OPEN

Medicine & Science IN Sports & Exercise

The Official Journal of the American College of Sports Medicine
www.acsm-msse.org

. . . Published ahead of Print

Maximal Fat Oxidation Rates in an Athletic Population

REBECCA K. RANDELL[1], IAN ROLLO[1], TIMOTHY J. ROBERTS[1], KORTNEY DALRYMPLE[1], ASKER E. JEUKENDRUP[2], and JAMES M. CARTER[1]

[1]The Gatorade Sports Science Institute, Global Nutrition R&D, PepsiCo, Leicester, United Kingdom; [2]School of Sports Exercise and Health Sciences, Loughborough University, Loughborough, United Kingdom

Accepted for Publication: 11 August 2016

Medicine & Science in Sports & Exercise, Publish Ahead of Print
DOI: 10.1249/MSS.0000000000001084

Maximal Fat Oxidation Rates in an Athletic Population

REBECCA K. RANDELL[1], IAN ROLLO[1], TIMOTHY J. ROBERTS[1],

KORTNEY DALRYMPLE[1], ASKER E. JEUKENDRUP[2] AND JAMES M. CARTER[1]

[1]The Gatorade Sports Science Institute, Global Nutrition R&D, PepsiCo, Leicester, United Kingdom; [2]School of Sports Exercise and Health Sciences, Loughborough University, Loughborough, United Kingdom

Address for Correspondence:

Rebecca K. Randell

Gatorade Sports Science Institute

PepsiCo Global Nutrition R&D

Beaumont Park

4 Leycroft Road

LEICESTER

LE4 1ET

United Kingdom

Tel: +44(0) 116 236 8848

Email: rebecca.randell@pepsico.com

Acknowledgments

The results of this study are presented clearly, honestly and without fabrication or inappropriate data manipulation and statement that results of the present study do not constitute endorsement by ACSM. R.R, J.C, I.R, T.R and K.D are employees of The Gatorade Sports Science Institute, a division of PepsiCo, Inc. A.J is a consultant for The Gatorade Sports Science Institute. The views expressed in this article are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc. Financial support for this study was provided by the Gatorade Sports Science Institute, a division of PepsiCo, Inc.

Short Title: Fat Oxidation in Athletes

ABSTRACT

Introduction: The aim of this study was to describe maximal fat oxidation (MFO) rates in an athletic population. **Method:** In total, 1121 athletes (933 males, 188 females), from a variety of sports and competitive level, undertook a graded exercise test on a treadmill in a fasted state (≥ 5 h fasted). Rates of fat oxidation were determined using indirect calorimetry. **Results:** Average MFO was 0.59 ± 0.18 g·min^{-1}, ranging from 0.17 – 1.27 g·min^{-1}. Maximal rates occurred at an average exercise intensity of 49.3 ± 14.8% $\dot{V}O_2$max, ranging from 22.6 – 88.8% $\dot{V}O_2$max. In absolute terms, male athletes had significantly higher MFO compared to females (0.61 and 0.50 g·min^{-1} respectively, $P < 0.001$). Expressed relative to fat free mass (FFM), MFO were higher in the females compared to males (MFO/FFM: 11.0 and 10.0 mg·kg·FFM^{-1}·min^{-1} respectively, $P < 0.001$). Soccer players had the highest MFO/FFM (10.8 mg·kg·FFM^{-1}·min^{-1}), ranging from 4.1 – 20.5 mg·kg·FFM^{-1}·min^{-1}, whereas, American Football players displayed the lowest rates of MFO/FFM (9.2 mg·kg·FFM^{-1}·min^{-1}). In all athletes, and when separated by sport, large individual variations in MFO rates were observed. Significant positive correlations were found between MFO (g·min^{-1}) and the following variables: FFM, $\dot{V}O_2$max, FATMAX (the exercise intensity at which the MFO was observed), percent body fat (%BF) and duration of fasting. When taken together these variables account for 47% of the variation in MFO. **Conclusion:** MFO and FATMAX vary significantly between athletes participating in different sports but also in the same sport. Although variance in MFO can be explained to some extent by body composition and fitness status, more than 50% of the variance is not explained by these variables and remains unaccounted for. KEYWORDS: Fat Oxidation; Athletes; Exercise Metabolism; Physiology

INTRODUCTION

Carbohydrate (CHO) and fat are the predominant energy sources during exercise (18). The absolute and relative contributions of CHO and fat are dependent upon a number of variables; of these, exercise intensity has been reported to be the single most important factor influencing substrate utilisation (15, 34). In general, fat oxidation increases from low to moderate intensity and then decreases from moderate to high (8, 18). The contribution of fat and CHO to energy expenditure is sometimes measured using prolonged (30-120 min), continuous exercise bouts, varying in intensity and with each intensity performed on a separate day (34). However, multi-day approaches make the interpretation of results difficult because of the day-to-day variation in metabolism (as a result of diet and other factors) and increases the variability of substrate oxidation (37).

In order to describe fat oxidation over a wide range of exercise intensities a protocol was validated, that was relatively quick and allowed measurements to be recorded in a single visit to the laboratory (1). The protocol, often referred to as a FATMAX test, provides a measure of maximal fat oxidation (MFO; the highest rate of fat oxidation observed at various intensities), as well as the exercise intensity (most commonly represented as a percentage of maximal oxygen uptake (%$\dot{V}O_2$max)) at which MFO occurred (FATMAX). First developed on a cycle ergometer, the test involves continuous increases in work rate, every 3 min by 35 W, until exhaustion. Throughout the test breath by breath measurements are obtained and rates of fat oxidation are calculated (using stoichiometric equations) for each stage of the test. Since this inaugural study a treadmill FATMAX test protocol has also been developed (5). In addition, studies investigating

the reproducibility of MFO and FATMAX using this test protocol have found small intra-individual variation (1).

