considering the success of these runners and the importance of diet and lifestyle for optimum endurance running performance (American College of Sports Medicine, 2000), the diet and lifestyle practices of this unique group of runners warrants examination. Two recent investigations (Onywera et al., 2004; Chapter 2) reporting the nutritional and lifestyle practices of elite Kenyan endurance runners whilst preparing for major competition (Kenyan National Championships 2003 and Athens Olympic games 2004 national trials, respectively) found athletes did not consume fluids before or during training, and only infrequently consumed modest amounts of fluids immediately after training. This contributed to low daily fluid intake, mainly water (1.1 ± 0.3 ; 0.9 ± 0.5 L·d⁻¹, Onywera et al., 2004 and Chapter 2, respectively) and milky tea (1.2 ± 0.3 ; 0.9 ± 0.3 L·d⁻¹, respectively). These fluid intake and drinking habits were substan-

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tially less than previous recommendations of the ACSM (Convertino et al., 1996), which were 0.4-0.6 L of fluid 2-3 hr before exercise, 0.6-1.2 L·d⁻¹ while exercising, aiming at total replacement of all fluid lost during exercise, or at least up to the maximal amount tolerated; a pattern and volume of fluid replacement similar to that recommended by the NAAT (Binkley et al., 2002), and the US Army (Montain et al., 1999). The drinking behaviours reported previously (i.e., *ad libitum* in elite Kenyan endurance runners (Onywera et al., 2004; Chapter 2) are consistent with empirical observations that elite athletes typically do not adhere to prevailing fluid intake recommendations (for a review see reference Chevront & Haymes, 2001). Recently the ACSM has replaced their prior Position Stand (Convertino et al., 1996) with an updated one on exercise and fluid replacement (American College of Sports Medicine, 2007) that advocates drinking *ad libitum* (0.4-0.8 L·hr⁻¹) during exercise (with the lower value for slower, lighter individuals competing in cooler environments, and the higher value for faster, larger individuals competing in warmer environments) in order to prevent excessive dehydration (i.e., < 2 % body mass loss), and only aggressively ingest fluid and electrolytes before/after exercise if time does not permit consumption of normal meals and beverages to replace exercise induced fluid and electrolyte losses. These new recommendations (American College of Sports Medicine, 2007) appear to be more in keeping with previous observations of elite Kenyan endurance runners (Onywera et al., 2004; Chapter 2). However, their hydration status day-to-day during an important training period remains to be determined.

Therefore, the main aim of the present investigation was to assess the hydration status of elite Kenyan endurance runners during an important training period given their previously reported drinking behaviours in Chapter 2 that appear more in line with recent recommendations (American College of Sports Medicine, 2007). This investigation also provides a rare insight into the day-to-day practices of some of the most successful endurance runners in the world 1 week prior to major competition. Therefore secondary aims are to assess electrolyte balance and training load 1 week prior to major competition.

Table 3.1: Physical and anthropometric characteristics of elite Kenyan endurance runners (n = 14). Mean \pm SD is shown.

	Mean	SD
Age (y)	22	3
Height (cm)	170	5
BM (kg)	54.8	6.3
BMI ($\text{kg}\cdot\text{m}^{-2}$)	19	2
AD (m^2)	1.6	0.1
AD $\cdot\text{kg}^{-1}$ ($\text{cm}^2\cdot\text{kg}^{-1}$)	300	19
Body Fat (%)	7.5	1.4

3.2 Methods

3.2.1 Subjects

Fourteen elite Kenyan endurance runners (range of athletic discipline: 800 m-marathon) were invited to participate in this study (Table 3.1). All athletes gave their written informed consent prior to participating in the study (Appendix 1). The experimental procedures were in accordance with the Helsinki declaration and were approved by the local ethics committee at Kenyatta University, Nairobi, Kenya (Appendix 1). The athletes were highly trained and included World, Olympic and Junior Champions frequently competing in major national and international middle- and long-distance running events. Athletes were based at a high altitude training camp (Global Sports Training Camp, Kaptagat, Eldoret, Kenya) situated in the North Rift Valley (altitude: 2400 m a.s.l., daytime T_a : 8-24 °C, RH: 31-100 %) and were all heat and altitude acclimatised at the time of testing. The athletes were in a 10 day taper phase of their training cycle as the investigation was undertaken 1 week prior to the Kenyan national trials for the 2005 IAAF World Championships.

3.2.2 Experimental design

Subjects were monitored for a period of 5 training days during the course of a standard training week prior to major competition. Organised training runs were carried out mostly in groups that were influenced by athletic discipline and instructions from coach/manager. Training schedules typically incorporated up to 2 variable distance-training sessions per day (i.e., a morning run and a non-compulsory afternoon run) and 2 interval-training sessions per week (i.e., mid-morning run).

3.2.3 Experimental procedures

Body water compartments, urine osmolality and specific gravity, body mass, and body fat were measured each morning as follows. Body water compartments were estimated using a multifrequency bioimpedance analyser (Bodystat Multiscan 5000 Bioimpedance analyser, Bodystat Ltd, Isle of Man). Multifrequency bioimpedance allows total body water and extracellular water to be estimated; from these measurements intracellular water can also be deduced (Vanloan, 1990). The multifrequency bioimpedance measurements were taken after the subjects woke while they lay comfortably in a supine position for at least 10 min on a non-conductive surface with their arms and legs slightly abducted, ensuring consistent distribution of body water. Following this, subjects were asked to supply a 20 ml urine sample, which was analysed for osmolality by freezing point depression (Micro-osmometer 3300, Vitech Scientific, West Sussex, UK) and specific gravity (Combur test strips, Roche Diagnostics, East Sussex, UK) within 15 min to give an index of pre-training hydration status (Shirreffs & Maughan, 1998); subjects also provided a 20 ml urine sample before going to sleep each night. Body mass and percent body fat measurements were then made simultaneously after subjects had voided and before the consumption of any food or fluid using a leg-leg bioimpedance system equipped with a digital scale (Tanita Body Fat Analyzer, TBF 521, Tanita Corporation of America, Inc., Arlington Heights, IL) (Cable et al., 2001).

Prior to the morning training session on the first day of the 5 day in-

investigative period, height was recorded using a wall mounted stadiometer. AD was calculated from body mass and height as described by (DuBois & DuBois, 1916); following this, $AD \cdot kg^{-1}$ was also calculated.

A heart rate monitor (Suunto t6, Suunto Oy, Vantaa, Finland) was attached to record heart rate continuously throughout each training run. The HR_{peak} was considered the highest achieved heart rate in all training sessions completed by individual subjects throughout the recording period. T_i was monitored using a telemetric pill system (CorTemp, HQ inc., Palmetto, Florida, USA) that subjects consumed 8-10 h before the morning run (Easton et al., 2007). T_i was recorded continuously during the exercise period on the CorTempTM receiver that was secured to the small of the subject's back in a neoprene running pack (Hybrid music pak, NATHAN Human Propulsion Laboratories, Philadelphia, USA). The Timex BodylinkTM system (Timex Corporation, Middlebury, CT, USA) was used to determine the distance, time and running speed of the training runs by utilizing GPS technology. Athletes wore the Timex Performance device during individual and group runs. HR, T_i , and Timex data were recorded during all training sessions throughout the study period. Body mass was measured before and after each training session. Sweat loss and sweat rate were calculated from the change in body mass (the relatively small changes in body mass due to substrate oxidation and other sources of water loss were ignored). RPE (Borg, 1982) was reported at the end of each training run. Environmental conditions (i.e., T_a and RH) were recorded (C8600 10 channel microprocessor, Comark, Hertfordshire, UK) each morning and before and after every training session.

The dietary intake of ten subjects was measured daily during the 5 day investigative period. While at the training camp, meals and snacks were served at standard times each day: breakfast (08:00), mid-morning snack (10:00), lunch (13:00), afternoon snack (16:00), and dinner (19:00). Athletes selected their portion sizes *ad libitum* from the provided food. Samples of all foods and fluids consumed were chemically analysed (Food Industrial Research and Technological Development Company S.A., Athens, Greece) for energy (calculated by Atwater energy factors (Merrill & Watt, 1973)), carbohydrate (calculated "by difference", i.e., carbohydrate = 100 - fat - proteins -

moisture - ash), fat (measured by petroleumether extraction according to the Soxhlet method (Helrich, 1990)), protein (calculated from analysis by Kjeldahl titration method (Helrich, 1990)), moisture (determined by oven drying the sample at 105 °C for 4 hr (Helrich, 1990)), and Na⁺ and K⁺ content (both analysed by flame photometry). During the study period, subjects were required to weigh and record all food and drink consumed; individual digital weighing scales readable to 1 g were used. All food items were weighed before and after cooking and cooking method noted. Subjects were also required to continue weighing all food and drink when away from the camp (e.g., athletes occasionally walked to the local shop for snacks between training runs); samples of any food or drinks consumed were collected for chemical analysis. The weighed dietary intake data were used to determine energy intake and diet composition using results of the chemical analysis of foods. Metabolic water was determined by multiplying estimated energy expenditure by the fraction of energy in the diet from carbohydrate, protein, and fat (data derived from chemical analysis of foods). The oxidation of carbohydrate, protein and fat yields 0.60, 0.41, and 1.07 mL water·g⁻¹, respectively (Fjeld et al., 1988). Athletes did not receive any specific dietary recommendations from their coach/manager. One subject consumed a daily multivitamin.

Energy expenditure was assessed by PAR (Ainsworth et al., 2000). Subjects were instructed to record in detail their individual activities each day (including type, intensity and duration of activity). The Compendium of Physical Activities (Ainsworth et al., 2000) was used to assign specific activities with their respective MET. The total energy cost is expressed as a multiple of BMR. In the present study, BMR was calculated using the Schofield Equation (Schofield, 1985).

Nine of the ten subjects who recorded dietary intake during the 5 day investigative period also completed one 24 hr urine collection. The urine volume was measured and mixed thoroughly before a representative 20 mL sample was analysed for osmolality and specific gravity (as described above) and [Na⁺] and [K⁺] by flame photometry (Flame Photometer Model 410, Corning, Halstead, Essex, UK). During the 24 hr urine collection period

sweat samples were also collected during all training sessions from four skin sites (chest, forearm, back and thigh) by absorbent sweat patches applied to the skin surface (Tagaderm+Pad, 3M, Loughborough, UK). The gauze patches were covered with an adhesive non-porous film that held them in place and prevented evaporation of sweat. The patches were positioned before the start of each training session and remained in place throughout the session. All patches were placed on the right hand side of the body after preparation of the skin site by washing with deionised water and drying with a clean electrolyte-free gauze swab. The patches were removed after each training session and placed in sealed sterile containers until they were analysed. After weighing of the patches and elution of sweat with distilled water, the sweat collected was analysed for $[\text{Na}^+]$ and $[\text{K}^+]$ by flame photometry (as previously described). The $[\text{Na}^+]$ and $[\text{K}^+]$ were used to calculate total Na^+ and K^+ loss from sweat loss (i.e., body mass loss) during training runs. The total quantity of Na^+ and K^+ lost in the sweat and urine over the 24 hr period was used to calculate an estimate of total Na^+ and K^+ lost from the body over the course of a single day and compared to the total Na^+ and K^+ intake of the diet assessed by chemical analysis of all food and fluids consumed during the 24 hr period.

3.2.4 Data analysis

Data are expressed as the mean \pm SD or median (range) as appropriate following a test for the normality of distribution. Paired t-tests were used to compare body mass loss during training sessions, pre training body mass in the morning vs. pre interval training body mass, pre training body mass in the morning vs. pre training body mass in the afternoon, pre interval training body mass vs. pre training body mass in the afternoon, initial body mass vs. final body mass, energy intake vs. energy expenditure, morning urine osmolality vs. evening urine osmolality, morning urine specific gravity vs. evening urine specific gravity, Na^+ intake vs. Na^+ loss, and K^+ intake vs. K^+ loss. A one-way ANOVA for repeated measures was used to determine if there was a significant difference in daily total body water, extracellular

water and intracellular water compartments and body mass measured in the morning before training. Statistical power calculations (80 % power) were carried out using the daily body mass data obtained. Statistical significance was set at $p < 0.05$.

3.3 Results

Environmental conditions

Environmental conditions (i.e., T_a and RH) during the morning (06:00), interval (09:00), and afternoon training sessions (15:00) were 10.7 ± 1.6 °C and 75 ± 3 %RH, 17.9 ± 1.1 °C and 68 ± 4 %RH, and 21.1 ± 2.1 °C and 43 ± 11 %RH, respectively.

Body Mass and Fluid Balance

No correction was required for food and fluid intake during training sessions as no fluid or food was consumed. On the days when urinary losses were not recorded, body mass was not corrected for any urinary losses during training runs. Any body mass losses due to fecal losses during training runs were not corrected for. On average there was a significant body mass loss during the short, medium and long morning training runs (0.5 ± 0.4 kg, $p < 0.001$; 0.8 ± 0.4 kg, $p < 0.001$; 1.1 ± 0.4 kg, $p < 0.001$) as well as interval (0.7 ± 0.3 kg; $p < 0.001$) and afternoon (0.5 ± 0.4 kg; $p < 0.001$) training runs. This was equivalent to 0.8 ± 0.5 , 1.5 ± 0.5 , 2.0 ± 0.7 , 1.3 ± 0.5 and 1.0 ± 0.6 % body mass loss, respectively, and mean sweat rates of 1.0 ± 0.7 , 1.0 ± 0.4 , 0.8 ± 0.4 , 1.0 ± 0.4 and 0.9 ± 0.6 L·hr⁻¹, respectively. Despite significant loss in body mass, athletes that completed a morning run and an afternoon run in the same day, had no significant difference between pre training body mass in the morning and afternoon pre training body mass (56.1 ± 4.4 kg vs. 56.0 ± 4.0 kg; $p = 0.761$). In contrast, athletes that completed a morning run and an interval training session in the same day, commenced interval training with a significant loss in body mass (0.8 ± 0.5 kg; $p < 0.001$); post interval training, athletes had a mean body mass deficit

of 1.5 ± 0.6 kg, equivalent to 2.7 ± 1.0 % body mass loss. Nevertheless, athletes that completed an interval training session and an afternoon run in the same day, had on average regained all water lost via sweating and more as evidenced by a significant positive difference between pre training body mass prior to interval training and afternoon pre training body mass (53.5 ± 2.1 kg vs. 54.1 ± 2.4 kg; $p = 0.007$). Similarly, athletes that completed a morning run, interval training and an afternoon run in the same day had no significant difference between pre training body mass in the morning and afternoon pre training body mass (53.9 ± 2.5 kg vs. 53.6 ± 2.6 kg; $p = 0.400$). Mean total body water (31.4 ± 3.4 L; $p = 0.194$), extracellular water (14.2 ± 1.5 L; $p = 0.564$), intracellular water (17.1 ± 1.9 L; $p = 0.557$), and pre training body mass (53.6 ± 6.8 kg; $p = 0.302$) were well maintained day-to-day throughout the investigative period. Mean osmolality and specific gravity of urine supplied by the athletes in the morning was not significantly different from the evening sample supplied before sleeping (osmolality: 522 ± 117 vs. 505 ± 98 mOsmol \cdot kg $^{-1}$, respectively; $p = 0.685$; specific gravity: 1.017 ± 0.004 vs. 1.016 ± 0.004 , respectively; $p = 0.388$).

Energy Balance, Physical Activity and Diet Composition

The reported energy intake assessed by chemical analysis of all food and fluids consumed was not significantly different from the estimated energy expenditure assessed by PAR (12.3 ± 1.5 MJ \cdot d $^{-1}$ vs. 13.6 ± 2.2 MJ \cdot d $^{-1}$; $p = 0.154$; $n = 10$). Body mass on day 1 and day 5 did not differ significantly (55.9 ± 6.1 kg vs. 55.6 ± 6.2 kg; $p = 0.167$; $n = 10$). Physical activity level was 2.1 ± 0.3 (i.e., ADMR/BMR). The diet consisted mainly of carbohydrate (79.0 ± 2.6 %, 9.8 g \cdot kg $^{-1}$ BM \cdot d $^{-1}$) compared with protein (14.3 ± 2.1 %, 1.8 g \cdot kg $^{-1}$ BM \cdot d $^{-1}$) and fat (6.6 ± 1.0 %, 0.8 g \cdot kg $^{-1}$ BM \cdot d $^{-1}$).

Mean Na⁺ intake assessed by chemical analysis of all food and fluids consumed in a 24 hr period was not significantly different from Na⁺ loss during the same 24 hr period in sweat and urine assessed by 24 hr urine and training run sweat patch analysis (3245 ± 901 vs. 3254 ± 1070 mg \cdot d $^{-1}$; $p = 0.975$; $n = 9$). In contrast, mean K⁺ intake was significantly different from

Table 3.2: Sweat electrolyte concentration during training sessions calculated from four collection sites and 24 hr urinary losses (n = 9). Mean \pm SD is shown.

	Mean	SD
Sweat [Na ⁺] (mmol·L ⁻¹)	37.0	8.0
Sweat [K ⁺] (mmol·L ⁻¹)	4.6	1.1
Urine Na ⁺ loss (g·d ⁻¹)	2.3	1.2
Urine K ⁺ loss (g·d ⁻¹)	2.1	0.9

K⁺ loss in sweat and urine (3812 ± 489 vs. 2346 ± 846 mg·d⁻¹; $p < 0.001$; n = 9). All nine athletes completed a morning run (17.4 ± 2.8 km) with a further three completing an additional afternoon run (5.0 ± 1.0 km). Sweat electrolyte concentration obtained from the four collection sites and 24 hr urinary losses are shown in Table 3.2.

Daily fluid availability consisted mainly of water (0.7 ± 0.5 L·d⁻¹; 18.4 %) and milky tea (1.2 ± 0.4 L·d⁻¹; 31.6 %) with a small contribution from the intake of other fluids such as soft drinks and milk (0.4 ± 0.2 L·d⁻¹; 10.5 %). Other sources of daily fluid intake were water consumed as moisture in food (1.0 ± 0.1 L·d⁻¹; 26.3 %) and metabolic water production as a result of oxidation of carbohydrate, protein, and fat (0.5 ± 0.1 L·d⁻¹; 13.2 %) resulting in a mean total daily fluid intake of 3.8 ± 0.8 L·d⁻¹. Mean osmolality of the tea regularly consumed by the athletes was 281 ± 55 mOsmol·kg⁻¹; composition of the tea was 0.2 MJ·100g⁻¹ of energy, 1.0, 0.2 and 8.28 g·100g⁻¹ of protein, fat and carbohydrate, respectively, and 16.98 and 28.77 mmol·L⁻¹ of [Na⁺] and [K⁺], respectively.

Physiological Response to Running

Mean time, distance, speed, RPE, and % HR_{peak} for morning runs, interval training and afternoon runs is shown in Table 3.3. Training distance achieved over the 5 day recording period was 81.7 ± 11.3 km. Mean T_i and heart rate at 5 min intervals during morning and afternoon training sessions are shown in Figure 3.1. Average peak T_i during interval training was 39.5 ± 1.8 °C.

Table 3.3: Training load and physiological response to running during morning (i.e., AM), mid-morning (i.e., interval training) and afternoon (i.e., PM) training runs. Mean \pm SD is shown.

	Mean SD	
<hr/> Short Run - AM <hr/>		
Time (min)	30.3	0.5
Distance (km)	6.4	0.5
Speed (km·hr ⁻¹)	12.6	0.9
RPE (6-20)	10	2
% HR _{peak}	71	9
T _i (°C)	37.2	0.4
<hr/> Medium Run - AM <hr/>		
Time (min)	63.2	7.4
Distance (km)	14.0	1.5
Speed (km·hr ⁻¹)	13.3	2.0
RPE (6-20)	13	2
% HR _{peak}	78	10
T _i (°C)	37.3	0.4
<hr/> Long Run - AM <hr/>		
Time (min)	63.6	5.4
Distance (km)	18.2	1.4
Speed (km·hr ⁻¹)	17.2	1.6
RPE (6-20)	13	1
% HR _{peak}	81	7
T _i (°C)	37.9	0.6
<hr/> Interval Training <hr/>		
Time (min)	49.5	17.4
Distance (km)	5.6	2.1
Peak Speed (km·hr ⁻¹)	25.7	2.3
RPE (6-20)	16	2
Peak % HR _{peak}	96	4
T _i (°C)	37.9	0.5
<hr/> Run PM <hr/>		
Time (min)	33.4	6.9
Distance (km)	5.9	1.1
Speed (km·hr ⁻¹)	10.5	2.2
RPE (6-20)	9	2
% HR _{peak}	66	7
T _i (°C)	37.6	0.5

3.3. RESULTS

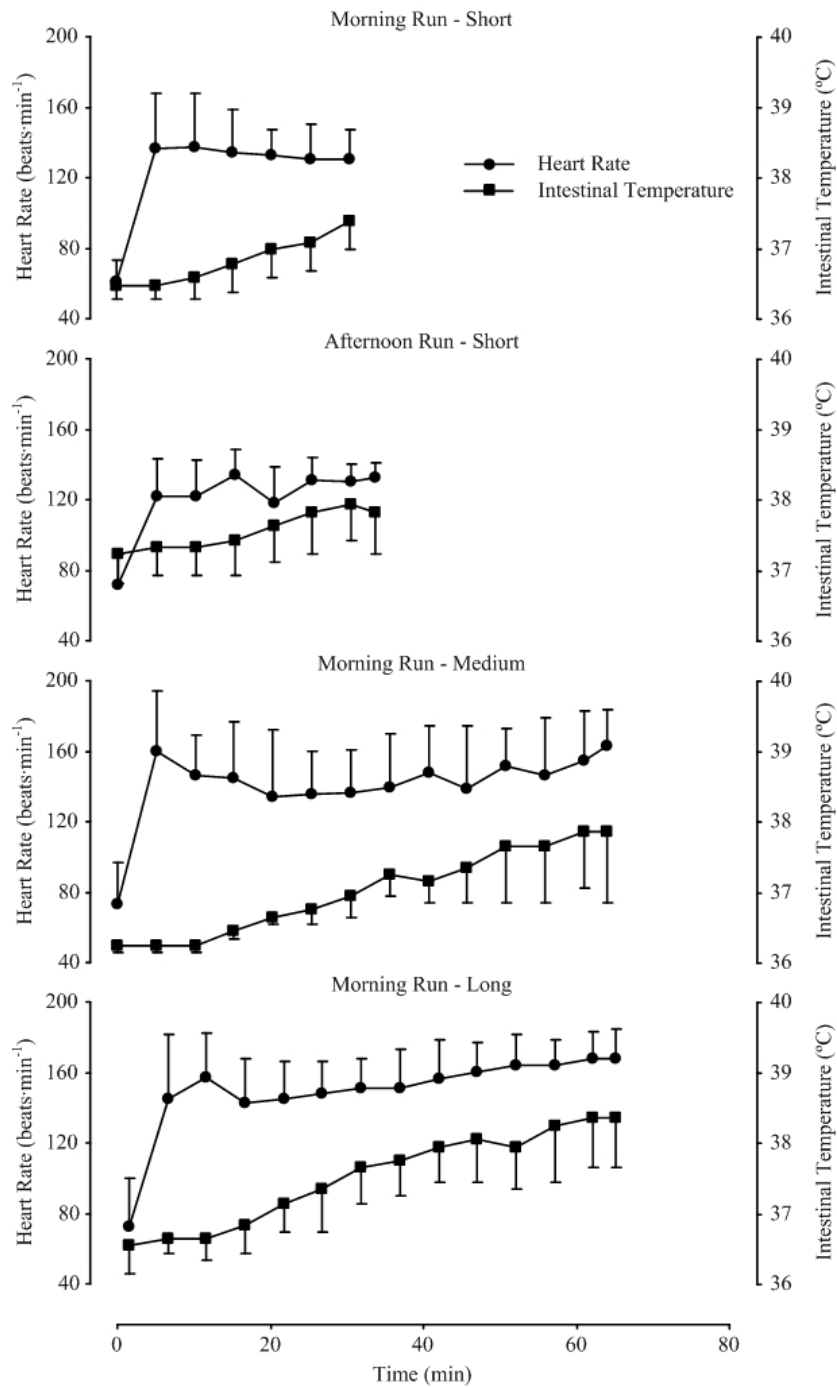


Figure 3.1: Intestinal temperature and heart rate at 5 min intervals for morning (short, medium and long) and afternoon training runs. Mean \pm SD is shown.

