CHANGES IN ENERGY EXPENDITURE AND DIETARY INTAKE IN RESPONSE TO DIFFERENCES IN TRAINING VOLUME IN MALE ENDURANCE ATHLETES

by

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Kinesiology

2011

ABSTRACT

CHANGES IN ENERGY EXPENDITURE AND DIETARY INTAKE IN RESPONSE TO DIFFERENCES IN TRAINING VOLUME IN MALE ENDURANCE ATHLETES

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Various studies have examined total daily energy expenditure (TDEE) or exercise energy expenditure (EEE) or changes in non-exercise activity thermogenesis (NEAT) and resting metabolic rate (RMR) in response to changes in exercise regimen. However, no study has examined the interaction of all these components contributing to TDEE during different training periods. There is also a lack of research addressing changes in dietary intake in response to changes in training regimen. The purpose of this study, therefore, was to examine changes in TDEE and its components, specifically EEE, NEAT, and RMR, along with alterations in dietary intake in male endurance trained athletes during high-volume (HV) and low-volume (LV) training periods. Secondarily, it was evaluated whether these athletes met current nutrition recommendations for sport and health.

Energy expenditure was measured in 15 male endurance athletes (age 23.6 ± 2.4) during two non-consecutive weeks – one week with about 13 hours of exercise training (HV) and another week with about 6 hours of exercise training (LV). Height (cm), weight (kg), and body composition were assessed according to standard procedures at the beginning and end of each week of data collection. RMR was measured in the middle of each week using indirect calorimetry. The SenseWear Pro3 Armband was used to measure NEAT while EEE was assessed via heart rate using individual regression equations. TDEE was then calculated by summing RMR, NEAT, and EEE. Dietary

information was obtained via an online food frequency questionnaire taken at the end of each week of data collection.

There was no difference in body composition between the two weeks of training. TDEE and EEE were significantly higher during the HV week, even though training intensity did not differ between the HV and LV training week. In addition, a trend towards higher RMR with higher training volume was observed, while NEAT remained relatively constant. There was a significant reduction in time spent in sedentary activity during the HV week while no differences in time spent in light, or moderate-to-vigorous activity occurred. TDEE and NEAT, however, were significantly correlated with time spent in different intensities and there was a positive relationship between RMR and time spent in vigorous activity. Dietary intake did not differ between the HV and LV week, and carbohydrates (CHO), fat, and protein contributed 51%, 33%, and 16%, respectively. Mean micronutrient intake of these athletes met or exceeded DRI micronutrient recommendations while reported intake for endurance athletes was well below recommendations for CHO, and fat intake exceeded current recommendations.

Neither NEAT nor energy intake (EI) differed during different training weeks. The reported caloric intake was significantly lower than TDEE during either training week and the high fat intake, low fiber consumption, and high sodium intake suggests that these athletes were generally consuming a typical Western diet and that they may need guidance to meet dietary guidelines for health and performance. The discrepancy between EI and EE was attributed to underreporting rather than an energy deficit. In addition increased training time did not reduce light and moderate activity, but rather reduced sedentary time in trained endurance athletes.

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor Dr. Joey C. Eisenmann for his guidance, assistance, and encouragement while pursuing my Ph.D. I also want to thank my committee, Dr. Joseph J. Carlson, Karin A. Pfeiffer, and James M. Pivarnik for their support and advice. Further, I want to address Kelly Turek, Allison Pomerantz, and Emily Niemyjski for their help with data collection and my fellow graduate students who provided feedback and additional feedback during the dissertation process. Of course the entire study would not have been possible without the subjects, who were very motivated and compliant. Finally, I want to thank my family for allowing me to follow my interests and supporting me throughout my graduate application. In addition, thanks to my wife, Christy, who believed in me even during difficult times.

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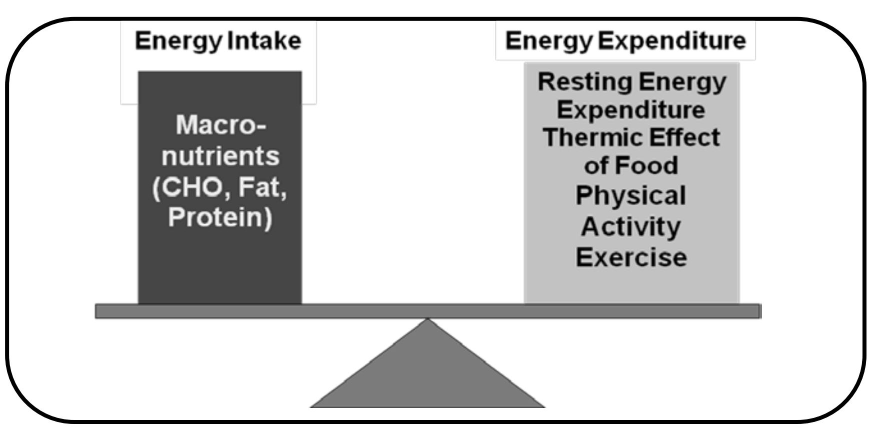
INTRODUCTION

Energy balance, i.e., the relationship between energy intake (EI) and energy expenditure (EE), is an important concept for human biology and health (Figure I.1). The increasing prevalence of overweight and obesity in various populations (Ogden et al. 2006) is generally thought to be related to a positive energy balance (Hill et al. 2003), which occurs when EI chronically exceeds EE (Levine and Kotz 2005). It has been suggested that a decline in EE, which has not been matched by an equivalent reduction in EI, is a major factor contributing to the current obesity epidemic (Hill and Melanson 1999). Currently, the average adult in the United States obtains less than 2 minutes of vigorous-intensity physical activity per day and between 6 and 10 minutes of moderate-intensity physical activity per day (Troiano et al. 2008). Furthermore, only 25-33% of the population meet physical activity recommendations despite various intervention programs aimed at promoting physical activity (Troiano 2005). Interestingly, randomized controlled trials have shown that increasing exercise energy expenditure (EEE) affects weight loss (Catenacci and Wyatt 2007) only modestly. Thus, overweight and obesity remains a problem in many industrialized countries despite considerable efforts to increase physical activity levels and the promotion of healthy eating patterns.

Figure 1.1: Components of Energy Balance (EI & EE)



One reason for the limited success of physical activity intervention studies on weight loss could be that total daily energy expenditure (TDEE) does not necessarily increase with increased systematically planned exercise due to a compensatory reduction in habitual physical activity (non-exercise activity thermogenesis, NEAT) outside the intervention program (Manthou et al. 2009). In addition to TDEE changes in EI in response to changes in exercise energy expenditure (EEE) need to be considered as well. It is possible that increased TDEE is compensated for by an increased EI. Similarly, energy expenditure may change in response to caloric restriction. For example Redman et al. (2009) showed that physical activity levels declined in response to caloric restriction. Nevertheless, it has been shown that caloric restriction results in weight loss (Avenell et al., 2004) and several studies (Hollowell et al. 2009, McLaughlin, Malkova and Nimmo 2006) have shown that habitual physical activity levels are maintained despite caloric restriction or exercise intervention programs, and consequently lead to weight reduction. Westerterp (2008) points out that different findings could be due to age-differences in the study population. In younger participants TDEE increased with exercise training, while in older subjects a compensatory decline in habitual physical activity was observed, which resulted in no change in TDEE. In summary, a reduction in EI or increased TDEE can lead to a negative energy balance, but other components of the energy balance equation may partially compensate for the induced changes.

Further, exercise intensity and length of the intervention have been shown to effect compensatory responses of habitual activity (Stubbs et al. 2002). Hunter and Byrne (2005) suggest that relatively high intensity exercises are more successful in inducing negative energy balance since this can partially offset the reduction in RMR that may occur in response to a negative energy balance (Astrup et al. 1999). On the other hand, Westerterp (2003) argues that due to the relatively short duration high intensity exercise does not have much impact on PAL (Physical Activity Level). In their opinion, engagement in moderate activities determines PAL. Concerning duration a longer intervention program would intuitively lead to more pronounced results. In their review, Westerterp and Plasqui (2004) displayed that resistance training interventions (2 hours per week) over 12 weeks did not lead to significant differences in PAL while a similar program over 18 weeks resulted in significantly higher PAL. Similarly changes in PAL in response to endurance training were more pronounced with longer intervention periods.

Despite inconsistent results concerning the relationship between caloric intake and TDEE there is evidence of central regulation involved in energy balance, but the exact pathways through which changes in physical activity may interact with nutritional intake and energy balance are not clearly understood (Stubbs et al. 2002). While the central regulation of appetite and nutritional intake is well established (Arora and Anubhuti 2006, Magni et al. 2009), the regulation of physical activity and TDEE is less clear. Although physical activity is a behavior, data from animal studies suggest that physical activity is influenced by biological factors including genetics (Lightfoot et al. 2004) and various physiological substances (e.g., hormones) and structures (e.g., estrogen/testosterone pathways) (Lightfoot 2008). Besides steroid and growth hormones, neuropeptides and appetite-related hormones influence physical activity or energy expenditure (Novak and Levine 2007). The interaction between EI and EE is strengthened by findings from Levine and Kotz (2005) who showed reduced physical activity levels with negative energy balance and a positive relationship between orexin, a protein related to increased food intake and physical activity. Finally, fast-response (fight-or-flight) and slow-response signals (leptin levels) derived from environmental cues as well as changes in biological substances have been shown to contribute to energy balance (Levine and Kotz 2005). In summary, similar neural pathways and substances are involved in the central regulation of EI and EE, which makes a possible interaction between these two components likely.

Given the current public health focus of energy balance and obesity, most studies mentioned previously targeted overweight and obese subjects. Considerably less information concerning energy balance in athletes is available, but the general concepts introduced above should hold true for this population as well. Even though Hill et al. (1995) argued that lean individuals are more likely to maintain energy balance with variations in TDEE due to a better adjustment of energy intake, athletes have also been shown to have an imbalance between EI and TDEE (Fudge et al. 2006, Nogueira and Da Costa 2005, Hill et al. 2003). Due to the high TDEE endurance athletes are likely to experience a negative energy balance which has been associated with an increased risk for infectious diseases (Gleeson and Bishop 2000), stress fractures (Joy and Campbell 2005), and overtraining syndrome (Saris 2001). In addition to the obvious health concerns observed with negative energy balance, performance may suffer as well. Further, in child and adolescent athletes a negative energy balance could lead to problems in normal growth and maturation (Roemmich, Richmond and Rogol 2001).

Several studies (Degoutte 2003, Ebine et al. 2000, Ebine et al. 2002, Ekelund et al. 2002, Motonaga et al. 2006, Hill and Davies 2001) have documented the energy expenditure in various sports, but did not consider TDEE. Other studies that have examined TDEE in athletes did not specify between different components of energy expenditure, such as exercise training vs. habitual physical activity (Ebine et al. 2000, Ebine et al. 2002, Hill and Davies 2001, Hill and Melanson 1999, Trappe et al. 1997). At this time, only one study has examined TDEE and EEE separately (Motonaga et al. 2006). Heart rate telemetry was used in this study, which has been shown to over-predict EE at rest or low-intensities due to additional factors that influence heart rate (e.g., psychological stress) as well as elevated post-exercise heart rate (Welk 2002). Further, Motanaga et al. (2006) only measured EE during 4 consecutive days without considering different periods of training intensity or training volume. As with other studies, EI was not considered, even though energy availability could potentially influence TDEE. Generally, there is a lack of research that has considered the interaction between EI and EE despite the well established fact that nutrition and energy availability influence performance, especially in endurance sports (Johnson, Stannard and Thompson 2004).

Considering the amount of energy required during ultra-endurance events (e.g., 8000 kcal/day during a cycling race) (Saris et al. 1989) or long-distance triathlon (Neumann, Pfützner and Hottenrott 2004, Kimber et al. 2002), endurance athletes face a serious challenge to meet their energy requirements. Loucks (2004) actually argues that there is an upper tolerable limit amount of EI and higher training or competition EE may result in a reduction in other components contributing to TDEE if energy balance is supposed to be maintained. This argument is supported by several studies (Westerterp et al. 1986, Dodd, Welsman and Armstrong 2008) that have shown a constant caloric intake despite increased TDEE due to sports training or competition. Since thermic effect of food (TEF) and resting metabolic rate (RMR) are very much physiologically predetermined, a reduction in habitual physical activity in athletes throughout the remainder of the day is possible. Under certain circumstances athletes, however, may deliberately pursue of negative energy balance to loose weight. Nevertheless, long-term energy balance should be maintained to ensure health and optimal performance. This is also reflected by the concept of periodization which alternates periods of high training loads with periods of lower training intensity and/or volume (Bompa and Haff 2009). During these low intensity periods a reduction in TDEE may allow for a compensation of the previously encountered negative balance.

To date, there is limited research on behavioral changes - nutritional adaptations as well as changes in habitual physical activity levels - related to changes in exercise intensity and volume in endurance athletes. Due to the importance of energy balance for health and performance, an understanding of the interaction between various components of energy balance will be beneficial to this population. With inconsistent results concerning the interaction of various components of energy balance in the general population and the unresolved questions concerning the influence of exercise and nutrient intake on habitual physical activity (Tappy, Binnert and Schneiter 2003), an examination of an athletic population with higher energy demands could establish a clearer picture of energy balance regulation. Therefore, such insights would not only be beneficial to athletes, but could also be utilized to address the current obesity epidemic and adjust current intervention programs.

In summary, research on the interaction between different components of TDEE (EEE, NEAT, RMR) and nutritional intake in the athletic population is limited despite its well established role on health and sports performance. Concerning total daily energy expenditure, exercise, habitual activity, resting metabolic rate, and thermic effect of food need to be considered. For energy intake, dietary composition (i.e. macronutrient content) may be important to consider as well, since macronutrients are metabolized differently and have been shown to influence appetite and satiety (Blundell et al. 1996). This study will examine the complex interaction of various components (TDEE, EEE, NEAT, RMR, and dietary intake) of energy balance during periods of different training volumes. While providing valuable information for athletes to ensure long-term energy balance this study will also contribute to the understanding of the regulation of energy balance in the general population.

OVERALL OBJECTIVE AND SPECIFIC AIMS

The overall objective of this dissertation is to provide a better understanding of the influence of endurance training at different training periods (i.e. volume) on TDEE and the interaction between individual components contributing to TDEE. The affect of different training volumes on time spent at different intensity will be examined as well. Further, EI and dietary adjustments to changes in exercise regimen in athletes will be addressed. The specific aims (as will be reported in manuscript form in Chapters 2 and 3 of the completed dissertation) are to:

1. Explore possible differences in TDEE and EEE between a high-volume and low-volume training week.

   H1.1: TDEE will be higher during the high-volume week compared to the low-volume week.

H1.2: EEE will be higher during the high-volume week compared to the low-volume week.

H1.3: The difference in TDEE will be more pronounced than the difference in EEE.

2. a. Examine whether NEAT changes in response to different training volumes.

H2a: NEAT will be lower during the high-volume week compared to the low-volume week.

2. b. Examine the relationship between NEAT and EEE at different training volumes.

H2b: NEAT will be inversely correlated with EEE.

3. Examine whether RMR changes in response to different training volumes.

   H3: RMR will be higher during the high-volume week compared to the low-volume week.

4. Explore possible changes in time spent at different intensities in response to different training volumes.

   H4: Time spent in moderate-to-vigorous activity will decrease in response to higher training volume.

5. Examine the relationship between time spent in different intensities and EE.

   H5.1: TDEE will be inversely related to sedentary time.

   H5.2: NEAT will be positively related to time spent in moderate-to-vigorous activity.

6. Explore whether EI is different from TDEE during a high-volume and a low-volume training week.

   H6.1: EI will be lower than TDEE during both weeks of data collection.

   H6.2: The difference between EI and TDEE will be more pronounced during the high-volume week compared to the low-volume week.

7. Examine the various relationships among RMR, NEAT, EEE and EI.

   H7a: EEE will be positively correlated with EI.

   H7b: NEAT will be positively correlated with EI.

8. a. Explore whether dietary intake differs between a high-volume and low-volume training week in endurance trained athletes.

   H8a: Dietary intake will be higher during the high-volume training week compared to the low volume training week.

8. b. Explore whether macronutrient content (%Fat, %CHO, %Protein) differs between high-volume and low-volume training.

   H8b: %CHO intake will be higher during the high-volume week compared to the low-volume week.

9. Examine whether endurance athletes are able to meet dietary macronutrient recommendations (g/kg and %contribution) during high-volume and low-volume training periods.

   H9: Endurance athletes will be able to meet current dietary recommendations when reported as %contribution but not when reported as g/kg.

FORMAT OF DISSERTATION

A detailed methodology will be provided according to the specific aims in chapter 2 and chapter 3. Chapter 1 provides a literature review on topics related to energy balance. A discussion of the neural regulation of energy intake and energy expenditure as well as assessment methods of these components will be addressed. The final section of the literature review will provide more detailed information on energy balance and its components in endurance athletes. In addition, the last chapter of the dissertation will summarize the overall findings and provide directions for future studies that may be included in the investigator's line of research.

SIGNIFICANCE OF DISSERTATION

The research from this dissertation will provide insight on the energy balance of endurance athletes and variability of various components of TDEE during different training periods. This is of interest since either form of energy imbalance, positive or negative, can be detrimental to health and athletic performance. Having a better understanding of potential factors that disrupt the energy balance allows for a better adjustment to face such risks during training and competition if necessary. For the general population, an increased understanding of the interaction between exercise, physical activity and nutrition may be beneficial, since most interventions designed to address the problem of overweight and obesity have been of limited success. New insights may allow researchers to address various components of energy balance more specifically and target potential risks that may disrupt energy balance.

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CHAPTER 1: LITERATURE REVIEW

COMPONENTS AND REGULATION OF ENERGY BALANCE
WITH A SPECIAL EMPHASIS ON ENDURANCE ATHLETES

The purpose of this review is to discuss the current evidence of biological and behavioral aspects of energy balance. The first section examines the current evidence on biological pathways and mechanisms related to energy balance. The next section will discuss the major components of total daily energy expenditure (TDEE) and their respective variability, with a special emphasis on the interaction between habitual physical activity and exercise. Further, biological regulatory processes regarding energy expenditure are addressed. It will also provide an overview of a variety of methods used to determine physical activity and energy expenditure. The third section follows up on assessment methods related to dietary intake. It continues with a discussion of the role of macronutrients for appetite and energy intake and leads into the final section by summarizing the nutritional guidelines for the athletic population. The last section puts a special emphasis on endurance athletes. Energy expenditure and energy intake are examined separately, before considering the concept of energy balance in athletes. By showing detrimental effects of energy imbalance, and the importance of energy balance for health and optimal performance a rationale for further investigation of the role of various components related to energy balance and their interaction is provided.

THE CONCEPT OF ENERGY BALANCE AND REGULATORY MECHANISMS

The current obesity epidemic is often attributed to a reduction in physical activity due to lifestyle changes and/or an increase in energy intake due to increased consumption of energy dense foods which results in a reduced satiety index (Prentice and Jebb 2004). These changes will result in a disruption of an individual’s energy balance. Energy balance is defined as equilibrium between energy intake, which is the sum of energy from foods, fluids, and supplement products, and energy expenditure (Rodriguez et al. 2009). TDEE is the sum of energy utilized at rest (basal/resting metabolic rate, BMR/RMR), the energy required for digestion of food (thermic effect of food, TEF), and activity energy expenditure (Rodriguez et al. 2009). Activity energy expenditure can be further divided into the energy expended in planned physical activity or exercise (exercise energy expenditure, EEE), and habitual physical activities of daily living or non-exercise activity thermogenesis (NEAT). While dietary intake is mainly voluntary, only activity energy expenditure can be altered substantially with behavioral adaptations as compared to other components of EE (Prentice and Jebb 2004).

Several studies have shown a critical relationship between EE and EI (Levine and Kotz 2005). Westerterp (2008) showed that dietary restriction is related to lower TDEE. It has been acknowledged that this reduction in energy balance is partly due to a reduction in body weight as a result of a negative energy balance, as well as a small reduction in TEF. The major reason (~60%) of the decreased TDEE with negative energy balance, however, has been attributed to a reduction in physical activity levels (Westerterp 2008). Similar results were reported in other studies using not only humans, but also primates and rodents (Levine and Kotz 2005). Overfeeding, on the other hand, was not shown to increase physical activity in the general population (Westerterp 2008). Levine et al. (1999), however showed that an extra 1000 kcal/day results in compensatory changes in NEAT, including increased fidgeting and other physical activity of daily life. Interestingly, Weinsier et al. (2000) showed no differences in RMR when adjusted for body composition between obese subjects and weight reduced normal-weight subjects, which contradicts a non-adjustable predetermined set point for energy balance. With constant energy intake several studies showed an increase in TDEE with increased exercise levels (Westerterp et al. 1992, Nogueira and Da Costa 2005). The increase in TDEE, however, was smaller than the additional EE due to exercise, which suggests some compensatory regulation, and in elderly no increase in TDEE was observed with exercise training when energy intake was held constant (Westerterp 1998).

Neural Regulation of Energy Balance

Levine and Kotz (2005) argue that biological regulatory mechanisms account for 75% of variability and susceptibility to fat gain, which is due to a disruption in energy balance. Several neural pathways have been discussed to be involved in such regulatory mechanisms and the hypothalamus is thought to be the neural center that integrates information from various sources and compares actual values of body fat with a reference value to determine necessary adjustments via EI and/or EE (Shin, Zheng and Berthoud 2009). Shin et al. (2009) further suggest a central mechanism to regulate physical activity according to EI and energy stores. They argue that physical activity, especially NEAT, may serve as a crucial thermoregulatory mechanism between energy storage and dissipation. Besides the hypothalamus, the caudal brainstem and the cortico-limbic systems, have been shown to play an important role in appetite control (Shin et al. 2009).

These regulatory centers receive feedback from mechano- and chemo-sensors that react to different components of ingested foods (Shin et al. 2009). Concerning energy availability, the pancreas is of particular interest since it responds to circulating fuels and gastrointestinal hormones with the release or suppression of the pancreatic hormones insulin, glucagon, amylin, and pancreatic polypeptide which provide feedback to the brain (Shin et al. 2009). Further, adipose tissue sends hormonal signals by the release of adipokines such as leptin, adiponectin and resistin to the brain and other organs. For example, lower levels of adiponectin were observed in obese subjects compared to lean subjects while leptin levels were higher in obese subjects compared to lean subjects (Silha et al. 2003, Roth and Reinehr 2010).

Prior to discussing the role of leptin, which is mainly released by adipocytes, ghrelin, another stomach derived peptide needs to be addressed since it is involved in energy balance (Delzenne et al. 2010) by stimulating appetite and energy intake (Pusztai et al. 2008). Interestingly, overweight or obese subjects displayed lower ghrelin levels than lean subjects (Tschoep et al. 2001). This phenomenon is explained by a down-regulation of plasma ghrelin concentrations with a positive energy balance (Shiiya et al. 2002). There is also a difference in response of plasma ghrelin level to how weight loss was induced. Cummings et al. (2002) showed an increase in plasma ghrelin levels with weight loss due to dietary restriction, while gastric bypass surgery resulted in suppression of ghrelin.

Other major metabolically active tissues like muscles and liver may also produce hormonal signals that help with the regulation of energy balance (Shin et al. 2009). The information from the peripheral signals is believed to be integrated in the arcuate nucleus (ARC), which is a collection of neurons in the hypothalamus (Woods et al. 1998). The ARC responds to a decline in body fat stores and has been shown to stimulate appetite, especially by responding to neuropeptide Y (NPY). Lower leptin and insulin levels have been shown to reduce inhibition of NPY, which stimulates energy intake while reducing energy expenditure (Woods et al. 1998). Since leptin is released by the adipose tissue higher levels in obese subjects are expected. Finally, polypeptide Y (PPY), a peptide that inhibits short-term food intake, especially high fat meals, has been shown to increase with weight loss and, therefore, should help with the maintenance of a lower body weight (Roth and Reinehr 2010). In summary, hormones related to energy balance are released and expressed in various locations of the body in response to body composition and energy availability. They interact with each other and are integrated in the hypothalamus to regulate energy expenditure and energy intake.