Numerous studies have since used the FATMAX test, performed on either a treadmill or cycle ergometer, to determine fat oxidation rates in trained (3, 12, 13, 25, 31), untrained (25, 31), obese and sedentary (35) adults. Although not an exhaustive list, the data presented in Table 1 shows the group average MFO and FATMAX of several key studies in this area. An interesting observation from these data is that large inter-individual differences exist in both MFO and FATMAX, within each study, and between studies that have recruited similar participants in terms of fitness level, age and body composition (Table 1).

In 2005 Venables et al. (35) performed a cross sectional study of 300 individuals, ranging in body composition and aerobic capacity and described MFO and FATMAX as well as the factors that influenced these parameters. The authors observed that on average MFO was 0.46 ± 0.01 $g \cdot min^{-1}$ with a wide range of 0.18 – 1.01 $g \cdot min^{-1}$ (35). MFO occurred at an average exercise intensity of 48 ± 1% $\dot{V}O_2max$, again with a wide range (25 – 77% $\dot{V}O_2max$). Fat free mass (FFM), self-reported physical activity, $\dot{V}O_2max$, sex and fat mass (FM) accounted for 34% of the variance, the authors speculated that habitual diet, phase of menstrual cycle (females only) and endurance training may also contribute to the remaining 66% of the variance that was unaccounted for. More recent studies, albeit using smaller sample sizes, have found no difference in MFO between low fat (< 25% body fat) and high fat (> 25% body fat) women (6) or in lean and obese individuals when matched for $\dot{V}O_2max$ (12).

Typically, athletes have higher rates of fat oxidation compared to untrained individuals at a given relative and absolute exercise intensity (3, 25, 31). This may be a result of endurance-type training which increases fat oxidation rates during submaximal exercise when performed at the same absolute intensity (23, 26). This type of training augments skeletal muscle and whole body adaptations to promote fat oxidation (19). In addition, the muscle phenotype of trained individuals often contains high intramuscular triglyceride (IMTG) content, located close to the mitochondria, suggesting an increased availability for oxidation (27). Periods of endurance-type training also increases mitochondrial mass which will allow greater fat oxidation and reduce the need for energy production through glycolysis at sub-maximal exercise intensities (33).

Currently there are no normative data on MFO rates and FATMAX from an athletic population. Furthermore, no study to date has compared fat metabolism of athletes ranging in age, body mass, $\dot{V}O_2$max and sporting activity. Therefore, the purpose of the present study was to establish MFO and FATMAX normative data in athletes and to investigate which physiological factors may account for any inter-individual variation.

PARTICIPANTS AND METHODS

General Design

Data were collected from two separate exercise physiology laboratories; 1) The Gatorade Sports Science Institute (GSSI), IMG Academy, Bradenton, Florida, US (GSSI US) and 2) GSSI, Loughborough University, Loughborough, UK (GSSI UK). Data were selected for analysis from athletes who performed an incremental treadmill test (FATMAX test) during a single visit to either test location. In total, data from 1121 athletes were included, of which 933 were male and

188 were female (819 athletes were tested at GSSI US and the remaining 302 were tested at GSSI UK), representing 27 different sports / events (Table 2). Whole body rates of fat oxidation were calculated during each stage of the exercise test, using indirect calorimetry, to establish MFO and FATMAX.

Participants

All volunteers were recruited via e-mail, personal visits / meetings, telephone calls or the athlete personally contacting the testing facility. The majority of the athletes were recruited from the student pool at the IMG academy, the student pool at Loughborough University and athletes local to the GSSI UK and GSSI US area.

The 1121 athletes recruited for this study ranged in competitive level. The inclusion criteria were the same for all athletes with the exception of age which was 16 – 60 *y* in GSSI UK and 13 – 40 *y* in GSSI US, due to subject availability proximal to the two laboratories. Additional inclusion criteria included regular training or participation in sporting activity, healthy (assessed by completion of a general health questionnaire) and no known cardiovascular or metabolic disorders. Local ethical approval was obtained for each of the study sites. For GSSI UK the study was approved by the South Birmingham NHS National Research Ethics Committee (West Midlands, UK). For GSSI US the study was approved by The Sterling Institutional Review Board, Atlanta, Georgia.

On initial contact the purpose and nature of the study and an in-depth explanation of the testing protocol was explained to all volunteers. Informed consent from all athletes was collected either

prior to the testing day or signed on-site on the morning of the test. In addition, if volunteers were under the age of 18, parental consent was obtained from. All volunteers were healthy as assessed by a general health questionnaire. Prior to testing medical clearance was obtained for all participants who completed the testing at GSSI US.

Experimental Design

Each athlete reported to the laboratory in a fasted state (≥ 5 h) having consumed their normal habitual diet and abstaining from strenuous physical activity and consumption of alcohol, tobacco and caffeine in the preceding 24 h. Before the initiation of the FATMAX test anthropometric (stature and nude body mass) and body composition measurements were obtained. Different techniques were used to measure body composition, due to availability of equipment at the time of testing. Therefore, athletes underwent body composition analysis using Dual-energy X-ray Absorptiometry (DXA) (Lunar iDXA, GE Healthcare, Buckinghamshire, UK) or Bioelectrical Impedance Analysis (BIA) (Inbody 720, Biospace Ltd, Colorado, U.S.A). To determine the agreement of measurement between the DXA and BIA, body composition using the two techniques was compared from a sample of 146 athletes. The level of agreement for percent body fat (%BF) and FFM (assessed using Intra-Class Correlation (ICC)) between the two techniques was ICC = 0.87 (95% CI = 0.46 – 0.95) and 0.99 (95% CI = 0.97 – 0.99) respectively. As a result of the strong absolute agreement found between the BIA and DXA, the body composition measurements from the two techniques were grouped for this data set.