3.4 Discussion

The main finding of the present investigation is that despite low daily fluid intake, elite Kenyan endurance runners remain well hydrated day-to-day during an important training period. The pattern and volume of fluid intake reported in the present study is consistent with previous observations of elite Kenyan endurance runners (Onywera et al., 2004; Chapter 2), and supports the principle of a daily *ad libitum* fluid and food intake strategy for elite Kenyan endurance runners during an important training period.

Fluid Intake and Hydration Status

Body mass loss as a result of sweating during running was fairly modest during training runs. A contributing factor may have been the relatively low body mass of the subjects in the present study (Table 3.1) that is similar to reported values of African endurance runners but less than Caucasian endurance runners (e.g., Saltin et al., 1995). In contrast, body fat (Table 3.1) is similar to values reported in the literature for both African and Caucasian endurance runners (e.g., Saltin et al., 1995). Epstein et al. (1983) suggest that thermoregulation is more efficient the greater the AD available for evaporation per unit of body mass; this is especially apparent when exercising in a hot dry environment. The $\text{AD}\cdot\text{kg}^{-1}$ of the runners in the present study (Table 3.1), is similar to values previously reported in Kenyan runners but greater than values reported in Caucasian endurance runners (e.g., Saltin et al., 1995). Therefore, a low body mass index coupled to a high AD may have resulted in the modest sweat losses observed, thus requiring relatively little fluid intake to compensate. In addition, mild ambient conditions and/or relatively low training duration/intensity (Table 3.3) may have also contributed to the modest fluid losses in the present investigation. Thus, sweat rate can be influenced by a number of factors, including meteorological variables (e.g., T_a , wind speed, RH), exercise intensity, state of fitness, level of heat acclimation, and the amount of insulative clothing worn. Indeed, it was found that sweat rates were similar throughout all training sessions despite lower

3.4. DISCUSSION

T_a during the morning run compared to the mid-morning and afternoon runs (10.7 ± 1.6 °C vs. 17.9 ± 1.1 °C and 21.1 ± 2.1 °C, respectively). This is likely explained by athletes wearing insulative clothing during morning runs that resulted in a greater than expected sweat loss for the T_a experienced.

Despite relatively low body mass loss during training runs, athletes had greater losses during interval training (2.7 ± 1.0 % body mass) as a result of accumulating a deficit from the preceding morning run since athletes ingested no fluid before and during training and infrequent and modest amounts immediately after. However, these losses may still arguably be within a tolerable range for dehydration that will not negatively affect performance, especially in the mild T_a experienced by the runners during the present investigative period (Maughan et al., 2004). Nevertheless, even though body mass loss was statistically significant during training runs and irrespective of whether the elite Kenyan endurance runners had completed 1, 2, or 3 training sessions over the course of a training day, they remained on average well hydrated throughout each day of the 5 day recording period with no heat strain evident at any time during training sessions (Figure 3.1). Maintenance of hydration balance over the 5 day recording period was evidenced by similar total body water and body mass values recorded each morning before training despite athletes incurring body mass deficits due to training runs. Daily hydration balance was further demonstrated by a similar pre training body mass in the morning and pre training body mass in the afternoon. It was also found that there was no significant difference in osmolality and specific gravity of the urine supplied by the athletes in the morning when compared to the evening sample. During the 5 day recording period, mean osmolality and specific gravity in the morning (519 ± 203 mOsmol·kg⁻¹; 1.017 ± 0.006 , respectively) and evening (502 ± 229 mOsmol·kg⁻¹; 1.015 ± 0.007 , respectively) were below values suggested to correctly classify dehydration in individuals (i.e., > 700 mOsmol·kg⁻¹ and a specific gravity ≥ 1.020 ; (American College of Sports Medicine, 2007)). Maintenance of hydration status, despite athletes losing body water during training, was achieved by water gained from the diet and fluid ingested throughout the day *ad libitum*. The pattern and volume of fluid intake reported in the present study is consistent with pre-

3.4. DISCUSSION

vious observations of elite Kenyan endurance runners (Onywera et al., 2004; Chapter 2) as fluid intake consisted mainly of water ($0.7 \pm 0.5 \text{ L}\cdot\text{d}^{-1}$; 18.4 %) and milky tea ($1.2 \pm 0.4 \text{ L}\cdot\text{d}^{-1}$; 31.6 %) with a small contribution from the intake of other fluids such as soft drinks and milk ($0.4 \pm 0.2 \text{ L}\cdot\text{d}^{-1}$; 10.5 %). Interestingly the mean osmolality of the milky tea regularly consumed by the athletes was isotonic ($281 \pm 55 \text{ mOsmol}\cdot\text{kg}^{-1}$), high in energy ($0.2 \text{ MJ}\cdot 100\text{g}^{-1}$) and had a modest $[\text{Na}^+]$ ($16.98 \text{ mmol}\cdot\text{L}^{-1}$) that is similar to conventional sports drinks. Furthermore, Shirreffs et al. (Shirreffs et al., 2007) found milk (a major constitute of the tea regularly consumed by the athletes) was effective at replacing sweat losses and maintaining euhydration following exercise induced dehydration (approximately 2 % body mass loss). Other sources of daily fluid intake were water consumed as moisture in food and metabolic water production resulting in a mean total daily fluid intake of $3.8 \pm 0.8 \text{ L}\cdot\text{d}^{-1}$.

Daily total *ad libitum* water intake ($0.29 \pm 0.1 \text{ L}\cdot\text{MJ}^{-1}$) in the present study was consistent with guidelines from the National Research Council (US) (1989) that suggest daily water intake requirements of $0.24 \text{ L}\cdot\text{MJ}^{-1}$ ($1.0 \text{ mL}\cdot\text{kcal}^{-1}$) for average energy expenditure and environmental exposure and $0.36 \text{ L}\cdot\text{MJ}^{-1}$ ($1.5 \text{ mL}\cdot\text{kcal}^{-1}$) for higher levels of physical activity, sweating and solute load and is similar to measured water loss ($0.28 \pm 0.03 \text{ L}\cdot\text{MJ}^{-1}$) in healthy young men observed in summer in North West Europe with a temperate climate (Westerterp et al., 2005). Expressing daily fluid intake relative to body mass, the runners in the present study ingested $42.6 \pm 13.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ ($68.4 \pm 14.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ when taking the water content of food into consideration). Kirsch and von Ameln (1981) reported that 13 European long distance runners (median body mass of 64.0 kg), training in similar environmental temperatures (18-24 °C; 20-40 %RH), maintained daily fluid balance with a mean fluid intake of $33 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$. Runners in the present study probably required greater daily fluid intake due to a greater training volume as the runners in the study by Kirsch and von Ameln (1981) trained just once a day. Drinking behaviours observed in the present study are similar to the findings of Adolph and Dill (1938) (i.e., ingestion lagged considerably behind output during exercise and was largely made up

at meals) and are consistent with the ACSM Position Stand on Exercise and fluid replacement (American College of Sports Medicine, 2007). Thus in the present study, elite Kenyan endurance runners seemed to perfectly adjust daily fluid intake to daily fluid needs by relying on their sensation of thirst and eating and drinking habits alone. However, it is undetermined whether this would hold under increased heat stress.

During training runs, the athletes did not consume fluid. This was likely the result of short duration training runs that typically lasted less than or about 1 hr (Table 3.3) and therefore did not require fluid replacement (Convertino et al., 1996). During longer duration exercise, Noakes et al. (1988) have proposed that an *ad libitum* fluid intake strategy is all that is necessary to offset any negative effects of dehydration. This has since been corroborated in several studies that have reported no benefit of drinking high rates of fluid compared to *ad libitum* (e.g., Saunders et al., 2005). The current ACSM Position Stand for exercise and fluid replacement (American College of Sports Medicine, 2007) suggests fluid intake should be *ad libitum* from 0.4 to 0.8 L·hr⁻¹ with the lower value for slower, lighter individuals competing in cooler environments, and, the higher value for faster, larger individuals competing in warmer environments. This agrees with fluid intake guidelines previously proposed by IMMDA (Noakes & Martin, 2002) that suggests athletes should consume fluid as dictated by thirst (i.e., *ad libitum*) but not more than 0.4 to 0.8 L·hr⁻¹. These guidelines have also been adopted by other organizations such as USA Track and Field (Casa, 2003). Similarly, the International Consensus Guidelines for the Prevention of Exercise-Associated Hyponatraemia invoke the same advice (Hew-Butler et al., 2005).

Diet Composition and Energy Balance

The diet fulfilled current recommendations for carbohydrate and protein intake for endurance athletes, typically 55-58 % (6-10 g·kg⁻¹BM·d⁻¹) of energy from carbohydrate, and 12-15 % (1.2-1.4 g·kg⁻¹BM·d⁻¹) of energy from protein (American College of Sports Medicine, 2000). In contrast, fat intake was very low (6.6 ± 1.0 %, 0.8 g·kg⁻¹BM·d⁻¹) and did not comply with current

recommendations, i.e., typically > 15 % of energy from fat (American College of Sports Medicine, 2000). Such a low fat diet may compromise intramuscular triacylglycerol concentration with presently unknown consequences in endurance exercise performance (Spriet & Gibala, 2004). Nevertheless, contrary to previous observations of elite Kenyan endurance runners in Chapter 2 and in the study by Onywera et al. (2004), who were training prior to major competition, the subjects in the present study appeared in energy balance during the recording period. It is likely this was due to the comparatively lower weekly training distance achieved during the present recording period compared to the earlier studies; this is illustrated by the lower physical activity level (i.e., ADMR/BMR) in the present study (2.1 vs. 2.3 (Onywera et al., 2004) and 2.3 (Chapter 2)).

Mean dietary K^+ intake was significantly different from mean K^+ loss in sweat and urine over a 24 hr recording period (3812 ± 489 vs. 2346 ± 846 $mg \cdot d^{-1}$; $p < 0.001$) equivalent to a mean difference of 1466 ± 846 $mg \cdot d^{-1}$. The finding of excess K^+ intake when compared to K^+ loss in sweat and urine are likely due to errors in collection of sweat [K^+] (Patterson et al. (2000) and or faecal losses which were unfortunately not measured in the present investigation. Holbrook et al. (1984) reported that although the range of Na^+ faecal excretion was low in 28 healthy adults investigated over a 1 year period (10-125 $mg \cdot d^{-1}$), the range of K^+ faecal loss was greater (112-846 $mg \cdot d^{-1}$). The mean dietary intake of Na^+ in the present study was similar to that in the study by Holbrook et al. (1984) (3245 vs. 3000 $mg \cdot d^{-1}$) whereas, K^+ intake in the present study was substantially greater (3812 vs. 2800 $mg \cdot d^{-1}$). This suggests subjects in the present investigation may have excreted more K^+ in faeces than reported previously (Holbrook et al., 1984) and thus may explain the apparent K^+ excess, however, this remains to be determined. In contrast, Na^+ intake was not significantly different from Na^+ loss (3245 ± 901 vs. 3254 ± 1070 $mg \cdot d^{-1}$; $p = 0.975$). Thus, elite Kenyan endurance runners do not require additional electrolyte supplementation above habitual dietary intake. This is further supported by early work by Pitts et al. (1944) who noted that subjects marching in the heat did not require further salt supplementation above that consumed in their

diet and is consistent with the new ACSM Position Stand (American College of Sports Medicine, 2007). It is acknowledged however that the determination of sweat electrolyte concentrations may have been effected by the collection method used in the present investigation as it has generally been observed that local sweat electrolyte concentration using the enclosed patch technique is higher than measurements using the whole-body technique (e.g., Lemon et al., 1986). Nevertheless, sweat $[\text{Na}^+]$ and $[\text{K}^+]$ in the present investigation (Table 3.1) are comparable to values reported in heat acclimatised individuals (Dill et al., 1938; Sawka & Montain, 2000).

Training Load

Training distance achieved over the 5 day recording period (81.7 ± 11.3 km) was substantially lower than that typically reported albeit over a 7 day training period in other elite endurance runners (e.g., Noakes, 2001). This was because athletes were in a 10 day taper phase of their training cycle as the investigation was undertaken 1 week prior to the Kenyan national trials for the 2005 IAAF World Championships. Nevertheless, the 5 day training distance achieved in the present investigation is similar to values reported (Noakes, 2001) for elite Kenyan athletes preparing for major competition prior to the cross-country season in Kenya ($80\text{-}100 \text{ km}\cdot\text{wk}^{-1}$). Indeed, similar to the current study, Noakes (2001) reported that during this period, athletes typically ran an easy run (30 min) each morning, with the final 800-1600 m being run at race pace, two interval training sessions per wk and two long runs (60 min). This resulted in 25 % of the training volume run at race pace or greater; this value is comparable to the weekly training load in the present investigation (i.e., 26 % of total weekly training time spent $> 80\%$ HR_{peak}). Indeed, training sessions in the present study were on average characterised by moderate to low intensity running interspersed with high intensity running such as interval training (Table 3.3). This was also reflected in lower mean peak T_i during morning and afternoon runs (Figure 3.1) compared to interval training sessions (38.6 ± 0.9 °C vs. 39.5 ± 1.8 °C, respectively). These findings corroborate previous investigations that indicate low to moderate

intensity training accounts for the majority of training time in endurance athletes (e.g., Esteve-Lanao et al., 2005). Typical examples of this type of training were the morning short (completed by middle-distance runners) and medium training runs (equivalent to a short run for long-distance runners) as well as afternoon runs (all runners). These runs typically served as a warm up (for interval training) and/or a recovery run that usually compromised periods of slow and fast running with hopping and bouncing exercises that resulted in a relatively low mean speed for the training distance achieved (Table 3.3). Whether the findings of the present investigation apply to elite Kenyan endurance runners during a period of greater training load/intensity is unknown and remains to be determined.

Conclusions

In conclusion, these results suggest habitual ad libitum fluid and food intake is adequate to maintain hydration and electrolyte balance on a daily basis in elite Kenyan endurance runners under mild ambient conditions and during a 10 day taper phase. The drinking and eating habits of the elite Kenyan endurance runners in the present study corroborate the new ACSM guidelines for fluid and electrolyte replacement (American College of Sports Medicine, 2007). However, this is a narrow sample of athletes and these findings may not apply to all athletes, in all sports or training scenarios.

4

Efficacy of new fluid intake recommendations for elite marathon running

4.1 Introduction

Fluid intake recommendations for endurance events such as the marathon have evolved extensively over the last few decades. During the first half of the twentieth century until the early 1970s, runners were typically advised not to ingest fluid during competitive marathon running (Noakes, 1993). However, from then onwards and until relatively recently, fluid intake recommendations have typically advocated total replacement of all fluid lost during exercise, or at least up to the maximum amount tolerated (Convertino et al., 1996; Montain et al., 1999; Binkley et al., 2002). Recently, the ACSM has replaced their prior Position Stand (Convertino et al., 1996) with an updated version on exercise and fluid replacement (American College of Sports Medicine, 2007) that promotes drinking $0.4\text{-}0.8\text{ L}\cdot\text{hr}^{-1}$ of fluid *ad libitum* during exercise with lower fluid volumes for slower, lighter individuals competing in cooler environments, and higher volumes for faster, larger individuals competing in warmer environments. These guidelines represent a compromise between preventing a level of dehydration that may negatively impact upon performance (i.e., $> 2\%$ body mass loss from water deficit (Wyndham & Strydom,

1969; Chevront & Haymes, 2001b; Coyle, 2004; Fudge et al., 2006; American College of Sports Medicine, 2007)) versus preventing excessive ingestion of fluid that could potentially cause hyponatraemia (i.e., serum sodium concentration $< 130 \text{ mmol}\cdot\text{L}^{-1}$ (Almond et al., 2005; Hew-Butler et al., 2005)). The efficacy of proposing a specific fluid intake range during exercise has been investigated in a study that modelled parameters that influence sweating rate (Montain et al., 2006). Montain et al. (2006) found that this rate (i.e., $0.4\text{-}0.8 \text{ L}\cdot\text{hr}^{-1}$) of fluid intake was sufficient to maintain body mass loss within 3 % and to prevent body mass gain in 50-90 kg subjects running a marathon at $8.5\text{-}15 \text{ km}\cdot\text{hr}^{-1}$ in cool and warm ambient conditions (i.e., $18 \text{ }^\circ\text{C}$ and $28 \text{ }^\circ\text{C}$, respectively). These authors suggested that factors that influence sweat rate such as body mass, running speed and ambient conditions be considered prior to adopting this specific fluid intake range, and where necessary adapting the strategy to suit the individual (Montain et al., 2006). However, in their calculations, these authors did not consider the fluid requirements of elite marathon runners (Montain et al., 2006). For example, maximum running speed calculated was $15 \text{ km}\cdot\text{hr}^{-1}$, whereas to win a major city marathon a male athlete must run faster than $19 \text{ km}\cdot\text{hr}^{-1}$. Furthermore, the environmental temperatures (i.e., $18 \text{ }^\circ\text{C}$ and $28 \text{ }^\circ\text{C}$) on the basis of which sweat rates and resultant body mass loss were estimated do not adequately reflect the lower environmental temperatures typically experienced in most major city marathons (Chevront & Haymes, 2001b) or indeed the ambient conditions encountered when the fastest marathons are run (Fudge et al., 2006). For example, the top ten fastest marathons of all time (up to 2004) were performed at a mean T_a of $7.3 \text{ }^\circ\text{C}$ (Fudge et al., 2006). This observation is not unexpected given the laboratory results of Galloway and Maughan (1997) that found the longest exercise duration at $10.5 \text{ }^\circ\text{C}$ ($93.5 \pm 6.2 \text{ min}$) vs. $3.6 \text{ }^\circ\text{C}$ ($81.4 \pm 9.6 \text{ min}$) vs. $20.6 \text{ }^\circ\text{C}$ ($81.2 \pm 5.7 \text{ min}$) vs. $30.5 \text{ }^\circ\text{C}$ ($51.6 \pm 3.7 \text{ min}$).

The principle of *ad libitum* fluid intake currently being advocated is in agreement with previous observations in elite Kenyan endurance runners during important periods of training (Onywera et al., 2004; Chapters 2-3). These elite Kenyan endurance runners did not consume liquids before or during

training, rarely consumed liquids after training, and only consumed modest amounts when they did drink. While the drinking behaviours of some of the best endurance runners in the world during training are well described (Onywera et al., 2004; Chapters 2-3), there is almost no information on what the best marathoners drink when racing (for a review of the marathon running literature see reference Cheuvront & Haymes, 2001b). Therefore, in the present study, retrospective video analysis was used to determine the drinking behaviours of the winning male and female elite runners in the 2006 and 2007 London Marathons in order to assess the efficacy of prevailing fluid intake recommendations for elite marathon running. To supplement this data, a mathematical model, similar to that used by Montain et al. (2006) was used to predict the effect of varying fluid intake rates on hydration status when body mass, running speed and environmental conditions are systematically varied. This method uses predicted sweat rates and a range of reasonable fluid intake rates to estimate percentage body mass loss. Fluid intake rate is considered adequate if body mass loss remains between 0 and 3 % for the duration of the race (Wyndham & Strydom, 1969; Cheuvront & Haymes, 2001b; Coyle, 2004; American College of Sports Medicine, 2007). Therefore, the efficacy of prevailing fluid intake recommendations for elite marathon running is assessed in the present study by considering both fluid intake behaviours of elite marathon runners and modelled fluid intake requirements.

4.2 Methods

4.2.1 Video analysis

A retrospective analysis of the drinking behaviors of the winning male and female runners of the 2006 and 2007 London Marathons was undertaken using video tapes provided by the British Broadcasting Corporation. Permission for the present investigation was given by the race organiser. Only the winners of each race were targeted as the images were recorded on a motorcycle that followed the lead groups; this resulted in maximum camera exposure for the race winners. Drinking stations for elite runners were placed

at or very near every 5 km of the course and from the video images the time spent ingesting fluid (sec) was measured; the assumption being that mouth contact with the water bottle equated to drinking time. The entire race was also monitored for any additional fluid that may have been ingested along the route (e.g., general water and sports drink stalls). Fluid intake (mL) for each athlete was estimated by multiplying the total duration spent ingesting fluid (sec) by 60 as Noakes (In Press) (and verified in the present lab, unpublished observation) measured the maximal flow rate of typical drinking bottles used by elite runners during major city marathons and found the maximal flow rate is approximately $60 \text{ mL}\cdot\text{sec}^{-1}$. This value was then used to calculate the fluid intake rate (i.e., $\text{L}\cdot\text{hr}^{-1}$) so that fluid intake could be compared to prevailing fluid replacement recommendations (American College of Sports Medicine, 2007) that promote drinking $0.4\text{-}0.8 \text{ L}\cdot\text{hr}^{-1}$ of fluid *ad libitum*. Data are expressed as the mean \pm SD.