Besides the brain, the liver has been hypothesized to monitor and respond to changes in energy availability and control of food intake. The “depletion-repletion model” hypothesizes that dietary intake is initiated when immediately available energy like blood glucose or fatty acids fall under a certain threshold and the intake is stopped once substrate levels are sufficiently replenished (Woods et al. 1998). Such a model, however, may only explain energy intake but does not provide an explanation for the matching of energy intake with expenditure since key parameters related to energy depletion and repletion correlate poorly with energy expenditure (Woods et al. 1998). To maintain long-term stability in fat stores and body weight a proper response to increased energy expenditure is necessary. While satiety peptides have been shown to alter meal size, they do not affect total caloric intake. For example administration of CCK, a peptide released from the gut that has been shown to reduce meal size, was shown to increase meal frequency in rats to maintain overall energy intake (West, Frey and Woods 1984).

Despite the existence of these regulatory mechanisms concerning EE and EI, the prevalence of overweight and obesity is increasing (Nguyen and El-Serag 2010). Shin et al. (2009) argue that a majority of the population gains less than 1 kg body weight/year and these small disruptions in energy balance may not be detected through biological regulatory mechanisms. Further, it was shown that exposure to a high-energy diet will cause a change to a higher set point, which will result in fat gain and an according progressive weight-gain (Shin et al. 2009). These authors also argue that body weight or adiposity is regulated at different levels under different environmental conditions and, therefore, suggest that there is no fixed reference or threshold value set in the brain.

This adaptability of energy regulatory processes is also referred to as “thrifty genotype” (Neel 1962). Chakravarthy and Booth (2004) hypothesize that the cycling of fuel stores driven by cycles of feast and famine as well as physical activity and rest during the hunter-gatherer period, have molded the selection of “thrifty” genes. During this area physical activity was necessary to get food and, therefore, these two components have been linked together. Similarly Prentice and Jebb (2004) argue that during the agrarian time an energy deficit occurred during planting, which was later compensated for by an energy surplus during harvest, resulting in an overall energy balance. In addition to genetic variability, the intra-uterine environment (Prentice 2005) as well as extrinsic factors like environmental conditions, peer influences and personal desires could result in a change in set points for EE or EI (Rowland 1998).

This long term regulation of energy balance also suggests that the onset of eating is not necessarily tied to immediate energy needs. Woods et al. (1998) suggest that signals proportional to fat stores become integrated with other regulators of food intake. For example, meal termination was not shown to be correlated with replenishment of depleted substrates and it seems that depletion signals such as leptin deficiency, food deprivation/restriction, or ghrelin administration stimulate food intake much more than satiety signals (leptin or glucose) inhibit food intake (Shin et al. 2009). Finally, it should be considered that the previously discussed appetite control mechanisms were established during periods of high energy flux. Schoeller et al. (1997), therefore, proposed the existence of a minimum threshold concerning the turnover rate of regulating substances to detect energy imbalances.

Exercise and Energy Balance

This theory of a higher energy flux in order to regulate energy balance may also help to explain why active people are better able to maintain energy balance and why physical activity at intensity levels between 60% VO2max (Cheng et al. 2009) and 70% VO2max (King and Blundell 1995, Lluch, King and Blundell 1998) have been shown to alter appetite control by increasing the sensitivity of physiological satiety signals, macronutrient preferences or food choices (Blundell et al. 2003). Martins et al. (2008) report a more direct regulation of appetite through physical activity via changes in satiety hormone secretion, especially PPY, glucagon-like peptide-1 and pancreatic polypeptide. It has been shown that exercise can trigger physiological changes in the secretion of these satiety hormones resulting in a reduction in appetite. These exercise induced changes could also explain why increased ghrelin levels, due to weight loss through exercise training do not lead to an increase in energy intake (Foster-Schubert et al. 2005). Further, it has been argued that ghrelin is more related to long-term energy balance than to acute appetite and food intake (Shin et al. 2009). This is supported by Popvic and Duntas (2005) who showed no changes in ghrelin levels during periods of higher energy expenditure in weight stable subjects (Popovic and Duntas 2005).

Similarly, Blundell et al. (2003) reported no adjustment in dietary intake during the first 2 days of a training regimen despite increased energy expenditure. This study, however, showed a compensatory increase in energy intake after the initial phase, but the compensation was only partial and incomplete. Such a reduced response to increased energy expenditure, resulting in a negative energy balance, has been observed up to 16 days and even after an increase in energy intake the compensation accounts for only 30% of energy cost of exercise (Martins et al. 2008). Interestingly, Erdmann et al. (2007) argue that ghrelin levels do have an acute effect on appetite, at least in normal weight subjects. This may be due to a difference in post post-prandial ghrelin levels between lean and obese subjects, with lean subjects showing a more pronounced decrease in ghrelin levels in response to a meal (Shiiya et al. 2002, Mittelman et al. 2010). It has, however, been concluded that the change in hunger sensation may not necessarily be reflected in a higher food intake (Erdmann et al. 2007).

While ghrelin seems to have only limited influence on physical activity, leptin, which is also related to adipocity and dietary intake, is believed to stimulate physical activity (Pelleymounter et al. 1995) and Salbe et al. (1997) have shown a direct relationship between leptin levels and physical activity. The increase in energy expenditure through leptin is suggested to be due to a stimulation of the sympathetic nervous system (Rowland 1998), but this hypothesis has not been clarified in humans (Ravussin and Tataranni 1996). Thorburn and Proietto (2000) actually argue that leptin does not appear to manipulate physical activity patterns in humans since lower leptin levels were reported in highly active, endurance trained subjects (Popovic and Duntas 2005). Hilton and Loucks (2000) argue that diurnal rhythm of leptin depends more on

CHO than fat stores, and higher exercise intensity in athletes may cause higher depletion of CHO stores. Nevertheless, leptin is also related to body fat content, and since athletes have a lower body fat content, lower leptin levels are to be expected. Decreased leptin levels in relation to exercise training have been shown to alter sensitivity of the brain to satiety signals, which would enhance the regulation of dietary intake (Martins et al. 2008). In addition, reduced leptin levels may be related to lower insulin levels along with higher insulin sensitivity with exercise (Popovic and Duntas 2005).

There should also be a differentiation between compensators and non-compensators when examining changes in appetite and food intake in response to exercise (Martins et al. 2008). In general, it has been shown that women increased their energy intake in response to a 3-day exercise program, while men did not show a change in energy intake (Martins et al. 2008), but exercise intensity may need to be considered as well. Especially after vigorous exercise a significant reduction in hunger was observed immediately after exercise, which is known as "exercise induced anorexia" (King et al. 1997). A reduction in acylated ghrelin along with increased levels of PPY are thought to be responsible for the suppression of appetite after aerobic exercise. The smaller effect in response to strength training could be due to the fact that only acylated ghrelin levels were reduced, while PPY levels did not change (Broom et al. 2009). Martins et al. (2008), however, acknowledged that this reduction in hunger is unlikely to impact subsequent EI. Nevertheless, a negative energy balance may be observed since hunger or EI does not increase acutely after starting an exercise program (Martins et al. 2008).

Despite a reduction in hunger and an accompanying energy deficit a prolonged reduction in body weight has not been observed in response to exercise programs. It is, therefore, suggested that other mechanisms may be applied to compensate for increased exercise energy expenditure. In addition the lack of exercise induced weight change could be explained by a change in body composition. While exercise may induce a loss of fat mass, an increase in lean body mass could occur. Further, movement economy and efficiency potentially increase with exercise training, which potentially reduces net exercise energy expenditure. Finally, a reduction in energy expenditure in non-exercise physical activity may provide additional compensation to maintain energy balance (Martins et al. 2008). Probably behavioral and metabolic compensatory mechanisms are activated in response to exercise induced energy deficits to ensure energy balance. Interestingly, previously active people who were forced into a more sedentary lifestyle initially did not match the reduced energy expenditure either, resulting in a positive energy balance and weight gain (Blundell et al. 2003).

Nevertheless, long-term coupling between energy intake and energy expenditure seems to be improved with regular exercise. The quicker adjustments in response to changes in energy expenditure may be due to adjustments between meals (Martins et al. 2008). If energy intake is reduced in one meal, there seems to be a compensatory increase in intake during the following meal. Long et al. (2002) supported the role of exercise in 'fine tuning' physiological mechanisms to regulate dietary intake by showing a better compensatory response when manipulating preload energy content before an actual meal. Sensitivity was shown to be increased up to 24 hours. This coupling between energy intake and energy expenditure, however, occurs only with higher energy expenditure levels.

Martins et al. (2008) propose that changes in appetite regulation in response to changes in physical activity or exercise patterns are still linked to adaptations at long-term signals, such as leptin, intermediate postabsorptive signals associated with macronutrient oxidation, and short-term satiety signals released by the gastrointestinal tract. No significant changes, however, have been shown in fasting insulin, glucose, triacylglycerol, or non esterified fatty acids plasma level sensitivity after a 6-week exercise intervention. Therefore, only short-term satiety signals, like cholecystokinin, GLLP-1, or PYY from the gastrointestinal tract seem to be responsible for appetite regulation with increased exercise levels. This conclusion is supported by a recent review which showed that in the absence of weight loss a change in exercise regimen does not cause changes in fasting leptin plasma (Martins, Truby and Morgan 2007). In highly trained individuals, however, a single prolonged exercise period (25 km swimming race) resulted in a significant reduction of plasma leptin levels. Leptin levels were also reduced after a 1-year intervention, even after adjusting for body mass index and fat mass. The authors proposed that changes in insulin sensitivity would alter leptin levels independently of changes in fat mass, since insulin and cortisol are known to modulate leptin synthesis. Leptin, therefore, has been suggested to be merely involved in long-term regulation of energy balance by stimulating energy expenditure while decreasing food intake (Blundell et al. 1996).

In summary it has been suggested that energy homeostasis is accomplished through a highly integrated and redundant neurohumoral system that tries to minimize short-term fluctuations in energy balance and fat mass by proper adjustments of energy expenditure and energy intake. If these fluctuations, however, occur within certain thresholds no change may be sensed, and overall a gradual upregulation of body fat stores may occur (Woods et al. 1998). Overall, energy balance is a complex bio-behavioral phenomenon that is influenced by genetic, physiologic, early-life, and demographic-environmental constraints (Prentice and Jebb 2004). In order to get a better understanding of these complex interactions, the following sections will examine the literature of the two major components of energy balance, EE and EI, separately.

ENERGY EXPENDITURE

Components of Total Daily Energy Expenditure

Total Daily Energy Expenditure (TDEE) consists of thermic effect of food (TEF), basal metabolic rate (BMR), and energy cost of physical activity, which is differentiated into Exercise Energy Expenditure (EEE) and habitual activity energy expenditure or NEAT. TEF refers to the energy required for ingestion and digestion of food, including absorption, transportation, oxidation and deposition of nutrients (Vermorel et al. 2005). Over a 24-hour period TEF contributes between 5% and 10% to TDEE, and about 12% of energy intake are utilized for digestion. TEF varies according to the composition of food, as it is lower for lipids and carbohydrates compared to protein (Vermorel et al. 2005). Especially variations related to fat absorption and oxidation potentially contribute to variability in TEF (Donahoo, Levine and Melanson 2004) but the variations in dietary macro-nutrient intake are unlikely to contribute substantially to variation in TDEE.

BMR consists of the sum of energy expenditure in tissues and organs during fasting and resting in thermoneutral conditions (Vermorel et al. 2005). BMR represents the energy required to maintain essential vital functions (Donahoo et al. 2004), including cell function and replacement, synthesis, secretion and metabolism of enzymes and hormones to transport proteins and other substances and molecules as well as energy required for the maintenance of body temperature, cardiac and respiratory muscles and brain function (FAO 2001). Often basal metabolism is assessed in less stringent conditions, and therefore, referred to as resting metabolism (RMR). On average RMR contributes 60%-75% to TDEE (Donahoo et al. 2004), but it can be as low as 45-50% in very active individuals where the energy expenditure due to physical activity is higher (Vermorel et al. 2005). Despite being only 7% of body weight, organ function contributes the majority to BMR (Vermorel et al. 2005).

Skeletal muscle and adipose tissue contribute 18-22% and 3-4%, respectively. Skeletal muscle is also the main predictor of BMR/RMR (Donahoo et al. 2004) which may explain higher RMR rates in trained subjects. In addition, RMR increases following higher training intensity due to excess postexercise oxygen consumption (EPOC) (Speakman and Selman 2003) which may be due to increased sympathetic nervous system activity (Ng et al. 1994). Several studies, however, did not show any differences in RMR between trained and untrained subjects after adjusting for lean body mass (Ribeyre et al. 2000, Vermorel et al. 2005). In addition, genetic factors and hormonal status influence BMR (Vermorel et al. 2005). Bitar et al. (1999) indicate that 7% of the variability in BMR is due to heredity. Further, environmental factors, especially temperature and humidity can alter BMR up to 10% (Hori, Tsujita and Yoshimura 1976)

Although RMR generally represents the largest component of TDEE, physical activity is perhaps the most important determinant of TDEE, since it is the most variable component and can thus greatly impact TDEE. Physical activity energy expenditure is generally considered to contribute between 33-39% and 42-47% in adolescent girls and boys, respectively (Vermorel et al. 2005), and Westerterp (2008) showed that a contribution between 5% and 50% in adults. Vermorel et al. (2005), however, argues that these results may overestimate physical activity energy expenditure because the measurements usually involve sedentary activities as well. Therefore, a division between sedentary or seated activities and "real" physical activities has been suggested (Vermorel et al. 2002). A contribution of 8.5%, 7.2%, and 8.3% to TDEE, respectively, for light (slow walking, shopping, recreation, playing quietly), moderate (fast walking, recreational sport, dancing) and team sport (PE lessons, training, competition) was shown in 8- to 10-year old children (Maffeis et al. 1996). Results of this study further showed that obese subjects had higher activity energy expenditure compared to normal weight subjects despite spending less time with physical activity (449 ± 126 vs. 563 ± 135 min) and more time performing sedentary activities (400 ± 129 vs. 295 ± 127 min). An explanation for these differences is the higher energy expenditure for any activity in obese subjects due to their higher body weight. In adults, very light activities (f.ex. sitting while completing various tasks) contribute more than 50% to TDEE (Dong, Block and Mandel 2004), while household chores, considered light or moderate activity, provide roughly 4%, and vigorous exercise contributes roughly 1.5% to TDEE (Dong et al. 2004). As expected, the contribution of occupational energy expenditure depends on the type of job (Dong et al. 2004).

A more common differentiation of physical activity energy expenditure has been the utilization of NEAT, which resembles habitual physical activities, and EEE. EEE refers to planned and structured physical activities while NEAT is defined as the energy expended during habitual activities like walking to work, typing, performing yard work or fidgeting (Levine 2003). NEAT has been shown to range between 100 and 800 kcal/day (Ravussin et al. 1986) and EEE depends on the actual engagement in exercise. Ribeyre et al. (2000) reported a 16.5% increase in TDEE in adolescents in a sports specialized class compared to controls even after adjustment for lean body mass. The higher energy expenditure was mainly due to more time spent exercising or training. During training days, however, lower NEAT values were reported for athletes, suggesting a partial compensation for the increase in EEE (Ribeyre et al. 2000).

The amount of compensatory behavior may depend on intensity and volume of exercise, but only a few studies examined the interaction between volume and intensity of exercise and the relationship to TDEE. It is logical that higher intensity for the same period of time will result in higher EE during exercise. Most studies, therefore, examined whether post-exercise EE also referred to as EPOC (Excess Post-exercise Oxygen Consumption) or RMR changed in response to different training intensities. Melanson et al. (2002) did not find any difference between RMR after high- or low-intensity exercise when total EEE was held constant. On the other hand Gore and Withers (1990) claimed that exercise intensity is the major determinant of EPOC, explaining 5 times more of the EPOC variance than duration or total work completed. This is in agreement with Laforgia et al. (1997) who showed that interval training, which requires intermittent engagement in higher intensities, results in higher EPOC than does continuous training. These results, however, were shown in athletes, and the authors acknowledged that intensities utilized in this study might be not feasible or safe for non-athletes. Therefore, it seems that higher intensity results in higher EPOC and TDEE, but most non-trained individuals may not be able to engage in an exercise of sufficient intensity to experience a prolonged EPOC, which may explain the results by Laforgia et al. (1997) which showed a relatively minor contribution of EPOC to TDEE.

Age, sex, and body size have also been shown to influence TDEE (Donahoo et al. 2004). Children, due to their smaller size lose more heat per gram body weight and, therefore, have a higher relative RMR compared to adults. On the other hand, body size is directly related to absolute RMR which leads to a higher TDEE in adults. Women, generally have been shown to have a 10% lower TDEE compared to men, which has been mainly attributed to differences in body composition (Donahoo et al. 2004). Higher fat free mass is related to higher EE (Ribeyre et al. 2000). In children and adolescents, the energy cost of growth needs to be considered (Butte, Wong and Garza 1989) and in females pregnancy and lactation will increase TDEE as well (Forsum et al. 1992). Along with sex differences, a genetic contribution to TDEE has been reported as well. Westerterp (2008) suggests a genetic contribution as high as 72% to the variance in physical activity EE in adults. Lower genetic contributions to variability in physical activity and resulting TDEE were reported by Perusse et al. (1989) but these authors also acknowledged that spontaneous physical activity is partly influenced by genetics.

While acknowledging the biological constraints on TDEE Levine and Kotz (2005a) also point out the role of the environment, especially concerning NEAT. Dauncy (1981) showed a 5-7% increase in TDEE during relatively mild conditions (22°C) when wearing only shorts. In severe cold conditions (10°C) EE due to shivering has been reported to be equal to an oxygen consumption of 42±5% of VO_2max (Vermorel et al. 2005). Increased muscle tone and metabolic rate contributed to a higher TDEE, but the major component seems to be an alteration of physical activity. Since most people in industrialized countries dress accordingly and indoor temperatures are held fairly constant, thermoregulation or behavioral adjustments due to changes in temperature should not contribute significantly to variability in TDEE. Generally, the social and physical environment seems to have a bigger impact on physical activity in children and adolescents, but physical activity or exercise is an important component on TDEE at every age. Physical activity and more so exercise not only increase EE during the actual activity, but contribute to a higher TDEE due to increased post-exercise EE. Finally higher activity levels may lead to changes in body composition, which potentially affect RMR as well.

In summary, TDEE consists of various components that are influenced by biological and environmental constraints. The various components cannot be completely separated from each other, since higher activity EE may influence RMR levels. Further, activity can alter appetite and dietary intake which will influence TEF. In order to control TDEE and its components a central regulation of EE similar to the regulation of dietary intake has been suggested.

Regulation of Energy Expenditure

Since TDEE needs to be regulated in order to maintain energy balance, and physical activity is the most variable contributor to TDEE, it is likely that there is a regulatory mechanism for physical activity. Based on various animal studies this so-called ‘activity stat’ is hypothesized to be located in the hypothalamus. Thorburn and Proietto (2000) reported that lesions in the ventromedial hypothalamus caused a decrease in physical activity, while lesions in the paraventricular nucleus did not result in changes in activity patterns. Reduced physical activity levels were reported with lesions in the amygdala, while higher activity levels were seen with septal lesions (Rowland 1998). Further, decreased playful activities were observed after injuries to the dorsomedial thalamus, parafascicular area of the thalamus, and caudate nucleus. On the other hand, hypophysectomy markedly increased exploratory motor activities in rats. The specific location of a physical activity regulatory center remains to be determined, but the previously mentioned results strongly indicate a central involvement in the regulation of physical activity. There are also certain neural messenger molecules that are related to alteration in physical activity. For example, Kiwaki et al. (2004) showed that orexin injected in the paraventricular nucleus results in increased habitual activity independently of alterations in appetite. Iron deficiency has been related to reduced physical activity levels in rats (Rowland 1998). Even though not per se a messenger molecule, it is hypothesized that iron deficiency alters iron-dependent synthesis of CNS neurotransmitters and/or decrease the number of dopamine receptors in the central nervous system (Youdim, Ben-Shachar and Yehuda 1989), which may cause a downregulation of physical activity levels.

Sex hormones, have been shown to alter physical activity as well. Contrary to humans, female animals are generally more active than males. The simulating role of oestrogen on physical activity is indicated by reduced physical activity levels in rodents after removing the ovaries (Thorburn and Proietto 2000, Lightfoot 2008). Thorburn and Proietto (2000) also reported that oestrogen deficient aromatase knockout mice are less active. There is speculation that oestrogen modulates several neurotransmitters, including dopamine and/or serotonin, which are supposed to be involved in the regulation of activity (Morgan, Schulkin and Pfaff 2004). The influence of dopamine is undermined by Rhodes et al. (2001) who showed that altered dopaminergic functioning is one of the primary characteristics of highly active mice. In male rats several studies showed a decline of physical activity after castration (Lightfoot 2008). Interestingly, implantation of testes into either male or female rats increased physical activity to a lesser extent than ovarian implants in either sex. Therefore, it has been suggested that testosterone regulates physical activity primarily through aromatization into oestrogen (Lightfoot 2008). Testosterone administration in normal rodents has not been shown to alter activity levels and testosterone levels were not significantly correlated to 24-hour wheel-running activity.

Besides the stimulating effect of oestrogen, a reduction in oestrogen may cause reduced physical activity levels due to a reduction in nitric oxide production, which reduces pancreatic peptide (PP) levels (Thorburn and Proietto 2000). PP is secreted in response to a meal and is a potent energy balance signal in the brain, specifically in the hypothalamus, and in nuclei of the midbrain, pons, and medulla. Direct ingestion of PP into the brain as been shown to induce locomotor activity in rodents (Nakajima et al. 1994). In humans increased PP levels are related to increased physical activity levels in anorexic patients (Uhe et al. 1992), while PP levels are reduced in inactive obese subjects (Lassmann et al. 1980).

Of additional support for a central activity stat is the observation that physical activity levels decline with age in both animals and humans (Rowland 1998, Westerterp and Meijer 2001). Thorburn and Proietto (2000) argue that the decrease in endogenous melatonin during aging is related to the decreased physical activity in older subjects. Interestingly the observed decline in basal metabolic rate with age is fairly similar to the decline in physical activity levels. Overall, there is some evidence that the regulation physical activity is related to appetite circuits and other peripheral signals, but an independent regulation of physical activity is hypothesized as well. The exact regulation of activity energy expenditure, however, has not been clarified (Levine and Kotz 2005). Current research further suggests that the regulation of physical activity levels is also coupled with other components contributing to TDEE. Especially the interaction between habitual energy expenditure, EEE and TDEE has been of interest, since that may possibly explain the limited success of physical activity interventions concerning weight control.

Variability of Exercise Energy Expenditure, Habitual Physical Activity Energy Expenditure, Resting Metabolic Rate, and TDEE

Despite a suggested central regulation of energy expenditure, TDEE can vary considerably in a population. For example, Wickel and Eisenmann (2006) reported TDEE ranging between 33.7 kcal/kg/day and 68.9 kcal/kg/day. To examine TDEE properly, variations in the separate components of TDEE need to be addressed. RMR does not change significantly when measured under standard conditions and it has been shown that habitual physical activity 24 hours prior to testing does not explain variability in RMR measurements (Donahoo et al. 2004). These authors argue that prior food intake rather than habitual physical activity, excluding exercise, causes minor changes in RMR. Food intake, however, will most likely cause alterations in TEF rather than RMR. Donahoo et al. (2004) showed a variability of roughly 20% for TEF during habitual dietary intake.

Especially protein consumption is related to changes in TEF. In addition, an increase in TEF was shown with lower temperatures (Westerterp-Plantenga et al. 2002). Further, lean body mass influences TEF. An increase in TEF was observed during weight gain while TEF was decreased during weight loss (Leibel, Rosenbaum and Hirsch 1995). Recently, a genetic contribution to variations in TEF was found as well (Donahoo et al. 2004).