The exercise test protocol was adapted from previously described and validated protocols (1, 35). In the current study the exercise test was performed on a treadmill (h/p/cosmos sports & medical,

Germany). The test started at an initial velocity of 5.0 km/h at a gradient of 1% for three min. The speed then increased to 7.5 km/h. From this point, speed was increased by 1 km/h every 3 min until a respiratory exchange ratio (RER) of 1 was reached. The speed then remained constant and the gradient was increased by 1% every 1 min to determine "maximum" values. The test ended when athletes reached voluntary exhaustion. The criteria for a maximum test was if two out of the three following criteria were achieved: 1) levelling off in $\dot{V}O_2$ with further increases in workloads (< 2 mL·kg·bm^{-1}); 2) Heart rate (HR) within 10 beats/min (bpm) of age predicted maximum or 3) Respiratory exchange ratio (RER)) exceeded 1.10. Respiratory gas measurements ($\dot{V}O_2$ and $\dot{V}CO_2$) were collected continuously using a Moxus Modular $\dot{V}O_2$ system (AEI technologies, Pittsburgh, USA). Heart rate (Polar RS800CX, Polar Electro Ltd, Kempele, Finland) was measured continuously and rate of perceived exertion (RPE) was recorded during the final min of each 3 min stage (7).

Indirect calorimetry and Calculations

To calculate substrate metabolism the breath-by-breath data was averaged in 10 s increments, calculated automatically by the Moxus Modular $\dot{V}O_2$ system. This raw data was then analysed manually for each athlete. In more detail, the first 90 s and last 30 s of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) recorded during each stage of the test were excluded from analysis. The remaining 60 s of data was averaged for each stage. Using this averaged data fat and carbohydrate oxidation rates were calculated for each stage of the test using Stoichiometric equations (9), assuming that protein oxidation was negligible throughout the test, this enabled the determination of MFO (g·min^{-1}) and FATMAX (%$\dot{V}O_2$max) for each athlete.

$$\text{Fat oxidation } (g \cdot min^{-1}) = 1.718VO_2 - 1.718VCO_2$$

$$\text{CHO oxidation } (g \cdot min^{-1}) = 4.170VCO_2 - 2.965VO_2$$

Statistical Analysis

Data analysis was performed using MINITAB 17. Data are expressed as means, with ranges in parentheses, unless otherwise stated. Sex and Age differences in anthropometric characteristics, MFO, MFO/FFM and FATMAX were identified using an independent t-test. To assess sport group differences in all variables a one-way analysis of variance (ANOVA) was conducted.

Bivariate correlation analyses were conducted between absolute ($g \cdot min^{-1}$) and relative ($mg \cdot kg \cdot FFM^{-1} \cdot min^{-1}$) MFO with the following as independent variables; age, sex, %BF, fat mass (FM), FATMAX and $\dot{V}O_2$max. Bivariate correlation analysis between FFM and MFO was performed only when MFO were expressed in absolute terms ($g \cdot min^{-1}$). Multiple regression analyses were then conducted on absolute ($g \cdot min^{-1}$) and relative ($mg \cdot kg \cdot FFM^{-1} \cdot min^{-1}$) MFO with all the significant predictors found in the bivariate correlations. Multiple regressions analyses were conducted on the whole data set and on each sport category.

RESULTS

Athlete Characteristics

The data presented in this study are from a diverse cohort of athletes including athletes who participate in team sports and individual sports / events (Table 2), while the competitive level ranged from recreational to elite / professional. The physical characteristics of all athletes can be found in Table 3.

Substrate Metabolism

The average absolute MFO and relative (MFO/FFM) MFO of the combined 1121 athletes was 0.59 ± 0.18 g·min^{-1} and 10.2 ± 2.6 mg·kg·FFM^{-1}·min^{-1} respectively, occurring at a FATMAX of 49 ± 15% $\dot{V}O_2$max. The lowest absolute MFO rate was 0.17 g·min^{-1} whereas the highest MFO rate measured was 1.27 g·min^{-1}. A large range was also observed with fat oxidation rates when expressed relative to FFM (3.4 – 20.5 mg·kg·FFM^{-1}·min^{-1}).

Sex Differences

Of the 1121 athletes tested, 934 were male and 188 were female. On average the male athletes were significantly heavier, had greater FFM and lower %BF (Table 3). Absolute rates of MFO (g·min^{-1}) were significantly greater in the males compared to the female athletes (0.60 ± 0.18 and 0.50 ± 0.14 g·min^{-1}, respectively). When expressed relative to FFM, maximal rates of fat oxidation were significantly higher in the female athletes compared to the males (11.0 ± 2.7 and 10.0 ± 2.7 mg·kg FFM^{-1}·min^{-1}, respectively).

Age Differences

To determine if level of maturation had an impact on fat oxidation, the athletes were grouped into two age categories; 18 *y* or greater (using the assumption that these individuals had reached Tanner stage 5) and under 18 *y*. Of the 1121 athletes tested, 496 were 18 *y* and greater and 625 were less than 18 *y*, the average age in these two groups was 23 ± 7 and 15 ± 1 *y* respectively. The over 18 *y* group were significantly heavier and had greater FFM compared to the under 18s. Absolute MFO rates were significantly greater in the over 18 *y*. However, when expressed relative to FFM, recorded fat oxidation rates were higher in the under 18 y olds (Table 3).

Sport type

Comparisons of anthropometric and fat metabolism variables were conducted between athletes who competed in different sports. For this analysis, only sports which had N > 40 were included. The Metabolic Equivalent (MET) is not differentiated for Rugby League, Rugby Union and Australian Football League therefore these sports have been grouped for analysis. In addition, the results from Field Hockey and Lacrosse are grouped; these sports are relatively similar in the style of play and both have a MET value of 8 (17). On average, absolute MFO rates were highest in the rugby group (0.72 ± 0.17 g·min^{-1}; range 0.38 – 1.09 g·min^{-1}) and significantly greater than those athletes who play soccer, tennis, baseball and golf ($P<0.05$). When expressed relative to FFM the highest average fat oxidation rate was observed in soccer players (MFO/FFM: 10.9 ± 3.0 mg·kg FFM^{-1}·min^{-1}; range 4.10 – 20.5 mg·kg FFM^{-1}·min^{-1}), this was significantly greater than the MFO/FFM rates observed in basketball, baseball, rugby and American football players. Results for all variables broken down by sport can be found in Table 4.