4.2.2 Mathematical modeling

Body water loss/gain was modelled for subjects of various body mass (45, 55, 65 and 75 kg) running a 42.2 km marathon equivalent to (hr:min:sec) 2:04:00 (i.e., $20.4 \text{ km}\cdot\text{hr}^{-1}$) and 2:30:00 (i.e., $16.9 \text{ km}\cdot\text{hr}^{-1}$) pace in cold ($7.3 \text{ }^\circ\text{C}$) and warm ($24.8 \text{ }^\circ\text{C}$) ambient conditions with water consumption rates ranging from $0\text{-}2 \text{ L}\cdot\text{hr}^{-1}$ in $0.1 \text{ L}\cdot\text{hr}^{-1}$ increments. These criteria and conditions were chosen as they encompass the typical range of body mass (Tittel & Wulscherk, 1992; Onywera et al., 2004; Chapters 2-3) and race pace of elite male and female marathon runners as well as the typical range of weather conditions encountered in major city marathons. For example, the average T_a of the top ten fastest marathon times is $7.3 \text{ }^\circ\text{C}$ while the average temperature at summer Olympic Games is $24.8 \text{ }^\circ\text{C}$ (Fudge et al., 2006). This approach permits a range of fluid intakes that reflect elite marathon running to be approximated. The body water loss/gain was calculated using the following equations:

$$\text{SR} = (\text{BM} \times (\text{V})) \div 732 \times (1 - ((\text{R} + \text{C})/\text{H})) \text{ (Montain et al., 2006)}$$

$$R = (T_{sk} - T_r) \times 5.2 \text{ (Kerlake, 1972)}$$

$$C = (T_{sk} - T_a) \times V^{0.5} \times 8.3 \text{ (Kerlake, 1972)}$$

$$H = BM \times S \times 4 \text{ (Kerlake, 1972; Gonzalez-Alonso et al., 1999)}$$

$$FB = FI - SR \times t \text{ (Montain et al., 2006)}$$

$$\%BML = FB/BM_i \times 100 \text{ (Montain et al., 2006)}$$

where SR is sweating rate ($L \cdot hr^{-1}$), BM is body mass (kg), V is running speed ($km \cdot hr^{-1}$), R is radiative heat loss ($W \cdot m^{-2}$), C is convective heat loss ($W \cdot m^{-2}$), $V^{0.5}$ is the square root of the velocity of air over the skin that is assumed to be equivalent to running speed ($m \cdot sec^{-1}$), H is heat production ($W \cdot m^{-2}$), S is running speed ($m \cdot sec^{-1}$), FB is fluid balance (L), FI is fluid intake (L), t is time (hr), %BML is percentage body mass (kg) loss, BM_i is initial body mass (kg), $T_{sk} - T_a$ is the temperature difference between skin temperature and ambient temperature ($^{\circ}C$), and finally $T_{sk} - T_r$ is the temperature difference between skin temperature and the mean radiative temperature (assumed to be the same as ambient temperature (Nielsen, 1996)) of nearby surfaces ($^{\circ}C$). Skin to ambient temperature gradient was $16.4^{\circ}C$ and $5.9^{\circ}C$ for cold and warm weather conditions, respectively as predicted by Nielsen (1996). The sweating rate equation assumes that sweating and sweat evaporation are 100 % efficient. No attempt was made to adjust for respiratory water loss, oxidative metabolism, oxidative breakdown of glycogen and protein and potential urine or faecal losses (Montain et al, 2006). The rate of fluid intake required to maintain body mass loss $< 3\%$ was considered optimal for endurance running as this allows enough time to accrue for performance to be significantly compromised after 2 % body mass loss has been attained (Montain et al., 2006).

4.3 Results

Video Analysis

The female (F06) and male (M06) 2006 London Marathons were won in (hr:min:sec) 2:19:36 and 2:06:39, respectively. The female race started at 9.00 am and the male at 9.45 am resulting in a mean T_a of 9.3 ± 0.5 °C and 9.9 ± 0.9 °C, respectively; mean RH was 82.7 ± 4.1 % and 84.3 ± 2.9 %, respectively. In 2007, the female (F07) and male (M07) races were won in (hr:min:sec) 2:20:38 and 2:07:41, with a mean T_a of 15.7 ± 2.6 °C and 17.7 ± 2.8 °C; mean RH was 48.1 ± 8.9 % and 54.7 ± 8.9 %, respectively. Figure 4.1 displays the duration spent ingesting fluid at each drinking station and fluid consumed between stations; the mean duration spent ingesting fluid at drinking stations for F06, M06, F07 and M07 were 9 ± 1 , 6 ± 3 , 5 ± 2 and 1 ± 1 sec, respectively. F06 and M06 did not consume any additional fluid during the race resulting in total drinking durations of 56 and 38 sec, respectively. On the other hand, F07 and M07 ingested fluid for 4 and 20 sec, resulting in estimated total drinking durations of 43 and 31 sec, respectively. Applying a flow rate of $60 \text{ mL}\cdot\text{sec}^{-1}$ (Noakes, In Press) to the total drinking durations of the elite runners (Figure 4.1), resulted in estimated fluid intakes for F06, M06, F07 and M07 of 3360, 2280, 2559 and 1860 mL, respectively that equates to fluid intake rates of 1.5, 1.1, 1.1 and $0.9 \text{ L}\cdot\text{hr}^{-1}$, respectively. The composition of each athletes drink is unknown.

Mathematical Modeling

The predicted sweat rates for 45-75 kg subjects running in cold (7.3 °C) and warm (24.8 °C) ambient conditions at (hr:min:sec) 2:04:00 and 2:30:00 marathon pace are shown in Table 4.1. The estimated mean sweat rate across all conditions was $1.2 \pm 0.4 \text{ L}\cdot\text{hr}^{-1}$ (range: 0.6 - $1.9 \text{ L}\cdot\text{hr}^{-1}$), although it is recognized that sweat rates can be much higher in some individuals in hotter conditions (e.g., $3.7 \text{ L}\cdot\text{hr}^{-1}$ was reported for Alberto Salazar when preparing for the 1984 Olympic Marathon (Armstrong et al., 1984)). The corresponding percentage body mass loss as a result of varying rates of fluid

4.3. RESULTS

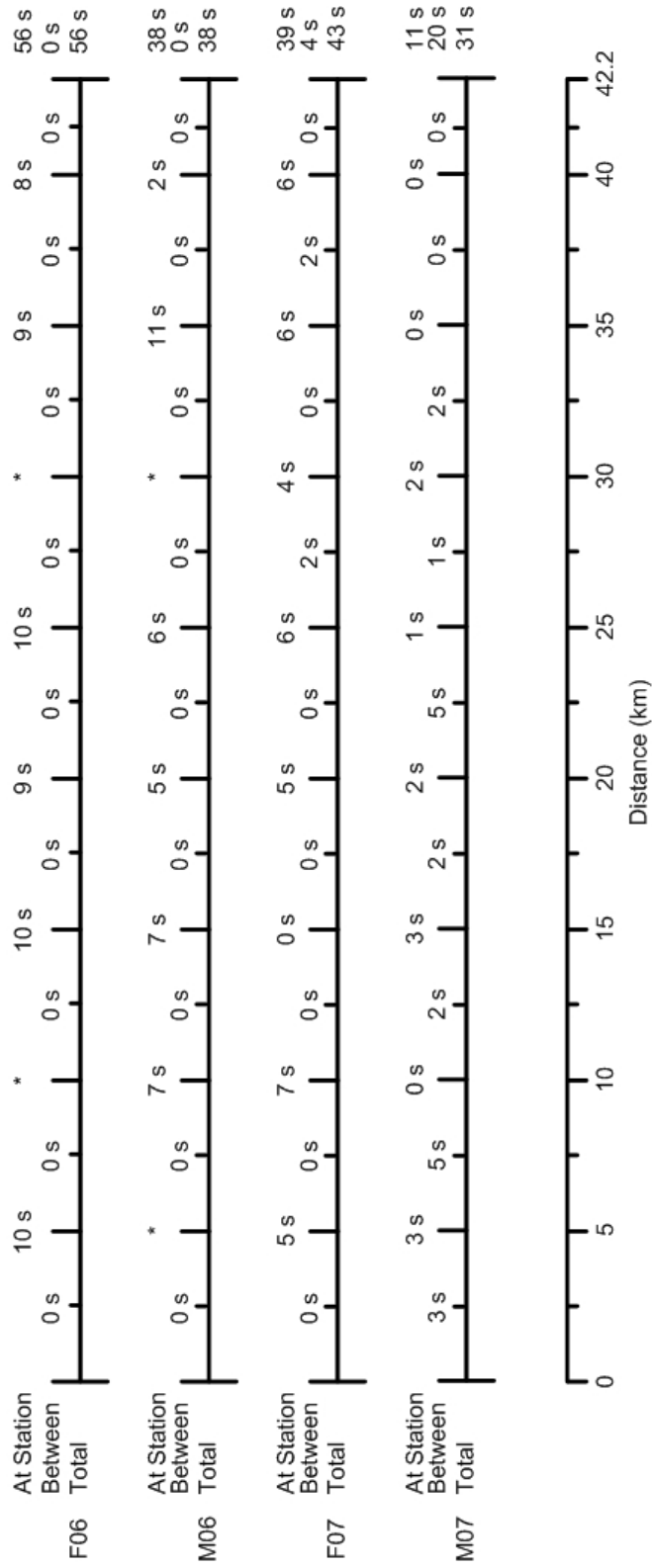


Figure 4.1: Time spent ingesting fluid at each of the 5 km drinking stations and between stations for the female and male winners of the 2006 and 2007 London Marathons. *No data recorded.

intake (0-2 L·hr⁻¹ in 0.1 L·hr⁻¹ increments) are also shown in Table 4.1. Across all conditions (i.e., weather conditions, body mass and running pace), no fluid intake during racing results in a > 3 % loss in body mass loss. Considering prevailing fluid intake recommendations of 0.4-0.8 L·hr⁻¹, this range of fluid intake is not adequate to prevent a > 3 % body mass loss and to prevent body mass gain across all conditions investigated (Table 4.1). For example, although 0.4 L·hr⁻¹ is adequate for a small (45 kg) and slower (16.9 km·hr⁻¹) individual competing in a cold (7.3 °C) environment to maintain body mass loss < 3 % and prevent body mass gain, a large (75 kg) and fast (20.4 km·hr⁻¹) individual competing in a warm (24.8 °C) environment consuming 0.8 L·hr⁻¹ is estimated to have a body mass loss of 3.1 %.

4.4 Discussion

This investigation provides a unique snapshot of drinking behaviours of elite runners during a major city marathon. As demonstrated in Figure 4.1, the drinking behaviours of the male and female winners of the 2006 and 2007 London Marathon are diverse. For example, the mean duration spent ingesting fluid at 5 km drinking stations for F06, M06, F07 and M07 were 9 ± 1 , 6 ± 3 , 5 ± 2 and 1 ± 1 sec, respectively. F06 and M06 did not consume any additional fluid during the race resulting in total drinking durations of 56 and 38 sec, respectively. On the other hand, F07 and M07 ingested fluid away from drinking stations for 4 and 20 sec resulting in estimated total drinking durations of 43 and 31 sec, respectively. The consumption of fluids away from drinking stations by both the winning athletes in the 2007 race may reflect the warmer ambient conditions (9.3-9.9 °C vs. 15.7-17.7 °C). However, it is interesting to note that the warmer conditions did not result in greater total drinking durations as the highest estimated time ingesting fluid was by F06 followed by F07 who drank for longer than M06 who drank for longer than M07 (Figure 4.1). Noakes (In Press) measured the maximal flow rate of typical drinking bottles used by elite runners during major city marathons and found the maximal flow rate is approximately 60 mL·sec⁻¹ (verified in the present lab, unpublished observation). Applying this flow rate to the total

Table 4.1: Predicted sweat rates and resultant percentage body mass loss/gain for 45-75 kg subjects running in cold (7.3 °C) and warm (24.8 °C) ambient conditions at (hr:min:sec) 2:04:00 and 2:30:00 marathon pace with varying rates of fluid intake (0-2L·hr⁻¹ in 0.1 L·hr⁻¹ increments). Grey shading highlights percentage body mass loss > 3% as well as percentage body mass gains > 0%. T_a (°C); BM (kg); V (km·hr⁻¹); SR (L·hr⁻¹).

T _a	BM	V	SR	Fluid intake (L·hr ⁻¹) and Resultant Body Mass Loss (%)																				
				0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
7.3	45	20.4	0.8	-3.5	-3.0	-2.5	-2.1	-1.6	-1.2	-0.7	0.2	0.7	1.1	1.6	2.1	2.5	3.0	3.4	3.9	4.4	4.8	5.3	5.7	
	55	20.4	1.0	-3.9	-3.5	-3.1	-2.7	-2.4	-2.0	-1.6	-1.2	-0.9	-0.5	-0.1	0.3	0.6	1.0	1.4	1.8	2.1	2.5	2.9	3.3	3.6
	65	20.4	1.3	-4.2	-3.8	-3.5	-3.2	-2.9	-2.6	-2.3	-1.9	-1.6	-1.3	-1.0	-0.7	-0.3	0.0	0.3	0.6	0.9	1.2	1.6	1.9	2.2
7.3	75	20.4	1.6	-4.4	-4.1	-3.8	-3.5	-3.3	-3.0	-2.7	-2.4	-2.2	-1.9	-1.6	-1.3	-1.1	-0.8	-0.5	-0.2	0.0	0.3	0.6	0.9	1.1
24.8	45	20.4	1.1	-4.9	-4.5	-4.0	-3.6	-3.1	-2.6	-2.2	-1.7	-1.3	-0.8	-0.3	0.1	0.6	1.0	1.5	2.0	2.4	2.9	3.3	3.8	4.3
	55	20.4	1.4	-5.1	-4.7	-4.3	-4.0	-3.6	-3.2	-2.8	-2.5	-2.1	-1.7	-1.3	-0.9	-0.6	-0.2	0.2	0.6	0.9	1.3	1.7	2.1	2.4
	65	20.4	1.6	-5.2	-4.9	-4.6	-4.2	-3.9	-3.6	-3.3	-3.0	-2.6	-2.3	-2.0	-1.7	-1.4	-1.1	-0.7	-0.4	-0.1	0.2	0.5	0.9	1.2
24.8	75	20.4	1.9	-5.3	-5.0	-4.7	-4.4	-4.2	-3.9	-3.6	-3.3	-3.1	-2.8	-2.5	-2.2	-2.0	-1.7	-1.4	-1.1	-0.9	-0.6	-0.3	0.0	0.2
7.3	45	16.9	0.6	-3.2	-2.6	-2.1	-1.5	-0.9	-0.4	0.2	0.7	1.3	1.8	2.4	2.9	3.5	4.1	4.6	5.2	5.7	6.3	6.8	7.4	7.9
	55	16.9	0.8	-3.6	-3.2	-2.7	-2.3	-1.8	-1.4	-0.9	-0.5	0.0	0.5	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1	4.5	5.0	5.5
	65	16.9	1.0	-4.0	-3.6	-3.2	-2.8	-2.4	-2.0	-1.7	-1.3	-0.9	-0.5	-0.1	0.3	0.6	1.0	1.4	1.8	2.2	2.6	3.0	3.3	3.7
7.3	75	16.9	1.3	-4.2	-3.9	-3.5	-3.2	-2.9	-2.5	-2.2	-1.9	-1.5	-1.2	-0.9	-0.5	-0.2	0.1	0.5	0.8	1.1	1.5	1.8	2.1	2.5
24.8	45	16.9	0.9	-4.8	-4.3	-3.7	-3.2	-2.6	-2.1	-1.5	-0.9	-0.4	0.2	0.7	1.3	1.8	2.4	2.9	3.5	4.1	4.6	5.2	5.7	6.3
	55	16.9	1.1	-5.0	-4.5	-4.1	-3.6	-3.2	-2.7	-2.3	-1.8	-1.4	-0.9	-0.5	0.0	0.5	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1
	65	16.9	1.3	-5.1	-4.7	-4.3	-4.0	-3.6	-3.2	-2.8	-2.4	-2.0	-1.7	-1.3	-0.9	-0.5	-0.1	0.3	0.7	1.0	1.4	1.8	2.2	2.6
24.8	75	16.9	1.6	-5.2	-4.9	-4.5	-4.2	-3.9	-3.5	-3.2	-2.9	-2.5	-2.2	-1.9	-1.5	-1.2	-0.9	-0.5	-0.2	0.1	0.5	0.8	1.1	1.5

drinking durations of the elite runners measured in the present investigation (Figure 4.1), resulted in estimated fluid intakes for F06, M06, F07 and M07 of 3360, 2280, 2559 and 1860 mL, that equate to fluid intake rates of 1.5, 1.1, 1.1 and 0.9 L·hr⁻¹, respectively. These estimated fluid intake rates are greater than prevailing fluid intake recommendations of *ad libitum* 0.4-0.8 L·hr⁻¹ proposed by the ACSM (American College of Sports Medicine, 2007) and IMMDA (Noakes & Martin, 2002). It is recognised, however, that these estimated fluid intakes are the maximum that may be ingested (as this is dependant on the pressure applied to the bottle) and also that these estimates do not take in to consideration the size of the athletes mouth (which is likely to be smaller in females). Nevertheless, the data do suggest that it is improbable that *ad libitum* 0.4-0.8 L·hr⁻¹ proposed by the ACSM (American College of Sports Medicine, 2007) and IMMDA (Noakes & Martin, 2002) is likely to apply to all the elite marathon runners. Therefore, prevailing fluid intake recommendations are insufficient for elite marathon running.

Interestingly, M07 was the only athlete who did not drink anything from 35-42.2 km amounting to approximately 22 min. Montain and Coyle (1993) demonstrated the time course for physiological benefits (reduced heart rate and core temperature as well as improved blood volume and osmolality) as a result of fluid consumption probably requires 40-60 min so that the fluid is ingested and assimilated into the body. It may be suggested then that M07 may have had a fluid intake behaviour, during the last part of the race at least, that was the closest to optimum out of all the drinking behaviours observed for racing performance as consuming fluid towards the end of a marathon race will essentially leave fluid in the gastrointestinal tract that will be of no benefit physiologically but will actually add unnecessary body mass. Indeed being mildly dehydrated towards the end of a marathon race may actually be an advantage as theoretically it will lower the energy cost of running at the same relative sub-maximal speed (Armstrong et al., 1985; Sawka & Montain, 2000; Coyle, 2004; Fudge et al., 2006). To test this hypothesis, Armstrong et al. (2006) ran 10 endurance runners four times for 10 min, twice each at 70 and 85 % of their $\dot{V}O_{2max}$. At each intensity, subjects ran once euhydrated and once dehydrated (by 5.5 and 5.7 % relative

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body mass loss, respectively). These authors found that $\dot{V}O_2$ (expressed relative to body mass) was not significantly different and concluded that a reduction in body mass had no effect on running economy and therefore no performance impact. However, Armstrong et al. (2006) may have wrongly interpreted their findings. Reducing body mass will in turn reduce the energy cost per unit distance, so the finding that running economy expressed in $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ is not significantly improved when hypohydrated is not surprising as the reduction in body mass will be cancelled out by the reduction in energy cost per unit distance. What is more pertinent is the absolute O_2 cost at the same relative speed. At 85 % $\dot{V}O_{2max}$ the fractional utilisation of $\dot{V}O_{2max}$ was 3.2 % lower when hypohydrated compared to euhydration (i.e., 86.6 vs. 89.8 % $\dot{V}O_{2max}$, respectively). This difference was not found to be statistically significant but in terms of a performance effect for an elite runner completing the last part of a marathon race, this may well have a performance impact (Hopkins et al., 1999).

Despite the scarcity of data to support an ergogenic effect of drinking *ad libitum* at present, drinking *ad libitum* throughout a marathon appears to confer no major disadvantage over drinking to replace all fluid losses or at least up to the maximal amount tolerated (McConell et al., 1997; Daries et al., 2000; Chevront & Haymes, 2001a; Kay & Marino, 2003; Saunders et al., 2005). For example Daries et al. (2000) ran 8 endurance runners twice for 2 hr with subjects ingesting a carbohydrate electrolyte drink either *ad libitum* or in set volumes that approximated full replacement of sweat loss. It was found that the higher rates of fluid ingestion did not alter plasma volume and osmolality and did not improve 2 hr running performance. An important consequence of drinking *ad libitum* however is that it typically results in modest dehydration. A review (Chevront & Haymes, 2001b) of the endurance running literature reported no effect of dehydration on core temperature for losses of body mass up to 3.1 % (mean: < 2.5 %), whereas a positive relationship was found between the level of dehydration and rise in core temperature when losses were greater than 3 % body mass. Consequently, the present study uses a mathematical model to estimate fluid intake rates for elite marathon runners with varying body mass and running

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speeds in typical ambient conditions that are required to keep body mass loss $< 3\%$ and prevent body mass gain (Table 4.1). It was found that across all conditions (i.e., weather conditions, body mass and running pace) no fluid intake resulted in body mass loss $> 3\%$ which suggests marathon running performance may be impaired in those who drink nothing at all. Considering prevailing fluid intake recommendations of $0.4\text{--}0.8\text{ L}\cdot\text{hr}^{-1}$, this range of fluid intake was found to be inadequate even when applying the ACSM (American College of Sports Medicine, 2007) and IMMIDA (Noakes & Martin, 2002) important caveat of the lower value for slower, lighter individuals competing in cooler environments, and the higher value for faster, larger individuals competing in warmer environments. For example, although $0.4\text{ L}\cdot\text{hr}^{-1}$ is adequate for a small (45 kg) and slower ($16.9\text{ km}\cdot\text{hr}^{-1}$) individual competing in a cold ($7.3\text{ }^{\circ}\text{C}$) environment to maintain body mass loss $< 3\%$ and prevent body mass gain, a large (75 kg) and fast ($20.4\text{ km}\cdot\text{hr}^{-1}$) individual competing in a warm ($24.8\text{ }^{\circ}\text{C}$) environment consuming $0.8\text{ L}\cdot\text{hr}^{-1}$ may have a body mass loss of 3.1% . The larger, faster individual running in warm ambient conditions will require, albeit marginally, more fluid per hour (i.e., $0.9\text{ L}\cdot\text{hr}^{-1}$) to prevent body mass loss $> 3\%$. Therefore, as can be seen in Table 4.1, the range of fluid intake rates predicted to limit body mass loss to $< 3\%$ and prevent body mass gains across all conditions is wide. For example at $7.3\text{ }^{\circ}\text{C}$, running at (hr:min:sec) 2:04:00 marathon pace, a 75 kg runner drinking $1.6\text{ L}\cdot\text{hr}^{-1}$ is estimated to result in body mass loss of 0% , whereas a 45 kg runner drinking at the same fluid intake rate is estimated to gain 3.9% of body mass which is almost certainly undesirable (Almond et al., 2005). Therefore, in contrast to the theoretical study by Montain et al. (2006) and the ACSM (American College of Sports Medicine, 2007) and IMMIDA (Noakes & Martin, 2002) recommendations that suggest drinking *ad libitum* $0.4\text{--}0.8\text{ L}\cdot\text{hr}^{-1}$ during exercise for the general population (Noakes & Martin, 2002), the present study is unable to propose a practical fluid range for elite runners given the wide range demonstrated (Table 4.1); the drinking behaviours of the winners of the 2006 and 2007 London Marathons reported in the present study (Figure 4.1) corroborate this contention as the estimated fluid intake rate is dissimilar to that which is recommended ($0.9\text{--}1.5$ vs. 0.4--

0.8 L·hr⁻¹, respectively). Nor is it practical to introduce a caveat similar to that proposed by the ACSM (American College of Sports Medicine, 2007) and IMMADA (Noakes & Martin, 2002) as this would require a large number of iterations to satisfy all the possible combinations and situations. Given this, it is only sensible to suggest drinking fluid *ad libitum* in order to prevent body mass loss < 3 % for elite marathon runners. Of course a pre-planned strategy to limit body mass to < 3 % is desirable but as can be seen from Table 4.1, sweat rate is dependant on ambient conditions and race pace which cannot always be predetermined. For example, ambient conditions at the New York City Marathon has been reported to change by as much as 17 °C from start to finish in the same race (Cheuvront & Haymes, 2001b) and clearly marathon racing at the elite level can vary in pace throughout.