In contrast to habitual physical activity, exercise has been shown to influence RMR due to EPOC (Laforgia et al. 1997). Eliakim et al. (1996) showed a 4% increase in energy expenditure with endurance training in adolescent females. With training a change in muscle volume was observed as well and the increase in lean body mass potentially increases TDEE even higher than the energy expenditure attributed to exercise (McLaughlin et al. 2006). Such findings may be explained by Westrate & Hautvast (1990) who reported a 23% increase in TEF the day after a glycogen-depleting exercise. Nevertheless, this change was not significantly different compared to baseline. Another explanation is that increased exercise might lead to a more healthy and active lifestyle resulting in an increase in NEAT (Westerterp 2008). This adaptation is of particular interest since in the general population NEAT contributes the majority of activity energy expenditure (Donahoo et al. 2004). Therefore, these authors argue that lifestyle and cultural milieu are the prime predictors of TDEE and a variety of studies have shown that built environment as well as social environment influence physical activity (McNeill, Kreuter and Subramanian 2006).

In addition, seasonal variability in activity energy expenditure (EEE and NEAT) needs to be considered (Katzmarzyk, Craig and Bouchard 2001). In general higher activity levels are observed during the summer, while lower activity levels occur during the winter months (Buchowski et al. 2009). In athletes seasonal variability relates more to changes in exercise regimen due to competition or off-season rather than adjustments in NEAT since EEE is the major contributor to TDEE. With higher EEE, as observed in endurance athletes during high volume training, a compensatory reduction of NEAT has been reported (Nogueira and Da Costa 2005). Two explanations are provided for such compensatory responses. First, the extremely high EEE in athletes may limit the opportunity for dietary intake adaptations, which necessitates a reduction in energy expenditure in other components to maintain energy balance. Second, it can be argued that higher training intensities induce higher fatigue post-exercise, which may lead to a reduction in NEAT (Westerterp 2008). Westerterp et al. (1992) have shown increased TDEE in subjects training for a marathon, but the increase in TDEE was less than the energy expenditure attributed to training. These results along with some other studies suggest some compensatory behavioral changes in response to increased EEE (King et al. 2007).

When examining compensatory behavior in non-athletic samples results are less clear. Based on a review of the current literature Westerterp (2008) proposes that older adults compensate for increased EEE, and therefore, do not increase TDEE with the implementation of exercise programs, while younger participants will increase TDEE with increased exercise energy expenditure. Hollowell et al. (2009) report contradicting results by showing an increase in TDEE in older subjects. This study, however, was conducted in a low-active sample including overweight and obese subjects where an increase in TDEE may have been tolerated more easily, but similar results were also reported in lean individuals (McLaughlin et al. 2006). An important differentiation between these studies and research on TDEE in athletes is that in all studies examining non-athletic populations NEAT remained the major contributor to activity energy expenditure, despite an increase EEE, while in athletes EEE is the major contributor.

Another explanation for inconclusive results may be the method used to determine energy expenditure. A variety of methods has been used to determine energy expenditure, and while there are certain criterion measures, there is currently no single best measurement that assesses energy expenditure in its full complexity, by considering the different components contributing to TDEE. Therefore, the following section provides an overview of commonly used methods to determine various components of TDEE.

Measurement of Energy Expenditure

A variety of methods have been used to measure physical activity and/or energy expenditure and several comprehensive reviews have been written on the topic (Ainslie, Reilly and Westerterp 2003, Corder et al. 2008, Prince et al. 2008). Each method has some limitations in assessing intensity or rate of physical activity, duration, and/or frequency while considering surrounding environmental and social conditions. Despite limitations all methods have been found to be useful in particular circumstances (Montoye 2000). The methods utilized range from measuring physiological variables such as heart rate or oxygen consumption and energy flux, as well as heat production, biomechanical measurements and time/motion analysis to observation, and subjective methods like diaries, questionnaires or interviews. In general, there is an inverse relationship between feasibility and validity of the assessment method. Higher accuracy often puts a higher burden on participants and researchers or may be too expensive for large scale studies (Corder et al. 2008). To structure the various methods that have been utilized a general differentiation between subjective, objective and criterion measurements has been made.

Criterion Measures for Energy Expenditure. While several methods provide very accurate estimations of energy expenditure or exercise intensity they might not be feasible for prolonged measurements or large sample sizes. These methods are used to validate more feasible approaches and include direct observation, double labeled water (DLW), indirect, and direct calorimetry.

DLW assesses energy expenditure using an orally ingested radio-labelled isotope ($^{2}H_{2}{}^{18}O$) (Speakman 1998). In the following days ^{2}H is eliminated as water and ^{18}O is eliminated as water and CO_2. The difference in elimination of labeled hydrogen and oxygen is proportional to CO_2 production, which can be used to calculate energy expenditure. A minimum of 3 days of measurement is required, but usually observation periods range from 5 to 14 days (Sirard and Pate 2001, Welk 2002). The major advantage of DLW is that it is unobtrusive and accurately assesses free-living TDEE. Isotopes, however, are expensive and sometimes difficult to obtain, which does not allow for large sample sizes. Further, accurate dietary records during the measurement period are needed for accurate results, and DLW only measures total daily energy expenditure and does not provide any information on PA patterns (Sirard and Pate 2001). The only way to determine activity energy expenditure is to measure RMR, and estimate TEF. These values can then be subtracted from TDEE resulting in activity energy expenditure.

Direct calorimetry is based on the relationship between heat dissipation by evaporation, radiation, conduction, and convection and energy expenditure (Ainslie et al. 2003). In order to obtain accurate measurements, participants need to stay in a thermally-isolated chamber, which limits the assessment of free-living energy expenditure. However, an advantage of direct calorimetry over DLW is the ability to assess energy expenditure of specific activities, which allows for a differentiation between activity energy expenditure, TEF, and RMR. Indirect calorimetry estimates energy expenditure by measuring expired gases and calculating oxygen consumption and CO_2 production, which requires gas analyzers (concentration and flow meter). Assessments usually rely on open-circuit systems utilizing room air, while closed systems are used to determine resting metabolic rate (Ainslie et al. 2003). Even though portable systems are available, there are limitations in assessing free living energy expenditure. Further, measurement times remain limited, since the participant needs to wear a mask or mouthpiece to collect the expired air. Usually, participants will be asked to perform a variety of tasks to obtain information concerning energy expenditure for different types of activities using either direct or indirect calorimetry. These values may then be used as estimates of energy expenditure in physical activity records. Indirect calorimetry is often used to validate heart rate monitors, pedometers, and accelerometers (Sirard and Pate 2001) due to its accessibility and other feasibility issues.

The previously mentioned techniques really focus on energy expenditure but do not provide information on the type of activity people engage in. This information can only be gained via direct observation, which makes this technique a more comprehensive criterion measure for physical activity. Direct observation, however, has a relatively high experimenter burden and may influence participants physical activity (Sirard and Pate 2001).

Objective Measures. A variety of feasible and un-obtrusive objective measures have been used to assess physical activity and estimate energy expenditure accordingly. Pedometers were one of the first approaches to objectively assess physical activity. Pedometers only provide step counts during a given time. Therefore, no information on intensity as well as non-ambulatory activity is gained. Even though pedometers only provide steps/day they have been shown to accurately indicate physical activity/energy expenditure since locomotor activities are the main pattern of physical activity in various populations (Sirard and Pate 2001, Welk 2002).

Accelerometers have become increasingly popular in recent years (MSSE Supplement, 2005), since they provide additional information on intensity by quantifying accelerations of body parts or the entire body to quantify physical activity (Welk 2002). Uni-axial, omni-directional and tria-axial models are available but all share the same problem of not being able to properly assess cycling and increased energy expenditure when walking on a gradient or due to carrying loads, which may result in significant underestimation of energy expenditure (Ainslie et al. 2003). There are also some limitations in accurate assessment of high intensity exercises (Corder et al. 2005). Results of several studies suggest a ceiling effect at around 10 METs (King et al. 2004, Corder, Brage and Ekelund 2007). Of additional concern is that movement counts cannot be compared between different models. Therefore Corder et al. (2008) suggest to implement a more universally comparable approach of acceleration (m/s^2) to summarize accelerometry data.

Finally the conversion of movement counts to units of energy expenditure remains problematic (Mâsse et al. 2005). The most common approach is to use regression equations established during simultaneous measurement of oxygen consumption and acceleration at various activities, but other methods (e.g., decision trees and artificial neural networks) have been proposed as well (Corder et al. 2008). Westerterp (1999) reported validity coefficients for estimations of energy expenditure between $r = 0.25$ and 0.91 in adults. This wide range is due to the use of different monitors and different placements (e.g. hip, low back, ankle) as well as different activities utilized during calibration. Therefore, Ainslie et al. (2003) conclude that motion sensors are not sufficiently accurate to quantify overall energy expenditure in free-living individuals but can effectively differentiate between PA levels of groups.

Heart rate (HR) monitoring is another commonly used approach to determine energy expenditure. HR monitoring does not depend on type of physical activity, since it relies on the physiological relationship between HR and oxygen consumption (Welk 2002). At lower intensities this relationship is less pronounced since factors other than exercise intensity (e.g., stress, emotion, caffeine or medication) can alter heart rate. Further, there is a large inter-individual variation in heart rate response at different intensities, which necessitates some form of individual calibration (Corder et al. 2008). Usually this involves simultaneous measurements of oxygen consumption and HR in a person to establish an individual regression equation. To address the problem of environmental influence on heart rate at lower intensities the FLEX method has been introduced, which distinguishes between sedentary activities and physical activity (Leonard 2003). Using this approach, a heart rate below the FLEX point, which is generally determined as the average between highest sedentary HR and lowest heart rate during light physical activity, is equated to energy expenditure at rest. When heart rate is above the FLEX point energy expenditure is determined based on a previously established individual regression equation (Leonard 2003).

The necessity to establish individual heart rate-VO_2 relationships is a limitation, since it increases experimenter and participant burden. In addition, activities used during calibration will influence the accuracy of the regression equation (Corder et al. 2008). Of additional concern is the delay in heart rate response to exercise (Corder et al. 2005) and an elevated post-exercise heart that would indicate higher physical activity levels (Corder et al. 2008). Nevertheless, heart rate has been reported to be a valid means to assess PA and energy expenditure in lean subjects (Sirard and Pate 2001).

Subjective Measures. Subjective assessments of PA, including questionnaires, interviews, and activity diaries (logs), have the potential to determine type and mode of physical activity, but the accuracy of information gained via subjective reports depends largely on the ability of participants to accurately report their activities. Recall errors, deliberate misrepresentations, social desirability or other reporting bias provide a potential threat to accurate assessment of physical activity with subjective methods. In addition, the recorded information needs to be converted into some variable of energy expenditure. Nevertheless, self-reports have been widely used in epidemiological research due to the low cost and low subject burden. While reliability coefficients are relatively high (r = 0.70 – 0.95), validity coefficients are only moderate compared to DLW (r = 0.50 – 0.56) (Welk 2002).

Diaries, using 15-minute epochs, are considered the most accurate subjective method to assess physical activity levels in adults (Sirard and Pate 2001). Bratteby et al. (1997) reported a mean difference between energy expenditure based on diary records and DLW of 1.2%. The participant burden, however, is substantial which limits its use to a small and motivated sample. Reactivity (i.e. change physical activity pattern during recording period) is of concern with this method just as the problem of accurately recording physical activities. Commonly subjective methods are used to determine physical activity patterns rather than TDEE.

Combined Measures. At this time there is no single best method to determine physical activity and/or TDEE. The previously discussed methods have been shown to accurately provide energy expenditure estimations at group levels, but are not accurate enough for individual-level estimates (Welk et al. 2007). Mechanical measurements have been shown to only respond accurately to certain types of movements and are limited in the ability to accurately assess higher intensities, while heart rate has been shown to overestimate energy expenditure at rest, (Corder et al. 2005). Given these limitations, a combination of several assessment methodologies has been suggested to increase accuracy.

Commonly heart rate and motion sensors have been combined. For example, Brage et al. (2004) used branched modeling to give different weightings on heart rate and acceleration based on the level of heart rate and physical movement. A combination of measurements was generally shown to increase accuracy of results (Corder et al. 2005), but in some instances the small increase in accuracy may not warrant the increased participant burden resulting from wearing more than one device (Welk 2002). Lately single measurement devices have been introduced to combine several measurements. The Actiheart ® (CamNtech, Cambridge, UK) combines heart rate and accelerometry and its accuracy in assessing energy expenditure has been shown in adults (Brage et al. 2005) and children (Corder et al. 2005). As with other single devices, positioning of the Actiheart is important since it impacts movement registration (Brage et al. 2005).

Another device that combines motion sensors and physiologic measures is the SenseWear Armband ® (SWA, BodyMedia, Pittsburgh, PA). The SWA is worn on the triceps of the right arm and uses non-invasive biometric sensors to assess heat flux, galvanic skin response, skin temperature, near-body-temperature, and motion via bi-axial accelerometry. The proprietary algorithms also incorporate gender, age, height and weight when estimating energy expenditure. Several studies have shown its accuracy in determining energy expenditure at low and moderate- intensities (Calabro, Welk and Eisenmann 2009, Jakicic et al. 2004, Malavolti et al. 2007). The accuracy at high intensities, however, remains questionable, since there seems to be a ceiling effect, similar to that observed with accelerometers (Drenowatz and Eisenmann 2011, Koehler et al. 2010).

The IDEEA (Intelligent Device for Energy Expenditure Activity; MiniSun LLC, Fresno, CA) is another multi-sensor unit that uses a series of electrodes along with a complex neural network to determine motion (Welk et al. 2007). Even though the IDEEA only uses accelerometry it can detect activity patterns and, therefore, provides an interesting alternative as criterion measure in free living situations, as pattern recognition is not possible with direct or indirect calorimetry and DLW. The IDEEA has been shown to accurately detect the type, onset, duration, and intensity of most fundamental movements and energy estimations form the IDEEA were 99% accurate compared to indirect calorimetry (Zhang et al. 2003). This study also showed that body weight, height, BMI, and age did not influence accuracy.

Length of Measurement Period. Besides the accurate assessment of energy expenditure there is some discussion on the length of the measurement period to obtain representative data on TDEE. A period of 4 to 9 days of monitoring including 2 weekend days has been suggested for reliable estimations of activity patterns in youth when using accelerometers (Trost et al. 2000). Mattocks et al. (2008) specify further that 3 days of monitoring are required to achieve a reliability coefficient of 0.7, 5 days are required for a coefficient of 0.8, and 11 days of monitoring are necessary for a coefficient of 0.9. These authors argue that more than 420 minutes of monitoring are sufficient to be considered a valid day, while other studies required at least 600 minutes of monitoring time per day (Corder et al. 2008). Interestingly, Corder et al. (2008) did not show differences in reliability when using 420 minutes or 600 minutes in 11-year-old participants. Since there are no detailed recommendations on monitoring time for pedometers, heart rate monitoring or combined measurements, similar monitoring periods are suggested (Corder et al. 2008). Finally, seasonality should be considered when assessing average values for TDEE and Mattocks et al. (2007) argue that a single week of data collection may not be representative due to considerable annual intra-individual variation.

In summary, there is currently not one best method to accurately determine various components of TDEE in a free-living situation. A combination of methods may provide the most accurate estimations for TDEE, EEE, NEAT, and RMR. To fully examine energy balance, nutrition needs to be considered as well. Therefore, the next section will discuss the regulation on nutritional intake, with a special emphasis on the role of macronutrients. Further, various methods to measure dietary intake will be addressed. Since the following research will focus on energy balance in athletes, concerns when assessing athletes’ energy intake will be emphasized, and finally current dietary recommendations for athletes will be summarized.

DIETARY INTAKE

Nutritional intake is regulated via appetite and satiety. Even though, hunger, which strongly correlates with food intake has a clear biological function it needs to be examined in a context of social and physiological variables (Blundell et al. 1996). Gerstein et al. (2004) point out that individuals do not eat solely on hunger, but that taste is usually the main reason for eating a specific food. Along with this argument, the decrease in taste is given as major reason for termination or reduction of food intake. It has also been argued that energy dense foods including those high in fat and simple sugars are more palatable, while low-energy-dense foods that typically contain more water and less fat tend to be less pleasant.

Central and peripheral mechanisms interact with environmental features to control human appetite (Blundell et al. 1996). Afferent information from ingested food via chemo- and mechanoreceptors in the mouth provides primarily positive feedback concerning nutrient intake, while signals from the stomach and small intestine predominantly provide negative feedback concerning food consumption. This information is sent to the brain via the vagus nerve to regulate nutritional intake. Macronutrients have been shown to influence total energy intake and regulatory mechanisms, and, therefore need to be addressed in more detail.

The role of macronutrients and food density on dietary intake

Foods of varying macronutrient composition have been shown to exert different effects on satiation and satiety (Blundell et al. 1996). Protein is commonly referred to as the most satiating of all macronutrients, followed by CHO and fat. Interestingly, Westerterp-Plantenga (2004) argues that very low fat intake (< 15%) due to fat substitution does not lead to a lower caloric intake, which suggests reduced satiety despite high CHO and protein intake. Further, it has been shown that fat prolongs satiety, which potentially reduces meal frequency. This, however, did not lead to a change in total daily caloric intake (Melanson et al. 1999). Despite some inconsistencies at extreme macronutrient distribution, high-fat diets have been shown to increase energy intake (Donahoo et al. 2008) due to low satiety levels of fat compared to protein and CHO. The increased caloric intake with high-fat diets is also referred to as *passive overconsumption*, since physiological satiety signals during a single meal are overcome by high-fat foods (Blundell et al. 1996). Further, it has been argued that the degree of oxidative metabolism of glucose and free fatty acids in the liver provides information for appetite control, with fatty-acid oxidation suppressing appetite (Blundell et al. 1996).

Rolls (2009) further argues that people tend to eat a consistent weight or volume of food. Therefore, high-density foods (i.e. higher amount of kcal/g of food) will result in a higher caloric intake than low-density foods. Generally, energy density is determined by macronutrient content, with high-fat foods providing higher energy density. In addition water content of food needs to be considered with a high moisture content lowering energy density even in high fat foods. When energy density is held constant, even large variations in macronutrient content (20% to 60% fat) do not significantly change ad libitum energy intake (Rolls 2009). On the other hand, ad libitum energy intake changed with variations in energy density despite constant macronutrient content. These findings suggest that dietary energy density has a stronger effect on dietary intake than does macronutrient content. It is hypothesized that physiologic cues associated with different energy density or macronutrient content may not have enough time to signal satiety during a meal, and that the amount of food intake provides more immediate feedback.

Alteration of energy density in one meal can impact total daily caloric intake as well. A reduction of 16% in energy intake in one meal was not compensated for by additional meals or increased intake during other eating occasions (Rolls 2009). The lack of a compensatory response might be due to a prolonged satiety with less dense foods due to slower gastric emptying (Rolls 2009). A reduction in energy density through water enrichment of foods, however, was shown to provide only short term reduction in energy intake. A reduction in fat content on the other hand reduced energy intake for periods between 5 days and 11 weeks (Rolls 2009) but prolonged reduction of energy dense foods eventually increased the amount of food being consumed.

Nevertheless, energy density of foods has been defined as key element in energy intake (Prentice and Jebb 2004). Since satiety seems to be more related to the volume of food than it is to energy content an increase in fat content results in a higher caloric intake and leads to a positive energy balance. This disruption in energy balance can occur over several weeks without any apparent cognitive or physiologic recognition. Even in lean subjects, who presumably have relatively intact regulatory mechanisms, no measureable regulatory response by either reducing food intake or increasing energy expenditure was observed in response to an increase in energy density of their diet (Prentice and Jebb 2004). Similarly, Blundell et al. (1996) report that subjects who were exposed to a high-fat diet consumed more calories and gained more weight than subjects forced to consume low-fat foods. Some studies even showed an additional stimulation of food intake in response to high-fat diets through oral sensory effects (Smith and Greenberg 1992, Tordoff and Reed 1991).

In addition to macronutrient content several peptides are involved in the regulation of dietary intake. Ghrelin levels have been shown to decrease after meal consumption but several other peptides respond specifically to particular macronutrients (Moran 2009) and effects appear to vary depending on body size and composition, and gender (Orr and Davy 2005). CCK, a peptide secreted from the gut during meals that mediates satiation in the hypothalamus is stimulated by protein and fat. When administered exogenously CCK has been shown to reduce the meal size (Woods et al. 1998). With fat intake there is also an increase amino-acid procolipase, which has been shown to decrease food intake in rats (Blundell et al. 1996) while NPY increases food intake and fat deposition (Beck 2006). Interestingly, Blundell et al. (1996), showed a more pronounced increase in NPY in response to CHO intake in rats.

Overall, various results suggest that dietary fat provides only a weak suppressive effect on subsequent food intake. Higher fat consumption does not result in a strong compensatory reduction in food intake, while foods high in protein or starch have been shown to be more satiating, and, therefore, result in lower energy intake (Blundell et al. 1996). Accurate assessment of energy intake, however, has been shown to be difficult. As with the measurement of energy expenditure a variety of methods are available to determine energy intake, but at this point most methods deal with the same concerns of underreporting or under-consumption due to reactivity to the assessment.

Assessment of Nutritional Intake

Retrospective (diet-recall, food-frequency questionnaire, diet history) and prospective (diet records, duplicate portion) dietary assessment tools have been used to examine nutritional intake. Ideally a complete nutrition assessment should include dietary information, anthropometry, body composition, and haematological and biochemical testing as well as a clinical examination (Magkos and Yannakoulia 2003). This may provide some feedback on the accuracy of the dietary information obtained. Of particular concern is the problem of under-reporting the food consumed, which is believed to occur with most dietary assessments (Hill and Davies 2001a). A major predictor of under-reporting is BMI or fat mass which is directly proportional to the magnitude of underreporting (Trabulsi and Schoeller 2001), but lean subjects have been shown to under-report their dietary intake as well (Maurer et al. 2006).

Retrospective methods examine recent food intake and rely on the subject's memory and honesty to report dietary intake. Prospective methods, on the other hand, monitor ongoing food consumption. Prospective dietary records may be more accurate, since they don't rely on participants' memory of food intake, but they require more subject cooperation, since a continuous food diary needs to be kept. Due to the higher participant burden, Trabulsi and Schoeller (2001) point out that prospective methods might lead to a decreased dietary intake. Energy deficits of 20-27% have been shown when comparing diet records with doubly labeled water measurements (Trabulsi and Schoeller 2001). Further, it was shown that the magnitude of under-reporting increases with a longer monitoring period, since prolonged recording periods may lead to recording fatigue. On the other hand, it has been suggested that longer recording periods increase the accuracy of a dietary assessment (Trabulsi and Schoeller 2001). Overall, differences in recording accuracy between prospective and retrospective methods seem to be minimal and accuracy has been shown to depend more on subject characteristics (Trabulsi and Schoeller 2001). As with assessment of energy expenditure utilization of various dietary assessment methods depends on the research question and sample size.

The most accurate, but also most laborious method to assess dietary intake is the duplicate portion method. In this case food samples are collected over several days and each meal is chemically analyzed for energy and nutrient content. Despite the high accuracy this method is rarely used due to the high subject and researcher burden. Diet history, on the other, hand is very easy to administer, but is used only infrequently due to the inaccuracy and high reliance on participants' memory (Magkos and Yannakoulia 2003). A commonly used method that provides more accurate information is a food frequency questionnaire (FFQ). FFQs usually consider the last year or previous 6 months (Block, Block and Block 1993). Other options to obtain typical dietary information are repeated dietary recalls of 24-hour intake or a record of dietary intake over several days.

The length of dietary recalls or food diaries is usually between one and seven days (Thompson and Byers 1994). Once again the length of the recording period depends mainly on the research question and outcome measure (e.g., total energy intake, macronutrient content, micronutrient content). Due to the large intra-individual day-to-day variation of food intake, a 1-day record cannot adequately assess average food intake. It can, however, be used in large groups to determine average intake of a specific population (Magkos and Yannakoulia 2003). To estimate average individual intake with recall or diary, a minimum of 3 days, including weekdays and weekend-days, is recommended (Ribas-Barba et al. 2009). If specific macro- or micronutrient consumption is of interest, longer recording periods are needed (e.g.,. 42 days for Vitamin A) (Ribas-Barba et al. 2009). As expected, under-reporting in caloric intake also leads to lower values in macro- and micronutrient intake and needs to be considered in interpretation of dietary data. Finally, the population of interest may influence results of the dietary assessment and needs to be considered when deciding on a particular method.