Determinants of MFO in an athletic population

Bivariate correlation analyses were performed on the whole data set with MFO expressed in absolute terms (MFO; g·min^{-1}) or when scaled for FFM (MFO/FFM; mg·kg FFM^{-1}·min^{-1}) as the dependant variable. With MFO as the dependant variable; FATMAX (r = .20, P = .000), $\dot{V}O_2$max (r = .20, P = .000), BF% (r = -.09, P = .03), Fast Duration (r = .05, P = .02) and FFM (r = .55, P = .000) were all significant predictors. These variables were entered into the regression model and, when combined, accounted for 47% of the variance in MFO.

When MFO/FFM was the dependant variable; FATMAX (r = .36, P = .000), $\dot{V}O_2$max (r = .17, P = .000), Body Mass (r = -.23, P = .02), BF% (r = .19, P = .000) and Fast Duration (r = .06, P = .05) were all significant predictors. These variables were included in the regression model and, when combined, accounted for 29% of the variance.

Discussion

This is the first time that fat oxidation rates from a large athletic cohort, varying in sporting activity and competitive level, have been reported. The main observation of the present study is that large individual differences in MFO exist between all individuals, independent of sport (0.17 – 1.27 g·min^{-1}).

In general, studies that measure MFO, as the primary finding, report only the group average and fail to recognise the individual differences among the sample population. The range of oxidation rates observed in the present study are similar to what have previously been observed from a heterogeneous sample population (0.18 – 1.01 g·min^{-1})(35) despite the group average being ~0.13 g·min^{-1} lower when compared to the group average observed in our athletes (mean; 0.46 ± Standard Error; 0.01 g·min^{-1} and Mean; 0.59 ± SD; 0.18 g·min^{-1}, respectively).

Fat oxidation rates in different sports

Due to the large data set we were able to compare fat metabolism from athletes who participated / competed in different sports. On a group average basis, some sports displayed much higher absolute fat oxidation rates compared to others. For example, MFO of rugby players were ~0.23 g·min^{-1} higher than golfers. In addition, when expressed relative to FFM, soccer players

displayed the highest rates of fat oxidation, ~ 1.6 mg·kg FFM^{-1}·min^{-1} higher than that of American footballers. However, despite these apparent sport differences in average fat metabolism, it is again evident that inter-individual differences within a sport exist. This is interesting when considering a sport like golf which is an individual, non-positional sport, where we reported MFO as low as 0.21 g·min^{-1} and as high 0.97 g·min^{-1}. To establish the variables that may account for this variance a multiple regression analysis was conducted. We found $\dot{V}O_2$max, BF%, FATMAX, Fast Duration, and FFM to account for 47% of the variation in absolute rates of fat oxidation. This is, in part, similar to Venables et al. (35) who found 34% of the variance to be accounted for by FFM, self-reported physical activity, $\dot{V}O_2$max, gender, and fat mass. Possible explanations for the potential relationship between these variables and fat oxidation are discussed below.

$\dot{V}O_2$max and Maximal Fat Oxidation Rates

In 2003, Achten and colleagues (3) reported significantly higher MFO in athletes when the group was spilt into individuals who had a $\dot{V}O_2$max higher or lower than the group mean (0.56 ± 0.14 g·min^{-1} vs. 0.48 ± 0.15 g·min^{-1}, respectively). Our findings support this observation by finding a significant positive correlation between MFO and $\dot{V}O_2$max. More recently, a strong positive correlation was found between MFO and $\dot{V}O_2$max when measured during an incremental FATMAX test (r = 0.72) (28) and during an interval session (six 4-min self-paced running bouts, separated by 2-min) (r = 0.86) (17). However, the strong correlation found in these latter studies may be a consequence of the low sample size used in the analysis (N = 16 and N =18, respectively).

Body Composition and Maximal Fat Oxidation Rates

In the present study body composition of the athletes (in terms of BF% and FFM) ranged significantly due to the variety of different sports in which they participated (Table 4). We observed that FFM was the single most significant variable in predicting MFO. In addition, a significant negative correlation was found between BF% and MFO, albeit to a much lesser extent than FFM. In 1990, Wade et al. (36) reported a strong and highly significant correlation between RER (during steady state exercise) and percent body fat ($r = 0.54$). However, more recent studies have either found a small relationship (35) or no difference (6) in fat oxidation when body fat percentage is taken into account. In 2001, Goodpaster and colleagues (14) found greater intramuscular triglyceride content and oxidative capacity of skeletal muscle in trained individuals compared to sedentary lean individuals. Taken together this suggests that it is the location of fat (and not total body fat percentage *per se*), as well as the oxidative capacity of functional muscle tissue, that may be accountable for higher rates of fat oxidation.

Fast Duration and Maximal Fat Oxidation Rates

In the present study all athletes were tested in the fasted state, defined as ≥ 5 hours following any food or fluid consumption which contained calories. Bivariate analysis on our data found a significant but weak correlation between fasting duration and maximal fat oxidation rates. This is unsurprising as Montain et al. (1991) (24) found the magnitude of increase in blood glycerol (indicative of increased lipolysis) during exercise to be directionally proportional to the length of fasting duration. In addition, when a very large amount of glucose is ingested prior to a FATMAX test, maximal fat oxidation rates have been reported to be suppressed by 28% compared with no carbohydrate ingestion (2).

Habitual Diet

Our data set has reported MFO as low as 0.17 and as high as 1.27 $g \cdot min^{-1}$, and although we have established variables that contribute to 47% of this variance, 53% of the variance is still unaccounted for. Inaugural work in 1920 (20) highlighted that diet is likely to be an important factor which could contribute to an individual's fat oxidation rate. In 2001, Helge et al. (16) manipulated the diet and training regime of 13 healthy males. During a 7 week period subjects consumed a low-CHO diet (21% CHO and 62% fat) or a low-fat diet (65% CHO and 20% fat), whilst following the same training protocol. After the 7 week period subjects completed a steady state exercise bout during which substrate metabolism was measured. Helge et al. (16) found that the respiratory exchange ratio (RER) was significantly lower (indicative of higher fat utilisation) in the subjects who had consumed the low-CHO diet.