Conclusions

This study aimed to assess the efficacy of prevailing fluid intake recommendations, which propose drinking *ad libitum* 0.4-0.8 L·hr⁻¹ during exercise, for elite marathon running. The estimated fluid intake rates (i.e., L·hr⁻¹) of the winning male and female runners during the 2006 and 2007 London Marathons were varied and out with the prevailing fluid intake recommendations. The mathematical model applied in the present study supports this pattern of fluid intake as it predicts drinking *ad libitum* 0.4-0.8 L·hr⁻¹ is insufficient to maintain body mass < 3 % and prevent body mass gain. The present analysis suggests that the best strategy for competitive marathon running in temperate conditions is to drink *ad libitum* as long as body mass loss is kept within acceptable limits, possibly < 3 %.

5

Accelerometry and heart rate to measure $\dot{V}O_2$

5.1 Introduction

Chapter 2 used acclerometry and PAR to assess physical activity patterns in elite Kenyan endurance runners. Unfortunately the precise quantification of physical activity and or energy expenditure using PAR and accelerometry can be erroneous. PAR is an indirect method whereas a major limitation of accelerometry is the failure to quantify net external work such as uphill walking, cycling, swimming, or load bearing activities (Strath et al., 2005). A further commonly used tool for measuring physical activity is heart rate monitoring (Strath et al., 2005); however, the precise quantification of physical activity and energy expenditure at the population level using heart rate is also difficult and prone to errors (Livingstone et al., 1990; Luke et al., 1997; Strath et al., 2005). For example, heart rate can be affected by factors other than physical activity (e.g., age, gender, training status, emotional state etc.) especially at low exercise intensities (Livingstone et al., 1990; Luke et al., 1997). However, combining methodologies of accelerometry and heart rate may to a large extent overcome some of these limitations and in doing so improve the assessment accuracy of physical activity and energy expenditure (Strath et al., 2000; Treuth & Welk, 2002; Brage et al., 2004; Plasqui & Westerterp, 2005; Strath et al., 2005).

A number of studies have reported improved accuracy to predict physical activity and energy expenditure when combining accelerometry and heart rate compared to their respective individual methods (Avons et al., 1988; Haskell et al., 1993; Moon & Butte, 1996; Luke et al., 1997; Eston et al., 1998). For example, Heskell et al. (1993) reported an R^2 value improved from 0.69 to 0.82 when arm motion, as assessed by accelerometry, was combined with heart rate monitoring during arm ergometer exercise. Subsequent studies have therefore explored various calibration methods utilising the combined methodologies (Treuth et al., 1998; Rennie et al., 2000; Strath et al., 2001; Strath et al., 2002; Brage et al., 2003; Brage et al., 2004). Combining methodologies thus seems promising, but it remains to be determined whether laboratory defined relationships between heart rate, accelerometer counts and $\dot{V}O_2$ will also apply in free-living situations (Strath et al., 2005). Indeed, studies have reported that despite increased energy demands as a result of increasingly faster running speeds, output from some motion sensors plateau (Haymes & Byrnes, 1993; Nichols et al., 2000; Brage et al., 2003). For instance, Brage et al. (2003) investigated whether a commonly used accelerometer (Nichols et al., 2000; Strath et al., 2001; Strath et al., 2002; Brage et al., 2003; Brage et al., 2004; Chapter 2), the Computer Science Applications (CSA) Model 7164 (now also known as the MTI accelerometer; Manufacturing Technology Inc., Fort Walton beach, FL, USA), could predict $\dot{V}O_2$ during walking (3-6 km·hr⁻¹) and running (8-20 km·hr⁻¹) on a motorised treadmill and in the field. It was found that CSA output rose linearly ($R^2 = 0.92$, $p < 0.001$) with increasing speed until 9 km·hr⁻¹ but levelled-off at $\sim 10\,000$ counts·min⁻¹ during running (8-20 km·hr⁻¹). This phenomenon will render it impossible for regression models to accurately predict during vigorous exercise, and hence may not exploit the full benefits of combining these methodologies. Brage et al. (2003) hypothesized that this limitation may be due to biomechanical factors such as a reduced vertical component with increasing speed. However, device dynamics to a certain degree may also be a limiting factor. The Nyquist-Shannon sampling theorem (Nyquist, 1928; Shannon, 1949), also known as the Whittaker-Shannon theorem (Jerri, 1977), states that the sampling frequency (of the device) must be greater

than twice the frequency of the input signal to allow reconstruction of the original signal from the sampled version. Once data have been sampled using a standard accelerometer, the output is filtered so as to eliminate external artefacts such as electrical noise and vibrations; this is generally termed band pass filtering. Hence, the frequency range of band pass filtering must include the maximum frequency elicited during running, and the sampling frequency must be twice this frequency. In considering the requirements for mechanical properties of accelerometers for measuring activity during running, it is noteworthy that vertical frequencies can be as high as, but are generally, below 10 Hz at the centre of mass (Kram et al., 1998). A further consideration for the mechanical properties of accelerometers is the amplitude of accelerations that can be sampled. For example, Bhattacharya et al. (1980) reported vertical peak accelerations ranging from 0.9-5.0 g measured at the lower back during running (8.1-11.3 km·hr⁻¹). Considering the CSA accelerometer has a sampling frequency of 10 Hz, band pass filtering of 0.21-2.28 Hz, and can measure ± 2.13 g the device may not be adequate for fast running. Bouten et al. (1997) have suggested accelerometers must be able to measure up to ± 6 g at the waist and between 0 and 20 Hz. However, to date no study has investigated the outputs from a number of different accelerometers with various sampling frequencies, band pass filtering ranges and peak acceleration amplitudes during fast running.

The main aim of the present investigation therefore, was to assess whether biomechanical and/or device limitations cause the observed levelling off of accelerometer counts during running. This was achieved by investigating the outputs from a number of accelerometers, uni- and tri-axial, with various sampling frequencies, band pass filtering ranges and peak acceleration amplitudes. It was hypothesised that accelerometers with device dynamics that more closely satisfied the sampling frequency, band pass filtering, and peak acceleration amplitude required for fast running, would yield the greatest relationship between running speed and accelerometry output. A secondary aim of this investigation was to assess the feasibility of generating prediction equations from the combined use of accelerometry and heart rate that could be employed during fast running up to world record marathon running pace.

Table 5.1: Physical characteristics of the subjects ($n = 16$) who participated in the present study. Mean \pm SD is shown.

	Mean	SD	Range
Age (y)	23	3	19-31
Height (cm)	182.9	5.7	170.5-192.0
BM (kg)	76.3	8.0	68.5-100.0
BMI ($\text{kg}\cdot\text{m}^{-2}$)	23	2	20-28
$V(\text{TH})$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	38.1	4.0	30.1-43.4
$\dot{V}\text{O}_{2peak}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	60.3	4.2	55.0-67.8

5.2 Methods

5.2.1 Subjects

Sixteen endurance-trained males (Table 5.1) gave their written informed consent to take part in the present study that was approved by the local Ethics Committee (Appendix 2) and was performed according to the code of ethics of the World Medical Association (Declaration of Helsinki).

5.2.2 Experimental design

All subjects completed two incremental exercise tests on a motorised treadmill (Woodway PPS55 Med, Weil am Rhein, Germany) at standard room temperature (20-21 °C) with at least one week separating each test. The first test was a continuous incremental test to volitional exhaustion in order to determine the ventilatory threshold ($V(\text{TH})$) and $\dot{V}\text{O}_{2peak}$. The second assessment involved a discontinuous incremental exercise test to volitional exhaustion to assess the relationships between accelerometry counts and walking and running speeds, accelerometry counts and heart rate, and accelerometry counts and $\dot{V}\text{O}_2$.

5.2.3 Experimental procedures

Subjects reported to the laboratory on the day of testing following a 3 h fast and having refrained from alcohol, caffeine and strenuous exercise the day before. Upon arrival at the laboratory, body mass (Avery Berkel 33/448, W&T Ltd, UK) and height (Leicester height measure, Invicta Plastics Ltd, UK) were measured prior to each test.

Heart Rate and Gas Exchange Measurements

Heart rate and gas exchange measurements were obtained in the same manner for both tests. A heart rate transmitter belt (Suunto t6, Suunto Oy, Vantaa, Finland) was attached to the chest to record heart rate continuously. Subjects were equipped with a head-set, which supported the mouthpiece, and a nose clip. Gas exchange variables were determined breath-by-breath using algorithms developed by Beaver et al. (1986). Respired volumes were measured with a bi-directional turbine transducer (VMM; Alpha Technologies, Laguna Niguel, CA, U.S.A.) calibrated with a 3 L syringe using a range of different flow profiles (Hans Rudolph, Kansas City, MO, U.S.A.). Respired gas concentrations were measured every 20 ms by a quadruple mass spectrometer (QP9000; Morgan Medical, Gillingham, Kent, U.K.) which was calibrated against precision-analysed gas mixtures. Barometric pressure was measured using a standard mercury barometer.

Accelerometry

The four accelerometer devices used for the present study were: 1) a uni-axial Computer Science Applications (CSA) 7164 model (now also known as the MTI accelerometer; Manufacturing Technology Inc., Fort Walton beach, FL, USA) sensitive to body accelerations in the vertical direction; 2) a uni-axial ActiGraph GT1M model (Manufacturing Technology, Inc., Florida, USA) sensitive to body accelerations in the vertical direction; 3) a tri-axial 3dNX™ model (BioTel Ltd., Bristol, UK) sensitive to body accelerations in the vertical, anterior-posterior and medial-lateral directions; and 4) a uni-axial Ac-

5.2. METHODS

Table 5.2: Technical specifications of the accelerometers used in the present study.

Accelerometer	Sampling Frequency (Hz)	Band Pass Filtering (Hz)	Amplitude (\pm g)
CSA	10.00	0.21-2.28	2.13
ActiGraph GT1M	30.00	0.25-2.50	2.00
3dNX TM	100.00	0.20-10.00	10.00
ActiHeart	32.00	1.00-7.00	2.50

tiHeart model (Cambridge Neurotechnology Ltd., Papworth, UK) sensitive to body accelerations in the vertical direction. The CSA, ActiGraph GT1M, and 3dNXTM devices were secured to the subject's waist by means of an elastic belt. The CSA and ActiGraph GT1M devices were placed on the right hip and the 3dNXTM device was placed on the left hip. Finally, the ActiHeart device was placed on the subject's upper left chest. Placement of the ActiHeart device required light preparation of the skin in order to apply two standard ECG electrodes (Blue Sensor, Medicotest, Ølstykke, Denmark) to the chest, onto which the unit was clipped. The medial electrode was placed at the level of the third intercostals space on the sternum and the lateral electrode placed on the same horizontal level and as lateral as possible on the major pectoral muscle. The technical specifications of each accelerometer are listed in Table 5.2.

Continuous incremental exercise test to volitional exhaustion

During this test, the subjects were asked to complete a 5 min warm-up at 8 km·hr⁻¹ that was immediately followed by the incremental test. Initially, the speed was continually increased by 1 km·hr⁻¹ every min until the V(TH) had been passed. The V(TH) was determined as the $\dot{V}O_2$ at which: a) the break point in the relationship between $\dot{V}O_2$ and $\dot{V}CO_2$ occurred ("V-slope technique"; (Beaver et al., 1986)) and b) the ventilatory equivalent for O₂ ($\dot{V}E/\dot{V}O_2$) started to increase systematically without a concomitant increase in the ventilatory equivalent for CO₂ ($\dot{V}E/\dot{V}CO_2$) (Whipp et al., 1986). The treadmill gradient was subsequently elevated at a rate of 1 % every min (while

speed was maintained at the supra $V(\text{TH})$ pace) in order to ensure a work-rate which would elicit exhaustion (Kranenburg & Smith, 1996). $\dot{V}O_{2peak}$ was defined as the highest $\dot{V}O_2$ value achieved during the last 30 sec of the test. Following this point, the treadmill speed was reduced to $4 \text{ km}\cdot\text{hr}^{-1}$ and the gradient was returned to 0 % to allow the subject to actively recover for at least 5 min.

Incremental exercise test to volitional exhaustion

The second test was an incremental exercise test to volitional exhaustion that involved a continuous walking phase (3, 5 and $7 \text{ km}\cdot\text{hr}^{-1}$) and a discontinuous running phase (8, 10, 12, 14, 16, 18, and $20 \text{ km}\cdot\text{hr}^{-1}$ or until volitional exhaustion). The treadmill gradient remained at 0 % and the velocity was increased at a constant rate for each 3 min bout (see Figure 5.1 for a full explanation of the protocol). The running phase was discontinuous to allow adequate rest ($4 \text{ km}\cdot\text{hr}^{-1}$ for 3-5 min) between bouts so that subjects could complete the high velocity running bouts. $\dot{V}O_2$ and heart rate for each 3 min exercise bout were determined as the mean of the last 30 sec to ensure steady state values were achieved. All movement data from the accelerometers are expressed in $\text{counts}\cdot\text{min}^{-1}$ and are the mean of 3 min at each speed, disregarding the periods corresponding to changes in speed (i.e., ~ 1 min). Once volitional exhaustion was reached, the treadmill speed was reduced to $4 \text{ km}\cdot\text{hr}^{-1}$ to allow the subject to actively recover for at least 5 min.

5.2.4 Data analysis

Data are expressed as the mean \pm SD or median (range) as appropriate following a test for the normality of distribution. The Pearson product moment correlation coefficient (r) was used to assess the relationship between accelerometer counts from each device and speed, speed and $\dot{V}O_2$, speed and heart rate, accelerometer counts and $\dot{V}O_2$, and accelerometer counts and heart rate following statistical power calculations (80 % power). Prediction of $\dot{V}O_2$ from accelerometer counts and heart rate was completed by linear regression. Similarly, prediction of $\dot{V}O_2$ from a combination of accelerometer

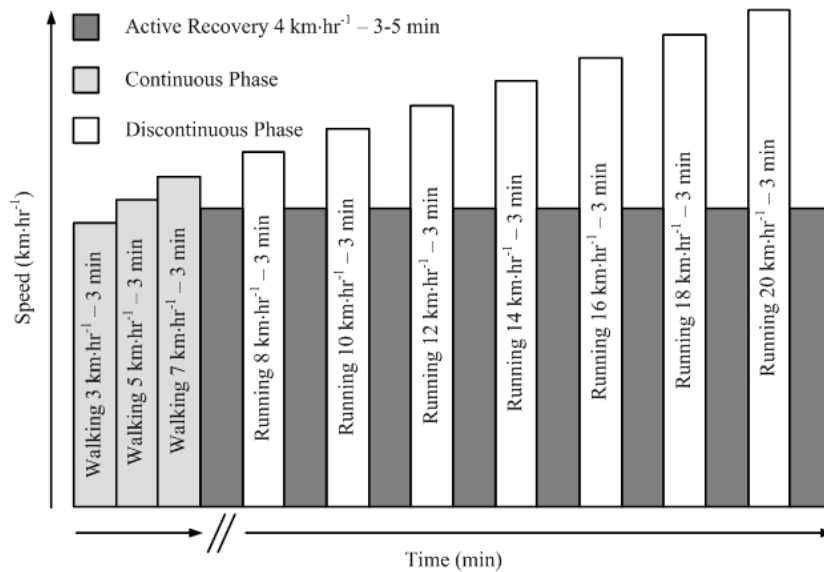


Figure 5.1: Exercise protocol consisting of a continuous walking phase ($3 \text{ km}\cdot\text{hr}^{-1}$ to $7 \text{ km}\cdot\text{hr}^{-1}$) with 3 min bouts, and a discontinuous running phase ($8 \text{ km}\cdot\text{hr}^{-1}$ to $20 \text{ km}\cdot\text{hr}^{-1}$ or until voluntary exhaustion) with 3 min bouts (3-5 min rest between bouts).

counts and heart rate was completed by multiple linear regression (Brage et al., 2003). Multiple linear regression was also completed with the subject's individual data in order to generate individually calibrated equations to predict $\dot{V}\text{O}_2$. Normality of regression residuals was explored by agreement of their frequency distributions with the superimposed normality curve. Statistical significance was set at $p < 0.05$. All statistical analysis was completed using the software package SPSS, version 11.0 (SPSS, Inc., Chicago, IL, USA).

5.3 Results

Relationships between accelerometer counts, speed, heart rate, and $\dot{V}\text{O}_2$

The relationships between accelerometer counts and speed are reported up to and including $20 \text{ km}\cdot\text{hr}^{-1}$, while the relationships between accelerometer counts, $\dot{V}\text{O}_2$ and heart rate are reported up to and including $18 \text{ km}\cdot\text{hr}^{-1}$

since most subjects did not complete the full three minutes at 20 km·hr⁻¹.

Accelerometry outputs from the ActiGraph GT1M, 3dNXTM, ActiHeart, and CSA increased linearly with walking speed ($r = 0.954$, $p < 0.001$; $r = 0.968$, $p < 0.001$; and $r = 0.960$, $p < 0.001$; $r = 0.956$, $p < 0.001$, respectively). Tri-axial 3dNXTM output during running rose in a linear manner with speed up to and including 20 km·hr⁻¹ ($r = 0.892$, $p < 0.001$). However, ActiGraph GT1M and ActiHeart output plateaued at a running speed corresponding to ~14-16 km·hr⁻¹. CSA output also levelled off, but at a running speed corresponding to ~10-12 km·hr⁻¹. These relationships are illustrated in Figure 5.2. The individual relationships between speed and 3dNXTM output for body accelerations in the vertical, anterior-posterior and medial-lateral directions are presented in Figure 5.3. $\dot{V}O_2$ (mL·kg⁻¹·min⁻¹) and heart rate also rose linearly with speed during walking ($r = 0.906$, $p < 0.001$; $r = 0.644$, $p < 0.001$, respectively) and running (i.e., up to and including 18 km·hr⁻¹) ($r = 0.906$, $p < 0.001$; $r = 0.644$, $p < 0.001$, respectively).

ActiGraph GT1M, 3dNXTM, ActiHeart, and CSA accelerometer counts rose linearly with $\dot{V}O_2$ (mL·kg⁻¹·min⁻¹) during walking ($r = 0.906$, $p < 0.001$; $r = 0.913$, $p < 0.001$; $r = 0.901$, $p < 0.001$; and $r = 0.704$, $p < 0.001$, respectively). During running 3dNXTM accelerometer output rose linearly with $\dot{V}O_2$ (mL·kg⁻¹·min⁻¹) up to and including 18 km·hr⁻¹ ($r = 0.873$, $p < 0.001$). Conversely, the relationships between ActiGraph GT1M, ActiHeart, and CSA outputs with $\dot{V}O_2$ (mL·kg⁻¹·min⁻¹) during running increased in a non-linear manner. These relationships are illustrated in Figure 5.4. Heart rate rose linearly with $\dot{V}O_2$ (mL·kg⁻¹·min⁻¹) during walking ($r = 0.648$, $p < 0.001$) and running ($r = 0.663$, $p < 0.001$).

ActiGraph GT1M, 3dNXTM, ActiHeart, and CSA accelerometer counts rose linearly with heart rate during walking ($r = 0.490$, $p < 0.001$; $r = 0.589$, $p < 0.001$; $r = 0.568$, $p < 0.001$; and $r = 0.541$, $p < 0.001$, respectively). 3dNXTM accelerometer output rose linearly with heart rate ($r = 0.722$, $p < 0.001$) during running. In contrast, the relationships between ActiGraph GT1M, ActiHeart, and CSA outputs with heart rate during running increased in a non-linear manner. These relationships are illustrated in Figure 5.4.

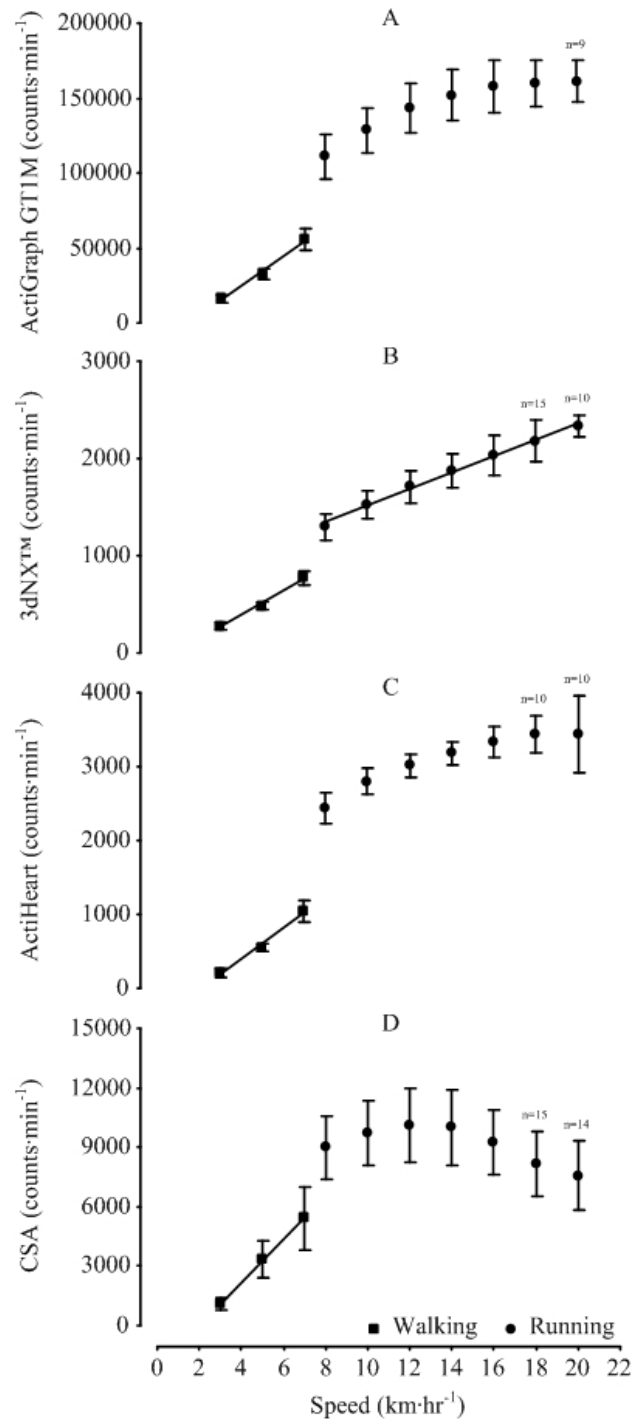


Figure 5.2: ActiGraph GT1M (graph A; $n = 11$, unless otherwise stated), 3dNXTM (graph B; $n = 16$ unless otherwise stated), ActiHeart (graph C; $n = 12$, unless otherwise stated), and CSA (graph D; $n = 16$, unless otherwise stated) outputs plotted against treadmill speed. Mean \pm SD is shown.