Nutritional Assessment in Athletes. In athletes, a 3- to 7-day monitoring period is generally believed to provide accurate estimations of habitual energy intake and macronutrient consumption (Black 2001). The most common approach to properly assess dietary intake are multiple 24-hour recalls; generally over 3 to 4 days (Magkos and Yannakoulia 2003). A major advantage is minimal subject burden, since face-to-face or phone interviews can be scheduled around participants' daily activities. Accurate data collection interviews usually last 15 to 30 minutes (Magkos and Yannakoulia 2003). To further reduce subject burden FFQs may be administered as a one-time assessment. FFQs consist of a detailed list of foods and beverages or categories of foods and beverages with options to indicate the frequency and amount consumed within a specified time period. Amounts are usually estimated by portion size and household measures, with the time period varying from 1 day to several months. FFQs are usually established by reviewing a large number of diet records or recalls to determine the most common food items in a particular population. Using population based FFQs in athletes might be problematic, since athletes, especially in endurance sports, have different dietary patterns due to increased energy demands (Magkos and Yannakoulia 2003). In endurance athletes energy expenditures of up to 9000 kcal/day are observed (Westerterp et al. 1986), which requires the consumption of larger amounts of foods during regular meals. Using standard serving sizes to report dietary intake, therefore, might not be appropriate in assessing an athlete's diet.

As observed in the general population athletes may alter their usual dietary intake during the monitoring period and/or fail to accurately report their food intake or due to inadequate quantification of meals consumed (Magkos and Yannakoulia 2003). Observed discrepancies between reported energy intake and measured energy expenditure ranging 22% (Schulz et al. 1992) to 32% (Edwards et al. 1993) in weight stable endurance runners lead to the belief that athletes possess superior metabolic efficiency. This theory, however, has been dismissed as the discrepancies between reported energy intake and energy expenditure in weight stable athletes have now been attributed to under-reporting or under-recording of dietary intake (Magkos and Yannakoulia 2003). The under-reporting of dietary intake can be explained by intentional or unintentional omission of foods consumed and/or by intentional or unintentional under-eating during the study period (Magkos and Yannakoulia 2003).

Using doubly-labeled water to validate self-reported energy intake in athletes Magkos and Yannakoulia (2003) showed that under-reporting accounts for 10 to 45% of total energy expenditure, and the discrepancy is due to under-recording rather than under-eating (Hill and Davies 2001a, Ebine et al. 2000). Under-reporting, however, is highly variable among individual athletes. In female distance runners misreporting ranged between +26% and -44% (Schulz et al. 1992). Misrepresentation of dietary intake may become even more pronounced when a change in exercise volume occurs. For example Westerterp et al. (1986) showed that despite an increase in energy expenditure from week 1 to weeks 2 and 3 during the Tour de France self-reported energy intake did not increase. The lack of change in body weight despite a suggested energy deficit indicates progressive under-recording with increased energy expenditure.

As expected there is a strong, positive correlation between energy expenditure and reported energy intake ($r = 0.94$), but there also seems to be a trend for increased under-reporting as energy expenditure increases (Magkos and Yannakoulia 2003). This latter observation is probably due to less accurate estimations of the amount of food consumed, and possibly forgetting to report some snacks. Poslusna et al. (2009) showed that eating frequency is the best predictor for underreporting in men. As many as 9 discrete meals and snacks per day have been observed in athletes with snacks accounting between 17-22% and 30-37% of total energy intake (Magkos and Yannakoulia 2003). Similarly, Magkos and Yannakoulia (2003) emphasize the importance of considering serving size, snacking, and water and beverage consumption. Especially sports drink consumption is of concern, since these beverages will add to the caloric intake. Finally, athletes have been shown to consume substantial amounts of supplements including ergogenic aids that include energy sources, cellular metabolites and other components to enhance performance which may alter the dietary assessment.

In summary, the assessment of nutritional intake is perhaps more challenging than the assessment of physical activity. Athletes comprise a population subgroup with special nutritional needs, which may limit the applicability of methods developed for the general population. Westerterp and Goris (2002) argue that physical and psychological characteristics of study participants need to be considered when selecting and evaluating nutritional intake. At this point there is no single best method to accurately determine dietary intake and the choice of the dietary assessment tool will depend on the research question and feasibility. Most often total energy intake is of concern, but macronutrient content of the diet may be of interest as well. Since macronutrients are metabolized differently a proper dietary content of different nutrients should be assessed in addition to total caloric intake. This may be even more important for athletes to ensure their ability to meet metabolic demands.´

Current dietary recommendations for athletes

The role of proper dietary intake to reach full athletic potential is well recognized (Magkos and Yannakoulia 2003). Besides the need for a higher total caloric intake due to increased energy expenditure dietary recommendations for athletes do not differ much from those for the general population. Only CHO content should be increased to maintain high performance levels (Rodriguez et al. 2009).

Macronutrient intake. A consumption of CHO between 60% and 70% of total caloric intake has been suggested for endurance athletes (Williams 1998). This is higher than the recommended 45-65% for the general population. An increased CHO intake is necessary to replenish glycogen stores after exercise. Muscle glycogen has been shown to be the major fuel at about 75% VO_2max, which is considered a typical training intensity of endurance sports. During prolonged vigorous intensity exercise CHO can be oxidized at a rate of 3-4 g/min (Maughan 2002, Maughan and Piehl Aulin 1997) resulting in a depletion of CHO during exercises sustained for more than two hours. Despite higher CHO intakes of endurance athletes, Williams (1998) argues that athletes generally do not achieve these recommendations due to their high total energy requirements. For example, a total CHO intake of 500g for a 70 kg athlete would result in 7 g CHO/kg but would only provide 50% in a 4000 kcal/day diet. Therefore, CHO intakes should be assessed per body weight. The recommendation for CHO in athletes is 6-10 g/kg per day (Burke et al. 2001, Williams 1998).

Complete recovery from glycogen depletion has been shown to take 24 to 48 hours and proper post-exercise CHO intake is crucial to enable athletes to sustain high-intensity training in successive training session (Maughan 2002). It is recommended that CHO intake occurs as soon as possible after training with a consumption of at least 1-2 g/kg of body mass or 50-100 g total within the first hour (Maughan 2002). It has also been shown that glycogen resynthesis is mainly determined by the amount of CHO rather than the type (Ivy 2000). This also explains why a high-CHO diet may result in greater improvements in performance compared to a high-fat diet. If glycogen stores are depleted and athletes need to rely on fatty acid metabolism exercise intensity needs to be reduced, despite a higher capacity to oxidize fatty acids in endurance trained athletes (Maughan 2002). This would result in lower training stimuli and consequently lower adaptive changes in functional capacity. Nevertheless fat intake should still contribute 20%-35% of total energy intake to an athlete's diet, with saturated, monounsaturated, and polyunsaturated fatty acids each contributing roughly 10% (Rodriguez et al. 2009).

In addition to glycogen replenishment after exercise and proper fat intake, sufficient protein intake is necessary to allow for adaptive changes in muscle structure and function (Maughan 2002). The recommended protein intake is up to 1.7 g/kg body weight (Rodriguez et al. 2009) or between 10% and 35% of total energy intake (Burke 2007). An energy intake of 1.7 g in a 70 kg athlete consuming a total of 4000 kcal/day would result in about 12% of total energy intake from protein. Overall, it is emphasized that in addition to adequate total caloric intake athletes need to ensure proper intake of fat, protein, and CHO since macronutrients are metabolized differently with all contributing to optimal performance (Loucks 2004).

Micronutrient intake. Along with increased energy intake micronutrient intake needs to be higher as well, but if athletes maintain a diverse diet and meet energy demands, no supplements should be necessary (Nogueira and Da Costa 2005). While micronutrients do not provide energy directly, they are important for a variety of bodily functions. It has been suggested that micronutrient needs are increased in active people due to biochemical adaptations of exercise. Further, routine exercise may increase the turnover and loss of several micronutrients because of increased needs for building, repairing, and maintaining lean muscle tissue (Rodriguez et al. 2009). While the status of all micronutrients should be monitored, a special emphasis needs to be put on calcium and Vitamin D (bone health, muscle contraction, nerve conduction), B-vitamins (energy metabolism), iron (oxygen transport), magnesium (cellular metabolism), and zinc (building and repair of tissue, metabolism, immune status). In addition, proper intake of antioxidants like vitamin C and E, β-carotene and selenium are important for immune status (Rodriguez et al. 2009).

Finally proper hydration status should be ensured, since a loss above 2% body weight can compromise aerobic exercise performance (Rodriguez et al. 2009). Fluid intake of 5-7 ml/kg body weight at least 4 hours prior to exercise is recommended to optimize hydration levels. Especially in events lasting longer than 1 hour, beverages containing 6-8% carbohydrate are recommended to maintain glucose levels. In addition to the replenishment of glycogen stores with hydration, fluids containing sodium and potassium help to replace electrolytes lost in sweat (Rodriguez et al. 2009). To re-establish hydration post-exercise 1L of fluid for every kg of body weight lost is recommended.

In summary, sufficient macro- and micronutrient intake in addition to proper hydration are important components for optimal physical performance. Besides the amount of dietary intake, timing and frequency of food consumption has implications for metabolism and nutrient availability. Several strategies (i.e. CHO loading, pre-hydration) have been incorporated according to specific nutrition and performance goals (Burke et al. 2003). Athletes who consume an adequate amount of caloric intake from a variety of foods do not need nutritional supplements (Nogueira and Da Costa 2005), but high-CHO intake with low micronutrient density and the elimination of one or more food groups, or dietary restriction, especially below 65% of estimated energy requirements, may require supplementation to meet micronutrient guidelines.

CONSIDERATIONS FOR ENDURANCE ATHLETES

In the previous sections, the general concept of energy balance and the interaction and assessment of contributing components has been discussed. Due to increased energy flux athletes face some additional challenges in maintaining energy balance. Energy expenditure and energy intake will be addressed separately prior to discussing the mechanisms used to ensure overall energy balance. Finally detrimental effects of a negative energy balance will be discussed which will provide the rationale for further examination of the interaction between various components of energy balance in relation to different training volumes.

Energy Expenditure in Endurance Sports

Duration, frequency, and intensity of exercise influence energy expenditure for different types of exercise. Further, heredity, age, sex, body size, FFM, and prior nutritional status contribute to variability in energy expenditure (Rodriguez et al. 2009).

Several studies have used DLW to assess TDEE in various endurance sports. Schulz and Schoeller (1994) reported TDEE of roughly 7000 kcal/day in male endurance athletes. During ultra-endurance competitions like stage races in cycling TDEE as high as 9000 kcal/day were reported (Westerterp et al. 1986), while for runners TDEE of 6500 kcal/day were shown (Hill and Davies 2001b). In Japanese soccer players average TDEE during the season (2 games/week and training) was roughly 3500 kcal/day (Ebine et al. 2002). These levels of TDEE are similar to TDEE during moderate training periods in runners and swimmers (Ebine et al. 2000). In comparison, TDEE of 2400 kcal/day was reported for sedentary subjects of similar height and weight.

For female athletes lower values of TDEE were shown. Edwards et al. (1993) reported TDEE of 3000 kcal/day for female runners with an average training volume of 10 km/day and Horton et al. (1994) reported similar values for endurance trained cyclists. Considerable lower TDEE for females compared to males was also reported in cross-country skiers (4300 kcal/day vs. 7200 kcal/day in males) (Sjodin et al. 1994). Similar values were shown for light weight rowers (4000 kcal/day) (Hill and Davies 2002). Trappe et al. (1997) reported TDEE of 5600 kcal/day in female swimmers during high volume training periods. TDEE, however, dropped to about 3500 kcal/day during low volume training periods in swimmers (Jones and Leitch 1993). In female cyclists a drop from 3150 kcal/day to 2250 kcal/day occurred when comparing cycling to non-cycling days (Horton et al. 1994). In this sample TDEE on non-cycling days was no longer significantly different from sedentary control subjects (2100 kcal/day).

DLW, however, does not provide any information on energy expenditure during training or competition since it does not provide any information on the different components contributing to it. Motanga et al. (2006) examined energy expenditure in 19- to 21-year-old male endurance athletes via heart rate response. They reported an EEE of roughly 2550 kcal/day, which contributed 49.3% to their total energy expenditure while spending only 7.3% of the entire day execercising/training. NEAT contributed 38.7% to TDEE (~1720 kcal/day). A significant correlation between TDEE and EEE energy expenditure was shown (r = 0.99), while NEAT was not significantly related to TDEE (r = 0.37).

There is only limited data available for energy expenditure during different competitions. For example, average energy expenditure during a 90-minute soccer game was shown to range between 1350 kcal (Bangsbo 1994) and 1500 kcal (Reilly 1997). In endurance events, reported energy expenditures are considerably higher. Even in recreational runners energy expenditure during a marathon was roughly 2400 kcal in females and 2800 kcal in males (Loftin et al. 2007). Similar values were reported for 50 km cross-country skiing races (Neumann et al. 2004). These authors also reported energy expenditures of roughly 3000 kcal for Olympic-distance triathlons and an average of 8500 kcal for Ironman events. While these studies provide information on the energy cost of competition, no information on TDEE is given. Except the long-distance triathlon, the reported values were for competitions lasting between 90 minutes/2 hours and 4-5 hours. Thus, there are several hours of waking time left, where people will engage in different activities, which may contribute substantially to TDEE (Motonaga et al. 2006).

Overall the previously reported values of either TDEE or EEE clearly show increased energy expenditure of athletes during training or competitions. To ensure optimal performance and/or optimal physiological training adaptations proper dietary intake is necessary. Long-term success will only be possible when energy balance is maintained and necessary nutrients are replenished. Of particular interest is proper CHO intake, since this is the major fuel and glycogen stores are usually depleted during prolonged exercise (Trappe et al. 1997).

Dietary Habits of and Compliance with Current Recommendations

With increasing knowledge concerning the role of nutrition for successful performance athletes often try to seek an advantage by employing various nutritional strategies during competition (Maughan 2002). Nutritional interventions, however, may have a bigger impact on performance by providing adequate support for consistent intensive training and promoting physiological and biochemical adaptations. Generally, it has been shown that athletes are able to meet dietary recommendations unless they engage in some form of restrictive dietary behavior. Burke et al. (2003) examined athletes in various sports, and reported that athletes comply with current recommendations, especially endurance athletes. It might actually be easier for endurance athletes to meet recommendations due to their high caloric intake.

For example, male cyclists reported an energy intake above 60 kcal/kg/day, and their CHO intake was between 8 and 11 g/kg/day (Burke 2001). Concerning protein intake, most endurance athletes reported an intake between 1.2 and 2.0 g/kg, which resulted in mean intakes of 12 to 17% of total energy intake (Nogueira and Da Costa 2005, Burke et al. 2003). Mean reported fat intakes ranged from 30 to 37% of total energy expenditure in males and from 26 to 33% in females (Nogueira and Da Costa 2005). Due to the high energy intake, micronutrient recommendations are generally met as well (Burke 2001). Athletes also seem to be very successful in promoting rapid recovery after exercise by consuming substantial amounts of CHO within the first hour post exercise (Burke et al. 2003). Proper nutritional practices were reported during stage races where a variety of practical constraints and suppression of appetite after exhaustive exercise might limit nutritional intakes (Burke 2001).

Considering non-endurance athletes, most male athletes achieve a daily CHO intake of 60% of total energy intake with an average intake of 7.7 g/kg (Burke et al. 2003). Female athletes reported slightly lower intakes (6.2 g/kg) resulting in CHO consumption below dietary recommendations. As has been mentioned previously, a common strategy to guarantee proper caloric intake is to increase the number of eating occasions throughout the day (Burke 2001). Endurance athletes reported at least 5 and up to 8-10 occasions of food/drink per day. For cyclists 9 discrete meals and snacks were shown which provided almost 40% of total energy intake (Burke 2001). In other athletes snacks contributed 23% of total energy intake (Burke et al. 2003). Additionally, differences in caloric and nutrient content between meals were shown according to training intensity. At lower training-volume periods CHO and protein contributed less to total caloric intake, which resulted in an increased fat intake (García-Rovés et al. 2000).
Several studies have shown that athletes adjust their dietary intake according to energy expenditure at different parts of the season (Nogueira and Da Costa 2005). During low volume training periods average energy intakes of 3130 kcal/day were reported with 57 %, 16%, and 27% from CHO, protein, and fat respectively (García-Rovés et al. 2000). The relative contribution of macronutrient did not differ significantly between low- and high training periods, but due the increased energy demands absolute intake increased to

5400 kcal/day. Dietary intake per body weight was 11.3, 2.6, and 2.6 g/kg body weight for CHO, protein, and fat, respectively during high volume training compared to 6.5, 1.8, and 1.4 g/kg for CHO, protein, and fat during the low volume training period (García-Rovés et al. 2000). Nogueira and Da Costa (2005), however, reported that the increased energy intake to meet increased energy demands during high-volume training was mainly due to increased CHO intake. Burke (2001) also showed a significant positive correlation ($r=0.78$, $p < 0.001$) between reported energy intake and training energy expenditure. This study actually showed some dietary restraint during recovery days. Along with changes in caloric intake differences in vitamin A, pyridoxine, vitamin D, iron, phosphorous, sodium, and zinc intakes between periods of different training intensities were shown as well (García-Rovés et al. 2000). At all stages, however, micronutrient intake was above recommendations.

Despite adjustments in dietary intakes during training seasons, Nogueira and DaCosta (2005) reported that the increase in energy intake could not fully compensate for the increase in energy expenditure. It was, therefore, concluded that endurance athletes fall into a negative energy balance during high volume training periods. On the other hand, Burke (2001) argues that cyclists are successful in meeting energy requirements above 6000 kcal/day during stage races like the Tour de France, since reported changes in body mass were less than 1 kg. Dietary intake in these athletes was on average 84 kcal/kg/day with a CHO intake of 12-13 g/kg/day. To achieve these amounts 49% of total energy intake and roughly 60% of total CHO intake was consumed during the race. Sports drinks provided the majority of nutrition during the stage, resulting in fluid intake of 4.5 L per stage. The differences in the results among studies examining energy intake and energy balance in endurance athletes may be explained by accurate assessment of dietary intake as many authors were concerned about potentially underreporting of dietary intake among athletes.

While total caloric intake was lower in runners compared to cyclists, the eating pattern and macronutrient distribution of dietary intake was fairly similar. Bear and Niekamp (1995) reported total daily energy expenditure and intakes of roughly 3500 kcal/day with a CHO intake of 7.5 g/kg or 61.2% of total caloric intake. Mean protein intake was 1.56 g/kg or 12.8% of total caloric intake and micronutrient intake of these subjects was above 66% of the RDA. Generally, accurate CHO intake pre- and post-competition was shown, but post-competition intake was delayed which could result in slower recovery. Overall, it has been shown that athletes who maintain energy balance are able to meet dietary recommendations concerning macro- and micronutrients. Some athletes, however, may achieve energy balance, but not meet current recommendations. The most common shortcoming is CHO intake. For example Clark et al. (2003) showed that college athletes are at risk for low CHO intakes while achieving energy balance due to higher protein and fat consumption. Low CHO intake may also lead to insufficient caloric intake which may lead to insufficient micronutrient intake (Clark et al. 2003).

Besides adequate dietary intake behavioral adaptations may occur to maintain energy balance. Therefore, Maughan (2002) emphasizes the need of increased energy intake with higher EEE unless there is a compensatory reduction in energy expenditure elsewhere. There may also be a difference between sports where performers have a low body fat content, but a high energy turnover, like in marathon running or cycling, and sports that require low body fat content with relatively low energy turnover, as in gymnastics. Interestingly, Maughan and Piel Aulin (1997) showed an inverse relationship between energy intake and body fat content in runners. This was explained by a positive relationship between energy intake and training volume and a negative relationship between body fat and training volume, which undermines the necessity for sufficient fat stores to tolerate high-volume training.

Energy balance in Athletes, especially endurance sports

While obesity places a large burden on our society, athletes usually face a different concern - that is, athletes need to insure adequate energy intake to meet their increased energy expenditures and maintain energy balance and body weight, especially during high volume training. The teleoanticipation hypothesis suggests a close monitoring of energy expenditure over a prolonged period of time to avoid homeostatic disturbances that could lead to injuries (St. Clair Gibson, Schabort and Noakes 2001). This hypothesis is supported by studies examining energy expenditure at the major 3-week cycling competitions (Giro d'Italia, Tour de France, Vuelta a Espana). Lucia et al. (2001) showed, using heart rate monitoring, that relatively shorter competitions (Vuelta a Espana) are completed at higher intensities, while longer competitions (Tour de France) lead to a lower average heart rate. Overall the summated heart rate "scores" for the entire race were fairly similar (Lucia et al. 2003). Similar results were reported for runners (Esteve-Lanao et al. 2005, Billat et al. 2003) and cross-country skiers (Seiler and Kjerland 2006), which suggests that there is an upper tolerable limit of energy expenditure in endurance events.

Loucks (2004) argues that during prolonged sports participation at high intensity, energy intake, especially carbohydrate intake, is the limiting factor to performance and that maximum capacity of dietary intake will ultimately limit energy expenditure if energy balance is to be maintained. A reduction in glycogen availability will lead to a reduction in exercise intensity due to a reduced ability to resynthesize ATP. Of interest are the findings by Hampson et al. (2001) who showed that starting with lower glycogen stores leads to a down-regulation of power output at the beginning of a time trial to preserve glycogen for the final part of the stage. This suggests that endurance athletes have a strong sense of their energy reserves and adjust their intensity accordingly to optimize the competitive result (Foster et al. 2005). To avoid such impairments in performance athletes are trying to adjust their CHO intake accordingly. In soccer players it was shown that energy and CHO intake during intensive pre-season training periods are significantly higher than during the competitive season, where energy expenditure is reduced (Hickson et al. 1987).

Besides nutritional changes according to changes in energy expenditure a compensatory down-regulation of habitual physical activity in response to higher EEE during endurance training has been discussed (Almeras et al. 1991). Vallières et al. (1989) reported a significantly lower increase in TDEE in female swimmers than would be expected from the energy cost of their training. Similarly, Stubbs et al. (2002b) showed a decline in habitual energy expenditure values (TDEE – EEE) with increased EEE. On the other hand, Almeras et al. (1991) showed no decrease in physical activity pattern during non-exercise time. As in the general population results for compensatory down-regulation of NEAT in response to increased EEE are inconclusive in athletes. At this point there is only limited research available, since most studies examined either EEE or TDEE only, when examining periods of different energy expenditures.

Research on dietary adjustments is inconclusive as well. Several studies have shown large discrepancies between energy intake and energy expenditure in weight stable athletes. For example a difference between energy intake and TDEE of up to 58% was reported in female swimmers (Edwards et al. 1993), and Westerterp et al. (1986) reported a caloric intake of up to -39% in male cyclists. Nevertheless, these subjects maintained their body weight, which suggests that energy intake has been underreported. Trappe et al. (1997), however, point out that short-term energy deficits of up to 2500 kcal/day would result in a fat loss of only 0.27 kg/day, which may not be detectable over the relatively short measurement periods (5 days). Therefore, it is possible that endurance athletes experience an energy deficit during competitive events or short periods of high volume training, but are able compensate for such an imbalance via a positive energy balance during recovery periods. The tolerance of short-term energy deficits is supported by Stubbs et al. (2002b) who showed that increased TDEE from 2800 kcal/day to 4000 kcal/day due to increased exercise did not increase dietary intake. In females, a slight, but incomplete dietary adaptation was observed, but the authors still concluded that proper adaptation of dietary intake in response to increased energy expenditure may take several weeks (Stubbs et al. 2002a). Overall, long-term energy balance seems to be of more concern than achieving day-to-day energy balance in athletes. Various mechanisms have been shown to contribute to the maintenance of energy balance, but results from these studies are equivocal. There is, however, agreement that a long-term disruption of energy balance impairs performance and poses health risks.