It is possible that habitual diet may be responsible for some of the additional variance in MFO. Coyle et al. (10) found a 27% decrease in fat oxidation rates during exercise when subjects consumed a high CHO diet (of which 88% of the total energy intake was CHO and <2% fat) compared to a moderate CHO diet (68% CHO and 22% fat). Stoa et al. (2016) (32) supported this finding more recently by observing a 31% decrease in fat oxidation rates when a one-day CHO rich diet was consumed (62.6% CHO, 20.1%, protein, 12.4% fat) compared to a diet that was rich in fat (26.8% CHO, 23.2% protein, 47.1% fat). However, it should be noted that these aforementioned studies administered extreme diets; for example, high CHO, high / negligible fat. Using a different approach, Robinson et al. (2015) (28) found a significant positive correlation between 24-h habitual fat intake (% of total energy intake) and 24-h fat oxidation rates, although it is still to be determined if this correlation would exist under exercise conditions.

Genetics

Although outside of the scope of this paper, the genetic factors that contribute to metabolism, especially that of endogenous fat and CHO warrant mention. Recently, Roke and colleagues (2016) (29) demonstrated that individuals who were major carriers of the *FADS2 gene* (involved in the encoding of enzymes responsible for the endogenous production of Omega-3s) had increased alpha-linolenic acid (a pre-cursor for the endogenous production of Omega-3s) conversion efficiency, which was also associated with increased whole-body fat oxidation at rest. Furthermore, previous research estimated that genetic factors contributed at least 40% to the inter-individual variation in fatty acid levels (22). Similarly, Sarzynski et al. (2015) (30) demonstrated that a number of single nucleotide polymorphisms were responsible for over 30% of the variation in circulating triglyceride concentration change in response to a longitudinal endurance training program. Therefore, and taken together, it is reasonable to assume that genetics, or epigenetics, contribute significantly to the unexplained variance reported in the present study in MFO and FATMAX.

Practical implications

The results of the present study raise the question of whether sports nutrition strategies should be personalised based on the metabolism of the individual athlete? The considerable variation in fat oxidation between sports and between athletes within the same sport would suggest that individualised strategies may be advantageous to aid the athletes specific goals i.e. body fat loss, weight maintenance, performance. However, long term studies are required to determine the implications of this approach for body composition, training and performance-orientated outcomes.

Conclusion and Implications

In conclusion, this is the first study to present fat metabolism data from a large athletic population. The average MFO observed in this athletic cohort was greater than that previously reported, in a heterogeneous population. In addition, this is the first normative data for MFO and FATMAX in athletes categorised by age, sex and sport. However, our results show large variation in fat metabolism between individuals and also within athletes who participate/ compete in the same sport. Finally, $\dot{V}O_2$max, FFM, FATMAX, BF% and fast duration account for approximately 47% of the variance in MFO. Future research should further investigate the role of genetics, habitual diet, and endogenous substrate availability on fat oxidation rates in athletic and healthy populations.

Acknowledgments

The results of this study are presented clearly, honestly and without fabrication or inappropriate data manipulation and statement that results of the present study do not constitute endorsement by ACSM. R.R, J.C, I.R, T.R and K.D are employees of The Gatorade Sports Science Institute, a division of PepsiCo, Inc. A.J is a consultant for The Gatorade Sports Science Institute. The views expressed in this article are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.

The authors thank Shankang Qu (PepsiCo, Inc. employee) for statistical analysis of the data. They also thank the study participants for their time and effort. Financial support for this study was provided by the Gatorade Sports Science Institute, a division of PepsiCo, Inc.

References

1. Achten J, Gleeson M, Jeukendrup AE. Determination of the exercise intensity that elicits maximal fat oxidation. *Med Sci Sports Exerc*. 2002;34(1):92-7

2. Achten J, Jeukendrup AE. The effect of pre-exercise carbohydrate feedings on the intensity that elicits maximal fat oxidation. *J Sports Sci*. 2003;21(12):1017-24

3. Achten J, Jeukendrup AE. Maximal fat oxidation during exercise in trained men. *Int J Sports Med*. 2003;24(8):603-8

4. Achten J, Jeukendrup AE. Relation between plasma lactate concentration and fat oxidation rates over a wide range of exercise intensities. *Int J Sports Med*. 2004;25(1):32-7

5. Achten J, Venables MC, Jeukendrup AE. Fat oxidation rates are higher during running compared with cycling over a wide range of intensities. *Metabolism*. 2003;52(6):747-52

6. Blaize AN, Potteiger JA, Claytor RP, Noe DA. Body fat has no effect on the maximal fat oxidation rate in young, normal, and overweight women. *J Strength Cond Res*. 2014;28(8):2121-6

7. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377-81

8. Brooks GA, Mercier J. Balance of carbohydrate and lipid utilization during exercise: the "crossover" concept. *J Appl Physiol (1985)*. 1994;76(6):2253-61

9. Brouwer E. On simple formulae for calculating the heat expenditure and the quantities of carbohydrate and fat oxidized in metabolism of men and animals, from gaseous exchange (Oxygen intake and carbonic acid output) and urine-N. *Acta Physiol Pharmacol Neerl*. 1957;6:795-802

10. Coyle EF, Jeukendrup AE, Oseto MC, Hodgkinson BJ, Zderic TW. Low-fat diet alters intramuscular substrates and reduces lipolysis and fat oxidation during exercise. *Am J Physiol Endocrinol Metab*. 2001;280(3):E391-8

11. Croci I, Borrani F, Byrne N, et al. Reproducibility of Fatmax and fat oxidation rates during exercise in recreationally trained males. *PLoS One*. 2014;9(6):e97930