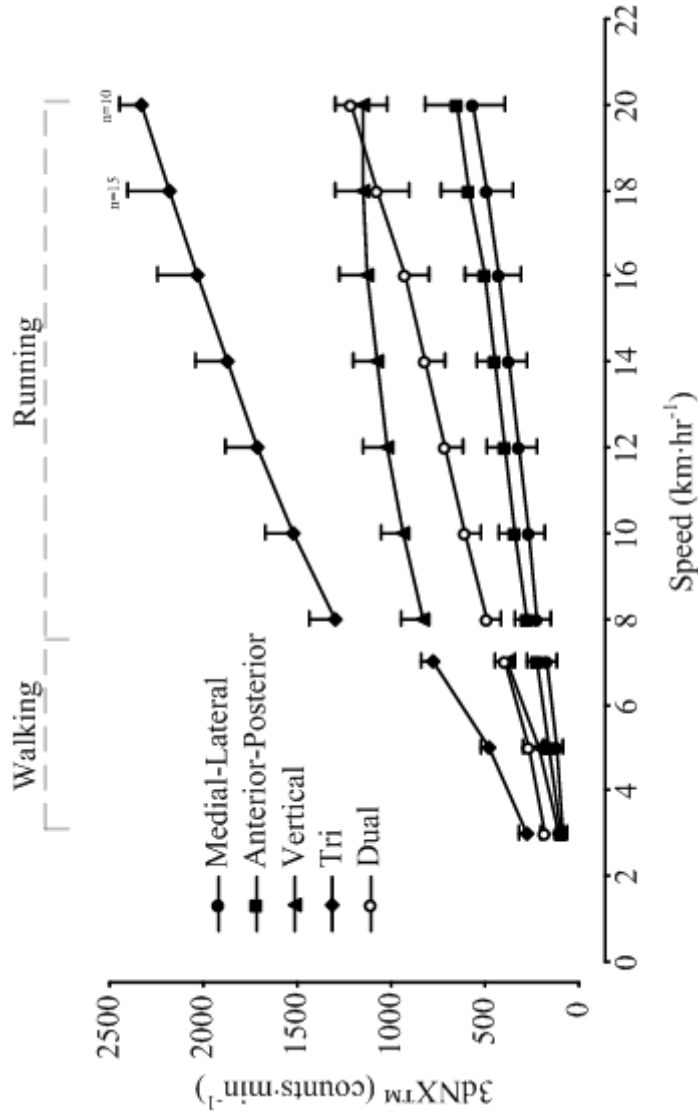


Figure 5.3: The relationships between walking and running speed and 3dNX™ outputs (n = 16 unless otherwise stated) for body accelerations in the vertical, anterior-posterior and medial-lateral directions. The sum of all three directions (i.e., tri) and the sum of the anterior-posterior and medial-lateral directions (i.e., dual) is also presented. Mean ± SD is shown.

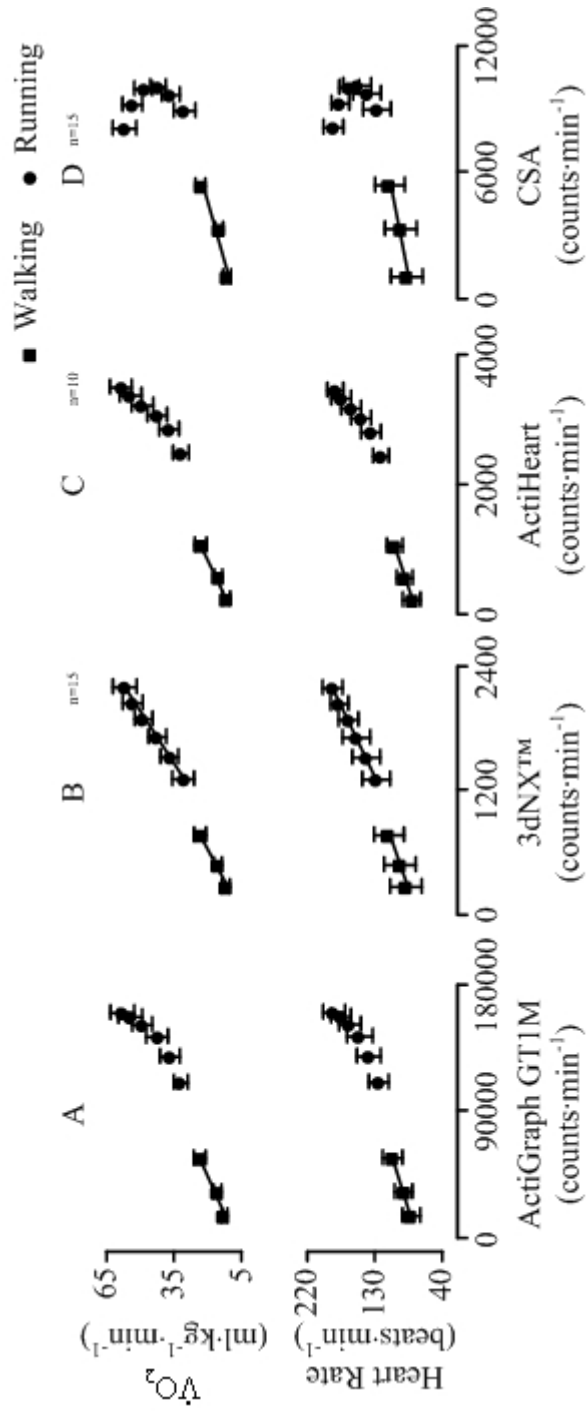


Figure 5.4: ActiGraph GT1M (graph A; $n = 11$, unless otherwise stated), 3dNX™ (graph B; $n = 16$ unless otherwise stated), ActiHeart (graph C; $n = 12$, unless otherwise stated), and CSA (graph D; $n = 16$, unless otherwise stated) outputs, plotted against $\dot{V}O_2$ and heart rate. Mean \pm SD is shown.

$\dot{V}O_2$ prediction models

The linear regression models for heart rate and accelerometer outputs are presented in Table 5.3. The relationships between ActiGraph GT1M, ActiHeart, and CSA accelerometer outputs and $\dot{V}O_2$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were non-linear during running. As a result only walking models are presented for these devices. Regression residuals were normally distributed for all models presented.

5.4 Discussion

The present investigation was the first to investigate the outputs from a number of accelerometers with various sampling frequencies, band pass filtering ranges and peak acceleration amplitudes during fast running. It was found that accelerometers with device characteristics that more closely satisfied the sampling frequency, band pass filtering, and peak acceleration amplitude required to track acceleration during fast running, yielded a better relationship between running speed and accelerometry output. Furthermore, uni-axial accelerometer output plateaus at fast running speeds due to the biomechanics of running (i.e., a plateau in vertical acceleration at high running speeds) in contrast to tri-axial 3dNXTM accelerometer output that has a linear relationship with speed up to and including world record marathon pace.

Relationships between accelerometer counts, speed, heart rate, and $\dot{V}O_2$

All devices used in the present investigation (Table 5.2) had an output that rose linearly over the walking speed range (i.e., 3-7 $\text{km}\cdot\text{hr}^{-1}$) (Figure 5.2). However, three out of the four devices investigated had outputs that had a tendency to plateau at fast running speeds (Figure 5.2). Our results are consistent with previous studies that used the CSA activity monitor during walking and running (Nichols et al., 2000; Brage et al., 2003). That is, CSA output was linear during walking but not during running when accelerometer output levelled off at $\sim 10\,000$ $\text{counts}\cdot\text{min}^{-1}$ at a speed corre-

Table 5.3: $\dot{V}O_2$ prediction models with accelerometer outputs and heart rate as predictors during walking and running. Key: Mean of prediction equations calibrated with individual subject data (MI); Accelerometry output (CPM (counts \cdot min $^{-1}$)).

	$\dot{V}O_2$ Prediction Models	R^2	SEE
Walking (3-7 km \cdot hr $^{-1}$)			
HR	$\dot{V}O_2 = -5.614 + 0.244 \times \text{HR}$	0.42	4.02
CSA	$\dot{V}O_2 = 10.624 + 0.001.881 \times \text{CPM}$	0.48	3.86
CSA + HR	$\dot{V}O_2 = 1.120 + 0.121 \times \text{HR} + 0.001417 \times \text{CPM}$	0.54	3.62
CSA + HR MI	-	0.99	0.18
ActiGraph GT1M	$\dot{V}O_2 = 7.847 + 0.0002646 \times \text{CPM}$	0.81	2.17
ActiGraph GT1M + HR	$\dot{V}O_2 = 1.825 + 0.07839 \times \text{HR} + 0.0002317 \times \text{CPM}$	0.85	1.94
ActiGraph GT1M + HR MI	-	1.00	0.00
3dNX TM	$\dot{V}O_2 = 5.258 + 0.02315 \times \text{CPM}$	0.83	2.20
3dNX TM + HR	$\dot{V}O_2 = 0.161 + 0.07105 \times \text{HR} + 0.02027 \times \text{CPM}$	0.85	2.06
3dNX TM + HR MI	-	1.00	0.00
ActiHeart	$\dot{V}O_2 = 9.207 + 0.01257 \times \text{CPM}$	0.81	2.17
ActiHeart + HR	$\dot{V}O_2 = 4.028 + 0.06649 \times \text{HR} + 0.01118 \times \text{CPM}$	0.82	2.07
ActiHeart + HR MI	-	1.00	0.00
Running (8-18 kkm \cdot hr $^{-1}$)			
HR	$\dot{V}O_2 = -6.387 + 0.321 \times \text{HR}$	0.59	6.35
3dNX TM	$\dot{V}O_2 = -1.014 + 0.02573 \times \text{CPM}$	0.76	4.88
3dNX TM + HR	$\dot{V}O_2 = -9.371 + 0.123 \times \text{HR} + 0.01942 \times \text{CPM}$	0.80	4.45
3dNX TM + HR MI	-	0.99	1.28

sponding to 10-12 km·hr⁻¹. Brage et al. (2003) attribute this observation to biomechanical limitations. In particular, below 4 km·hr⁻¹, vertical power predominates during walking, however, at faster running speeds, vertical acceleration becomes constant while horizontal power increases (Cavagna et al., 1976). Those authors argue that without a concomitant increase in vertical acceleration during increasingly faster running speeds, there will not be an increase in CSA output since it measures only in the vertical plane; hence the plateau. Our data are consistent with this hypothesis as outputs from the other uni-axial accelerometers, ActiGraph GT1M and ActiHeart, also plateaued, albeit at higher speeds corresponding to 14-16 km·hr⁻¹. A possible explanation may be superior device electronics (Table 5.2). That is, these devices may to a greater degree fulfill the sampling rate and band pass filtering range required for running (i.e., the frequency range of band pass filtering must include the maximum frequency observed during running, and the sampling frequency must be twice this frequency to allow reconstruction of the original signal from the sampled version). The maximum frequency observed during running is less than 10 Hz (Kram et al., 1998); therefore accelerometers intended for measuring physical activity during running must have a sampling frequency of at least 20 Hz and band pass filtering of at least 10 Hz. The electronic properties of both the ActiGraph GT1M and ActiHeart accelerometers fulfill these criteria better than the CSA (Table 5.2). A further consideration for the electronic properties of accelerometers is the amplitude of accelerations that can be sampled. The ActiGraph GT1M, ActiHeart, and CSA may be limited as Bhattacharya et al. (1980) reported vertical peak accelerations ranging from 0.9-5.0 g measured at the lower back during running. However, this is unlikely to be a major factor in the levelling-off of accelerometer outputs during fast running since output from the vertical axis of the 3dNXTM accelerometer also plateaued (Figure 5.3) despite an acceleration range of ± 10.0 g (Table 5.2). Regardless of a plateau in the vertical axis, the compound tri-axial 3dNXTM accelerometer output (i.e., the sum of vertical, anterior-posterior and medial-lateral accelerations) did have a linear relationship between output and running speed up to world record marathon pace (i.e., up to and including 20 km·hr⁻¹) (Figure

5.2). A previous investigation (Cavagna et al., 1976) reported that despite running from 7 to 32 km·hr⁻¹, vertical power is almost constant whereas horizontal power increases by a factor of > 10. Our data corroborates this as Figure 5.3 suggests that a reduction in vertical acceleration at ~14-16 km·hr⁻¹ was compensated for by a concomitant increase in accelerations in the anterior-posterior and medial-lateral directions. This likely explains why 3dNXTM accelerometer output has a linear relationship with speed up to and including 20 km·hr⁻¹. Thus, for metabolic assessment of walking and slow running/jogging, when using only acceleration counts and not heart rate, the ActiGraph GT1M and ActiHeart devices are adequate, and are therefore probably sufficient for use in most epidemiological studies for which they are intended. However, for the assessment of fast running (i.e., > 16 km·hr⁻¹), a tri-axial accelerometer, such as the 3dNXTM device, is necessary (Plasqui et al., 2005).

$\dot{V}O_2$ prediction models

The relationships between heart rate and accelerometer outputs, and $\dot{V}O_2$ and accelerometer outputs followed a similar pattern observed in the relationships between accelerometer outputs and speed (Figure 5.3). All devices had a linear relationship over the walking speed range, whereas only accelerometer output from the 3dNXTM device had a linear relationship during running. As expected heart rate also rose linearly with $\dot{V}O_2$ during walking and running. However, the relationship between heart rate and $\dot{V}O_2$ yielded the lowest R^2 value during walking (Table 5.3), a finding consistent with previous investigations that reported a limitation of heart rate as a predictor of $\dot{V}O_2$, especially during low intensity exercise (Livingstone et al., 1990; Luke et al., 1997). However, including heart rate as a co-predictor for $\dot{V}O_2$ during both walking and running yielded greater R^2 values and lower SEE than single-measure models that use accelerometer outputs alone (Table 5.3). The CSA accelerometer yielded the lowest predictive power when combined with heart rate during walking, with little difference between the remaining three devices. However, for an indirect estimation of $\dot{V}O_2$ during running,

the 3dNX™ accelerometer, in combination with heart rate, was the most accurate.

The $\dot{V}O_2$ prediction models presented here are not intended for use at the population level. Rather, this investigation was designed to 1) explore the levelling-off phenomenon of accelerometer counts with increasing speed during running and 2) examine the feasibility and accuracy of combining heart rate and accelerometer counts to estimate $\dot{V}O_2$ during walking and running. Indeed, prediction models calibrated with subject's individual data further improve $\dot{V}O_2$ estimation compared to population prediction models, as evidenced by greater mean R^2 values and lower SEE (Table 5.3). The possible reasons for this may be variations in biomechanical characteristics of locomotion and the different heart rate vs. speed relationships between individuals. Differences in movement (e.g., vertical oscillations) between individuals would undoubtedly result in under/over estimation of metabolic cost if measured by accelerometry. With this in mind, and the concept that vertical (Kram & Taylor, 1990; Heise & Martin, 2001) and horizontal (Chang & Kram, 1999) forces are major determinants of metabolic cost during running, a further application of accelerometry may be a discriminatory role for differences between individuals in running economy or changes in running economy within individuals. It follows that excessive changes in momentum in the vertical, anterior-posterior and medial-lateral directions may be wasteful in terms of metabolic energy consumption (Heise & Martin, 2001). Indeed, Heise and Martin (2001) reported less economical runners (i.e., those with a higher $\dot{V}O_2$ for a given speed) demonstrated higher total and net vertical impulses. This may be reflected in a larger accelerometer output for a given speed in less economical runners. However, although promising, this is yet to be determined.

Conclusions

In summary, both uni- and tri- axial accelerometer outputs have a linear relationship with speed during walking. However, during fast running, uni-axial accelerometer output plateaus due to biomechanical and device limitations.

5.4. DISCUSSION

In contrast, the tri-axial 3dNXTM accelerometer output has a linear relationship with speed up to and including world record marathon pace. The combined methodologies of heart rate and accelerometry predict $\dot{V}O_2$ better than either predictor alone. Moreover, prediction models calibrated with subject's individual data further improve $\dot{V}O_2$ estimation compared to population prediction models.

6

General Discussion

6.1 Energy balance and diet composition

A number of studies have reported the energy balance status of Kenyan runners (Mukeshi & Thairu, 1993; Christensen et al., 2002; Onywera et al., 2004). Chapter 3 is the only investigation to have used the gold-standard doubly labelled water method to measure energy expenditure. It is acknowledged however that at present there is no gold-standard method for measuring energy intake; in the present series of studies food was prepared, cooked and eaten in front of the research team at the training camp in order to reduce errors in underrecording. Indeed underreporting was 13 % and was almost entirely accounted for by undereating (9 %) suggesting athletes had accurately recorded all food and water consumed. It was found that the athletes studied were, on average, in negative energy balance prior to Athens Olympic trials. These results corroborate the findings of Onywera et al. (2004), Mukeshi and Thairu (1993) and anecdotal observations in elite Kenyan endurance athletes. For example, the Kenyan winner of the women's 2004 London Marathon, former marathon world-record holder Margaret Okayo weighed only 39 kg at the time of the race although her usual body mass is 43 kg. Similarly, the winner of the 2005 Chicago marathon, Felix Limo also from Kenya, had a starting weight of 59 kg but has a typical body mass of 64 kg. Concerns have been raised however with regard to the health and future performance implications of over-frequent body mass cycles in elite athletes before and

6.1. ENERGY BALANCE AND DIET COMPOSITION

after competition (Onywera et al., 2004). The ACSM and the American Dietetic Association and the Dieticians of Canada (American College of Sports Medicine, 2000) state that periods of negative energy balance can promote lethargy, increase risk of injury and illness, prolong recovery from strenuous exercise, and reduce exercise performance. Onywera et al. (2004) suggested that this mechanism might explain the high incidence of world class athletes in Kenya who initially do well on the international racing scene but then disappear from athletics prematurely, presumably through injury or “burn-out”. This reasoning lacks solid experimental data and remains speculative. At present there is a lack of well controlled investigations on the effect of negative energy balance on long term health of elite runners; mainly because of the difficulty involved in designing and conducting such studies.

Body mass reduction induced by a hypo-caloric diet in training athletes does not seem to reduce performance, $\dot{V}O_{2max}$, strength, or endurance as long as dietary intake provides sufficient carbohydrate and protein to maintain glycogen stores and muscle mass, respectively (McMurray et al., 1985; Fogelholm et al., 1989; Horswill et al., 1990). For example, McMurray et al. (1985) reported that 7 days of 1000 kcal·d⁻¹ dietary deficit induced by exercise did not reduce exercise capacity in six endurance-trained males consuming a diet sufficient in carbohydrate and protein. Furthermore, it was found that subjects were not as glycogen-depleted due to the negative energy balance as may have been expected. These authors suggested this was due to the subjects utilising twice as much fat during sub-maximal exercise compared to the controls as evidenced by indirect calorimetry. Therefore, in the short term, it may be that the benefits of being as light as possible before racing outweigh the potential negative consequences providing that athletes are consuming a diet high in carbohydrate with sufficient protein as is typically the case in Kenya (as demonstrated in chapters 2-3). This is in contrast to what appears to be the case in athletes from industrialised countries where carbohydrate intake can be at the lower end of the range recommended for endurance athletes (e.g., 6.1 g·kg⁻¹BM·d⁻¹, Moses et al., 1991), especially when a typically western diet of 55-58 % carbohydrate (American College of Sports Medicine, 2000) is consumed. Costill and Miller (1980) reported that

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runners consuming a diet high in carbohydrate (70 %) training two hours per day for three days compared to runners consuming a normal diet (40-60 %) were better able to maintain muscle glycogen. In addition to the favourable diet composition of the Kenyan elite runners demonstrated in chapters 2 and 3 the timing of their post-training meal was always within 60 min of exercise, i.e., in line with current recommendations for maximising glycogen re-synthesis rates after exercise (American College of Sports Medicine, 2000). The ability of the Kenyan athletes apparently spontaneously: 1) to consume the correct amount of carbohydrate; and 2) to do this at the right moment, is striking since they are not exposed to nutritional guidelines and advice compared to elite athletes in western countries. As a result, considering the success of these athletes on the international racing circuit, it is conceivable that their diet and lifestyle is conducive to elite performance and that the reported loss in body mass prior to competition may be beneficial for performance.

The concept of reducing body mass to improve endurance running performance by way of reducing the energy cost of locomotion at a sub-maximal velocity is not new (Buskirk & Bettham, 1960; Cureton et al., 1978; Cureton & Sparling, 1980; Taylor et al., 1980; Myers & Steudel, 1985; Jones et al., 1986; Williams & Cavanagh, 1987; Taylor, 1994; Noakes, 2000). Taylor et al. (1980) reported that when a human or animal carries extra mass while walking and running, the energy cost per unit distance increases in direct proportion to the added load expressed as a percentage of body mass. For example, when a 60 kg subject carries an extra 5 kg (i.e., about 8 % of body mass), their metabolic rate, at a given speed of locomotion, increases by about 8 %. Cureton et al. (1978) demonstrated that the addition of 5, 10 and 15 % respectively of body mass: 1) increased the energy requirement of running at sub maximal speeds, without affecting absolute $\dot{V}O_{2max}$; 2) lowered the work rate at $\dot{V}O_{2max}$; and 3) lowered the pace that could be maintained for a given period of time. Any excess body fat carried by an endurance runner can thus be expected to reduce performance because it increases the energy required to work at any given level of physical activity without contributing to the energy-producing capacity. Conversely, reducing

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body fat mass should enhance running performance by reducing the energy required to run at the same sub-maximal speed. Interestingly, although an example from road cycling rather than running, Coyle (2005b) reported that the seven times Tour de France Grand Champion (1999-2005), Lance Armstrong, improved his power-to-body-mass ratio ($\text{W}\cdot\text{kg}^{-1}$) when cycling at a given percentage of $\dot{V}\text{O}_{2max}$ (e.g., 83 %) by 18 % between 1992 and 1999 (i.e., 4.74 vs. 5.60 $\text{W}\cdot\text{kg}^{-1}$ at a $\dot{V}\text{O}_2$ of 5.0 $\text{L}\cdot\text{min}^{-1}$). A major feature of the Tour de France compared to other professional road cycling races is the four to six high mountain stages which can comprise three or more long (>10 km) climbs (5-10 % mean gradient) that require competitors to work against gravity (Lucia et al., 2003). As a result, a high power-to-body-mass ratio at maximal or near to maximal intensities is an important determinant of success for uphill cycling (Lucia et al., 2003). The reduction in body mass by Lance Armstrong from 78.9 kg in 1992 to \sim 72.0 kg during his victories in the Tour has been suggested to account for around one-half (8-9 %) of his improved power to body mass ratio with the remainder accounted for by improved mechanical efficiency (Coyle, 2005b). Martin et al. (2005) highlight the timing of testing may have been a limitation of this study and therefore stress caution in interpretation of Coyle's results (Coyle, 2005b). Accordingly these authors suggested that a reduction in body mass and training "may be equally, if not more, important to Armstrong's performance than the 9 % improvements in cycling efficiency". Indeed, in his book, Coyle (2005a) quotes Lance Armstrong as saying "Losing weight is the single most important thing you can do. You have to train. You have to be strong, of course. But if you're too heavy, it's all over." The book details some of his training goals leading up to his 2004 Tour de France victory and corroborates this statement. Six-months prior to the race Armstrong weighed 79.5 kg and his goal was to be 5.5 kg lighter for racing; by the time of the race he weighed 74.0 kg, increased his power-to-body-mass ratio to 6.6 $\text{W}\cdot\text{kg}^{-1}$ from 5.9 $\text{W}\cdot\text{kg}^{-1}$ and concurrently went on to win the Tour.