Concerns related to energy imbalance

While moderate exercise levels are generally associated with health benefits concerning chronic diseases as well as reduced risk of minor illness and infections, high volume training may increase the risk of infections (Maughan 2002), particularly if energy intake does not match the increased energy expenditure. Negative effects of increased exercise levels are attributed to increased levels of free radicals (Maughan 2002), which can be counterbalanced by a higher intake of antioxidant nutrients. Adequate dietary CHO intake may provide additional benefits by minimizing the rise in plasma levels of stress hormones like cortisol, catecholamines, and growth hormone, which have been shown to negatively affect immunity (Nieman and Pedersen 1999). Recent research suggests that especially in endurance sports carbohydrate availability is a limiting factor for reproductive and skeletal health (Loucks 2004). Since large shifts in CHO or fat oxidation or in glycogen stores have not been shown to lead to changes in ad libitum macronutrient intake a conscious effort may be necessary to ensure proper dietary intake.

Low energy intake is of particular concern, since inadequate energy intake relative to energy expenditure compromises performance and negates the benefits of training. Female athletes have been shown to be more prone to low energy intake. Except for cross-country skiers it has been shown that female endurance athletes consume only about 70% of energy and CHO compared to male athletes when caloric intake is normalized for body weight (Loucks 2004). Therefore, a cutpoint of at least 30 kcal per kg fat free mass/day has been suggested for female athletes (Rodriguez et al. 2009). Currently no such cutpoint has been established for males. Negative energy balance ultimately leads to loss of lean tissue mass which results in a loss of strength and endurance. Further, it compromises immune, endocrine, bone health, oxygen carrying capacity of blood (anemia) and musculoskeletal function (Rodriguez et al. 2009); all of which are detrimental to performance. Finally, long-term energy deficit may result in nutrient deficiencies which could lead to metabolic dysfunctions and lower resting metabolic rate (RMR) (Rodriguez et al. 2009).

As has been shown previously there is only a limited biological drive to match energy intake to activity induced energy expenditure (Truswell 2001). Many studies actually showed a suppression in hunger after a single bout of exercise above 60% of VO2max (Blundell and King 1998). Further, King et al. (1997) showed that two 50-minute bouts of exercise at 70% VO2max in a single day did not increase ad libitum food intake for up to two days. Even during 40 weeks of marathon training resulting in a 20% increase in energy expenditure no increase in energy intake was reported (Westerterp et al. 1992). On the other hand, food deprivation leading to a similar energy deficit does increase hunger and would stimulate higher energy intake (Hubert, King and Blundell 1998). All these results show the body’s limited ability to automatically increase energy intake in response to increased energy expenditure. Therefore, it is argued that appetite cannot be used as a reliable indicator of either energy balance or specific macronutrient requirements in athletes (Loucks 2004).

A chronic energy deficit has been shown to lead to various metabolic substrate and hormone abnormalities that are indicative of a higher mobilization of fat stores (Loucks 2004). Increased fat metabolism results in a slower metabolic rate and leads to a decline in glucose utilization, which impairs performance. Scarce metabolic fuels also impair physiologic function such as immune function, growth and maintenance of tissue and bone mineral density as well as reproductive development. Such metabolic and reproductive disruptions have been shown in male and female athletes. While female athletes are generally at risk for energy imbalances, a higher prevalence of an energy deficient has been shown in male endurance athletes and men in sports with weight classes (Loucks 2004). Energy deficiency in male wrestlers has been shown to induce growth hormone resistance with IGF-I suppression despite elevated growth hormone levels during the season. There is also a reduction in testosterone levels which reduces anabolic stimulation and leads to a decline in lean body mass (Loucks 2004). Besides lower levels in sex hormones, suppressed albumin levels are a common biomarker related of energy deficiency (Loucks 2004). Since it has been shown that proper dietary intake can reverse the adverse effects of energy deficiency, it is believed that low energy availability rather than stress of exercise disrupts the reproductive system.

When examining energy balance in athletes, Loucks (2004) points out that body weight is not a reliable indicator since protein and glycogen stores are associated with a higher water content than fat stores, and therefore a small weight gain due to increased protein or glycogen stores could counterbalance fat loss, which would result in no weight change despite a negative energy balance. Even though there are no specific recommendations for body fat percentage in endurance sports a minimum of 5% in males and 12% in females is considered within the healthy range (Heymsfield et al. 2005). Optimal body fat percentages, however, may be much higher than these minimum values depending on sport and biological constraints (Rodriguez et al. 2009).

In summary, the importance of energy balance for optimal performance has been acknowledged by scientists, coaches, and athletes (Rodriguez et al. 2009). To this point, however, research focused either solely on TDEE or activity expenditure in relation to dietary intake. There has been only limited research that examined the interaction between various components of total energy expenditure in relation to changes in training volume and according behavioral adjustments. The extent of compensatory responses in habitual physical activity and dietary intake in response to different training volumes has not been addressed in endurance athletes. Therefore, the following research will examine the relationship and interaction between various components of energy expenditure and energy intake. Specifically, nutritional adaptations and changes in NEAT and EEE in response to changes in training regimen will be studied.

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CHAPTER 2:

TOTAL DAILY ENERGY EXPENDITURE AND ITS RELATIONSHIP

TO EXERCISE, HABITUAL ACTIVITY, AND RESTING METABOLIC RATE

IN YOUNG MALE ENDURANCE ATHLETES DURING

HIGH-VOLUME AND LOW-VOLUME TRAINING

ABSTRACT

BACKGROUND. Previous studies have examined total daily energy expenditure (TDEE) or training/exercise energy expenditure (EEE) in endurance athletes. However, there is limited research on the contribution of various components contributing to TDEE during different training periods. The purpose of this study was to examine changes in TDEE and its components, specifically EEE, habitual activity energy expenditure / non-exercise activity thermogenesis (NEAT), and resting metabolic rate (RMR) in endurance trained athletes during high- volume and low-volume training periods. In addition, changes in time spent at different intensities in response to different training volumes was explored.

METHODS. Energy expenditure was measured in 15 male endurance athletes (age 23.6 ± 2.4 years) during 2 non-consecutive weeks – one week of high volume (HV, >13 hours) training and another week of low volume (LV, < 7 hours) of training. Height (cm) and weight (kg) was measured according to standard procedures and %fat was assessed via BodPod at the beginning and end of each training period. RMR was measured in the middle of each week using indirect calorimetry. The SenseWear Pro 3 Armband was used to measure NEAT, and EEE was assessed via heart rate using individual regression equations established during a VO_2max test performed at the beginning of each week. Time spent in different intensities was assessed using previously established MET cutpoints and with RMR indicating 1 MET.

RESULTS. There was no difference in height (182.1±3.4 cm), weight (73.4±9.7), or %Fat (10.8±3.8) between the two training periods. TDEE and EEE were significantly higher during the HV week compared to the LV week (4824±773 vs. 4080±637 and

1285±269 vs. 639±267 kcal/day, respectively) even though no difference in training intensity was observed. While there was a trend towards higher RMR during HV (2276±383 vs. 2150±240 kcal/day; p=0.08) no difference in NEAT (1262±350 vs. 1291±285 kcal/day) occurred. Time spent in sedentary activities was significantly reduced during HV (1051±91 vs. 1108±89 min/day), but there were no differences in time spent in light or moderate-to-vigorous activity when training time was not considered. NEAT was also inversely correlated with time spent sedentary (r=-0.83, $p<0.01$), while a positive relationship between NEAT and time spent in light and moderate activity was observed (r=0.66 and r=0.77, respectively, $p<0.01$). Further, RMR was positively correlated with time spent in vigorous activity (r=0.53, p=0.01).

CONCLUSION. These athletes did not show a compensatory behavior in response to high volume training. The difference in TDEE was greater than what could be attributed to differences in EEE. The increase in RMR on top of increased EEE explained the difference in TDEE between the two training periods, while there was no change in NEAT. Further, increased training time did not reduce light and moderate-to-vigorous activity, but rather reduced sedentary time in trained endurance athletes.

Key Words: average daily metabolic rate, physical activity level, activity-induced energy expenditure, exercise training

INTRODUCTION

The assessment of total daily energy expenditure (TDEE) in athletes is important to provide proper recommendations for training, recovery, and diet. Reported TDEE in athletes ranges from 4,500 kcal/day in middle- and long-distance runners during a regular training period (Motonaga et al. 2006) to 8,600 kcal/day in cyclists during the Tour de France (Westerterp et al. 1986). Most studies examining TDEE in athletes (e.g., swimmers, speed skaters, rowers, cross-country skiing, cycling**)** used the doubly labeled water (DLW) method (Ebine et al. 2002, Ekelund et al. 2002, Hill and Davies 2002, Hill and Davies 2001, Sjodin et al. 1994, Trappe et al. 1997, Westerterp et al. 1986). While the DLW method is considered the gold standard for determining TDEE, it does not provide information on the habitual physical activity or non-exercise activity thermogenesis (NEAT) and exercise energy expenditure (EEE) (Vermorel et al. 2005) nor the intensity of physical activity (i.e., light, moderate, vigorous).

Intuitively, the increased TDEE in endurance athletes is probably due to their increased EEE experienced during training, but higher resting metabolic rate (RMR) values have also been reported in endurance trained athletes (Almeras et al. 1991). It is important to consider that the higher RMR may be due to increased energy expenditure during recovery after an intense and prolonged training period (i.e., excess post exercise oxygen consumption or EPOC) (Laforgia et al. 1997). As many highly competitive endurance athletes engage in more than one training session a day, it is possible that these athletes never return to a true resting metabolic state during the day. Indeed, Eliakim et al. (1996) showed a 4% increase in RMR with endurance training. Besides the effect of EPOC, changes in body composition (Eliakim et al. 1996) as well as increased TEF

(Westrate and Hautvast 1990) have been suggested as potential factors increasing RMR. In summary, higher EEE and higher RMR have been shown to contribute to increased TDEE in athletes.

Athletes, however, do not maintain a constant training volume and intensity throughout the year. Instead, training volume (intensity, duration, and frequency) is altered according to specific predetermined goals to allow for proper recovery, adaptation, and performance (Zaryski and Smith 2005). Generally, a higher training volume will occur early in the season, while at the end of the season and during the post-season training volume will be reduced to allow for tapering and recovery. For example, in male elite cyclists the average TDEE during a cycling training camp was 4970 kcal/day compared to only 2700 kcal/day on a resting day (Vogt et al. 2005). Similar differences in TDEE were shown when comparing male cross-country skiers in training and non-athletic controls (4025 kcal/day vs. 3140 kcal/day) (Almeras et al. 1991).

The difference in EEE is most likely the biggest contributor to differences in TDEE between high- and low-volume training, but other components of TDEE may also be influenced. While RMR may increase in response to increased training volume, Almeras et al. (1991) suggested that higher EEE during training may result in a lower NEAT in athletes. Two possible explanations are provided for such a compensatory response. First, the higher EEE and a potential increase in RMR may limit the opportunity for dietary intake adaptations, which necessitates a reduction in energy expenditure in other components to maintain energy balance (Nogueira and Da Costa 2005). Second, it can be argued that higher training intensities induce higher fatigue post-exercise, which may lead to a reduction in NEAT (Westerterp 2008). In contrast, a possible increase in NEAT due to a more active lifestyle in response to increased exercise levels has been discussed as well (Westerterp 2008).

Overall, there is insufficient evidence to clearly establish the interactions among various components of TDEE in response to different training volumes. While Westerterp et al. (1992) showed a lower increase in TDEE than the energy expenditure attributed to training in marathon runners, McLaughlin et al. (2006) argue that changes in TDEE may be more pronounced than the energy expenditure attributed to exercise. In addition, there is only limited research on possible changes in time spent at different intensities in response to exercise training. As was discussed for adaptations in NEAT in response to changes in exercise volume, it could be argued that time spent in sedentary activity increases in response to exercise due to post-exercise fatigue and time spent in light or moderate activity intensity decreases. At the same time, Westerterp (2008) addresses the potential of a more active lifestyle in response to increased exercise, which would reduce time spent in sedentary activities.

A better understanding of TDEE and its components is necessary to provide proper information regarding nutritional intake during different training periods in athletes. Maintaining energy balance has been shown to be crucial for health and performance (Nogueira and Da Costa, 2005). While high-volume training may result in a negative energy balance, which increases the risk of injuries (Joy and Campbell 2005), infectious disease (Gleeson and Bishop 2000) or overtraining syndrome (Saris 2001), low-volume training may lead to a positive energy balance resulting in weight gain (Hill et al. 2003) – the latter which has larger implications for the obesity epidemic. Thus, Motonaga et al. (2006) argue that optimal performance can only be achieved if energy balance is maintained throughout the season. In addition, possible changes in time spent at different intensities in response to training need to be considered since it has been shown that time spent in sedentary activity is related to various chronic diseases independent of physical activity and energy expenditure (Hamilton, Hamilton and Zderic 2007).

Therefore, the purpose of this study was to examine changes in TDEE and its components, specifically EEE, NEAT, and RMR, in endurance trained athletes during high- volume and low-volume training periods. Further, differences in time spent in sedentary, light, and moderate-to-vigorous activity between a high-volume and low-volume week will be assessed. Finally, relationships between various components of TDEE and time spent at different intensities were examined.

METHODS

Subjects and study design. Fifteen male endurance trained athletes (23.6 ± 3.4 years) participated in the study for two non-consecutive weeks (mean 3 weeks, range 1 – 6 weeks between measurement periods), engaging in a high-volume and low-volume training week in random order. Sample size was established based on power calculations (power = 0.9) using reported differences in TDEE between training and non-training days (McLaughlin et al. 2006, Ribeyre et al. 2000). Using a sample size of 15 and a power of 0.9 differences as low as 400 kcal/day in TDEE could be detected assuming a previously reported standard deviation of 400 kcal/day (McLaughlin et al. 2006, Ribeyre et al. 2000). Power calculations using differences in EEE between training and non-training days (Martin et al. 2002, Vogt et al. 2005) provided even stronger power. Subjects who suffered from injury obtained prior to data collection or during data collection were excluded from the study. Further, subjects were excluded if they were purposefully trying to lose or gain weight.

Subjects were recruited through local running, cycling and triathlon clubs as well as word of mouth. General information about the study was distributed via e-mail and personal conversation. Interested subjects were then given more detailed information about the study. Upon agreement of participation, periods of data collection were identified based on the subject's training and competition schedule. In 9 subjects the first week of data collection was a high volume week followed by a low volume, with 6 subjects completing the study in reverse order. Data collection occurred during fall 2010. The study protocol was approved by the University's Biomedical Institutional Review Board and is in accordance with the Declaration of Helsinki. Each subject signed an informed consent and completed a health/medical history questionnaire prior to data collection.

Study Protocol. During each week of data collection participants reported to the laboratory three times – at the beginning, middle, and end of the training period. Assessments were performed in identical manner during high-volume and low-volume training weeks. During the first visit, height and weight were obtained by standard procedures (Malina 1995) and body composition was assessed via air displacement plethysmography (BodPod, Life Measurement, Inc., Pittsburgh, PA). Subjects were told to refrain from eating for 3 hours prior to reporting to the lab and avoid strenuous exercise for 6 hours prior to the body composition assessment. The BodPod has previously been shown to be reliable and valid. Noreen & Lemon (2006) reported a coefficient of variation of 0.15% and a standard error of measurement (SEM) between two BodPod measurements of 0.001 kg/L. The intra-class correlation coefficient (ICC) was significant at 0.996. Concerning validity, a non-significant mean difference between DXA and BodPod of 0.5% body fat was reported in female college athletes (Ballard, Fafara and Vukovich 2004). In a heterogenous male sample a high correlation (r=0.94) between DXA and BodPod was reported, but the difference between these two methods was 2.2% body fat (Ball and Altena 2004). These authors, however, showed that the difference was significantly lower in lean subjects ($p<0.001$), which makes the BodPod an adequate tool to assess body composition in a lean athletic male sample.

Following anthropometric assessments, subjects performed a maximal exercise test on a treadmill based on the following protocol from the British Association of Sport and Exercise Science for endurance athletes (Beashel and Taylor 1996): The warm up consisted of a 3 minute walk at 3.5 mph at 0% incline after which the speed was increased to 8 mph and subjects ran for 2 minutes at 0% incline. Following these initial 5 minutes, the incline increased by 0.5% every 10 seconds, while speed remained at 8 mph. The subjects continued the test until volitional exhaustion, which was indicated by holding on to a railing on the left and right side of the treadmill. Prior to leaving the laboratory subjects were given a Polar RS400 HR monitor (Lake Success, NY) and a SenseWear Armband Pro 3 (SWA, BodyMedia, Pittsburgh, PA) along with a verbal and written explanation on how and when to use these devices. The SWA was also initialized prior to giving it to the participant.

During the second visit RMR was measured. Since there are no differences in RMR values between spending the night prior to testing at home or at the testing site (Turley, McBride and Wilmore 1993), subjects spent the night at home and reported to the laboratory in the morning after on overnight fast, prior to having breakfast. They rested in the supine position for 15 minutes in a room with a temperature between 22°C and 24°C. Following the rest period, a ventilatory hood was placed over the subject's head and expired gases were measured for up to 20 minutes. The final visit consisted of anthropometrics and assessment of body composition. At this time subjects returned the SWA and the heart rate monitor. Heart rate data and SWA data were downloaded after each week of data collection and prepared for subsequent data analysis.

Assessment of TDEE. A combined methods approach was used to determine TDEE, and included assessments of RMR, NEAT and EEE. RMR, NEAT and EEE were initially determined as kcal/min and then summed accordingly to calculate TDEE.

RMR was assessed via indirect calorimetry (Parvo Medics True One ® 2400, Sandy, UT) during each week of data collection. The Parvo Medics system has been shown to be an accurate metabolic measurement tool for RMR. Compared to the Deltrac II Metabolic Montior (VIASYS Healthcare, Inc., SensorMedics, Yorba), which has been well established as a criterion reference system for RMR measurements (Alam et al. 2005) no significant differences in RMR ($p > 0.9$) or RER ($p = 0.7$) could be shown (Cooper et al. 2009). Concerning reliability the Parvo Medics system had a Coefficient of Variation (CV) of 4.8% (Cooper et al. 2009). Since Compher et al. (2006) argue that less than 20 minutes of rest before testing are sufficient to dissipate the effect of activities of daily living, such as getting to the laboratory, athletes rested in a supine position for 15 minutes prior to placing the ventilatory hood over the subject. Following the suggested protocol by Compher et al. (2006) the first 5 minutes of measurement were deleted. The average of 5 consecutive minutes with a CV of less than 10% was then used to determine RMR (kcal/min). Daily RMR was then calculated by multiplying the minute value by 1440.

NEAT and energy expenditure during sleep was assessed using the SWA, which is a non-invasive multi-sensor device that measures heat flux, galvanic skin response, skin temperature, near body temperature, and body motion via 2-axis accelerometry. The SWA is worn on the right triceps and starts to collect data once it is in direct contact with the skin. Data are sampled at 32 Hertz and stored in one-minute intervals. Based on proprietary algorithms the SWA provides minute-by-minute information on exercise intensity and energy expenditure. To assess sleep EE, subjects wore the SWA for at least two nights in addition to wearing it during waking hours for the entire period of data collection. Average sleep energy expenditure (kcal/min) was incorporated for nights when the SWA was not worn. Missing data during the day was interpolated based on the average energy expenditure (kcal/min) 5 minutes prior and 5 minutes post the missing data interval.

Various studies have shown accurate estimations of energy expenditure with the SWA at rest, low, and moderate intensities (Malavolti et al. 2007, Welk et al. 2007, St-Onge et al. 2007). At higher intensities, however, the SWA has been shown to underestimate energy expenditure due to a plateau at about 10 METs (Koehler et al.

2010, Drenowatz and Eisenmann 2011). Therefore, heart rate was used to determine EEE.

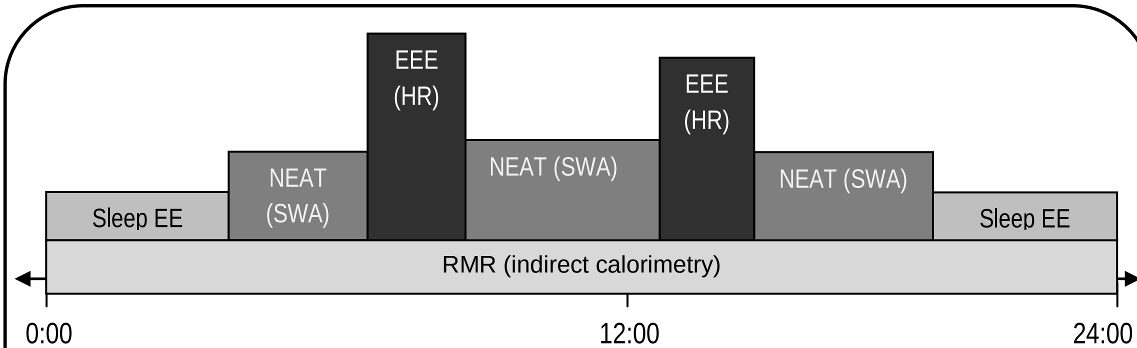
Estimating energy expenditure from heart rate (HR) is based on the assumption that there is a linear relationship between HR and oxygen consumption (VO_2) (Booyens and Hervey 1960). While this assumption may be problematic at lower intensities, it is well established for submaximal exercise of moderate to vigorous intensity, and Crouter et al. (2004) have shown that HR monitoring provides a reasonably accurate estimate of energy expenditure. A measurement error of less than 0.64 kcal/min (Bradfield, Huntzicker and Fruehan 1969) or 1.2% (Ceesay et al. 1989) has been shown when HR was compared to indirect calorimetry. Compared to DLW, HR has been shown to provide similar values of energy expenditure (Livingstone et al. 1990). Individual regression equations to determine EEE from HR were established based on the maximal exercise tests results performed at the beginning of each week of data collection. With the HR-VO_2 curve only being used for EEE, the standard protocol of assessing sedentary and light activities to determine the FLEX-HR was not necessary. Since the SWA was worn during the VO_2max test and during the exercise, skin temperature was available as well, but due it was not included in the regression analysis, since temperatures did no differ much during data collection. Since HR is a commonly used training tool for endurance athletes, measurement errors due to reactivity should have been minimal.

During the VO_2max test expired gases were measured with the Parvo Medics True One ® 2400 system (Sandy, UT). HR and VO_2 were recorded in minute-by-minute increments. The Parvo Medics system has been shown to measure VO_2 and CO_2

production accurately at various intensities compared to the Douglas bag method (Crouter et al. 2006). A coefficient of variation of 4.7% for VO_2 and 5.7% for VCO_2 between measurements on two separate days indicated high reliability.

Data Management. Minute-by-minute HR data (bpm) was exported into Microsoft Excel and converted to kcal/min based on the individual HR-VO_2 regression equation. To obtain true EEE (kcal/min), RMR (kcal/min) was subtracted from the EEE obtained via the HR regression equation. Similarly, SWA minute-by-minute values were exported into Microsoft Excel and corrected for RMR by subtracting the RMR value obtained via SWA during the RMR measurement. TDEE was then calculated by adding EEE (based on HR regression), NEAT including sleep (assessed via SWA), and RMR (assessed via indirect calorimetry). Figure 2.1. displays the contribution of the different components to TDEE.

<u>Figure 2.1: Determination of TDEE using SWA and HR Data (sum of kcal/min)</u>



For each minute there is a baseline RMR value. NEAT or EEE was added onto RMR for each minute and the minute-by-minute values were summed up for

Time spent in different intensities was also calculated based on energy expenditure (kcal/min). Using the individual resting energy expenditure as 1 MET, time spent in sedentary (< 1.5 METs), light (1.5 – 2.9 METs), moderate (3 – 6 METs) and vigorous (> 6 METs) activities were obtained by examining minute-by-minute data for each day of both measurement periods.

Statistical analysis. Descriptive statistics (mean and standard deviation) were calculated for each training period. After ensuring that data was normally distributed the following hypothesis were tested using parametric statistical tests.