12. Croci I, Hickman IJ, Wood RE, Borrani F, Macdonald GA, Byrne NM. Fat oxidation over a range of exercise intensities: fitness versus fatness. *Appl Physiol Nutr Metab*. 2014;39(12):1352-9

13. Gonzalez-Haro C, Galilea PA, Gonzalez-de-Suso JM, Drobnic F, Escanero JF. Maximal lipidic power in high competitive level triathletes and cyclists. *Br J Sports Med*. 2007;41(1):23-8

14. Goodpaster BH, He J, Watkins S, Kelley DE. Skeletal muscle lipid content and insulin resistance: evidence for a paradox in endurance-trained athletes. *J Clin Endocrinol Metab*. 2001;86(12):5755-61

15. Hawley JA, Leckey JJ. Carbohydrate Dependence During Prolonged, Intense Endurance Exercise. *Sports Med*. 2015;45 Suppl 1:S5-12

16. Helge JW, Watt PW, Richter EA, Rennie MJ, Kiens B. Fat utilization during exercise: adaptation to a fat-rich diet increases utilization of plasma fatty acids and very low density lipoprotein-triacylglycerol in humans. *J Physiol*. 2001;537(Pt 3):1009-20

17. Hetlelid KJ, Plews DJ, Herold E, Laursen PB, Seiler S. Rethinking the role of fat oxidation: substrate utilisation during high-intensity interval training in well-trained and recreationally trained runners. *BMJ Open Sport Exerc Med*. 2015;1(1):e000047

18. Jeukendrup AE. Regulation of fat metabolism in skeletal muscle. *Ann N Y Acad Sci*. 2002;967:217-35

19. Kiens B, Essen-Gustavsson B, Christensen NJ, Saltin B. Skeletal muscle substrate utilization during submaximal exercise in man: effect of endurance training. *J Physiol*. 1993;469:459-78

20. Krogh A, Lindhard J. The Relative Value of Fat and Carbohydrate as Sources of Muscular Energy: With Appendices on the Correlation between Standard Metabolism and the Respiratory Quotient during Rest and Work. *Biochem J*. 1920;14(3-4):290-363

21. Lanzi S, Codecasa F, Cornacchia M, et al. Fat Oxidation, Hormonal and Plasma Metabolite Kinetics during a Submaximal Incremental Test in Lean and Obese Adults. *PLoS One*. 2014;9(2):e88707

22. Lemaitre RN, Siscovick DS, Berry EM, Kark JD, Friedlander Y. Familial aggregation of red blood cell membrane fatty acid composition: the Kibbutzim Family Study. *Metabolism*. 2008;57(5):662-8

23. Martin WH, 3rd, Dalsky GP, Hurley BF, et al. Effect of endurance training on plasma free fatty acid turnover and oxidation during exercise. *Am J Physiol*. 1993;265(5 Pt 1):E708-14

24. Montain SJ, Hopper MK, Coggan AR, Coyle EF. Exercise metabolism at different time intervals after a meal. *J Appl Physiol (1985)*. 1991;70(2):882-8

25. Nordby P, Saltin B, Helge JW. Whole-body fat oxidation determined by graded exercise and indirect calorimetry: a role for muscle oxidative capacity? *Scand J Med Sci Sports*. 2006;16(3):209-14

26. Phillips SM, Green HJ, Tarnopolsky MA, Heigenhauser GF, Hill RE, Grant SM. Effects of training duration on substrate turnover and oxidation during exercise. *J Appl Physiol (1985)*. 1996;81(5):2182-91

27. Proctor DN, Sinning WE, Walro JM, Sieck GC, Lemon PW. Oxidative capacity of human muscle fiber types: effects of age and training status. *J Appl Physiol*. 1995;78(6):2033-8

28. Robinson SL, Hattersley J, Frost GS, Chambers ES, Wallis GA. Maximal Fat Oxidation during Exercise is Positively Associated with 24-Hour Fat Oxidation and Insulin Sensitivity in Young, Healthy Men. *J Appl Physiol (1985)*. 2015;118(11):1415-22

29. Roke K, Jannas-Vela S, Spriet LL, Mutch DM. FADS2 genotype influences whole-body resting fat oxidation in young adult men. *Appl Physiol Nutr Met* 2016;In Press

30. Sarzynski MA, Davidsen PK, Sung YJ, et al. Genomic and transcriptomic predictors of triglyceride response to regular exercise. *Br J Sports Med*. 2015;49(23):1524-31

31. Stisen AB, Stougaard O, Langfort J, Helge JW, Sahlin K, Madsen K. Maximal fat oxidation rates in endurance trained and untrained women. *Eur J Appl Physiol*. 2006;98(5):497-506

32. Stoa EM, Nyhus LK, Borresen SC, et al. Day to day variability in fat oxidation and the effect after only 1 day of change in diet composition. *Appl Physiol Nutr Metab*. 2016;41(4):397-404

33. Tarnopolsky MA, Rennie CD, Robertshaw HA, Fedak-Tarnopolsky SN, Devries MC, Hamadeh MJ. Influence of endurance exercise training and sex on intramyocellular lipid and mitochondrial ultrastructure, substrate use, and mitochondrial enzyme activity. *Am J Physiol Regul Integr Comp Physiol*. 2007;292(3):R1271-8

34. van Loon LJ, Greenhaff PL, Constantin-Teodosiu D, Saris WH, Wagenmakers AJ. The effects of increasing exercise intensity on muscle fuel utilisation in humans. *J Physiol*. 2001;536(Pt 1):295-304

35. Venables MC, Achten J, Jeukendrup AE. Determinants of fat oxidation during exercise in healthy men and women: a cross-sectional study. *J Appl Physiol*. 2005;98(1):160-7

36. Wade AJ, Marbut MM, Round JM. Muscle fibre type and aetiology of obesity. *Lancet*. 1990;335(8693):805-8

37. White MD, Bouchard G, Buemann B, et al. Reproducibility of 24-h energy expenditure and macronutrient oxidation rates in an indirect calorimeter. *J Appl Physiol*. 1996;80(1):133-9