Both professional road cyclists and elite endurance runners may benefit from a reduction in body mass prior to major competition, but due to the differing nature of the respective sports (i.e., uphill cyclists must overcome

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gravity in a body-mass-supported sport) the effect on performance may be dissimilar due to mass distribution within the body. For example, a limitation in some of the energy cost of locomotion studies (e.g., see Cureton et al., 1978) is that the extra mass was added only to the trunk and not distributed between trunk and limbs, as would be expected when gaining weight. Indeed, the handicap effect is larger on running when extra mass is added distally; Myers and Steudel (1985) compared adding weight proximally to the centre of mass (i.e., the waist) and distally on the limbs (i.e., foot/ankle) during running and reported that the energy cost was increased by a factor of 1.5-5.5 by the latter. Similarly, Jones et al. (1986) measured the energy cost of wearing shoes of varying weight during running and walking and reported an average increment in $\dot{V}O_2$ cost of 1% per 100 g of weight added. In his 2003 review, Larsen (2003) has postulated the low BMI of elite Kenyan endurance runners combined with the fact the majority of their body fat is distributed proximally, with the mass of the lower limbs being kept to a minimum, especially in the calf and thigh area, may result in superior running economy. Evidence favouring superior running economy in Kenyan endurance runners compared to Caucasian athletes is presented by Saltin et al. (1995). In that study, Kenyan runners exhibited better running economy compared to their Scandinavian counterparts whilst running at sub-maximal running speeds even though their absolute $\dot{V}O_{2max}$ was not different. Whether these anthropometric factors are indeed typical of Kenyans and responsible, in part at least, for their outstanding running performances remains to be determined. Evidence from studies of non-elite runners however, also suggests that running is not the exercise mode of choice for subjects with a high fat mass. Westerterp et al. (1992) studied the effect of an increase in physical activity on energy balance and body composition in subjects not participating in any sport before the start of the experiment and prepared to run a half-marathon competition after 44 weeks. Of 370 respondents to an advertisement in the local media, 16 women and 16 men, age 28-41 years and BMI of 19.4-26.4 kg·m⁻², were selected. Nine subjects withdrew from the study within 20 weeks of the start of the training. Reasons for giving up were “not enough time to join the training” (n = 3), “injuries” (n = 5) and “not able

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to keep up with the training” ($n = 1$). The BMI values of the subjects who completed and who withdrew were $19.4\text{--}25.7 \text{ kg}\cdot\text{m}^{-2}$ and $23.4\text{--}26.4 \text{ kg}\cdot\text{m}^{-2}$, respectively. All dropouts had a BMI above the group mean of $22.9 \text{ kg}\cdot\text{m}^{-2}$. Although manifestly obese subjects were excluded by the selection criteria, most subjects with a BMI over 24 could not cope with the training. The body fat percentages of the drop-out women and men were higher than 24 and 35 %, respectively. These results of course support the intuitive belief that extra fat mass may be undesirable for optimal athletic performance both in the general population and in elite endurance athletes.

Further evidence for a possible ergogenic effect on endurance running as a result of reducing body mass may be found by considering the evolution of human dietary patterns and bioenergetics (for a review see Leonard & Ulijaszek, 2002). Around 2.5 million years ago there was a dramatic change in climate that reduced the amount of tropical forests and led to a dramatic increase in open, drier grassland in central Africa (Foley, 1987). Undoubtedly this increased high quality food availability which led to grazing animals becoming a more attractive choice for energy provision. The change from a shaded environment, which required low levels of physical activity to obtain food, to an open environment exposed to oppressive solar radiation, necessitated hard physical exertion to run prey to thermoregulatory exhaustion or compete with other scavengers, such as wild dogs and hyenas, for carcasses containing marrow, brain and other tissues (Carrier, 1984; Bramble & Lieberman, 2004). Bramble and Lieberman (2004) have proposed that endurance running over extended time periods is a distinct and unique characteristic of humans. Such running prowess allowed our early human ancestors in the Savannah environment to exploit protein rich resources and was a key step in evolution of Homo. The genetic make up of contemporary humans has not changed since the emergence of the anatomically modern human, *Homo sapiens sapiens*, despite radical changes in living conditions and lifestyle during over approximately 50 000 years since then (Vigilant et al., 1991; Wilson & Cann, 1993). Consequently, men and women today have genes that evolved in a hunting gathering era lasting several millions of years. Cordain et al. (1998) suggest that today’s endurance runners may be the closest humans

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to our ancestors in terms of daily physical exertion. Although not a perfect model, hunter-gatherer societies are the best available gauge for assessing the physical activity levels of early *Homo*. Societies such as the Ache, !Kung, Agta, Hazda, Hiwi, Efe, San, and Inuit may provide the best available snapshot of physical activity and eating patterns for which we are genetically engineered (Cordain et al., 1998) and allow a good comparison with today's elite athletes. Jenike (2001) has suggested that seasonal variation in energy intake may have been "a near-universal characteristic of hunter-gatherer societies". As a result, Chakravarthy and Booth (2004) proposed that "cycling of food stores, blood insulin, insulin sensitivity, and metabolic regulatory proteins, driven by cycles of feast-famine and physical activity-rest, have moulded the selection of 'thrifty' genes and genotype, some with functions that are predominately for glycogen conservation and replenishment, as the speculation is made that our ancestors were more likely to survive with these adaptations than without them". An example of the importance of muscle glycogen to survival during evolution is the observation that complete muscle glycogen replenishment can occur (in some circumstances at least) within one to two hr after exhausting exercise with an adequate carbohydrate diet, whereas liver glycogen may only be replenished by about 50 % after four hr (Terjung et al., 1974). Considering the importance of endurance running in hunting and scavenging (Bramble & Lieberman, 2004), this invites the intriguing possibility that *Homo* may have evolved to be able to run when faced with a reduction in body mass as a result of food shortage and possibly explains why humans as a result of training adapt to conserve glycogen and use fat as an energy source during endurance exercise (Mole et al., 1971). However, it is also clear that there must have been a limit to how much body mass *Homo* could lose before this would affect their ability to hunt and compete for food. Heinrich (2001) proposed that "when we need food, having the speed and mobility to chase it down is obviously advantageous". This implies that smallness and lightness may have benefited *Homo* in capturing prey. Recent investigations carried out on endurance runners corroborate this statement (Marino et al., 2000; Marino et al., 2004). For example, two studies by Marino et al. (2000, 2004) reported that heavier

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runners display a greater degree of heat retention than lighter individuals and that this may be a major factor limiting the performance of physically larger and heavier athletes in distance running events. Furthermore, it was reported that heavier runners self-selected a slower running speed than lighter runners when running in the heat and that this speed was inversely related to body mass. This suggests that excess body mass would not be advantageous for endurance running in the savannah environment, nor equally in an Olympic marathon due to thermoregulatory limitations. Another example in nature of a similar body mass “trade-off” can be seen in small birds in which studies of flight mechanics (Blem, 1975; Hedenström, 1992) suggested that extra body mass would decrease flight performance and hence increase predation risk (Witter & Cuthill, 1993). However, these birds must build up large fat stores in order to support migration. Hence body mass is a good indicator of the balance between starvation and predation risk and presumably this will greatly reflect the species vulnerability. Indeed, MacLeod et al. (2005) suggest that the decline of the house sparrow in the UK by 60 % between 1970 and 2000 (Gregory et al., 2002) may be due to mass-dependant predation as the birds are unable to increase body mass in an attempt to reduce their high starvation risk; house sparrows are the most frequent prey for cats and sparrow hawk predation (MacLeod et al., 2005). Hence, the quantity of “extra” body mass that is acceptable is intrinsically linked to the extent of mobility required for either hunting or risk aversion in order to survive in most animals. Elite endurance running performance today may be regarded as the equivalent of hunting, competing, and/or scavenging for food that has occupied most human existence on the planet (Åstrand & Rodahl, 1986). Therefore, it is not surprising that elite endurance runners, such as Margaret Okayo, Felix Limo and other athletes studied (Onywera et al., 2004; Chapters 2-3), reduce body mass prior to racing.

6.2 Hydration and electrolyte balance

Onywera et al. (2004) reported low daily fluid intake in elite Kenyan endurance runners that consisted of primarily water ($1.1 \pm 0.3 \text{ L}\cdot\text{d}^{-1}$) and

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milky tea ($1.2 \pm 0.3 \text{ L}\cdot\text{d}^{-1}$). This pattern of fluid intake is corroborated in Chapter 3 as fluid intake also consisted of primarily water ($0.9 \pm 0.5 \text{ L}\cdot\text{d}^{-1}$) and milky tea ($0.9 \pm 0.3 \text{ L}\cdot\text{d}^{-1}$). Furthermore, these elite athletes did not consume liquids before or during training and only infrequently consumed modest amounts of liquids after training. Such fluid intake is substantially less than the previous recommendations of the ACSM (Convertino et al., 1996), which were 0.4-0.6 L of fluid 2-3 hr before exercise, $0.6\text{-}1.2 \text{ L}\cdot\text{hr}^{-1}$ while exercising, aiming at total replacement of all fluid lost during exercise, or at least up to the maximal amount tolerated; a pattern and volume of fluid replacement similar to that recommended by the NAAT (Binkley et al., 2002), and the US Army (Montain et al., 1999). These recommendations evolved from investigations that established a relationship between extent of dehydration and rise in core temperature (Wyndham & Strydom, 1969; Costill et al., 1970; Gisolfi & Copping, 1974; Montain & Coyle, 1992). However, the extrapolation of results from many of these early studies to widespread recommendations for athletes exercising out-of-doors is inappropriate mainly due to inadequate facing wind speed and/or high environmental temperatures (Adams et al., 1992; Chevront et al., 2004; Saunders et al., 2005). Adams et al. (1992) found that the rate of whole body cooling may be different when exercising in the laboratory compared to outdoors. The authors reported that subjects had higher whole body temperatures (rectal and oesophageal) when exercising in wind-still conditions ($0.75 \text{ km}\cdot\text{hr}^{-1}$) compared to a facing wind velocity of $11.25 \text{ km}\cdot\text{hr}^{-1}$. Similarly, a previous study that compared wind-still conditions ($0.75 \text{ km}\cdot\text{hr}^{-1}$) to an air velocity of $15.5 \text{ km}\cdot\text{hr}^{-1}$ found rectal and skin temperatures to be significantly higher in the wind-still conditions (Shaffrath & Adams, 1984). More recently, Saunders et al. (2005), compared the temperature of subjects cycling at $33.0 \pm 0.4 \text{ }^\circ\text{C}$ in four different wind velocities: $0.2 \text{ km}\cdot\text{hr}^{-1}$ (wind-still conditions), $10 \text{ km}\cdot\text{hr}^{-1}$ (to replicate many laboratory studies), and 100 % and 150 % of calculated road speed facing wind velocities based on the equation of DiPrampero et al., (1979). At the same time, $58.8 \pm 6.8 \%$ of sweat losses were replaced with oral liquids. The authors reported that in wind-still or low facing wind velocities, excessive heat storage occurs while exercising at moderate and high

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intensities, due to a failure of the environment to absorb and dissipate heat as evidenced by higher sweat rates during wind-still conditions. Thus the interpretation of classic studies (Wyndham & Strydom, 1969; Costill et al., 1970; Gisolfi & Copping, 1974; Montain and Coyle, 1992) used as evidence to support previous specific fluid intake guidelines (e.g., Convertino et al., 1996) is incorrect for athletes exercising outdoors. Indeed, these studies (Wyndham & Strydom, 1969; Costill et al., 1970; Gisolfi & Copping, 1974; Montain & Coyle, 1992) may have underestimated the body's ability to adapt to mild dehydration since they were performed on subjects exercising in unnaturally low facing wind speeds and "High Risk" thermal loads. For example, at least two of the studies (Gisolfi & Copping, 1974: 33 °C, 38 % RH; Montain and Coyle, 1992: 33 °C, 50 % RH) stand out as being performed in weather conditions that would be in the "High Risk" zone for thermal injury as suggested by the ACSM (American College of Sports Medicine, 1987). Furthermore, the facing wind speed, the main route for heat loss via convection, in three out of the four studies was well below that when actually racing outdoors (DiPrampero et al., 1979). This may perhaps in part explain the subsequently published excessive fluid intake guidelines (Saunders et al., 2005).

The inadequacy of laboratory experiments to simulate out-of-doors exercise is substantiated by empirical observations that elite athletes typically do not adhere to prevailing fluid intake recommendations (for a review see reference Cheuvront & Haymes, 2001b). Indeed the drinking behaviours (i.e., *ad libitum*) reported previously in elite Kenyan endurance runners (Onywera et al., 2004) corroborate this view. Recently the ACSM has replaced their prior Position Stand (Convertino et al., 1996) with an updated one on exercise and fluid replacement (American College of Sports Medicine, 2007) that advocates drinking *ad libitum* ($0.4\text{-}0.8\text{ L}\cdot\text{hr}^{-1}$) during exercise (with the lower value for slower, lighter individuals competing in cooler environments, and the higher value for faster, larger individuals competing in warmer environments) in order to prevent excessive dehydration (i.e., $< 2\%$ body mass loss). These new recommendations (American College of Sports Medicine, 2007) appear to be more in keeping with previous observations of elite Kenyan

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endurance runners. The purpose of Chapter 3 therefore was to investigate whether the low daily fluid intakes reported by Onywera et al. (2004) and in Chapter 2 are sufficient to maintain hydration balance day-to-day during a period of important training in elite Kenyan endurance runners. Chapter 3 reported low daily fluid intake consisting mainly of water ($0.7 \pm 0.5 \text{ L}\cdot\text{d}^{-1}$; 18.4 %) and milky tea ($1.2 \pm 0.4 \text{ L}\cdot\text{d}^{-1}$; 31.6 %) with a small contribution from the intake of other fluids such as soft drinks and milk ($0.4 \pm 0.2 \text{ L}\cdot\text{d}^{-1}$; 10.5 %). Hydration balance despite this relatively low fluid intake over the 5 day recording period was evidenced by similar total body water and body mass values recorded each morning before training despite athletes incurring body mass deficits due to training runs. Daily hydration balance was further demonstrated by a similar pre training body mass in the morning and pre training body mass in the afternoon. It was also found that there was no significant difference in osmolality and specific gravity of the urine supplied by the athletes in the morning when compared to the evening sample. During the 5 day recording period, mean osmolality and specific gravity in the morning and evening were below values suggested to correctly classify dehydration in individuals (American College of Sports Medicine, 2007). Maintenance of hydration status, despite athletes losing body water during training, was achieved by water gained from the diet and fluid ingested throughout the day *ad libitum*. This is in keeping with the new ACSM fluid intake recommendations that advocates drinking *ad libitum* ($0.4\text{-}0.8 \text{ L}\cdot\text{hr}^{-1}$) during exercise.

The efficacy of proposing a specific fluid intake range (i.e., $0.4\text{-}0.8 \text{ L}\cdot\text{hr}^{-1}$) during exercise has been investigated in a study that modelled parameters that influence sweating rate (Montain et al., 2006). Montain et al. (2006) found that this rate (i.e., $0.4\text{-}0.8 \text{ L}\cdot\text{hr}^{-1}$) of fluid intake was sufficient to maintain body mass loss within 3 % and to prevent body mass gain in 50-90 kg subjects running a marathon at $8.5\text{-}15 \text{ km}\cdot\text{hr}^{-1}$ in cool and warm ambient conditions (i.e., $18 \text{ }^\circ\text{C}$ and $28 \text{ }^\circ\text{C}$, respectively). These authors suggested that factors that influence sweat rate such as body mass, running speed and ambient conditions be considered prior to adopting this specific fluid intake range, and where necessary adapting the strategy to suit the individual (Montain et

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al., 2006). Therefore Chapter 4 uses a mathematical model, similar to that used by Montain et al. (2006), to predict the effect of varying fluid intake rates on hydration status when body mass, running speed and environmental conditions are systematically varied so that they are more in keeping with present day elite endurance runners. To supplement this analysis, a retrospective video analysis was used to determine the actual drinking behaviours of the winning male and female elite runners in the 2006 and 2007 London Marathons as there is almost no information on what the best marathoners drink when racing (for a review of the marathon running literature see reference Cheuvront & Haymes, 2001b). The mathematical model demonstrated that drinking *ad libitum* 0.4-0.8 L·hr⁻¹ for elite marathon runners is inadequate to limit body mass loss < 3 % and prevent body mass gain in 45-75 kg subjects running in cold (7.3 °C) and warm (24.8 °C) ambient conditions at (hr:min:sec) 2:04:00 and 2:30:00 marathon pace. This was corroborated by the derived total drinking durations of the winning male and female elite runners in the 2006 and 2007 London Marathons that were 56, 38, 43 and 31 sec that equate to fluid intake rates of approximately 1.5, 1.1, 1.1 and 0.9 L·hr⁻¹, respectively. These fluid intake rates are greater than prevailing fluid intake recommendations of *ad libitum* 0.4-0.8 L·hr⁻¹. These findings and analysis suggest that the best strategy for competitive marathon running in temperate conditions is to drink *ad libitum*. An important consequence of drinking *ad libitum* however is that it typically results in modest dehydration. A review (Cheuvront & Haymes, 2001b) of the endurance running literature reported no effect of dehydration on core temperature for losses of body mass up to 3.1 % (mean: < 2.5 %), whereas a positive relationship was found between the level of dehydration and rise in core temperature when losses were greater than 3 % body mass. Coyle (2004) suggests that a range of 1-2 % may be tolerable in temperate conditions and that > 2 % may be tolerated in colder environments. The above reasoning poses the interesting possibility that there may exist a tolerable range for dehydration that will not impact negatively on running performance, but which may even confer an advantage by preventing the increases in body mass due to consumption of large volumes of fluid (Armstrong et al., 1985; Sawka & Montain, 2000; Coyle, 2004).

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Indeed, the simple concept of reducing body mass while keeping power constant, and thereby reducing the energy cost of running, is certainly valid. In fact, Wyndham and Strydom (1969) reported no correlation with percent dehydration and core temperature until a 3 % weight deficit had occurred. Similarly, Ladell (1955) found a linear correlation between percent dehydration and an increase in core temperature only beyond 2.5 kg of body mass loss. Figure 6.1 depicts a theoretical model to highlight the potential effects of no fluid intake, *ad libitum* intake, and total fluid replacement on performance. Here *ad libitum* fluid intake may present a balance between drinking enough fluid to maintain an optimal zone of tolerable dehydration and reducing the absolute energy cost of movement by reducing the athlete's body mass. Once beyond a tolerable range of dehydration or due to extreme thirst, the gradient of the curve flattens; in this situation there may be a more progressive decline in performance. To test whether modest dehydration towards the end of a race may confer any performance advantage, Armstrong et al. (1985) induced dehydration via diuretic administration leading to a significantly reduced plasma volume. However, diuretic-induced dehydration may be an ineffective method for replicating exercise-induced dehydration, as it typically produces an iso-osmotic hypovolaemia, resulting in a much greater ratio of plasma to body water loss (Sawka & Montain, 2000). In addition, the direct effect of the diuretic on the brain was not considered. A further study by Armstrong et al. (2006) ran 10 endurance runners four times for 10 min, twice each at 70 and 85 % of their $\dot{V}O_{2max}$. At each intensity, subjects ran once euhydrated and once dehydrated (by 5.5 and 5.7 % relative body mass loss, respectively). They found that $\dot{V}O_2$ (expressed relative to body mass) was not significantly different and concluded that a reduction in body mass had no effect on running economy and thus no performance gain. However, Armstrong et al. (2006) may have wrongly interpreted their findings. Reducing body mass will in turn reduce the energy cost per unit distance, so the finding that running economy expressed in $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ is not significantly improved when hypohydrated is not surprising as the reduction in body mass will be cancelled out by the reduction in energy cost per unit distance. What is more pertinent is the absolute $\dot{V}O_2$ cost at the same relative

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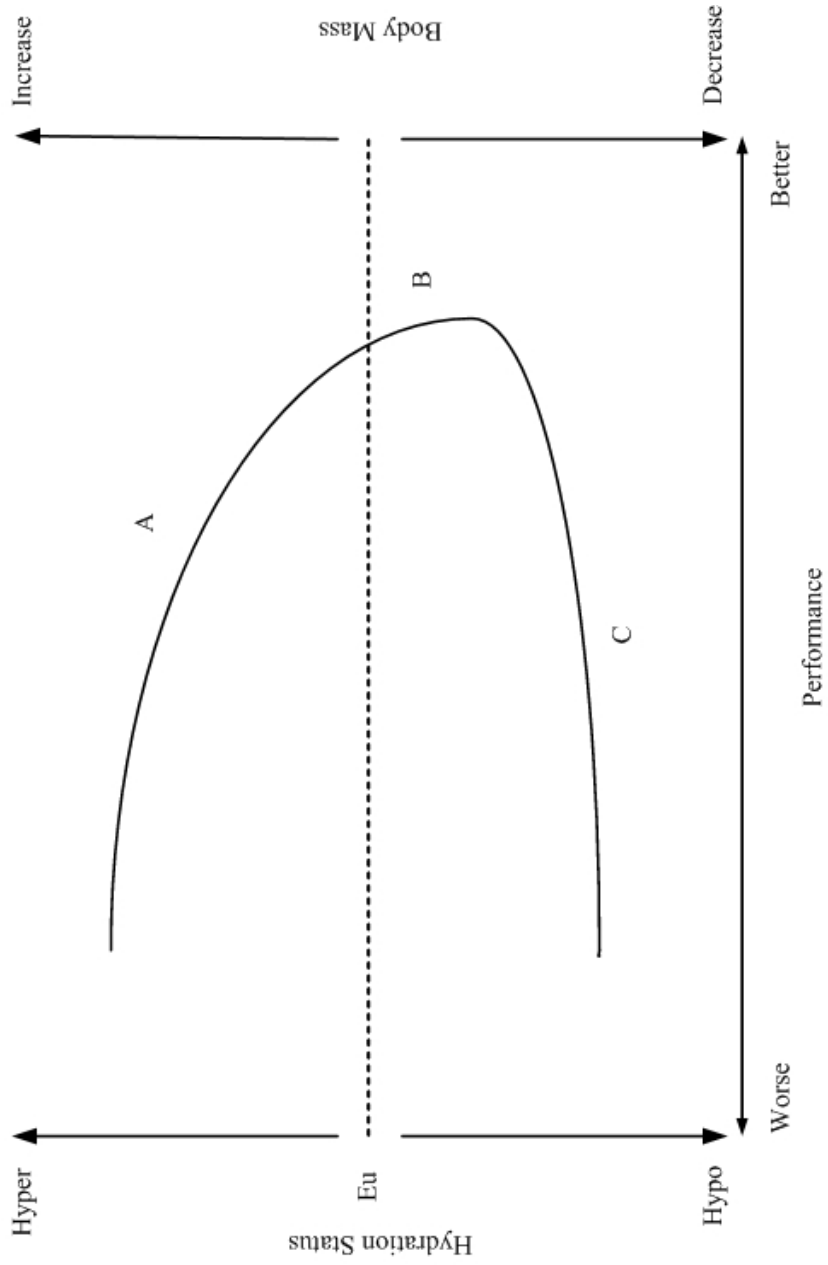


Figure 6.1: Theoretical model illustrating effect of varying rates of fluid ingestion (i.e., A) an excess fluid intake; B) an *ad libitum* fluid intake and C) no fluid intake on running performance.

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speed. At 85 % $\dot{V}O_{2max}$ the fractional utilisation of $\dot{V}O_{2max}$ was 3.2 % lower when hypohydrated compared to euhydration (i.e., 86.6 vs. 89.8 % $\dot{V}O_{2max}$, respectively). This difference was not found to be statistically significant but in terms of a performance effect for an elite runner completing the last part of a marathon race, this may well have a performance impact (Hopkins et al., 1999). Thus, further well controlled studies are required to test the validity, the performance, and the health implications of runners completing the last part of a race mildly dehydrated, but with a reduced energy cost of running.