H1a: *TDEE and EEE will be higher during a high-volume training week compared to a low-volume training week.*

H1b: *The difference in TDEE will be smaller than the difference in EEE.*

H2: *NEAT will be lower during a high-volume training week compared to a low-volume training week.*

H3: *RMR will be higher during a high volume training week compared to a low-volume training-week.*

H4: *Time spent in sedentary activities will be higher during a high-volume training week compared to a low-volume training week.*

H5: *Time spent in moderate-to-vigorous activity outside training will be lower during a high-volume training week compared to a low-volume training week.*

H6: *TDEE and NEAT will be inversely correlated with time spent sedentary.*

H7: *TDEE and NEAT will be directly correlated with time spent in moderate-to-vigorous activity.*

H8: *RMR will be directly correlated with time spent in vigorous activity.*

Hypotheses one through five were tested using dependent t-tests and hypotheses six through eight were tested using Pearson correlation. Significance level was set at an alpha level of $p < 0.05$ and all statistical analyses were performed in PASW 18.0.

RESULTS

Physical characteristics assessed at the beginning of each week of data collection and the time spent training for each week (high volume vs. low volume) are shown in Table 2.1. Average training time was twice as much during the high volume week compared to the low volume week (13.4 hours/week vs. 6.2 hours/week, respectively). All subjects possessed a VO_2max above 60 ml/kg/min and were lean (% fat range 5.4 to 17.3). An inverse relationship between VO_2max and fatness (%Fat and fat mass) was shown during each week of data collection ($r = -0.70$, $p = 0.01$, respectively). There were no significant differences in height (range 164.1 – 192.1 cm), weight (range 48.8 – 84.0 kg), BMI (range 18.3 – 24.6), %Fat, Fat mass, or fat free mass between the two weeks of data collection for measurements taken at the beginning of each week ($p > 0.05$). Except for a significant change in body weight during the high volume week (0.5 kg gain), no changes in anthropometric characteristics occurred during either week of training.

Figure 2.2 provides the average values for TDEE and its components during the high volume and low volume training weeks expressed per day while Table 2.2 displays components of TDEE per minute. There was a significant difference in TDEE between the high- and low-volume week (4824 ± 773 kcal/day vs. 4080 ± 638 kcal/day, $p < 0.01$). The physical activity level (PAL, determined as TDEE/RMR) was also significantly higher during the high volume week compared to the low volume week (2.1 ± 0.2 vs. 1.9 ± 0.2, $p < 0.01$).

Table 2.1: Physical characteristics of the sample (N=15) at the beginning of each week of data collection. Energy Expenditure values are averages for each week. Values are mean ± SD.

	High Volume Week	**Low Volume Week**
Training Time (min/day)	114 ± 17	54 ± 19
Height (cm)	182.1 ± 7.2	182.1 ± 7.2
Weight (kg)	73.4 ± 9.7	73.4 ± 9.7
Change in Weight (kg)	0.5 ± 0.6 *	0.0 ± 1.1
BMI (kg/m^2)	22.0 ± 1.8	22.1 ± 1.9
Change in BMI	0.1 ± 0.2	0.0 ± 0.3
%Fat	10.6 ± 3.9	11.0 ± 3.7
Change in %Fat	0.4 ± 1.3	0.2 ± 1.2
Fat Mass (kg)	8.0 ± 3.4	8.3 ± 3.3
Change in Fat Mass (kg)	0.4 ± 1.0	0.1 ± 0.9
Fat Free Mass (kg)	65.4 ± 8.0	65.1 ± 7.5
Change in Fat Free Mass (kg)	0.0 ± 1.3	-0.1 ± 1.0
VO_2max (ml/kg/min)	67.6 ± 5.5	66.6 ± 5.9

Change … pre- to post/measurements during each week of data collection (* $p < 0.02$)

Table 2.2: Components contributing to TDEE during the high and low volume training periods. Values are mean ± SD.

	High Volume Week	**Low Volume Week**
TDEE (kcal/day)	4823.7 ± 773.4	4070 ± 637.3
PAL (Physical Activity Level)	2.1 ± 0.2	1.9 ± 0.2
RMR (kcal/min)	1.6 ± 0.3	1.5 ± 0.2
NEAT (kcal/min)	1.1 ± 0.3	1.0 ± 0.2
Training EE (kcal/min)	11.3 ± 2.6	11.6 ± 2.5

Figure 2.2: Components of TDEE during high- and low volume week (Values ± SD)

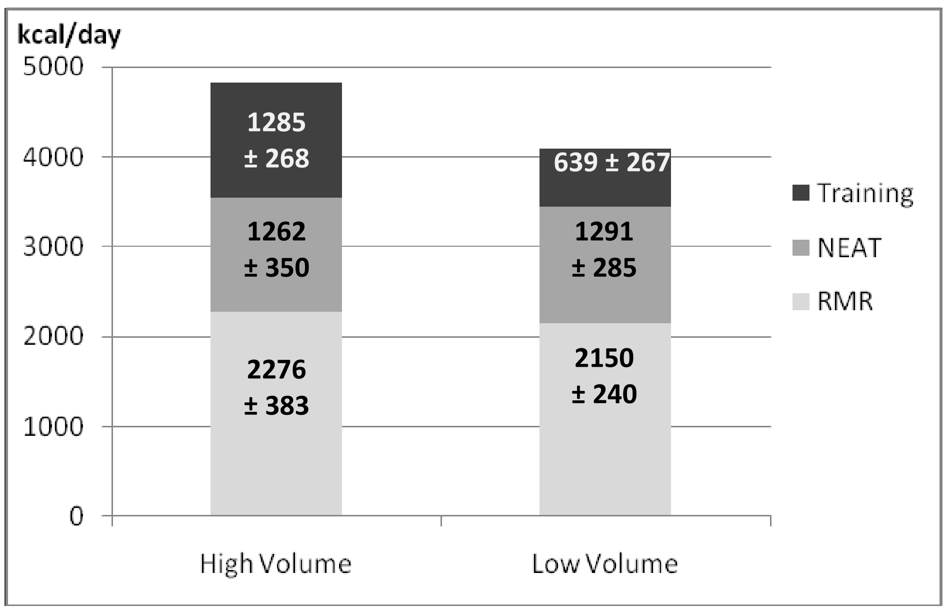
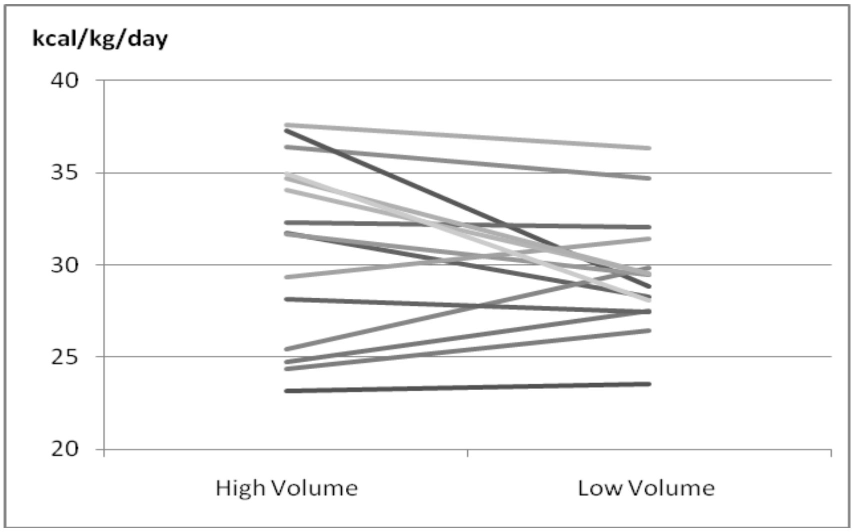


Figure 2.3: Individual Changes in RMR during the high- and low volume training period



EEE was significantly higher during the high volume week compared to the low volume week as well. This difference was due to increased training time since training intensity (kcal/min) did not differ between the two training weeks (Table 2.2). While no difference in NEAT occurred, a trend towards a higher RMR during the high volume week compared to the low volume week was observed (p = 0.09). The lack of significance may have been due to the wide inter-individual variability of RMR during the high volume week (inter-individual CV = 16.8%). Figure 2.3 shows the individual changes in RMR between the high volume and low volume training week to emphasize the tendency of a higher RMR with increased training volume. During low volume training, a lower RMR occurred in 9 subjects, while 4 subjects showed an increased RMR. Two subjects displayed a constant RMR during each measurement (change of 0.3 kcal/kg/day or 28 kcal/day). With no change in NEAT, the differences in EEE and RMR accounted for the difference in TDEE between the high- and low-volume training week.

Indeed, the difference of 646 kcal/day in average EEE plus the average difference of 126 kcal/day in RMR exceed the difference in TDEE (740 kcal/day) by only 32 kcal/day.

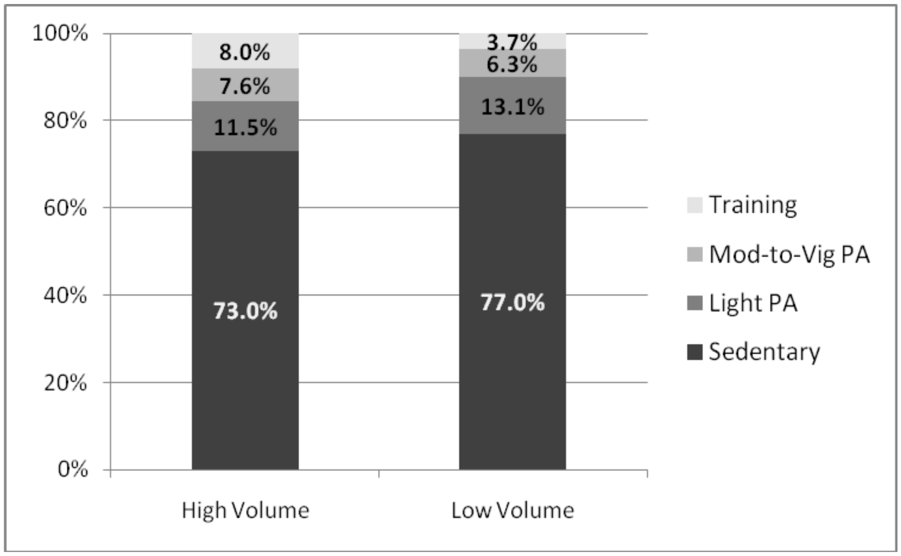
Table 2.3: Time spent at different activity intensities (min/day) among endurance athletes during the high and low volume training periods. Values are mean ± SD.

	High Volume Week	**Low Volume Week**
Sedentary (< 1.5 METs)	1051.2 ± 91.1 *	1108.3 ± 88.8
Light (1.5 – 2.9 METs)	164.9 ± 57.7	188.3 ± 79.7
Moderate (3 – 6 METs)	104.3 ± 44.4	85.6 ± 26.3
Vigorous (> 6 METs)	119.9 ± 16.8 *	57.7 ± 22.1
Vigorous (excl. training)	5.1 ± 3.0	5.2 ± 4.3

* significant difference between training weeks ($p < 0.01$)

Table 2.3 and Figure 2.4 show the amount of time spent at different intensities of activity. Again, training time was twice as high during the high-volume week compared to the low-volume week. Sedentary time was significantly lower during the high-volume week, while no significant differences were observed for time spent in light or moderate-to-vigorous activity. Excluding training time, only 5±3 minutes were spent in vigorous activity in either week of data collection (Table 2.3). There was also an inverse relationship between time spent sedentary and time spent in light and moderate activity ($r=-0.89$ and $r=-0.59$; $p \leq 0.05$). In addition, time spent in light activity was significantly correlated with time spent in moderate activity ($r = 0.56$, $p = 0.03$).

Figure 2.4: Average daily time spent in sedentary, light, moderate-to-vigorous activity and training



Concerning energy expenditure in relation to time spent at various intensities, TDEE was negatively correlated with time spent sedentary ($r = -0.64$; $p \leq 0.01$) and positively correlated with time spent in moderate activity ($r=0.69$, $p<0.01$). Similarly, NEAT was inversely related to sedentary time ($r = -0.83$; $p < 0.01$) and positively related to time spent in light and moderate activity ($r = 0.66$ and $r = 0.77$; $p < 0.01$, respectively). During the high volume week training EE was inversely related to time spent sedentary ($r = -0.54$; $p = 0.04$) and with higher variability in training time during the low volume week a significant positive relation between training EE and time spent in vigorous activity occurred ($r=0.90$; $p<0.01$). Further, there was a positive correlation between RMR and time spent in vigorous activity ($r = 0.53$; $p = 0.01$) during the low volume week.

There was also a significant relationship between training intensity and NEAT (kcal/min) during the high volume week ($r = 0.52$; $p < 0.05$). The lack of significance during the low volume week may be explained by the significantly higher intra-individual variability in training intensity during the low volume week (CV_{int} = 40.7% vs. 23.9%, $p < 0.01$). TDEE, however, remained fairly constant throughout each week of the training periods (intra-individual CV_{TDEE} = 14.2% and 15.0%, for high- and low-volume week, respectively). Finally, body composition was shown to influence various components of TDEE during the low-volume week. %Fat was inversely related to RMR ($r = -0.57$, $p < 0.03$) and positively related to NEAT ($r = 0.52$, $p < 0.05$). In addition, a significant correlation between BMI and TDEE occurred ($r = 0.52$, $p < 0.05$).

DISCUSSION

To my knowledge, this is the first study to examine various components of TDEE and their respective changes in response to changes in training regimen (e.g., high and low volume). It provides rich information on the TDEE, RMR, NEAT, and EEE as well as time spent in various intensities (sedentary, light, moderate, and vigorous) of male endurance athletes during periods of high- and low-volume training. As expected TDEE increased by 18% with higher training volume. The increase in TDEE, however, was higher than what could be attributed to EEE. It was further shown that TDEE remained fairly constant during either week of data collection and CV of the current study was similar to previously reported coefficients of variation (Wickel and Eisenmann 2006). No compensatory response in NEAT was observed and no adjustments in training intensity occurred in response to increased training time. However, during the high-volume week NEAT was significantly related to training intensity. Further, a tendency towards significance for higher RMR during the high-volume training period was observed. It was also shown that increased training time did not lead to a decrease in light, moderate, or vigorous activity but reduced the time spent in sedentary activities. In addition, time spent in sedentary activities was inversely related to TDEE and NEAT, while a positive relationship between NEAT and time spent in light or moderate activity was observed. Finally, it was shown that RMR was related to time spent in vigorous activity. RMR was also inversely related to %Fat while a positive relationship between %Fat and NEAT occurred. This increase in NEAT possibly contributed to the positive correlation between BMI and TDEE.

Even though a change in body weight (0.5 kg) was observed during the high-volume week, it was assumed that subjects maintained energy balance since no change in %Fat was observed in response to training. The small change in body weight is probably attributed to differences in hydration status and measurement error. Loucks (2004) also argued that body weight is not a good indicator of energy balance. Instead, changes in body composition, specifically fat mass and fat free mass, should be used to assess training-related changes in energy balance. In the current study, no change in body composition was observed within and between training periods and despite increased TDEE (and PAL) the suggested upper tolerable limit of PAL of 2.5 (Westerterp 2001) was not reached. A constant training intensity further suggests that athletes had sufficient energy available to maintain their training intensities. A potential increase in energy intake may have allowed the subjects to maintain training intensity and possibly energy balance.

Average TDEE (kcal/kg/day) during the high volume week was lower than previously reported values for TDEE in sub-elite middle- and long-distance runners during training days with two training sessions a day (Motonaga et al. 2006). In professional cyclists, however, similar values for TDEE adjusted for body weight were observed on training days, consisting of cycling for 160 km/day (Vogt et al. 2005). Grund et al. (2001) also reported TDEE between 4000 and 5000 kcal/day in endurance trained athletes which is similar to the results of this study. The difference in TDEE between the high- and low-volume training week was more pronounced than differences reported between an exercise (2844 kcal/day) and a non-exercise week (2462 kcal/day) in lean males (McLaughlin et al. 2006) but slightly smaller than that shown between cycling and non cycling days (Horton et al. 1994). The smaller difference compared to cyclists can be explained by the fact that athletes in the current study still engaged in 1 hour of training during their low volume week while Horton et al. (1994) compared training and non-training days. The contribution of EEE to TDEE (53% and 47%, during the high- and low-volume week, respectively) was also similar to previously reported studies of endurance athletes (Motonaga et al. 2006). While NEAT was similar compared to male varsity cross-country runners (Almeras et al. 1991) the contribution of NEAT to TDEE (26% and 32% during the high- and low-volume week, respectively) was lower than that reported by Motonaga et al. (2006). This study, however, did not assess RMR but rather used sleep energy expenditure, which may have resulted in higher NEAT since in this case RMR was included in habitual activity values during waking time.

Even though not statistically significant, results of the current study suggest a slight alteration in RMR in response to increased training volume. Several studies (Donahoo et al. 2004, McLaughlin et al. 2006) addressed potential increases in RMR due to changes in body composition. Other studies, however, showed no changes in sleeping metabolic rate or RMR (Bingham et al. 1989, Van Etten et al. 1997) and some have shown a reduction in RMR in response to training (Westerterp et al. 1992, Westerterp et al. 1994). Westerterp (1998) argues that a reduction in RMR would probably be a defense mechanism of the body in response to a negative energy balance. In contrast to these findings, results of the current study suggest an increase in RMR (+126 kcal/day) during high volume training despite no change in body composition. Sjodin et al. (1996) also reported higher RMR values in endurance athletes even when body composition was controlled for statistically. Ng (1994) argues that increased sympathetic nervous activity in response to high intensity training contributes to higher RMR in athletes. In addition, EPOC has been discussed as potentially influencing RMR (Speakman and Selman 2003) and with some athletes engaging in a training session the evening prior to the RMR measurement the next morning, EPOC may have still been present. Sjodin et al. (1996), however, reported a 13% to 16% higher RMR in elite cross country skiers 39 hours after their last training, which was not attributed to EPOC. Overall, Westerterp (1998) argues that there is no clear long-term effect of exercise on RMR, but acknowledged that TDEE is generally higher than the energy cost associated with training interventions. EPOC has also been discussed to increase NEAT (LaForgia, Withers and Gore 2006) which potentially could contribute to increased TDEE. In the current study no changes in NEAT were observed and rather an increase in EEE and RMR explained higher TDEE during the high volume week.

The lack of change in NEAT in this study is consistent with the findings of Almeras et al. (1991) who did not show a decrease in physical activity patterns during non-exercise time. Similarly, Van Etten et al. (1997) reported no change in non-training physical activity during a 18-week exercise training period. Several other studies

(Ribeyre et al. 2000, Westerterp et al. 1992, McLaughlin et al. 2006) have shown a decrease in NEAT with increased EEE, which was mainly attributed to post-exercise fatigue that would result in lower habitual physical activity (Westerterp 2008). The current study, however, showed a decrease in sedentary time with increased training. It was also shown that non-training vigorous activity was not related to time spent sedentary, whereas time spent in light and moderate intensity were inversely related to time spent sedentary. Westerterp (2008) suggested that higher exercise levels lead to a more active lifestyle which would increase time spent in light or moderate activity. This is supported by an average NEAT above 1200 kcal/day in the current study compared to NEAT values of up to 800 kcal/day in the general population (Ravussin et al. 1986). The positive relationship between light and moderate activity further supports the assumption of a more active lifestyle despite increased EEE. In addition, NEAT was more stable during the high-volume week, which suggests that a more regular exercise regimen helps to sustain a more active lifestyle.

The relatively high consistency of NEAT despite considerable variability in training time and EEE, especially during the low volume week also supports the hypothesis of a biological regulation of habitual physical activity rather than TDEE. Similar results were shown by Westerterp (1998) who did not show behavioral adaptation in response to increased exercise levels in young adults. A partial compensation, however, was observed in elderly subjects. Based on twin studies it is further argued that most of the variability in activity energy expenditure is explained by genetic factors (Westerterp 2008) which supports the hypothesis of a neural regulatory center for physical activity and energy expenditure. Specifically the hypothalamus has been suggested as a key area for the physiological control of energy expenditure (Shin et al. 2009, Thorburn and Proietto 2000) with leptin being an important messenger molecule to regulate physical activity (Pelleymounter et al. 1995). Interestingly, Martins et al. (2008) suggest that sensitivity to leptin rather than the concentration affect physical activity. While the exact regulation of activity energy expenditure is not fully understood, Levine and Kotz (2005) suggest a tight interaction between various components contributing to TDEE.

The contribution of EEE to TDEE along with increased post-exercise energy expenditure (Yoshioka et al. 2001) and the observed reduction in sedentary time may provide some additional benefits for metabolic health. Owen et al. (2010) propose that too much sedentary time is different from insufficient exercise. Increased sedentary behavior has been associated with increased risk for coronary heart disease independently of physical activity (Hamilton, Hamilton and Zderic 2004). In the present study, time spent at various intensities has been determined based on energy expenditure and EPOC may have resulted in higher energy expenditure after exercise, despite engagement in sedentary behavior. Interestingly, time spent in light or moderate activity was inversely related to time spent sedentary, while no relationship between time spent in vigorous activity and sedentary behavior was shown. NEAT was also only related to time spent in light or moderate activity, which supports the previously discussed possibility of a more active lifestyle with increased exercise. In particular, more than one exercise session a day may be beneficial since this leads to breaks in sedentary activity which can reverse the negative effects of sedentary behavior in addition to increase energy expenditure.

In summary, highly trained male endurance athletes did not show any compensatory adaptation in NEAT in response to high-volume training. There was also no adjustment in training intensity with increased training time. Further, a reduction in time spent in sedentary activities and a tendency towards increased RMR with increased training volume was shown. While this study examined endurance athletes, the results support the potential benefits of exercise interventions. Not only does exercise increase TDEE, but it reduces the time spent in sedentary activities which independently contributes to cardiovascular health (Owen et al. 2010, Hamilton et al. 2007). Further, the inverse relationship between NEAT and sedentary time shows the potential of a more active lifestyle with exercise. Even though the contribution of exercise to TDEE may remain relatively small in a previously sedentary population current results suggest a variety of positive effects in addition to an increase in TDEE. More research, however, is necessary to clearly evaluate the interaction between various components of TDEE in response to changes in an exercise regimen in different populations.

Future studies may also consider some of the limitations of the present study. Using endurance trained athletes, results of the present study may not necessarily be applicable to the general population. These athletes did not engage in a super-imposed intervention program, but rather followed their normal periodized training regimen. It also needs to be mentioned it is not known whether subjects just started their high-volume training period when data collection occurred or whether it was towards the end of a high volume training period. Subjects just starting a higher training volume may not display any compensatory response, while towards the end of a high-volume training period cumulative fatigue may cause behavioral changes. It was also not possible to ensure compliance with instructions on fluid and food intake prior to anthropometric measurements. Further, accurate assessment of dietary intake would provide information concerning nutritional adaptations in response to changes in training regimen. In addition, an observation period of one week may be too short to observe any adaptive behaviors. While the utilization of various methods to assess components of TDEE should be considered a strength of this study, potential of measurement errors still need to be considered when interpreting results of this study. Finally, a sample size of 15 may not have been sufficient to explore adaptive behavior in response to differences in training regimen despite a power of 0.89 for differences in TDEE. Nevertheless, the current study could be used as a framework for future studies examining changes in different components of TDEE in response to changes in exercise regimens.

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CHAPTER 3:

ENERGY EXPENDITURE AND DIETARY INTAKE DURING HIGH-VOLUME AND LOW-VOLUME TRAINING PERIODS AMONG YOUNG MALE ENDURANCE ATHLETES

ABSTRACT

BACKGROUND. Energy balance and nutritional intake are established contributors to athletic performance and health. Previous research, however, has not evaluated differences in energy expenditure in response to different training regimens or only assessed training/exercise energy expenditure (EEE) rather than considering total daily energy expenditure (TDEE) when examining dietary intake. The primary purpose of this study was to examine dietary intake in endurance trained athletes during a week of high-volume and a week of low-volume training while measuring EEE, resting metabolic rate (RMR) and non-exercise energy expenditure (NEAT) to calculate TDEE. A second purpose was to evaluate whether endurance athletes met current ACSM/ADA nutrition and performance recommendations for macro-nutrients and DRI recommendations for selected micronutrients .