Table 1. Mean (±SD) Maximal Fat Oxidation (MFO) rates ($g \cdot min^{-1}$) and FATMAX (% VO_2max) from published research. Data included in the table has been collected during a FATMAX test performed on a cycle ergometer or treadmill and in a fasted state

Authors	Participants	VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	Protocol	FATMAX (% VO_2max)	MFO ($g \cdot min^{-1}$)
Achten et al (2002)(1)	18 Moderately Trained Males	58.4 ± 1.8	Cycling	56 ± 3	0.56 ± 0.05
Achten et al (2003)(5)	12 Moderately Trained Males	66.9 ± 1.8	Cycling	62 ± 3	0.47 ± 0.05
Achten et al (2003)(2)	11 Moderately Trained Males	58.9 ± 1.0	Cycling	60 ± 2	0.46 ± 0.06
Achten et al (2003)(3)	55 Trained males	60.1 ± 0.3	Cycling	63 ± 10	0.52 ± 0.15
Achten et al (2004) (4)	33 Moderately Trained Males	62.3 ± 6.9	Cycling	63 ± 9	0.48 ± 0.17
Stisen et al (2006) (31)	8 Trained Females	53.8 ± 1.3	Cycling	56 ± 3	0.40 ± 0.06
Stisen et al (2006) (31)	9 Untrained Females	41.5 ± 1.7	Cycling	53 ± 2	0.32 ± 0.03
Nordy et al (2006) (25)	8 Untrained Males	46.5 ± 1.8	Cycling	44 ± 2	0.25 ± 0.03*
Nordy et al (2006) (25)	8 Trained Males	56.6 ± 1.3	Cycling	50 ± 1	0.46 ± 0.03*
Croci et al (2014)(11)	15 Moderately trained males	52.0 ± 7.7	Cycling	47 ± 9	0.28 ± 0.08
Croci et al (2014)(12)	12 Recreationally trained, Overweight, Males	39.0 ± 5.5	Cycling	47 ± 9	0.38 ± 0.19
Croci et al (2014)(12)	12 Recreationally trained, Lean, Males	39.0 ± 5.5	Cycling	45 ± 7	0.42 ± 0.16
Lanzi et al (2014)(21)	16 Lean Males	41.8 ± 1.8	Cycling	57 ± 2	0.35 ± 0.4 **
Lanzi et al (2014)(21)	16 Obese Males	25.2 ± 0.9	Cycling	47 ± 3	0.42 ± 0.3 **
Achten et al (2003)(5)	12 Moderately Trained Males	66.9 ± 1.8	Treadmill	59 ± 3	0.65± 0.05
Venables et al (2005)(35)	300 Males and Females	46.3 ± 0.7	Treadmill	48 ± 1	0.46 ± 0.01
Blaize et al (2014) (6)	7 Females (High Body Fat > 25%)	30 ± 0.4***	Treadmill	59 ± 5	0.49 ± 0.1
Blaize et al (2014) (6)	7 Females (Low Body Fat < 25%)	28 ± 0.6***	Treadmill	56 ± 11	0.39 ± 0.1
Robinson et al (2015)(28)	16 Moderately trained males	52 ± 6	Treadmill	58 ±17	0.60 ± 0.18

* Calculated from MFO $mg \cdot min^{-1}$
** Converted to $g \cdot min^{-1}$
***Converted to ($ml \cdot kg^{-1} \cdot min^{-1}$)

Table 2. Sports included in data set and number of athletes per sport

American Football (N=86)	Fitness* (N=24)	Running (N=42)
Australian Football League (N=2)	Golf (N=60)	Skiing / Snowboarding (N=2)
Baseball (N=125)	Gymnastics (N=1)	Soccer (N=285)
Basketball (N=164)	Handball (N=1)	Squash (N=3)
Boxing (N=3)	Lacrosse (N=43)	Tennis (N=140)
Cheerleading (N=1)	Martial Arts (N=7)	Track and Field (N=28)
Cross Country (N=2)	Motor Sports (N=3)	Triathlon (N=20)
Duathlon (N=1)	Rugby League (N=12)	Volleyball / Beach Volleyball (N=5)
Field Hockey (N=17)	Rugby Union (N=33)	Water Sports** (N=16)

*Fitness includes: occupation, performance, coach. **Water sports includes: paddle sport, rowing, wind surfing, dragon boat

Table 3. Athlete Characteristics and Fat Metabolism Grouped by Sex and Age

Variable	Combined Group (N=1121)	Males (N= 933)	Females (N = 188)	≥ 18 y± (N=496)	< 18 y (N = 625)
Age (y)	19 (13 – 54)	19 (13 – 54)	20 (13 – 51)	23 (18 – 54)*	15 (13 – 17)
Body Mass (kg)	72.7 (35.6 – 163.8)	74.9 (35.6 – 163.8)†	61.6 (36.5 – 91.1)	79.7 (39.2 – 144.5)*	67.1 (35.6 – 163.8)
Height (cm)	176.5 (143.4 – 211.5)	178.1 (143.4 – 211.5)†	168.1 (144.1 – 197.3)	180.2 (149.4 – 211.5)*	173.5 (143.4 – 207.7)
%BF	19.0 (4.4 – 46.2)	17.6 (4.4 – 46.2)†	25.4 (8.0 – 42.7)	17.7 (4.4 – 43.3)*	20.0 (4.4 – 46.2)
FFM (kg)	59.0 (20.1 – 107.5)	61.8 (27.1 – 107.5)†	45.7 (20.1 – 62.8)	65.9 (20.1 – 107.5)*	53.5 (27.1 – 95.0)
FM (kg)	13.9 (3.0 – 74.6)	13.5 (3.0 – 74.6)†	15.9 (3.3 – 38.3)	14.1 (4.2 – 52.8)	13.7 (3.0 – 74.6)
VO_2max (ml·kg^{-1}·min-$^{-1}$)	52.4 (30.5 – 74.4)	53.5 (30.5 – 74.4)†	47.3 (34.3 – 67.6)	52.7 (30.5 – 74.4)	52.2 (33.3 – 73.8)
MFO (g·min^{-1})	0.59 (0.17 – 1.27)	0.60 (0.17 – 1.27)†	0.50 (0.18 – 0.92)	0.64 (0.18 – 1.27)*	0.54 (0.17 – 1.22)
MFO/FFM (mg·kg FFM^{-1}·min^{-1})	10.2 (3.4 – 20.5)	10.0 (3.4 – 19.4)†	11.0 (3.5 – 20.5)	9.9 (3.5 – 17.7)*	10.3 (3.4 – 20.5)
FATMAX (% VO_2max)	49.3 (22.6 – 88.8)	48.6 (22.9 – 88.8)†	52.5 (22.6 – 86.7)	49.7 (22.6 – 85.2)	48.9 (23.5 – 88.8)