A further recommendation in the new ACSM Position Stand (American College of Sports Medicine, 2007) is to only aggressively consume electrolytes after exercise if time does not permit consumption of normal meals and beverages to replace exercise induced electrolyte losses. Chapter 3 therefore assessed electrolyte balance status in elite Kenyan endurance runners during an important training period as athletes regularly trained at least twice a day. It was found that mean dietary K^+ intake was significantly greater than mean K^+ loss in sweat and urine over a 24 hr recording period equivalent to a mean difference of $1466 \pm 846 \text{ mg}\cdot\text{d}^{-1}$ that was likely accounted for by faecal losses. Na^+ intake on the other hand was not significantly different from Na^+ loss. This suggests that elite Kenyan endurance runners consume a diet sufficient in electrolytes and thus do not require additional supplementation corroborating the recommendation of the new ACSM Position Stand (American College of Sports Medicine, 2007). This is perhaps not surprising as the sweat $[Na^+]$ and $[K^+]$ in Chapter 3 are comparable to values reported in heat acclimatised individuals (Dill et al., 1938; Sawka & Montain, 2000). Heat acclimatised individuals lose less Na^+ and K^+ in sweat and therefore require relatively less in their diet to replenish relatively small losses in body stores as a result of sweating.

6.3 Lifestyle and training

Factors of elite Kenyan endurance runner's lifestyle that are optimal for recovery are demonstrated in Chapters 2 and 3. For example Chapter 3 reported that elite Kenyan endurance runners: 1) consumed sufficient fluid

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to maintain hydration balance day-to-day (Convertino et al., 1996); 2) consumed sufficient electrolytes to maintain electrolyte balance day-to-day (American College of Sports Medicine, 2000); and 3) timing of their post-training meal was always within 60 min of exercise which is considered optimal to replenish post-exercise glycogen stores (American College of Sports Medicine, 2000). Another factor, that is sometimes overlooked, is rest. Rest is important as lack of recovery may result in the athlete being unable to train at the required intensity at the next training session or indeed perform optimally during subsequent competition. Chapter 1 used accelerometry and PAR (Ainsworth et al., 2000) to determine the physical activity patterns of elite Kenyan endurance runners during an important training period (1 week before the Kenyan Olympic trials and 5 months before the Athens 2004 Olympics). To the present authors knowledge there are no comparable data in elite western endurance runners, but it is fair to say that the time spent in light activity as assessed by accelerometry and the time spent relaxing as assessed by accelerometry is high. Taking these measures together it may be suggested then that rest is an additional important facet of elite Kenyan endurance runner's typical training practices.

Unfortunately the precise quantification of physical activity or energy expenditure using PAR and accelerometry can be erroneous. PAR is an indirect method hence why Chapter 2 used the gold standard doubly labeled water method to measure energy expenditure. In the case of accelerometry, studies have reported that despite increased energy demands as a result of increasingly faster running speeds, output from some motion sensors plateau (Haymes & Byrnes, 1993; Nichols et al., 2000; Brage et al., 2003). In particular, Brage et al. (2003) investigated whether the Computer Science Applications (CSA) Model 7164 which was used in Chapter 2 and is also a commonly used accelerometer in general (Nichols et al., 2000; Strath et al., 2001; Strath et al., 2002; Brage et al., 2003; Brage et al., 2004), could predict $\dot{V}O_2$ during walking (3-6 km·hr⁻¹) and running (8-20 km·hr⁻¹) on a motorised treadmill and in the field. It was found that CSA output rose linearly ($R^2 = 0.92$, $p < 0.001$) with increasing speed until 9 km·hr⁻¹ but levelled-off at ~10 000 counts·min⁻¹ during running (8-20 km·hr⁻¹). This phenomenon will ren-

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der it impossible to accurately predict $\dot{V}O_2$ during vigorous exercise, such as fast running, using accelerometry. Another commonly used method for measuring physical activity is heart rate. However the precise quantification of energy expenditure at the population level is also difficult and prone to errors. For example heart rate can be affected by factors other than physical activity (e.g., age, gender, training status, emotional state etc.) especially at low intensities (Livingstone et al., 1990; Luke et al., 1997). Combining methodologies may to a large extent overcome some of these limitations and in doing so improve the assessment accuracy of physical activity and energy expenditure (Strath et al., 2000; Treuth & Welk, 2002; Brage et al., 2004; Plasqui & Westerterp, 2005; Strath et al., 2005). Chapter 6 addresses these issues by assessing whether biomechanical and/or device limitations cause the observed levelling off of accelerometer counts during running. This was achieved by investigating the outputs from a number of accelerometers, uni- and tri-axial, with various sampling frequencies, band pass filtering ranges and peak acceleration amplitudes. A secondary aim was to assess the feasibility of generating prediction equations from the combined use of accelerometry and heart rate that could be employed during fast running up to world record marathon running pace. It was found that during running, uni-axial accelerometer outputs plateau due to the biomechanics of running, whereas, tri-axial accelerometer output has a linear relationship up to and including $20 \text{ km}\cdot\text{hr}^{-1}$. It was also found the combined methodologies predict better than either predictor alone; subject's individually calibrated data further improves estimation. These findings invite the intriguing possibility that combining tri-axial accelerometry with heart rate may be a viable tool for training monitoring and assessing physical activity patterns of elite runners on a day-to-day basis.

Training distance achieved in Chapter 2 was greater than that recorded in Chapter 3 ($> 117 \text{ km}$ vs. 82 km , respectively) although the later consisted of only 5 days whereas Chapter 2 was 7 days. Noakes (2001) reported athletes who were preparing for major competition prior to the cross-country season in Kenya completed on average $80\text{-}100 \text{ km}\cdot\text{wk}^{-1}$. Training schedules typically incorporated up to 2 variable distance-training sessions per day (i.e.,

a morning run and a non-compulsory afternoon run) and 2 interval-training sessions per week (i.e., mid-morning run). Chapter 3 reports in detail what these sessions consist of (i.e., distance, time and speed) but essentially the morning run typically served as either a warm up (for interval training), a recovery run that usually compromised periods of slow and fast running with hopping and bouncing exercises or lastly a long run. The afternoon run was optional and usually served as an easy/recovery session. The track sessions are the athletes “quality sessions” and consist of high intensity running. For example, a typical interval training sessions included 4 times 600 m at 1 min 30 sec pace and 6 times 400 m at 58 sec pace for the middle distance runners or 6 times 600 m at 1 min 33 sec pace and 6 times 400 m at 59 sec pace for the long distance runners. Similarly Noakes (2001) reported that elite Kenyan endurance runners typically ran an easy run (30 min) each morning, with the final 800-1600 m being run at race pace, two interval training sessions per week and two long runs (60 min). This resulted in $\sim 25\%$ of the training volume run at race pace or greater; this value is comparable to the weekly training load reported in Chapter 3 (i.e., 26% of total weekly training time spent $> 80\%$ HR_{peak}). These findings corroborate previous investigations that indicate low to moderate intensity training accounts for the majority of training time in endurance athletes (e.g., Esteve-Lanao et al., 2005). The findings in Chapters 2 and 3 provide a snapshot of training practices of elite Kenyan endurance runners during an important taper phase prior to major competition. However, to fully recognize the contribution the training process makes towards world class performance in elite Kenyan endurance runners a longitudinal investigation of training practices that consists of many training phases is required, perhaps the further development of combining technologies such as heart rate and accelerometry will aid this analysis due to their ease of use, wear ability and low cost.

6.4 Future directions

Chapter 6 demonstrated variations in biomechanical characteristics of locomotion and different heart rate vs. speed relationships between individuals.

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With this in mind, and the concept that vertical (Kram & Taylor, 1990; Heise & Martin, 2001) and horizontal (Chang & Kram, 1999) forces are major determinants of metabolic cost during running, a further application of accelerometry may be a discriminatory role for differences between individuals in running economy or changes in running economy within individuals. It follows that excessive changes in momentum in the vertical, anterior-posterior and medial-lateral directions may be wasteful in terms of metabolic energy consumption (Heise & Martin, 2001). Indeed, Heise and Martin (2001) reported less economical runners (i.e., those with a higher \dot{V}_{O_2} for a given speed) demonstrated higher total and net vertical impulses. This is a promising area for research as less economical runners may reflect larger accelerometer output for a given speed. Future studies should therefore focus on elucidating the role individual movement patterns have on energy consumption.

Chapter 2 and 3 reported elite Kenyan endurance runners consume comparatively large volumes of milky tea (0.9 ± 0.3 ; 1.2 ± 0.4 L·d⁻¹, respectively). The tea consumed by the runners is isotonic (mean osmolality 281 ± 55 mOsmol·kg⁻¹) and contains a considerable amount of sugar (8.28 g·100g⁻¹ carbohydrate). This suggests that the milky tea consumed by the Kenyan athletes may act as a replacement for a conventional sports drink (e.g., Gatorade Thirst Quencher: osmolality 280-340 mOsmol·kg⁻¹, 5.83 g·100g⁻¹ carbohydrate). A further advantage from drinking large volumes of tea is highlighted in the study by Murase et al. (2005). Those authors reported that supplementation with green tea extract improved time to exhaustion in mice during swimming (8-24 %; this was dose dependant). It was hypothesised this was due to increased lipid oxidation during exercise which spared muscle glycogen. This is a similar mechanism proposed for the ergogenic effect of caffeine (Graham & Spriet, 1991) and suggests tea may improve endurance capacity. Furthermore, tea in general contains a large amount of catechins, a group of very active flavonoids which possess considerable antioxidant power and have been shown to impede the actions of free radicals (Dufresne & Farnworth, 2001). These radicals have the potential to cause oxidative damage to a wide range of molecular structures and can be produced during exercise such as endurance running. Therefore future inves-

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tigation could assess the effects of large volumes of Kenyan tea on oxidative stress following exhaustive running whilst also assess its effectiveness as an ergogenic aid for endurance running capacity. Lastly further work should focus on assessing the viability of using Kenyan milky tea as an effective conventional sports drink replacement.

In Chapters 2 and 3 it was reported that on days when athletes completed high intensity training this was immediately preceded by an easy morning run lasting around 30 min and a warm up lasting approximately 15-20 min. Before the morning run after waking and between the morning run and the track session athletes did not consume any fluid or food. This may suggest that athletes entered their track session (i.e., their “quality session”) with, at best, modestly depleted glycogen stores (Gollnick et al., 1974). Considering there is no doubt that endurance performance is enhanced if muscle glycogen is fully replenished (Jeukendrup, 2004) it is not surprising that completing training in a glycogen replenished state will allow the athlete to train harder and longer and thus may even achieve a superior training response. Indeed, it is well established that training must stress the athlete in order to stimulate adaptation. Adaptation essentially occurs as a consequence of accumulation of specific proteins that is in turn the result of expression of specific genes. Interestingly it has been shown that muscle glycogen is a determining factor for the transcription of some genes. But contrary to the above hypothesis that proposes carbohydrate intake may result in longer and harder training sessions and thus a greater training stimulus, it has been demonstrated that low glycogen actually results in greater transcriptional activation of a number of genes that are important for exercise adaptation (Keller et al., 2001; Febbraio et al., 2002; Pilegaard et al., 2002). To test whether training with low muscle glycogen concentrations have a performance implication, Hansen et al. (2005) performed a study in which 7 untrained subjects completed 10 weeks of knee extensor training where one leg trained in a low glycogen state and the other in a high glycogen state. It was found that the leg that was trained with low glycogen resulted in a two-fold increase in exercise time to fatigue without any loss in power. It was also reported that the leg trained with low glycogen had a more pronounced increase in resting muscle

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glycogen content and the activity of fatty acid oxidation citrate synthase and 3-hydroxyacyl-CoA dehydrogenase, reaching significance for citrate synthase. Rauch et al (2005) have suggested that a confounding factor of that study (Hansen et al., 2005) was that the workload was identical for the two legs despite the rate of perceived exertion being greater in the glycogen-depleted state. This may suggest the low glycogen leg trained at a relatively higher intensity than the high glycogen leg resulting in improved adaptation, this remains to be determined though. Nevertheless it may be suggested that training with low glycogen at the same absolute intensity provides a greater stimulus for skeletal muscle adaptation than training with normal glycogen concentrations. This invites the intriguing possibility that the training and nutritional practices of elite Kenyan endurance runners investigated in Chapters 2 and 3 may act synergistically to enhance the training stimulus leading to skeletal muscle adaptation and hence enhanced endurance performance. What is unclear at present is whether an athlete training with lower glycogen concentrations resulting in greater acute adaptations is at any advantage over an athlete training with normal glycogen concentrations who can train harder for longer. Thus well-controlled studies are required to determine whether training with low muscle glycogen concentrations provides any further advantage compared to training with normal muscle glycogen concentrations, particularly in elite endurance runners.

Finally there is perhaps one country in the world that does compete with Kenya in endurance running and that is their close neighbour Ethiopia. For example Ethiopian Kenenisa Bekele is the World record holder, World champion and Olympic champion for 5000 m and 10000 m and is also the current World Cross-Country champion. His compatriot Haile Gebrselassie is the current marathon World record holder. As a result of their staggering success, Ethiopia has also received substantial attention from the scientific community. Similar to Kenya however, there is no conclusive genetic explanation for their success (Moran et al., 2004; Scott et al., 2005; Yang et al., 2007) but environmental factors do seem to play a significant role (Scott et al., 2003). For example, Scott et al. (2003) found that elite Ethiopian endurance athletes ($n = 114$) are of a distinct environmental background in

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terms of geographical distribution compared to the Ethiopian general population ($n = 111$). Indeed parallels may be drawn with the Kenyans as it appears many of the Ethiopian athletes studied are also from an altitudinous area on the Rift Valley called Arsi and Sherwa. Another interesting finding of that study was that many athletes also travelled large distance to school and that the majority (70 %) of them ran to school and back everyday. However in contrast to Kenya, the diet, hydration, lifestyle and training practices remain to be determined. Further insights in to the process leading to world-class endurance running performance would undoubtedly be gained from studying the Ethiopians and should therefore be a future priority for research in the exercise physiology field.

6.5 General conclusions

There are many explanations typically given for the Kenyan running phenomenon. Heavily cited arguments for the Kenyan's staggering success on the international road and track racing circuits over the last several decades are genetic superiority and environmental factors. Despite a number of investigations, genetic superiority remains to be determined, what is clear though is that the environmental factors that interact with genes to produce world-class performance are incredibly important. Therefore Chapters 2 and 3 detailed extensively the diet, hydration, lifestyle and training practices of a group of highly successful elite Kenyan endurance runners during important training periods. Chapter 4 explores the significance of the hydration practices reported in Chapters 2 and 3 (i.e., *ad libitum* fluid intake) have on marathon running performance and the wider implications for fluid intake recommendations for elite marathon running. Chapter 5 investigates novel technology that may further enhance our understanding of the physical activity patterns and training practices of elite Kenyan endurance runners on a day-to-day basis. The main findings of the research do not point to one single explanation for the Kenyan running phenomenon. The results suggest the explanation is likely to be complex in origin and that many individual factors may well aggregate to produce world class performance. The main

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findings are as follows:

It was found elite Kenyan endurance runners maintain energy balance during a taper phase but are in negative energy balance prior to major competition as assessed by the gold standard doubly labeled water method. Considering the relatively high carbohydrate content of their diet it is hypothesised the caloric deficit may not have a direct impact on their training performance. In fact the performance implications of reducing body mass as a result of energy deficiency is that the athletes will be lighter for competition and may thus be at an advantage as the energy cost per unit distance increases in direct proportion to the added load expressed as a percentage of body mass.

A further finding was that despite relatively low daily fluid intake that consisted of primarily milky tea and water, athletes remained hydrated day-to-day drinking *ad libitum*; a pattern of fluid intake that corroborates prevailing fluid intake recommendations. For elite marathon racing it was however found that drinking prevailing fluid intake recommendations that suggest a specific drinking range of *ad libitum* 0.4-0.8 L·hr⁻¹ are insufficient. It is therefore proposed the best strategy for competitive marathon running in temperate conditions is to simply drink to thirst (i.e. *ad libitum*) as long as body mass loss is kept within acceptable limits, possibly < 3 %.

It was also found that athletes remained in electrolyte balance day-to-day as a result of their diet, negating the need for further supplementation.

Measured physical activity patterns of elite Kenyan endurance runners strongly suggest rest between running training sessions is an important lifestyle factor.

The training load analysis supports the contention that elite endurance athletes spend the majority of their training time at low intensity with periods of high intensity work interspersed.

Chapter 5 is the first study to report an accelerometer that can operate up to and including 20 km·hr⁻¹. It was also found the combined use of tri-axial accelerometry and heart rate predict $\dot{V}O_2$ better than either predictor alone and that subject's individually calibrated data further improves $\dot{V}O_2$ estimation.

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It is proposed that future studies should focus on developing combined technologies such as accelerometry and heart rate in order to better understand physical activity patterns and energy expenditure of elite Kenyan endurance runners on a day-to-day basis over an extended period of time that incorporates multiple training cycles. Furthermore, future work should aim to elucidate the effect of training glycogen depleted may have on long term training adaptations particularly in elite endurance runners. Lastly further examination of the properties of the milky tea regularly consumed by the athletes in Chapters 2 and 3 may provide further clues to the Kenyan running phenomenon. In terms of progressing knowledge in to the training process leading to world-class performance it is suggested that similar studies to those presented here in Chapters 2-3 are conducted in Ethiopia due to their recent staggering success in endurance running.

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Appendix 1

UNIVERSITY OF GLASGOW
ETHICS COMMITTEE FOR NON CLINICAL
RESEARCH INVOLVING HUMAN SUBJECTS

RESEARCH SUBMISSION

Name of person(s) submitting research proposal: **Dr Yannis Pitsiladis**

Position held **Lecturer in IBLs**

Department/Group/Institute/Centre – **International Centre for East African Running Science (ICEARS), Institute of Biomedical & Life Sciences (IBLS)**

Name of Principal Researcher (if different from above) _____

Position held _____

Date of submission **November, 2004**

Project Title: **Effects of the ACSM recommended fluid replacement strategy for endurance athletes on thermoregulation and running performance in elite level Kenyan distance runners**

1. Describe the basic purposes of the research proposed.

Background of investigation

Kenyan middle- and long-distance runners have dominated the athletics world since the 1960s, particularly males. Some attempts at explaining this extraordinary success have included genetic endowment (e.g. Bale and Sang, 1998), a sociological aspect (e.g. Manners, 1997) and environmental conditions that could potentially enhance the physiological characteristics of the athlete (e.g. Scott et al, 2003). At present there appears to be no one individual factor to explain the astonishing success of the east African athletes; however, until recently diet and nutrition had not been comprehensively investigated.

Several studies have evaluated the nutritional approach by Kenyan athletes (Fudge et al, In press; Onywera et al, In press; Christensen et al, 2002; Mukeshi and Thairu, 1993). In particular, two recent studies from this laboratory (Fudge et al, In press; Onywera et al, In press) investigated the food and macronutrient intake of 10 elite Kenyan athletes over a seven day period. A noticeable finding was that fluid intake by the athletes in both studies was low and mainly in the form of water (Fudge et al, In press: 948 ± 542 ml; Onywera et al, In press: 1113 ± 269 ml) and tea (894 ± 307 ml; 1243 ± 348 ml, respectively). Indeed Noakes (2003) suggests that elite marathon runners may only consume about 200 mlhr^{-1} during racing. This figure and the daily fluid intakes reported by the above mentioned studies are substantially less than that recommended by the American College of Sports Medicine (ACSM, 1996), typically $1.2 - 2 \text{ Lhr}^{-1}$ during exercise. The rationale for recommending large volumes of water stems from laboratory research that reported a relationship between the extent of dehydration and a rise in rectal temperature (e.g. Galloway and Maughan, 2000). A progressive increase in core temperature may result in increased effort perception, reduced exercise performance and even heat stroke and death. Noakes (2003) however cautions against drinking copious volumes of fluid as potentially this may render the individual athlete susceptible to hyponatraemia and suggests that athletes should consume fluid *ad libitum*, in particular recreational runners as the risk is greater in those athletes who take longer to complete a race that may result in consumption of vast volumes of water.

Therefore purpose of this study is to determine whether drinking enough fluid to satisfy the ACSM and other major sporting governing bodies' guidelines is advantageous to elite Kenyan endurance runners. The study will be conducted in the field at the athletes normal training camp; it will last for two weeks and will compare consuming enough fluid to comply with recommendations as described by the ACSM (1996) with the habitual fluid intake of the athletes such that they are allowed *ad libitum* access to fluids.

2. Outline the design and methodology of the project. Please include in this section details of the proposed sample size.

Plan of Investigation

We propose to:

Compare directly the effects of the ACSM recommended hydration strategy on running performance in elite Kenyan runners with the fluid replacement strategies currently adopted.

Methods/Design of investigation

Approximately 10 members of the Kenyan athletic national team will be invited to take part in this study. Subjects will be required to read and sign the enclosed information sheet. Testing will take place at the Kaptagat High Altitude Training Camp, Eldoret, Kenya. A series of assessments will be carried out. These will include the following: extra-cellular water and total body water using multifrequency bioelectrical impedance, heart rate using a standard polar heart rate monitor, core temperature using a telemetric physiological monitoring system (HQInc., Palmetto, Florida, USA), food diaries and questionnaires to assess energy intake and physical activity diaries to assess energy expenditure. Daily urine collections will also be carried out to assess hydration status (Shirreffs, 2000) using urine osmolality and specific gravity. Subjects will be monitored daily over a two week training period. Subjects will be randomly assigned to either a 'sports drink' group or a control group for the first 7 days before crossing over to the other condition for a further 7 days. For the control week, athletes will be required to carry out their normal fluid replacement strategies accompanying training while during the intervention week athletes will be required to consume 500ml of water 1 hour prior to each training session and 300ml of carbohydrate/electrolyte drink for every 15 minutes of exercise immediately after exercise. Subjects will be instructed to carry out a weighted intake of food and fluid and an activity diary during each 7 day period.

Protocols

Training session analysis: Subjects will be monitored throughout the two week study periods. Extra-cellular water and total body water will be measured prior to each training session multifrequency bioelectrical impedance (Bodystat Multiscan 500). This non-invasive method involves placing two current-inducing electrodes and two detector electrodes on the dorsal surfaces of the right hand and foot and a small (and imperceptible) electrical current (500 Micro-Amps) introduced between these (Ross et al, 1989). Each athlete will be required to swallow a CorTemp Ingestible Temperature Sensor, or "pill" before training on selected training days (e.g. day 1 and day 6 of each training week). The pill is a small electronic device, which senses the body's temperature and transmits it through a radio wave signal to an external receiver (Rav-Acha et al, 2003). Heart rate and core temperature will be measured throughout exercise. Each athlete will be asked to complete a questionnaire immediately after each training session.

3. Describe the research procedures as they affect the research subject and any other parties involved.

All experiments will take place at the Kaptagat High Altitude Training Camp, Eldoret, Kenya. Dr Yannis Pitsiladis or a qualified (CPR-trained) and experienced colleague will be present at all tests.

Potential participants will be selected from the athletes training at the Kaptagat High Altitude Training Camp and will be identified by personal contact. They will be asked to meet with the investigators to discuss the project and whether they would be suitable as a subject. All subjects will be healthy individuals without a history of any significant medical problem(s). All subjects will be endurance-trained and therefore accustomed to strenuous exercise.