METHODS. Energy expenditure and dietary intake were measured in 15 male endurance athletes (age 23.6 ± 2.4) during non-consecutive weeks of high-volume (> 13 hours/week) and low-volume (< 7 hours/week) training. Anthropometric measurements including %Fat were taken at the beginning and end of each week of training. TDEE was calculated by summing RMR, measured via indirect calorimetry, NEAT measured with the SenseWear Armband, and EEE using heart rate telemetry. Dietary intake was assessed with the Block online food frequency questionnaire completed at the end of each week of data collection.

RESULTS. No differences in body composition were observed during either week of training. While TDEE was significantly higher during the high-volume week (4824 ± 773 vs. 4080 ± 637 kcal/day), no significant differences in energy intake were

observed across the two training periods (2662 ± 1299 vs. 2487 ± 1213 kcal/day). The mean macronutrient composition of the diet also remained unchanged with carbohydrates (CHO), fat, and protein contributing 51%, 33%, and 16%, respectively. Based on g/kg body weight, the reported CHO intake (4.5 g/kg) was below recommendations (7-10 g/kg) as was dietary fiber intake (25 g vs. 38 g recommended). Total fat intake (1.3 g/kg) was slightly above recommendations and saturated fat intake was borderline (10% of total EI). Protein intake(1.4 g/kg) met recommendations. On average key micronutrients met or exceeded DRI recommendations with the exception of vitamin D and potassium. On an individual basis, however, a significant portion of the overall population displayed deficient micronutrient intake.

DISCUSSION. Dietary intake was not altered in response to changes in training volume or TDEE. The reported dietary intake was significantly lower than TDEE. The high dietary intakes of fat, sodium and sugars, and low dietary fiber intake suggests that these athletes were generally consuming a Western diet. Even though average micronutrient intake were generally in accordance with DRI, a significant portion of the sample did not meet current recommendations. Overall, these endurance athletes may require some help to achieve desirable intakes for health and performance.. Specifically, the low CHO intake is of concern for performance since it is the predominant fuel during training exercise.

Key Words: energy balance, energy intake, total daily energy expenditure, dietary adaptation, dietary pattern

INTRODUCTION

Optimal athletic performance is a complex outcome and the result of a combination of a multitude of factors including body size and composition, physical work capacities, training, and nutrition (Hinton et al. 2004). Proper nutrition has been shown to improve energy production and efficiency during sports (Kirkendall 1993) and it has been argued that nutritional habits during different training periods are highly important for performance and health (García-Rovés et al. 2000). Endurance athletes, in particular, require high energy and nutrient intakes due to their increased exercise levels, the resulting increased energy turnover, and metabolic adaptations (Rodriguez et al. 2009). Despite the recognition of the importance of nutrition for athletic performance, several studies have reported sub-optimal dietary intakes in various athletic groups (Sugiura, Suzuki and Kobayashi 1999, Burke et al. 2001, Tanaka, Tanaka and Landis 1995, Hawley et al. 1995). This observation may be due to the fact that many endurance athletes try to maintain a low body weight or lose weight in order to improve performance (Hinton et al. 2004). Inadequate energy intake (EI), however, may lead to short- and long-term health problems that alter performance. In athletes, a negative energy balance is of particular concern since it has been associated with an increased risk for infectious diseases (Gleeson and Bishop (2000), a higher prevalence of stress fractures (Joy and Campbell 2005) and overtraining syndrome (Saris 2001).

Besides meeting total energy demands, athletes need to ensure proper intake of macro- and micronutrients (Rodriguez et al. 2009). Carbohydrate (CHO) intake is especially crucial in endurance sports to ensure optimal muscle and liver glycogen levels to maintain blood-glucose levels that will sustain training and performance intensities as long as possible (Brown 2002). While athletes who achieve caloric requirements are generally able to meet dietary recommendations (Burke 2001b), Clark et al. (2003) showed inadequate macro- and micronutrient consumption in college athletes despite energy balance. Results regarding energy balance in endurance athletes have been equivocal. For example, Nogueira and DaCosta (2005) reported that EI is insufficient to meet energy demands in endurance athletes, while Burke (Burke 2001) argues that most cyclists successfully met dietary requirements even during prolonged competition requiring more than 6,000 kcal/day.

The assessment of dietary intake and energy expenditure is a major challenge in determining energy balance in athletes, since dietary information is mainly obtained via self-report which may lead to misrepresentation of dietary intake. Westerterp et al. (1986) reported a caloric intake of -39% compared to total daily energy expenditure (TDEE), despite the maintenance of body weight in endurance athletes. Body weight, however, may not always be the proper way to determine energy balance. Trappe et al. (1997) pointed out that short-term energy deficits of up to 2500 kcal/day would result in a fat loss of only 0.27 kg/day, which may not be detectable over a relatively short period (5 days), especially if lean body mass increases in response to training (Niekamp and Baer 1995). Therefore, changes in body composition, rather than body weight should be used as indicator for energy balance. It could also be argued that endurance athletes may experience a negative energy balance during high-volume training or competition, which may be compensated for by a positive energy balance during recovery periods with low-volume training to remain overall long-term energy balance. In certain circumstances athletes may also deliberately pursue a negative energy balance to lose weight.

Studies examining dietary intakes at different times of a season (García-Rovés et al. 2000, Martin et al. 2002, Nogueira and Da Costa 2005) indicate that athletes generally adjust their dietary intake according to training volume and the energy cost of training. These studies, however, did not actually measure TDEE or only examined training energy expenditure. The primary purpose of this study was to examine dietary intake in endurance trained athletes during a week of high-volume and a week of low-volume training week while measuring exercise/training energy expenditure (EEE), resting metabolic rate (RMR) and non-exercise energy expenditure (NEAT) to calculate TDEE. Of special interest was whether athletes adjust their diet in response to changes in TDEE to maintain energy balance. A second purpose was to evaluate whether endurance athletes met current ACSM/ADA (American College of Sports Medicine / American Dietetic Association; Rodriguez et al. 2009) dietary recommendations for macronutrients and Dietary Reference Intake (DRI) (Institute of Medicine) for selected micronutrients related to performance and health.

METHODS

Subjects. Dietary intake and energy expenditure were assessed in 15 male endurance athletes (23.6 ± 3.4 years; average VO_2max 67 ± 5.7 ml/kg/min). Each subject engaged in one week of high-volume (> 13 hours of training per week) and one week of low-volume training (< 7 hours of training per week). Data collection occurred during fall 2010 for two non-consecutive weeks that were on average 3 weeks apart (range 1 - 6 weeks). The order of the measurement weeks was randomized based on the subjects' training regimens. Nine subjects started with the high-volume training week followed by a low-volume training week, while six subjects started with a low-volume week followed by the high volume week. Subjects who were trying to lose or gain weight were excluded from the study. The study protocol was approved by the University's Biomedical Institutional Review Board and is in accordance with the Declaration of Helsinki. Each subject signed an informed consent and filled out a basic health/medical history questionnaire prior to data collection.

Study Protocol and Data Collection. A detailed description of the study protocol and measurement of energy expenditure was provided in chapter 2. In short, EEE was determined via individual heart rate regression, which was established based on the VO_2max test performance at the beginning of each week of data collection. NEAT was measured using the SenseWear Pro 3 Armband (BodyMedia, Pittsburgh, PA) which was worn during waking time and for at least two nights. RMR was measured via indirect calorimetry after an overnight fast in the middle of each week of data collection. Each participant reported to the laboratory three times during each week of data collection. During the first visit, which marked the beginning of data collection, anthropometric measurements, including %Fat via air-displacement plethysmography *(*BodPod, Life Measurement Inc., Concord, CA) were taken and a VO_2max test was performed. The second visit consisted of a RMR measurement and during the third visit, marking the end of data collection, anthropometrics were assessed again. TDEE was calculated by summing RMR, NEAT, and EEE.

Dietary intake was assessed via the Block online semi-quantitative food frequency questionnaire (FFQ) 2005 (NutritionQuest, Berkeley, CA; www.nutritionquest.com), which is commonly used to assess nutritional intake (Koebnick et al. 2005) in adults. Using the standardized instruction, study participants completed the online FFQ at the end of each week of data collection (high-volume and low-volume). The Block FFQ asks respondents to evaluate the frequency and serving sizes of foods and beverages consumed over the past week. The analysis provides an estimate of the subjects' macro- and micronutrient intake as well servings per day of key food groups for each week of data collection. These estimated nutrient values were compared to current ACSM/ADA nutrition and performance macronutrient nutrition recommendations for athletes (Rodriguez et al. 2009) and Dietary Reference Intake (DRI, Institute of Medicine) for micronutrients.

FFQs have been shown to be as accurate as multiple 24-hour recalls or food records (Block et al. 1992, Koebnick et al. 2005) while considerably reducing the burden of the participant and investigator. Compared to four days of food records the Block FFQ displayed similar results (<1% difference) for total caloric intake (Block et al. 1992). For macronutrients average non-significant differences between food records and the FFQ were 3.1% and mean correlations were 0.61 (Block et al. 1992). These values have been reported for food records or 24-hour recalls as well, but Sawaya et al. (1996) reported that results from FFQs were the only dietary assessment that significantly correlated with energy expenditure when examining dietary recalls, diet records, and FFQs. Concerning reliability of the Block FFQ Boucher et al. (2006) reported similar nutrient intakes and a median Pearson correlation of 0.75 between two FFQs administered roughly 60 days apart from each other. This value was higher than previously reported correlations ranging between 0.5 and 0.7 (Cade et al. 2002).

Statistical analysis. Descriptive characteristics of anthropometric measurements were calculated and the relationship between TDEE and nutritional patterns were examined by testing the following hypotheses:

H1a: EI will be similar to TDEE during the low volume week.

H1b: EI will be lower than TDEE during the high volume week.

H2: EI will be higher during the high-volume training week compared to the low-volume week.

H3: EI will be significantly correlated with TDEE.

H4a: CHO will be significantly correlated with EEE.

H4b: Fat intake will be significantly correlated with NEAT.

H5: CHO intake will be higher during the high-volume training week compared to the low volume training week.

H6a: Average macronutrient intake of the sample will be in accordance with ACSM/ADA recommendations when expressed as % of total caloric intake, but not when referring to intake in g/kg.

H6b: Average intake of selected micronutrients intake of the sample will be in accordance with DRI.

Hypotheses 1, 2, and 4 were tested using dependent t-tests and Pearson correlations were used to test hypothesis 3. Pearson correlations were also performed to explore possible relationships between macronutrient consumption and body composition. The comparison of the subjects' dietary intake to current dietary recommendations (H5) was performed on a group level as well as on an individual level. Similarly hypothesis 6 was tested by comparing group means to current recommendations as well as comparing individual results to dietary guidelines. Differences in anthropometrics were also examined within (beginning and end) each week of data collection using dependent t-tests to determine whether subjects maintained energy balance. All analyses were performed in PASW 18.0 and statistical significance was set at $p \leq 0.05$.

RESULTS

Physical characteristics of the sample during high and low volume training are displayed in table 3.1. There were no differences in anthropometric measurements and body composition at the beginning of each week of data collection. No changes in body composition (BMI, %Fat, fat mass, fat free mass) occurred during either week of data collection but a significant increase in body weight during the high volume week was observed. This, however, was not reflected with any significant differences in any body composition measures. During the low volume training week, no changes in body weight occurred.

TDEE was significantly higher than EI during either week of data collection (Figure 3.1). While TDEE differed significantly between the high- and low-volume training week, mainly due to increased training time (114 vs. 54 min/day) and accordingly increased EEE, there was no significant difference in dietary intake between the two weeks of data collection. Individual data, however, indicated that subjects who reported a higher caloric intake adjusted their intake more in response to different training periods no matter whether they started data collection with a high-volume or a low-volume training week (Figure 3.2). With no change in body composition during either week of data collection it was assumed that participants maintained energy balance. Assuming accurate assessment of TDEE due to the utilization of various measurements, EI would have been underreported by -45% and -39% of TDEE during the high- and low-volume week, respectively.

Table 3.1: Physical characteristics of the sample (15 male endurance athletes) at the beginning of each week. Values are mean ± SD.

	High Volume Week	**Low Volume Week**
Height (cm)	182.1 ± 7.2	182.1 ± 7.2
Weight (kg)	73.4 ± 9.7	73.4 ± 9.7
Change in Weight	0.5 ± 0.6 *	0.0 ± 1.1
BMI	22.0 ± 1.8	22.1 ± 1.9
Change in BMI	0.1 ± 0.2	0.0 ± 0.3
%Fat	10.6 ± 3.9	11.0 ± 3.7
Change in %Fat	0.4 ± 1.3	0.2 ± 1.2
Fat Mass	8.0 ± 3.4	8.3 ± 3.3
Change in Fat Mass (kg)	0.4 ± 1.0	0.1 ± 0.9
Fat Free Mass (kg)	65.4 ± 8.0	65.1 ± 7.5
Change in Fat Free Mass (kg)	0.0 ± 1.3	-0.1 ± 1.0

Change … Difference between the beginning and end of each week of data collection
* significant change within week of data collection ($p < 0.05$)

Despite the lack of significant differences in EI between the high- and low-volume training period a significant relationship between total caloric intake and TDEE (r=0.69, p<0.01) as well as total caloric intake and EEE (r=0.60, p=0.02) was observed during the high volume week. During this week, intake of individual macronutrients (g/kg) was also significantly related to TDEE and EEE (r=0.54, p<0.05 for CHO and Protein; r=0.58, p<0.03 for fat; respectively). During the low volume week, only fat intake was significantly correlated with TDEE (r=0.52, p=0.05). Fat intake (g/kg), was also significantly correlated with NEAT during either week of data collection (r=0.55, p<0.04, respectively). In addition, a significant positive relationship between fat intake (g/kg) and body mass index occurred during the low volume week (r=0.59, p=0.02).

Figure 3.1: TDEE and EI in male endurance athletes during high- and low-volume training periods

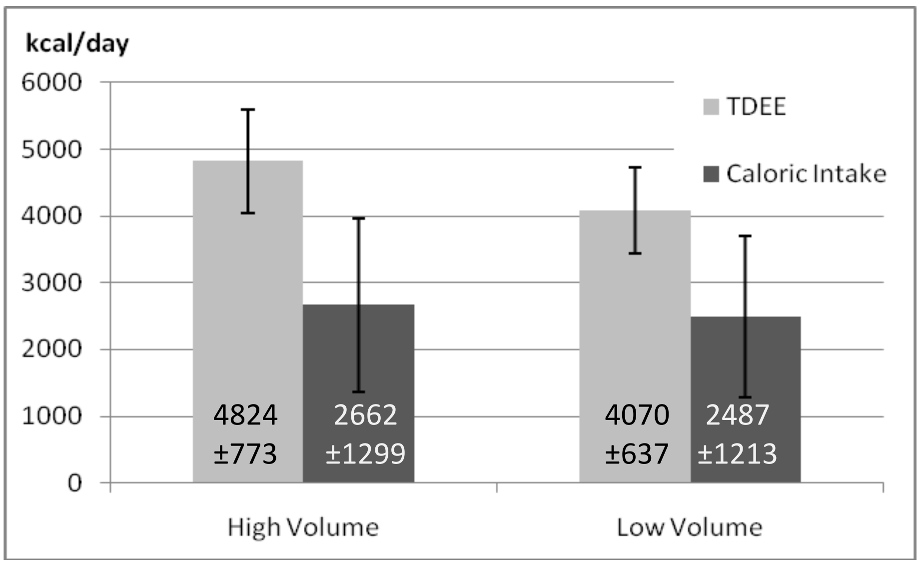

Figure 3.2: Individual changes in dietary intake from high- to low-volume training.

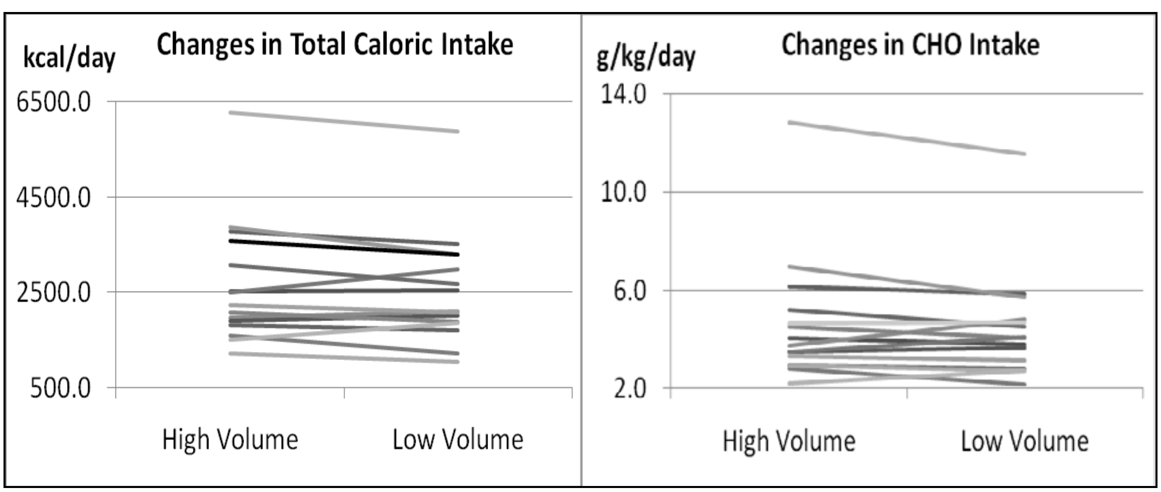

Figure 3.3: Macronutrient intake in during high- and low-volume training periods

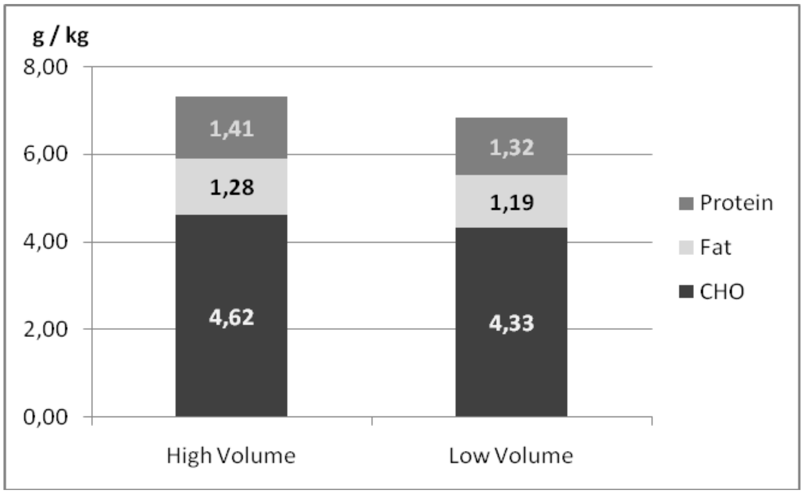

Table 3.2: Macronutrient intake of the sample (15 male endurance athletes) during high- and low-volume training, and comparison to sports nutrition recommendations. Values are mean ± SD.

	High Volume Week	**Low Volume Week**	**Sports Nutrition Recommendations**
CHO Intake (g/kg)	4.6 ± 2.6	4.4 ± 2.3	5 – 11
% CHO of total EI	*50.6 ± 3.8*	*51.0 ± 4.2*	*50 – 70*
% Simple CHO	*13.7 ± 7.3*	*13.3 ± 5.7*	*≤ 25*
Fiber (g/day)	24.8 ± 12.2	23.4 ± 11.2	≥ 38
Fat Intake (g/kg)	1.3 ± 0.5	1.2 ± 0.5	0.4 – 1.1
% Fat of total EI	*33.0 ± 2.8*	*32.7 ± 3.7*	*20 – 30*
% Sat. Fat	*10.6 ± 2.2*	*10.2 ± 4.9*	*≤ 10*
Protein Intake (g/kg)	1.4 ± 0.5	1.4 ± 0.5	1.2 – 1.7
% Protein of total EI	*16.5 ± 2.6*	*16.3 ± 2.1*	*10 - 30*

Recommendations based on ACSM/ADA "Nutrition and Athletic Performance", 2009

Figure 3.3 and Table 3.2 show the dietary composition during each week of training, along with the recommendations for dietary intake in athletes. There were no significant differences in macro- or micro-nutrient intake between the high-volume and low-volume training week when expressed in g/kg or as % contribution to total caloric intake. Comparing the dietary intake to current ACSM/ADA performance recommendations, fat intake (both % total caloric intake and g/kg) was above the recommendation, while CHO (g/kg) and fiber intake (g/day) were below the recommendation (Table 3.2).

Examination of individual data revealed that most participants (nine during high volume and eight during low volume) met the recommendations for % CHO intake but only four and three subjects actually consumed sufficient CHO when expressed as g/kg body weight during the high-volume and low-volume week, respectively. In seven subjects, fat consumption was above recommendations when expressed as g/kg body weight, but in 12 participants fat contributed more than 30% to their total caloric intake in both weeks of data collection. On average, protein intake was within the range of recommendations when reported as percent of total caloric intake, but only six subjects met protein intake targets in g/kg body weight. Four subjects reported protein intake below current recommendations (g /kg), while the protein intake of two subjects was above recommendations.

Average micronutrient intake exceeded current DRI except for Vitamin D and potassium (Table 3.3). Vitamin D intake was actually below DRI in all subjects and only three subjects met current recommendations for potassium. Individual examination further revealed that only one subject’s sodium intake was close to the current DRI of 1500 mg/day (1825 mg/day), with all other subjects exceeding 2000 mg/day. While average intake of other minerals was relatively close to current DRIs, calcium and magnesium intake were below recommendations in five subjects, zinc intake was below recommendations in three subjects and one subject's iron intake was below recommendations. Similarly, vitamin intake was below recommendations in one subject for vitamin B1 and B6, two for vitamin B3, and three for vitamin A. Interestingly, two subjects during the high volume week and five subjects during the low volume week did not meet vitamin C recommendations despite the average group intake being more than double the recommendations. Only two subjects reported taking multi-vitamin supplements.

Table 3.3: Micronutrient intake of the sample (15 male endurance athletes) during high and low volume training, and comparison to current recommendations based on DRI Reports (see www.nap.edu). Values are mean ± SD.

	High Volume	**Low Volume**	**DRI**
Vitamin B1 (Thiamin)(g/day) *	2.5 ± 1.5	2.4 ± 1.4	1.2 †
Vitamin B2 (Riboflavin)(mg/day) *	3.5 ± 1.5	3.2 ± 1.4	1.3 †
Vitamin B3 (Niacin)(mg/day) *	32.3 ± 17.7	30.3 ± 15.6	16 †
Vitamin B6 (Pyridoxine)(mg/day) *	3.0 ± 1.4	2.9 ± 1.5	1.3 †
Vitamin B12 (Cobalamin)(mg/day) *	8.4 ± 3.6	8.0 ± 4.2	2.4 †
Vitamin C (Ascorbic Acid)(mg/day)	154.8 ± 131.5	143.3 ± 115.0	90 †
Vitamin A (mcg/day)	1088.3 ± 300.8	1119.5 ± 464.8	900 †
Vitamin D (Calciferol)(IU)	303.3 ± 157.6	265.7 ± 131.1	600 ‡
Iron (mg/day) *	21.0 ± 12.7	20.3 ± 12	8 †
Magnesium (mg/day)	447.4 ± 183.4	410 ± 166.0	400 †
Calcium (mg/day)	1603 ± 662	1392 ± 619	1000 ‡
Sodium (mg/day) *	4204 ± 2075	3992 ± 2030	1500 ‡
Potassium (mg/day)	3621 ± 1309	3293 ± 1186	4700 ‡
Zinc (mg/day)	16.8 ± 7.5	14.9 ± 5.9	11 †

† RDA… Recommended Dietary Allowance; ‡ AI…Adequate Intake; * double the DRI

In summary, EI was lower than TDEE during either week of data collection and subjects did not adjust their dietary intake in response to differences in TDEE. Therefore, only hypothesis 1b can be accepted while hypothesis 1a and hypothesis 2 have to be rejected. Despite the lack of differences in dietary intake between a high-volume and a low-volume training week dietary intake was significantly correlated with TDEE, which confirms hypothesis 3. Hypothesis 4a needs to be rejected while hypothesis 4b was confirmed. With no differences in macronutrient intake hypothesis 5 is rejected as well. Macronutrient intake compared to dietary recommendations was sub-optimal, except for protein, while average micronutrient intake was adequate except for vitamin D, potassium and sodium. On an individual level, however, only 7 subjects displayed adequate micronutrient intake confirming refuting hypothesis 6b.