Values are means, ranges are in parentheses, for Age (years), Body Mass (kg), Height (cm), Percentage Body Fat (%BF), Fat Free Mass (FFM), Fat Mass (FM), Maximal Oxygen Uptake (VO_2max), Absolute (g·min^{-1}) and relative (mg·kg FFM^{-1}·min^{-1}) maximal fat oxidation (MFO), FATMAX (%VO_2max) for; total athletes (N=1121), males (N=933) , females (N=188), 18 y± (N=496) and < 18 y (N=625). † Significant difference (P<.05) from females; * significant difference (P<.05) from < 18 y.

Table 4. Athlete Characteristics and Fat Metabolism Grouped by Sport

Variable	Soccer (N=283)	Basketball (N= 164)	Tennis (N = 143)	Baseball (N=125)	American Football (N = 84)	Golf (N=60)	Field Hockey / Lacrosse (N=60)	Rugby* (N=47)
Age (y)	18b (13 – 53)	18b (13 – 35)	17bc (13 – 52)	16c (13 – 37)	18b (13 – 36)	17bc (13 – 27)	17bc (13 – 23)	21a (16 – 34)
Body Mass (kg)	66.6d (36.9 – 98.4)	80.5b (44.5 – 131.9)	64.6d (36.5 – 104.5)	72.7c (41.5 – 113.2)	92.6a (46.6 – 163.8)	65.7cd (36.3 – 105.4)	71.1cd (35.6 – 98.6)	91.8a (71.5 – 125.5)
Height (cm)	172.6d (147.3 – 195.7)	185.6ab (158.3 – 211.5)	172.5d (144.1 – 195.7)	176.3c (152.3 – 199.8)	181.5b (149.6 – 200.9)	172.4cd (143.4 – 191.4)	175.9cd (145.4 – 188.4)	182.7a (168.7 – 197.3)
%BF	17.7c (5.4 – 41.9)	18.3bc (4.4 – 35.7)	21.3a (7.7 – 42.7)	19.5abc (4.4 – 41.3)	20.8ab (8.3 – 46.2)	22.0a (12.1 – 39.4)	18.4abc (8.6 – 33.1)	16.7c (7.0 – 43.3)
FFM (kg)	54.9cd (20.1 – 88.3)	65.5b (35.7 – 107.6)	50.9e (27.5 – 75.2)	58.4c (32.0 – 92.3)	72.0a (36.8 – 103.7)	51.1de (29.1 – 75.3)	58.1c (27.5 – 78.0)	76.4a (60.5 – 95.0)
FM (kg)	11.6c (3.9 – 35.0)	14.6b (4.2 – 36.1)	13.8bc (4.4 – 38.3)	14.4b (3.0 – 39.6)	20.4a (5.9 – 74.6)	14.6bc (6.6 – 32.4)	13.1bc (6.5 – 32.6)	15.7b (5.9 – 52.8)
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	54.5a (32.2 – 71.6)	52.6ab (38.2 – 74.4)	51.8b (34.3 – 73.8)	50.9bc (38.7 – 68.1)	48.0d (30.5 – 62.6)	48.5cd (36.1 – 64.5)	54.9a (39.1 – 68.2)	52.3ab (33.3 – 63.7)
MFO ($g \cdot min^{-1}$)	0.58bc (0.17 – 1.11)	0.65a (0.22 – 1.20)	0.51d (0.25 – 0.88)	0.54cd (0.25 – 0.94)	0.65a (0.27 – 1.27)	0.49d (0.21 – 0.97)	0.63ab (0.31 – 1.04)	0.72a (0.38 – 1.09)
MFO/FFM ($mg \cdot kg\ FFM^{-1} \cdot min^{-1}$)	10.8a (4.1 – 20.5)	10.0cd (4.3 – 16.6)	10.2abcd (5.1 – 17.2)	9.5d (3.9 – 16.2)	9.2d (3.4 – 16.1)	9.8abcd (4.7 – 17.8)	10.8abc (6.0 – 16.8)	9.5bcd (4.8 – 14.4)
FATMAX (% VO_2max)	51.8a (22.9 – 88.8)	49.8ab (23.3 – 88.6)	47.5abc (25.4 – 84.4)	44.8bc (24.1 – 87.5)	43.7c (23.3 – 79.2)	47.1abc (22.6 – 86.9)	47.2abc (25.3 – 77.0)	53.5a (24.6 – 79.2)

Values are mean, ranges are in parentheses, for Age (years), Body Mass (kg), Height (cm), Percentage Body Fat (%BF), Fat Free Mass (FFM), Fat Mass (FM), Maximal Oxygen Uptake (VO_2max), Absolute ($g \cdot min^{-1}$) and relative ($mg \cdot kg\ FFM^{-1} \cdot min^{-1}$) maximal fat oxidation (MFO), FATMAX (%VO_2max) for athletes competing in different sports. Means that do not share a letter are significantly different. *includes data from Rugby League, Rugby Union and Aussie Football League (AFL) athletes