Close supervision of the subject is ensured at all times by the supervising investigator.

The risks associated with the procedures outline are negligible.

4. What in your opinion are the ethical considerations involved in this proposal? (You may wish for example to comment on issues to do with consent, confidentiality, risk to subjects, etc.)

Exercise has negligible risk in healthy adults.

The subjects will provide their written consent with the option to withdraw from training or testing at any point.

Urine will be handled, stored and disposed of according to standard health and safety procedures.

5. Outline the reasons which lead you to be satisfied that the possible benefits to be gained from the project justify any risks or discomforts involved.

It is envisaged that this research will benefit the identification of the correct hydration strategy for elite Kenyan distance runners during training and competition. The minimal risk and discomfort associated with the above procedures are considered to be worthwhile to gain the information required.

6. Who are the investigators (including assistants) who will conduct the research and what are their qualifications and experience?

Dr Yannis Pitsiladis (PhD MMedSci BA), Barry Fudge and Vincent Onywera (Phd Students). The principal investigator has wide ranging experience of such procedures over periods of up to 15 years without incident.

7. Are arrangements for the provision of clinical facilities to handle emergencies necessary? If so, briefly describe the arrangements made.

In the event of an untoward incident that is not an emergency, the supervising Principal Investigator will administer appropriate first aid, if necessary. The subject will not be permitted to leave the scene until he has fully recovered. The subject will be encouraged to contact his local doctor. The subject will be told that the Principal Investigator will conduct a follow-up by telephone at the end of the same day. The subject will also be provided with 24-hour contact numbers for the Principal Investigator.

8. In cases where subjects are identified from information held by another party (for example, a doctor or hospital) describe the arrangements whereby you gain access to this information.

N/A

9. Specify whether subjects will include students or others in a dependent relationship.

N/A

10. Specify whether the research will include children or those with mental illness, disability or handicap. If so, please explain the necessity of using these subjects.

N/A

11. Will payment be made to any research subject? If so, please state the level of payment to be made, and the source of the funds to be used to make the payment.

No

12. Describe the procedures to be used in obtaining a valid consent from the subject. Please supply a copy of the information sheet provided to the individual subject.

Each subject will be provided with a consent form outlining the testing procedures, which asks them for their written consent to participate in the project with the option to withdraw at any time (see enclosed copy). A verbal explanation will also be given and any queries answered. If there is some doubt of the subject's eligibility for the study, the subject will be excluded.

13. Comment on any cultural, social or gender-based characteristics of the subject which have affected the design of the project or which may affect its conduct.

All subjects are members of the Kaptagat High Altitude Training Camp, Eldoret, Kenya.

14. Give details of the measures which will be adopted to maintain the confidentiality of the research subject.

The information obtained will be anonymised and individual information will not be passed on to anyone outside the study group. The results of the tests will not be used for selection purposes.

15. Will the information gained be anonymized? If not, please justify.

Yes

16. Will the intended group of research subjects, to your knowledge, be involved in other research? If so, please justify.

No

17. Date on which the project will begin and end

Begin, **5/12/04**. end, **18/12/05**.

18. Please state location(s) where the project will be carried out.

Kaptagat High Altitude Training Camp, Eldoret, Kenya

References

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International Centre for East African Running Science
Institute of Biomedical and Life Sciences
University of Glasgow

SUBJECT INFORMATION SHEET

TITLE OF INVESTIGATION: Effects of the ACSM recommended fluid replacement strategy on thermoregulation and running performance in elite level Kenyan distance runners

We invite you to participate in an investigation that we believe to be of potential importance. In order to help you understand what the investigation is about, we are providing you with the following information. Be sure you understand it before you formally agree to participate. Ask any questions you have about the information that follows. We will do our best to explain and to provide any further information you require.

A team of University researchers will be staying at your training camp for approximately two weeks. The aim of the study is to determine whether implementing water intake guidelines suggested by major sporting governing bodies will improve the performance of elite Kenyan endurance runners. This will involve one week of training with your normal diet and fluid intake, while the second week consuming enough fluid to satisfy the guidelines including consumption of a sports drink at regular intervals. Training will follow your general schedule and will be exactly the same for both weeks. All food and water intake will be recorded for the duration of the study. In order to obtain results and to not interfere with your training, you will be required to swallow a harmless recording device, a small pill like object, that will enable the research team to monitor body temperature and heart rate; there is no risk involved in swallowing the pill. Your percentage body water will also be measured on each day of the study period. Your body water will be estimated by a bioelectrical impedance technique, which involves placing slightly adhesive small patches (“electrodes”) on your right hand and foot and introducing a very small and imperceptible electrical current between these. You will be required to collect urine (in containers to be provided) throughout the supplementation period. The urine will be analysed for colour and particle concentration (i.e. osmolality). We plan to use this information to determine your hydration status at various points during each day.

Your compliance with all aspects of the study is fundamental to the outcome of the research and will be strictly monitored. All information collected will be dealt with in the strictest confidence and will be subject to the Data Protection Act. The research group will not pass any details on to any other organisation, and the data will not be used for any purpose other than those stated.

We would respect your concerns and your decision should you not wish to participate in this research.

If you have concerns about any of the above procedures you should contact:

Dr Yannis Pitsiladis
Lecturer, Institute of Biomedical and Life Sciences
West Medical Building
University of Glasgow
Glasgow, G12 8QQ
Phone: +44 141 330 3858
Fax: +44 141 330 2915
E-mail: Y.Pitsiladis@bio.gla.ac.uk

Consent Form

I

give my consent to the research procedures that are outlined above; the aim, procedures and possible consequences of which have been outlined to me

Signature

Date

Signed _____ Date _____
(Proposer of research)

Appendix 2

UNIVERSITY OF GLASGOW
ETHICS COMMITTEE FOR NON CLINICAL
RESEARCH INVOLVING HUMAN SUBJECTS

RESEARCH SUBMISSION

Name of person(s) submitting research proposal **Dr Yannis Pitsiladis,**

Position held **Reader in IBLS and Director of International Centre for East African Running Science (ICEARS)**

Department/Group/Institute/Centre - **International Centre for East African Running Science (ICEARS), Institute of Biomedical & Life Sciences (IBLS)**

Name of Principal Researcher (if different from above) _____

Position held _____

Date of submission:

Project Title: **Estimation of aerobic power from accelerometers and heart rate during walking and running**

1. Describe the basic purposes of the research proposed.

Background of investigation

Physical fitness testing is common in health related situations for preventative and rehabilitative exercise programmes. Furthermore measurement of fitness is a key part in monitoring the progress of recreational and elite athletes as well as helping in identifying future sporting talent. Laboratory testing is the “gold standard” method for assessing cardiovascular fitness, such as maximal oxygen consumption and lactate threshold estimation, and allows repeatable, reliable and accurate results to be obtained. However, this is usually expensive, time consuming, does not allow multiple subjects to be tested at once and is not specific for athletes competing out of doors. On the other hand, many coaches and exercise prescription specialists use field-tests to evaluate physical fitness. These tests are typically quick, inexpensive, and can be tailored for individual or team needs. On the downside, field-testing is not as accurate as laboratory testing and produces only estimations of physical fitness parameters. The aim of this study therefore is to use data from heart rate and accelerometry to produce a more accurate estimation of physiological predictors of fitness. In particular, the relationship between activity counts measured by a triaxial accelerometer (3DNX triaxial accelerometer, BioTel Ltd., Bristol, UK) and treadmill running at high velocities will be assessed. The relationship to emerge will be used to model oxygen consumption and energy expenditure at fast running speeds utilising the “individualised” relationship between heart rate and oxygen uptake. Furthermore, validation of triaxial accelerometers with high running speeds in the field will also be investigated.

2. Outline the design and methodology of the project. Please include in this section details of the proposed sample size.

Methods/Design of investigation

We propose to study 50 endurance-trained subjects (mostly runners aged 17-40 yrs). Subjects will be in good health at the time of testing and regularly take part in strenuous exercise. Eligibility will be assessed by subjects undergoing a medical examination (as previously approved by the University Ethics Committee). Subjects will also be required to read and sign the enclosed information sheet and a high intensity consent form.

Testing will take place in the Laboratory of Human Physiology in the West Medical Building and an outdoor running track. The proposed protocol will include one visit to the laboratory and running track.

Protocols

Discontinuous Incremental Exercise Test: Each subject will perform a discontinuous incremental exercise test on a motorised treadmill in the laboratory. Subjects will be required to walk at 3, 5 and 7 km·hr⁻¹, for 3 minutes at each speed. They will then be allowed a 3 minute rest period; walking at 4 km·hr⁻¹. Following this rest period, the subject will be instructed to run at 8, 10, 12, 14, 16, 18, and 20 km·hr⁻¹ for 3 minutes at each speed, with a 3 minute rest interval between each bout walking at 4 km·hr⁻¹. The subject will be required to adhere to the protocol until volitional exhaustion, eliciting peak oxygen uptake (VO_{2 peak}). Subjects will be given a warm-up before the test and a warm-down after the test. The subject will wear 2 uniaxial accelerometers (The ActiGraph activity monitor 7164 model (previously CSA) and the Actigraph GT1M model, Manufacturing Technology, Inc., Florida, USA) and 1 triaxial accelerometer (3DNX triaxial accelerometer, BioTel Ltd., Bristol, UK) to record the activity counts per minute. Heart rate (Suunto t6, Suunto Oy, Vantaa, Finland) and gas exchange variables (breath-by-breath using a quadrupole mass spectrometer, QP9000, Morgan Medical, Gillingham, Kent, UK) will be measured throughout exercise as previously approved by the ethics committee.

Track Test: The progressive protocol (see above) will be repeated but this time applied to an indoor or outdoor running track. Oxygen uptake measurements however will not be obtained. Running speed will be controlled and monitored using a GPS system.

Validation

Standard cardiorespiratory variables measured using breath-by-breath gas analysis during the lab test will be compared to the values estimated from heart rate and accelerometry data using manufacturers equations.

3. Describe the research procedures as they affect the research subject and any other parties involved.

Dr Yannis Pitsiladis or a qualified (CPR-trained) colleague will be present at all tests. Dr Pitsiladis is trained in CPR and Advanced Life Support.

Potential participants will be identified either by personal contact or by advertisement. They will be asked to meet with the investigators to discuss the project and whether they would be suitable as a subject. All subjects will be healthy individuals without a history of any significant medical problem(s). All subjects will be endurance-trained and therefore accustomed to strenuous exercise to exhaustion. The good health of each subject will be established prior to the study by subjects undergoing a medical examination (as previously approved by the University Ethics Committee), which is supported by a written assurance from the subject. Subjects with a history of cardiorespiratory or neurological disease will be excluded from participation, as will those having an acute upper respiratory tract infection. Subjects who take drugs (recreational or performance enhancing drugs) or who have consumed alcohol within 48 h of an experiment will be excluded.

Close supervision of the subject is ensured at all times by the supervising investigator. The well-being of the subject is established at frequent intervals throughout all tests by asking the subject "Is everything alright?" Subjects are instructed, prior to the test, to respond to this question with a thumbs-up sign if everything is fine, and a thumbs-down sign if there is problem. If a problem is indicated, the investigator will ask further questions to establish whether there is a technical problem that could lead to potential hazard or whether the subject is feeling unwell. In either case, the test is immediately halted. All subjects are routinely instructed to cease exercising if they experience any discomfort or have any concern for their well-being.

The risks associated with performing maximal exercise are minimal as long as the subject is appropriately instructed and familiarised with the device prior to participation and also is appropriately supervised during the experiment. All exercise bouts are both preceded by a 5 min "warm-up" and by a 5 min "warm-down". The latter is of particular importance during high-intensity exercise, when the local accumulation of exercise metabolites can cause an "expansion" (or vasodilatation) of the blood vessels in the lower limbs, which can impair the adequate return of blood to the heart – predisposing to fainting on dismounting from the treadmill. This risk is minimised by having the subject exercise at a mild level during recovery to "wash away" these metabolites and therefore to restore the capacity of the involved blood vessels to their resting levels.

Some subjects experience difficulty swallowing while breathing through a mouthpiece and wearing a nose-clip, due to some transient build-up of pressure in the ears.

4. What in your opinion are the ethical considerations involved in this proposal? (You may wish for example to comment on issues to do with consent, confidentiality, risk to subjects, etc.)

The ethical concerns are minor. Exercise has negligible risk in healthy adults, although maximal exercise has a small risk of inducing myocardial ischaemia.

The subjects will undergo medical screening, complete a medical questionnaire and provide their written consent with the option to withdraw from training or testing at any point.

5. Outline the reasons which lead you to be satisfied that the possible benefits to be gained from the project justify any risks or discomforts involved.

It is envisaged that this research will identify whether the combined use of heart rate and accelerometry can be used to predict cardiorespiratory data from athletes during exercise in the field. The minimal risk and discomfort associated with the above procedures are considered to be worthwhile to gain the information required.

6. Who are the investigators (including assistants) who will conduct the research and what are their qualifications and experience?

Dr Yannis Pitsiladis PhD MMedSci BA, Chris Easton BSc, Barry Fudge BSc, Mr John Wilson, Mrs Heather Collin (Senior Technicians), and 3 BSc Honours Project Students; Olivia Haddow, Laura Irwin and Jonathan Clark. Dr Yannis Pitsiladis has wide ranging experience of exercise testing over periods of up to 10 years without incident..

7. Are arrangements for the provision of clinical facilities to handle emergencies necessary? If so, briefly describe the arrangements made.

In the event of an emergency, guidelines approved by the ethics committee will be followed.

In the event of an untoward incident that is not an emergency, the supervising Principal Investigator will administer appropriate first aid, if necessary. The subject will not be permitted to leave the laboratory until they have fully recovered. The subject will be encouraged to contact their local GP. The subject will be told that one of the principal investigators will conduct a follow-up by telephone at the end of the same day. The subject will also be provided with 24-hour contact numbers for both principal investigators.

8. In cases where subjects are identified from information held by another party (for example, a doctor or hospital) describe the arrangements whereby you gain access to this information.

N/A

9. Specify whether subjects will include students or others in a dependent relationship.

Some students may be recruited but will be under no pressure from staff to participate in the study.

10. Specify whether the research will include children or those with mental illness, disability or handicap. If so, please explain the necessity of using these subjects.

N/A

11. Will payment be made to any research subject? If so, please state the level of payment to be made, and the source of the funds to be used to make the payment.

NO

12. Describe the procedures to be used in obtaining a valid consent from the subject. Please supply a copy of the information sheet provided to the individual subject.

Each subject will be provided with a consent form outlining the testing procedures, which asks them for their written consent to participate in the project with the option to withdraw at any time (see enclosed copy). A verbal explanation will also be given and any queries answered. If there is some doubt of the subject's eligibility for the study, the subject will be excluded.

13. Comment on any cultural, social or gender-based characteristics of the subject which have affected the design of the project or which may affect its conduct.

None

14. Give details of the measures which will be adopted to maintain the confidentiality of the research subject.

The information obtained will be anonymised and individual information will not be passed on to anyone outside the study group. The results of the tests will not be used for selection purposes.

15. Will the information gained be anonymized? If not, please justify.

Yes

16. Will the intended group of research subjects, to your knowledge, be involved in other research? If so, please justify.

No

17. Date on which the project will begin (immediately) and end (November, 2006)

18. Please state location(s) where the project will be carried out.

Laboratory of Human Physiology (Lab 245), West Medical Building.

Outdoor track (Scotstoun stadium) and/or indoor track (Kelvin Hall).

References

Pulkkinen, A., Kettunen, J., Saalasti, S. & Rusko, H.K. (2003). Accuracy of VO₂ estimation increases with heart period derived measure of respiration. ACSM Congress, San Francisco, May 28-31, 2003. Abstract: Medicine and Science in Sports and Exercise 35(5): Supplement: 192.

Pulkkinen, A., Kettunen, J., Martinmäki, K., Saalasti, S., & Rusko, H. K. (2004). On and off- dynamics and respiration rate enhance the accuracy of heart rate based VO₂ estimation. ACSM Congress, Indianapolis, June 2-5, 2004. Abstract: Medicine and Science in Sports and Exercise 36(5): Supplement: 253.

Pulkkinen et al. Energy expenditure can be accurately estimated from HR without individual laboratory calibration. ACSM Congress, Nashville, June 1-4, 2005.

Rusko, H.K., Pulkkinen, A., Saalasti, S., Hynynen E. & Kettunen, J. (2003). Preprediction of EPOC: A Tool for monitoring fatigue accumulation during exercise. Medicine and Science in Sports and Exercise 35(5) Supplement: 183.

University of Glasgow
Institute of Biomedical & Life Sciences

INFORMATION SHEET

Study Title: Estimation of aerobic power from accelerometers and heart rate during walking and running.

You are being invited to take part in a research study. Before you decide whether to participate, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends, relatives and your GP if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of the study? Physical fitness testing is common in health related situations for preventative and rehabilitative exercise programmes. Furthermore measurement of fitness is a key part in monitoring the progress of recreational and elite athletes as well as helping in identifying future sporting talent. Laboratory testing is the “gold standard” method for assessing cardiovascular fitness, such as maximal oxygen consumption. However, the combined use of heart rate and accelerometry data (accelerometers are a small device attached to your waist that can measure movement) may allow an accurate estimation of physiological predictors of fitness outside the laboratory that is quick, easy and inexpensive. This investigation will therefore explore a way to predict oxygen consumption and energy expenditure at various running speeds using data generated from accelerometers and heart rate. Furthermore, validation of accelerometers with varying running speeds in the field will also be investigated.

Why have I been chosen? You have been selected as a possible participant in this investigation because you regularly take part in endurance activity and you are in good health. Fifty volunteers are being sought.

Do I have to take part? It is up to you to decide whether or not to take part. If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form and fill in a lifestyle questionnaire. If you decide to take part you are still free to withdraw at any time and without giving reason.

What will happen to me if I take part? You will be asked to visit the laboratory and outdoor (or indoor) running track once, where a series of assessments will be carried out. On your initial visit to the laboratory you will be medically examined by a qualified doctor followed by a discontinuous exercise test on a treadmill. You will be required to walk at 3, 5 and 7 km·hr⁻¹, for 3 minutes at each speed. You will then be allowed a 3 minute rest period of continuous walking at 4 km·hr⁻¹. Following this rest period you will be instructed to run at 8, 10, 12, 14, 16, 18 and 20 km·hr⁻¹ for 3 minutes at each speed (or until volition exhaustion), with a 3 minute rest interval of walking at 4 km·hr⁻¹ between each bout. Expired gas and heart rate will be recorded throughout the test via a rubber mouthpiece (see below) and heart rate monitor, respectively. You will wear 3 accelerometers whilst participating in the test. The track test will follow the same procedure as above, however expired gas will not be collected.

What are the possible disadvantages and risks of taking part? Exercise has a negligible risk in healthy adults, although maximal exercise has a small risk of myocardial infarction (“heart attack”). The primary symptom of myocardial infarction is chest pain on exertion. If you experience any unusual sensations in your chest during the experiment, you should cease exercising immediately.

You will breath through a rubber mouthpiece during the tests, in order for us to collect the air you breath out. This is similar to the equipment used for snorkelling. You will also wear a noseclip. You may experience difficulty swallowing while breathing through a mouthpiece and wearing a noseclip, due to some pressure in the ears. In addition some subjects experience increased salivation when breathing through a mouthpiece.

What are the possible benefits of taking part? We hope to find out more about how your body responds to physical exercise. This information will help us to decide whether the accelerometers can predict parameters of physical fitness accurately.

What if something goes wrong? If you are harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone’s negligence, then you may have grounds for a legal action but you may have to pay for it. The principal investigators, although not medically qualified are fully trained in Advanced Life Support. In the event of an untoward incident, the principal investigator(s) will provide basic life support including chest compressions and ventilation until emergency medical staff are on hand. You may want to consult your GP if you are experiencing any side effects from taking part in the study and should also inform the principal investigator.

Will my taking part in this study be kept confidential? All information about you that is collected during the course of the research will be kept strictly confidential.

What will happen to the results of the research study? Results will be published in a peer-reviewed scientific journal once the study is completed. You will automatically be sent a copy of the full publication. You will not be identified in any publication.

If you wish to find out more about this investigation, you can contact:

Dr Yannis P. Pitsiladis
Institute of Biomedical & Life Sciences
West Medical Building
University of Glasgow
Glasgow, G12 8QQ

Phone: 0141-330-3858
Fax: 0141-330-2915
E-mail: Y.Pitsiladis@bio.gla.ac.uk

CONSENT

Title of Investigation: Estimation of aerobic power from accelerometers and heart rate during walking and running.

I

Give my consent to the research procedures which are outlined above, the aim, procedures and possible consequences of which have been outlined to me.

Signature

Date

**UNIVERSITY OF GLASGOW
INSTITUTE OF BIOMEDICAL AND LIFE SCIENCES**

**SUBJECT'S QUESTIONNAIRE AND ASSENT FORM FOR
HIGH-INTENSITY EXERCISE TESTING**

If you feel unwell on the day of a proposed test, or have been feeling poorly over the preceding day or two, DO NOT TAKE PART in a high-intensity exercise test.
The considerations which follow apply to people who are feeling well at the time.

NAME _____

Sex (M/F) _____ Age _____ (yrs) Height _____ (m) Weight _____ (kg)

Exercise Lifestyle

a) What kind(s) of exercise do you regularly do (20+ min/session)? *(Please circle)*

Number of times per average week

Walking	1	2	3	4	5
Running	1	2	3	4	5
Cycling	1	2	3	4	5
Swimming	1	2	3	4	5
Skiing	1	2	3	4	5
Rowing	1	2	3	4	5
Gymnastics	1	2	3	4	5
Martial arts	1	2	3	4	5
Tune Up	1	2	3	4	5
Popmobility	1	2	3	4	5
Sweat Session	1	2	3	4	5
Weight training	1	2	3	4	5
Field athletics	1	2	3	4	5
Racquet sports	1	2	3	4	5
Rugby/soccer/hockey	1	2	3	4	5
Other(s) *	1	2	3	4	5

* *(Please specify)* _____

b) How long have you been exercising at least twice/week for at least 20 min/session?

Continued Over

Smoking*(Please tick one)*

Never smoked	_____
Not for > 6 months	_____
Smoke <10 per day	_____
Smoke > 10 per day	_____

IllnessesHave you ever had ...? *(Please circle Yes or No)*

Asthma	YES	NO
Diabetes	YES	NO
Epilepsy	YES	NO
Heart Disease	YES	NO
High Blood Pressure	YES	NO

Any other illness that could affect your safety in performing maximal exercise

YES	NO
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(If YES, please specify) _____**Symptoms**

Have you ever had any of the following symptoms to a significant degree?

i.e. have you had to consult a physician relating to any of the following?

(Please circle Yes or No)

Breathlessness	YES	NO
Chest Pain	YES	NO
Dizzy fits / Fainting	YES	NO
Heart Murmurs	YES	NO
Palpitations	YES	NO

Muscle or joint injury

Do you have / or have had any muscle or joint injury which could affect your safety in performing maximal exercise or strength testing or strength training?

YES	NO
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Medication

Are you currently taking any medication? YES NO

*(Please circle Yes or No)**(If Yes, please specify)* _____**Signature** _____**Date** _____