DISCUSSION

The main purpose of this study was to examine dietary intake in endurance trained athletes at different training intensities. Of primary interest was whether athletes are able to meet energy expenditure needs and whether macronutrient content changes in response to higher EEE. In addition, compliance with current dietary recommendations in these endurance athletes was assessed. It was shown that endurance athletes participating in this study did not adjust their dietary intake in response to different training periods. Despite the fact that EI was significantly lower compared to TDEE during either week of data collection no change in body composition was observed.

The small increase in body weight (0.5 kg) during the high volume week was primarily attributed to hydration status and measurement error. Loucks (2004) actually argued that body weight is not a reliable indicator when examining energy balance, since protein and glycogen stores are associated with increased water content. Further, increased lean body mass in response to high volume training (Niekamp and Baer 1995) could offset fat loss due to a negative energy balance. Trappe et al. (1997) further pointed out that short-term energy deficits of up to 2500 kcal/day would result in a fat loss of only 0.27 kg/day, which could be counterbalanced by increased protein or glycogen stores in response to training. Nevertheless, Motonaga et al. (2006) reported a significant weight loss with a negative energy balance of 730 kcal/day over 11 days in endurance runners. In the Motonaga et al. (2006) study, dietary intake was assessed via weighed food intake, which is considered to be more accurate than the more commonly used FFQs or food records to determine dietary behavior (Magkos and Yannakoulia, 2003). Overall, it was assumed that athletes in the current study maintained energy balance since %fat did not change throughout the time of data collection and differences in EI and TDEE may have been due to underreporting (Hill and Davies 2001). Previous studies using FFQs also reported significant underreporting in different populations (-15% to -28%) (Trabulsi and Schoeller, 2001).

Magkos and Yannakoulia (2003) suggest that the problem of underreporting might be even more pronounced in athletes when population-based FFQs are used since athletes have different dietary patterns and rely on different portion sizes due to their increased energy demands. Despite providing visual clues for portion size, two subjects specifically addressed the problem of estimating appropriate portion size when completing the FFQ. Burke (2001) further addressed the problem of an increased number of eating occasions in endurance athletes, which may make it more difficult to recall all foods consumed. Up to 9 discrete meals and snacks per day have been reported in endurance athletes with snacks contributing up to 37% of total EI (Magkos and Yannakoulia 2003). Omitting some of these smaller meals could result in significant underreporting of dietary intake and eating frequency was actually argued to be the best indicator for underreporting in men (Poslusna et al. 2009). Dietary recalls or food records face similar challenges and Ribas-Barba et al. (2009) argue that there is currently no single best method to assess nutritional intake. Due to the high subject burden using various methods to accurately assess TDEE, the utilization of a semi-quantitative FFQ nevertheless seemed to be justified. Magkos and Yannakoulia (2003) showed that a higher subject burden during a dietary assessment increased the risk for under-eating and under-reporting. Results by Sawaya et al. (1996), who showed that only FFQs compared to diet records and dietary recalls displayed a significant relationship between dietary intake and energy expenditure, provide further support for the utilization of a FFQ in this study.

With differences between reported dietary intake and measured energy expenditure in weight stable endurance runners between 22% (Schulz et al. 1992) and 32% (Edwards et al. 1993) it has been suggested that athletes possess a superior metabolic efficiency (Magkos and Yannakoulia 2003). Using DLW to accurately assess energy expenditure, however, showed increased energy expenditure in athletes and, therefore, the discrepancies between reported EI and energy expenditure were attributed to underreporting in weight stable athletes (Magkos and Yannakoulia 2003). In a review, Magkos & Yannakoulia (2003) reported that underreporting accounted for 10% to 45% of TDEE. Assuming accurate assessment of TDEE, the differences in the current study would still fall within that range. It has further been shown that underreporting of dietary intake increases with increasing TDEE (Magkos and Yannakoulia 2003), which is in accordance with findings of the current study. For example, EI did not change in professional weight stable cyclists over three weeks despite increasing energy expenditure (Westerterp et al. 1986). Blundell et al. (2003), however, argue that long-term coupling between EI and energy expenditure seems to be improved with regular exercise.

The relatively short observation time (1 week) during different training periods also may have contributed to the lack of dietary adjustments. Stubbs et al. (2002) did not show any adjustments in dietary intake over a period of 1 week in response to exercise training and Blundell et al. (2003) only showed incomplete adjustments during an exercise program lasting 16 days. Similarly, Martins et al. (2008) showed that compensatory dietary intake accounts for only 30% of energy cost of exercise during a 16 day training program. Other studies (Stubbs et al. 2002, Prentice and Jebb 2004, Westerterp et al. 1992) did not show any changes in dietary intake in response to changes in physical activity or TDEE either. For example, Westerterp et al. (1992) reported no adjustments in total caloric intake despite a 20% increase in TDEE during a 40 week marathon training program. The lack of dietary adjustment in response to increased training has been attributed to the reduction of hunger, especially after vigorous intensity exercise (Martins et al. 2008). Indeed, it appears there is a limited biological drive to match EI to activity induced energy expenditure following vigorous activity (Truswell 2001). Further, Rolls (2009) argued that people tend to eat a consistent amount of weight or volume of food and energy density of the food (i.e., dietary fat) is the major determinant of caloric intake. With no change in dietary pattern between the two weeks of observation in the current study a change in caloric intake, therefore, was unlikely.

In contrast to these findings, Garcia-Roves et al. (2000) reported changes in macronutrient composition during different training periods without any changes in total EI. Their subjects consumed a lower amount of CHO and protein during lower volume training periods which was compensated for by higher fat intake. Nogueira and DaCosta (2005) also reported higher CHO intake in response to higher training volume, but this increase actually resulted in higher EI in their athletes. Compared to previous studies of endurance athletes, CHO intake in the present study was lower (Burke 2001) while protein intake and fat intake were similar (Burke et al. 2003, Nogueira and Da Costa 2005). Clark et al. (2003) pointed out that college athletes are especially at risk for low CHO intakes while achieving energy balance due to higher protein and fat consumption. Despite the consideration of under-reporting the low CHO consumption in the athletes of the current study may be of concern, especially since the contribution of CHO to total EI was also on the lower end of current recommendations. With CHO being the primary fuel during exercise above 75% VO2max (Williams 1998) limited intake may hinder performance. Loucks (2004) argued that during prolonged sports participation CHO intake is the limiting factor to performance since glycogen stores have been shown to be depleted during prolonged exercise (Trappe et al. 1997, Williams 1998). Further, adequate CHO intake has been shown to minimize the rise in plasma levels of stress hormones like cortisol, catecholamines, and growth hormones which negatively affect immunity (Nieman and Pedersen 1999).

In addition to a low CHO intake, a low fiber intake was also reported. The low fiber intake and high fat consumption is typical of a Western diet (Cordain et al. 2005). In this study fat intake was also positively correlated with BMI. This was in contrast to Maughan and Piel Aulin (1997) who found an inverse relationship between EI and body fat content in runners. The major explanation for their finding was that increased training is related to increased dietary intake, but at the same time training volume is negatively correlated with body fat. The high sodium intake, which has been reported as a problem in current dietary patterns in many industrialized countries (Cordain et al. 2005), was also consistent with a Western diet. Athletes, however, do have increased sodium needs due to increased sodium loss with sweating (Valentine 2007). Therefore, sports drinks not only contain CHO to supply energy, but also provide sodium to avoid the negative aspects of hyponatremia (Murray 2007). The consumption of sports drinks during or post exercise could at least partially explain the high sodium consumption of these athletes.

As for sodium intake, there are currently no specific recommendations for athletes concerning micronutrient intake in general, but a higher consumption than current recommendations is suggested for optimal biochemical adaptations with exercise (Rodriguez et al. 2009). Specifically, routine exercise potentially increases turnover and loss of several micronutrients because of increased needs for building, repairing and maintaining muscle tissue. Of particular interest are calcium, iron, magnesium, zinc, and vitamins B, C, D and E (Rodriguez et al. 2009). Consistent with results shown by Garcia-Roves et al. (2000), average micronutrient intake in this sample met or exceeded current DRI except for vitamin D and potassium. Examining individual micronutrient intake results showed that less than 50% of this sample displayed adequate micronutrient intake.

The potential underreporting of dietary intake, however, needs to be considered when evaluating these results. Further, Ribas-Barba et al. (2009) argue that proper assessment of micronutrient intake and micronutrient status requires longer recording periods, exceeding one month.

Of particular concern may be the low vitamin D and potassium levels. Vitamin D is required for adequate calcium absorption and it contributes to bone health. Low vitamin D levels and/or lack of sun exposure may contribute to increased injury risks (Ruohola et al. 2006). With reported annual incidence rates of stress fractures of up to 21% (Kelly and Hame 2010) an appropriate intake of Vitamin D along with energy and hormonal balance needs to be emphasized (Nattiv 2000). Further, vitamin D and potassium are involved in homeostasis regulation in the nervous system and skeletal muscle (Rodriguez et al. 2009). Of additional concern are vitamin A and C, which are both related to immune function. A higher need for antioxidant nutrients has been suggested for endurance athletes due to the increased oxidative stress that accompanies intensive exercise training (Rodriguez et al. 2009). Further, vitamin C is needed for the synthesis of carnitine and red blood cells which are important components for aerobic capacity and fat metabolism. Especially during prolonged exercise fat metabolism is the primary fuel for exercise, which further emphasizes appropriate Vitamin C intake. Supplementation beyond current recommendations, however, has not been shown to increase performance and exceeding the tolerable upper intake levels may actually lead to a pro-oxidative effect with potential negative effects (Rodriguez et al. 2009). Excess vitamin C intake may also lead to gastrointestinal disturbances and kidney stones.

Despite the fact that EI did not differ between high- and low-volume training periods, there was a positive correlation between TDEE and EI in both weeks of training. This relationship has been observed in other studies (Magkos and Yannakoulia 2003, Burke 2001) and suggests some regulatory interaction between dietary intake and energy expenditure. Levine and Kotz (2005) suggest that biological regulatory mechanisms account for 75% of the variability and susceptibility to fat gain and a central mechanism to regulate physical activity according to EI and energy stores has been proposed. Energy expenditure or dietary intake set points, however, can be overridden by extrinsic factors like environmental conditions, peer influences and personal desires (Shin et al. 2009, Rowland 1998). Exercise has also been shown to support regulatory processes related to energy balance but Schoeller (1998) proposed a minimum threshold of a PAL of 1.75 in energy turnover rate for appropriate regulation of energy balance. While athletes in the current study exceeded this threshold during either week of data collection (PAL = 2.1 and 1.9 during high- and low-volume week, respectively), a stronger relationship between TDEE and EI occurred with a higher energy turnover during the high volume week. The significant relationship between NEAT and fat intake in these athletes further supports the hypothesis of a biological regulation of energy balance. Levine & Kotz (2005) consider NEAT as a crucial thermoregulatory mechanism between energy storage and dissipation since NEAT contributes the majority to activity energy expenditure in the general population.

In summary, the dietary pattern of these endurance athletes generally consisted of a typical Western diet and did not change in response to alterations in training regimen. The difference in EI and TDEE may be due to under-reporting, which has been previously hypothesized to explain a lower dietary intake in athletes (Schulz et al. 1992, Edwards et al. 1993, Magkos and Yannakoulia 2003, Westerterp et al. 1986). In subjects who reported higher caloric intake, some adjustments were observed. A more accurate assessment of dietary intake, therefore, may have shown some adjustments in dietary patterns in response to training regimens. Recently, cell phone technology has been introduced to obtain accurate information on dietary intake. Specifically, FIVR (Food Intake Visualization and Voice Recognizer) may provide more accurate information on dietary patterns by incorporating pictures and voice recordings (Weiss and others 2011). In addition to the problem of accurate assessment of dietary intake it should also be considered that the observation period was only one week each, which may not have been long enough for adaptations to occur.

It was also not known whether subjects just started their high- or low-volume training period or whether they have been engaging in the respective exercise volume for a prolonged period of time prior to data collection which could potentially lead to different adaptive behaviors. Further, fluid or food consumption prior to anthropometric measurements was not directly monitored. Subjects were asked to avoid food and drinks 3 hours prior to coming to the lab, but compliance could not be assessed. The small sample size may have been an additional limitation. Ribas-Barba et al. (2009) have shown that dietary assessments are more accurate on a population level compared to individuals. Finally, even though various measurements were combined to assess TDEE, energy expenditure may have been over-predicted. The differentiation of RMR, NEAT, and EEE, however, still was considered a strength of this study, since previous studies did not differentiate between these components when assessing dietary intake in response to energy expenditure.

Results of the current study also show that despite the importance of adequate dietary intake for optimal athletic performance, these athletes were not necessarily monitoring their diet closely in regards to meeting current recommendations during the non-competitive season. During competition or pre-competition, athletes may be more aware of their diet and even utilize specific sports nutrition or dietary supplements to enhance their performance. This discrepancy between performance and habitual dietary intake may be partially due to the available research since there is more research on the role of nutrition pre-, during, and post-training or competition and its impact on performance compared to evidence-based recommendations for habitual intake.

The lack of accurate assessment of overall dietary intake in any population makes it difficult to clearly establish a relationship between habitual intake and performance or health. Therefore, the development of accurate and applicable methods to assess daily dietary intake continues to be a critical area in order to enhance the understanding of the role of dietary intake on energy balance not only in endurance athletes but also in the general population. Athletes may be more willing to adjust their diet according to recommendations with easier methods to track dietary intake. While accurate CHO intake seems to be most crucial for optimal performance and health (Maughan 2002, Magkos and Yannakoulia 2003), Loucks (2004) argues that all macronutrients are vital since they are metabolized differently. In addition to performance-related aspects of adequate nutrition, energy balance needs to be maintained to reduce the risk of infections (Maughan 2002) and avoid compromises in musculoskeletal or metabolic functions

(Rodriguez et al. 2009). With adequate caloric intake micronutrient intakes are generally in accordance with current recommendations as well, which further ensures adequate health and contributes to optimal performance.

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CHAPTER 4:

SUMMARY OF FINDINGS AND FUTURE DIRECTIONS

The present study provides detailed information on energy expenditure and dietary intake of endurance athletes. To my knowledge, this is the first comprehensive study that examined resting energy expenditure (RMR), habitual energy expenditure (NEAT), exercise energy expenditure (EEE), and diet simultaneously during periods of low- and high-volume training. The major finding was that male endurance athletes did not adjust their habitual activity or dietary behaviors in response to changes in training volume. Overall, total daily energy expenditure (TDEE) was higher during high-volume training and this was primarily accounted for by the energy expenditure during training. RMR, however, also showed a tendency to increase with higher training volume. Training intensity was not related to training volume but increased training volume reduced the time spent sedentary. There were no changes in time spent in light or moderate activity with different training volume. Reported dietary intake was significantly lower compared to total daily energy expenditure (TDEE), but this was probably due to underreporting rather than under eating, since body composition (%fat, fat mass, fat free mass) did not change throughout the observation period. Finally, these athletes consumed a Western diet (e.g. low fiber, high fat, and high sodium content) with a carbohydrate (CHO) intake below recommendations for athletes, while protein intake was in accordance with recommendations. On average, micronutrient recommendations (Dietary Reference Intakes, DRI, Institute of Medicine) were generally met which supports the statement that with the consumption of a diverse diet and accurate caloric intake no micronutrient supplementation is necessary (Rodriguez and others, 2009).

TDEE was similar to previously reported TDEE in cyclists (Vogt and others, 2005) and runners (Motonaga and others, 2006). Results on specific interactions and the contribution of EEE to TDEE were also in agreement with previous reports (Motonaga and others, 2006). In accordance with reported results previous studies have also shown that exercise training does not lead to changes in habitual physical activity in young adults (Westerterp, 2008). Studies of endurance athletes, however, indicated at least a partial compensatory reduction in NEAT in response to increased energy expenditure with training (Nogueira and Da Costa, 2005; Westerterp and others, 1992). Nogueira & DaCosta (2005) argued that the extremely high EEE in athletes may limit the opportunity for dietary intake adaptations, which necessitates a reduction in energy expenditure in other components to maintain energy balance. Further, increased post-fatigue could lead to a reduction in NEAT (Westerterp, 2008). PAL levels in the current study, however, were well below reported upper tolerable limits (Westerterp and Plasqui, 2004) and, therefore, no adaptive responses in habitual behavior may have been required.

The lack of changes in dietary intake between high-volume and low-volume training weeks was consistent with previous studies as well (Martins and others, 2008; Westerterp and others, 1986). Martins et al. (2008) reported no changes in dietary intake with the incorporation of an exercise program in lean and obese populations and Westerterp et al. (1986) showed constant food intake despite increasing intensity during a 3 week cycling race. On the other hand, several studies reported at least partial dietary adaptations in response to changes in training regimen in athletes (Blundell and others, 2003; Martins and others, 2008). These studies, however, were conducted over a longer period of time. In addition, nconsistent results between studies can be partially attributed to problems in accurately assessing dietary intake, especially concerning under-reporting (Hill and Davies, 2001; Magkos and Yannakoulia, 2003), which has been shown to become more pronounced with increased TDEE (Managkos and Yannakoulia, 2003). Results of the present study underline this concern, since dietary intake was significantly lower (-42%) than TDEE without any changes in body composition throughout the observation period. Trappe et al. (1997) pointed out that short-term energy deficits of up to 2500 kcal/day would result in a fat loss of only 0.27 kg/day, which may not be detectable over the relatively short measurement periods. Further, Niekamp & Baer (1995) have shown increased lean body mass in response to training which may counterbalance fat loss in response to a negative energy balance. It could also be argued that endurance athletes experience an energy deficit during competitive events or short periods of high volume training, which would be compensated for by a positive energy balance during low volume training periods. Since a negative energy balance occurred during either training period the assumption of underreporting, however, seems likely.

Results of the present study also indicate that athletes may need guidance in achieving optimal dietary intake. Similarly to Clark et al. (2003) CHO intake was below recommendations, while fat intake was above current dietary recommendations for athletic populations. With CHO intake being considered as is the limiting factor to performance during prolonged sports participation at high intensity (Loucks, 2004) a low CHO consumption may be particularly problematic. Indeed, Hampson et al. (2001) showed that starting with lower glycogen stores leads to a down-regulation of power output at the beginning of a time trial to preserve glycogen for the final part of the stage. Loucks (2004) further reported that large shifts in glycogen stores have not been shown to lead to changes in ad libitum macronutrient intake and, therefore argues for a conscious effort to ensure proper dietary intake. This may be even more important during high volume training periods since hunger has been shown to be suppressed after intensive exercise bouts (King and others, 1997).

Although this study examined endurance athletes, several insights may be of interest to the general population as well. In addition to the lack of a compensatory response to increased EEE, results of the current study suggest increased RMR in response to higher training volume. Even if intensity and/or volume of exercise may not be sufficient for prolonged effects of EPOC, an increase in fat free mass in response to training could alter RMR (McLaughlin and others, 2006). The bigger impact, however, may be an increase in NEAT due to a more active lifestyle in response to exercise training (Westerterp, 2008). In addition, Drenowatz et al. (2011) showed a better diet quality in more active adolescents, which also supports a healthier lifestyle with increased physical activity. Further, increased energy expenditure has been shown to increase the sensitivity of regulatory mechanisms concerning energy balance (Schoeller and others, 1997). Finally, it was shown that increased exercise time reduced time spent in sedentary behavior but did not lead to adaptations in time spent in light and moderate activity. Even time spent in vigorous activity outside the exercise regimen remained constant. With sedentary behavior being an independent risk factor to various chronic diseases (Hamilton and others, 2004), the reduction in sedentary time would provide an additional benefit of increased exercise levels.

While this study supports the importance of physical activity for weight management and health several limitations need to be addressed. It remains questionable whether responses to increased exercise volume would be similar in a less trained population. The subjects in this study have experienced high volume training prior to data collection and the difference in training volume was due to periodization of training rather than a specific exercise intervention. Nevertheless, previous studies also suggested that increased EEE does not result in a compensatory response in lean (Westerterp, 2008) and overweight adults (Hollowell and others, 2009). There is also evidence that dietary compensation is only limited and incomplete in response to increased exercise (Martins and others, 2008) and possible changes in body composition in response to increased exercise may influence RMR, even if intensity and volume is not sufficient to affect EPOC (McLaughlin and others, 2006).

In addition to the specificity of the sample, the accuracy of the assessment methods needs to be addressed. While indirect calorimetry for RMR, the SenseWear Armband for NEAT, and heart rate telemetry for EEE have been shown to provide accurate results for energy expenditure, a certain measurement error still remains. Of bigger concern, however, was the dietary assessment. Trabulsi and Schoeller (2001) argue that there is currently no single best method to accurately determine habitual dietary intake and that the method largely depends on the research question. A food frequency questionnaire has been used to determine dietary intake since the assessment of TDEE already put considerable subject burden on the participants and previous studies did not show an advantage of multiple 24-hour recalls or food records (Trabulsi and Schoeller, 2001). Increased eating frequency and accurate estimations of serving size have been the primary concern in athletic populations (Magkos and Yannakoulia, 2003). Poslusna et al. (2009) showed that meal frequency is the best predictor for underreporting and with athletes consuming up to 9 discrete meals (Magkos and Yannakoulia, 2003) with snacks contributing up to 40% of total caloric intake (Burke, 2001) a significantly lower energy intake may be reported. Recently, cell phone technology has been used to assess dietary intake. Specifically, Weiss et al. (2010) suggest a Food Intake Visual and voice Recognizer (FIVR), where pictures as well as verbal descriptions of foods are recorded with cell phones for subsequent analysis. Further, compliance with the instructions concerning food and drink consumption as well as exercise prior to anthropometric measurements was not assessed and changes in hydration status as well as exercise close to body composition assessment could have altered results. Finally, sample size may be questioned as well. Differences in TDEE were assessed with a power of 0.89, but to establish clear relationships between other components of the energy balance a bigger sample may be necessary. When examining a more diverse sample with less pronounced differences in exercise regimen, a bigger sample size is most likely needed as well to accurately determine the effect of an exercise program on various components of energy balance.

Nevertheless, the current study provides a good framework for future studies that examine the interaction of RMR, NEAT, EEE, and dietary intake in response to changes in an exercise regimen. Accurate assessment of various aspects related to energy balance with reasonable subject and investigator burden may remain of primary concern but results gained could still provide important insights concerning the regulation of TDEE and dietary intake. Further, longer measurement periods may be necessary to obtain a better understanding of regulatory processes since it has been shown that behavioral as well as biological adaptations require some time and may not be detectable within one week. Inclusion of biomarkers (e.g., leptin or ghrelin levels) could provide additional insights into the regulatory processes of energy expenditure and energy intake as well.

Given the problem of overweight and obesity, continued research is warranted to fully understand the regulation of energy balance. Addressing different athletic populations would also help in ensuring energy balance which is necessary for optimal performance and health.

RECOMMENDATIONS FOR FUTURE RESEARCH

I plan to continue this line of research, which will hopefully provide further insight on the complex regulation of energy balance. A better understanding of the interaction of the components contributing to energy balance should help to develop more accurate and successful intervention programs to address the current problem of overweight and obesity as well as help athletes in achieving their full potential.

The following studies are suggested for future research:

- Follow various athletic populations over a longer period of time (3-4 weeks per training period) to better examine adaptations and potential changes in body composition in response to changes in exercise. In addition, this approach should clearly establish when in their respective training period data collection takes place – at the beginning of a new training cycle or towards the end of a consistent training volume.
- Examine adaptations in response to an exercise regimen in previously non-active or sedentary people. Further, a differentiation between normal weight and overweight or obese subjects should be made. In addition different age groups need to be studied, since previous studies suggested differences in adaptive behavior between young adults and elderly.

- The incorporation of different exercise programs need to be considered as well, since there may be a threshold where compensatory changes may start to occur.
- Finally a refinement of assessment methods, especially concerning dietary intake is needed. Using a single device to assess different components of TDEE, multiple day food logs or multiple 24-hour recalls may provide additional insights in the regulation of energy balance.

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