OPEN

Maximal Fat Oxidation Rates in an Athletic Population

REBECCA K. RANDELL[1], IAN ROLLO[1], TIMOTHY J. ROBERTS[1], KORTNEY J. 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; and* [2]*School of Sports Exercise and Health Sciences, Loughborough University, Loughborough, UNITED KINGDOM*

ABSTRACT

RANDELL, R. K., I. ROLLO, T. J. ROBERTS, K. J. DALRYMPLE, A. E. JEUKENDRUP, and J. M. CARTER. Maximal Fat Oxidation Rates in an Athletic Population. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 133–140, 2017. **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 and 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**: The average MFO was 0.59 ± 0.18 g·min^{-1}, ranging from 0.17 to 1.27 g·min^{-1}. Maximal rates occurred at an average exercise intensity of 49.3% ± 14.8% $\dot{V}O_{2max}$, ranging from 22.6% to 88.8% $\dot{V}O_{2max}$. In absolute terms, male athletes had significantly higher MFO compared with 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 with 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 to 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, $\dot{V}O_{2max}$, FATMAX (the exercise intensity at which the MFO was observed), percent body fat, 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. **Key Words:** FAT OXIDATION, ATHLETES, EXERCISE METABOLISM, PHYSIOLOGY

CHO and fat are the predominant energy sources during exercise (18). The absolute and relative contributions of CHO and fat are dependent on several variables; of these, exercise intensity has been reported to be the single most important factor influencing substrate utilization (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, multiday 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 increase the variability of substrate oxidation (37).

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 called 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 [% $\dot{V}O_{2max}$]) 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. Because of this inaugural study, a treadmill FATMAX test protocol has also been developed

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; E-mail: rebecca.randell@pepsico.com.
Submitted for publication May 2016.
Accepted for publication August 2016.

0195-9131/17/4901-0133/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000001084

(5). In addition, studies investigating the reproducibility of MFO and FATMAX using this test protocol have found small intraindividual 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 show the group average MFO and FATMAX of several key studies in this area. An interesting observation from these data is that large interindividual 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 woman with low fat (<25% body fat) and woman with high fat (>25% body fat) (6) or in lean and obese individuals when matched for $\dot{V}O_{2max}$ (12).

Typically, athletes have higher rates of fat oxidation compared with 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 submaximal 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, $\dot{V}O_{2max}$, 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 interindividual 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 (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

TABLE 1. Mean ± SD MFO rates ($g \cdot min^{-1}$) and FATMAX (% $\dot{V}O_{2max}$) from published research.

Authors	Participants	$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	Protocol	FATMAX (% $\dot{V}O_{2max}$)	MFO ($g \cdot min^{-1}$)
Achten et al. (1)	18 moderately trained males	58.4 ± 1.8	Cycling	56 ± 3	0.56 ± 0.05
Achten et al. (5)	12 moderately trained males	66.9 ± 1.8	Cycling	62 ± 3	0.47 ± 0.05
Achten and Jeukendrup (2)	11 moderately trained males	58.9 ± 1.0	Cycling	60 ± 2	0.46 ± 0.06
Achten and Jeukendrup (3)	55 trained males	60.1 ± 0.3	Cycling	63 ± 10	0.52 ± 0.15
Achten and Jeukendrup (4)	33 moderately trained males	62.3 ± 6.9	Cycling	63 ± 9	0.48 ± 0.17
Stisen et al. (31)	8 trained females	53.8 ± 1.3	Cycling	56 ± 3	0.40 ± 0.06
Stisen et al. (31)	9 untrained females	41.5 ± 1.7	Cycling	53 ± 2	0.32 ± 0.03
Nordby et al. (25)	8 untrained males	46.5 ± 1.8	Cycling	44 ± 2	0.25 ± 0.03*
Nordby et al. (25)	8 trained males	56.6 ± 1.3	Cycling	50 ± 1	0.46 ± 0.03*
Croci et al. (11)	15 moderately trained males	52.0 ± 7.7	Cycling	47 ± 9	0.28 ± 0.08
Croci et al. (12)	12 recreationally trained, overweight males	39.0 ± 5.5	Cycling	47 ± 9	0.38 ± 0.19
Croci et al. (12)	12 recreationally trained, lean males	39.0 ± 5.5	Cycling	45 ± 7	0.42 ± 0.16
Lanzi et al. (21)	16 lean males	41.8 ± 1.8	Cycling	57 ± 2	0.35 ± 0.4**
Lanzi et al. (21)	16 obese males	25.2 ± 0.9	Cycling	47 ± 3	0.42 ± 0.3**
Achten et al. (5)	12 moderately trained males	66.9 ± 1.8	Treadmill	59 ± 3	0.65 ± 0.05
Venables et al. (35)	300 males and females	46.3 ± 0.7	Treadmill	48 ± 1	0.46 ± 0.01
Blaize et al. (6)	7 females (high body fat >25%)	30 ± 0.4***	Treadmill	59 ± 5	0.49 ± 0.1
Blaize et al. (6)	7 females (low body fat <25%)	28 ± 0.6***	Treadmill	56 ± 11	0.39 ± 0.1
Robinson et al. (28)	16 moderately trained males	52 ± 6	Treadmill	58 ± 17	0.60 ± 0.18

Data included in the table have been collected during a FATMAX test performed on a cycle ergometer or treadmill and in a fasted state.
*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, and coach.
**Water sports includes: paddle sport, rowing, wind surfing, dragon boat.

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, except age, which was 16–60 yr in GSSI UK and 13–40 yr in GSSI US, because of 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 were explained to all volunteers. Informed consent from all athletes was either collected before the testing day or signed on site on the morning of the test. In addition, if volunteers were younger than 18 yr, parental consent was obtained. All volunteers were healthy as assessed by a general health questionnaire. Before 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 because of the 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., Boulder, CO). To determine the agreement of measurement between the DXA and the 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 intraclass correlation) between the two techniques was intraclass correlation = 0.87 (95% confidence interval = 0.46–0.95) and 0.99 (95% confidence interval = 0.97–0.99), respectively. As a result of the strong absolute agreement found between the BIA and the 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 $km \cdot h^{-1}$ at a gradient of 1% for 3 min. The speed then increased to 7.5 $km \cdot h^{-1}$. From this point, speed was increased by 1 $km \cdot h^{-1}$ every 3 min until an 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 of the three following criteria were achieved: 1) leveling off in $\dot{V}O_2$ with further increases in workloads (<2 $mL \cdot kg^{-1}$ body mass); 2) HR within 10 bpm of age predicted maximum, or 3) 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, PA). HR (Polar RS800CX; Polar Electro Ltd., Kempele, Finland) was measured continuously, and 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 were averaged in 10 s increments, calculated automatically by the Moxus Modular $\dot{V}O_2$ system. These raw data were then analyzed manually for each athlete. In more detail, the first 90 s and the 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 these averaged data, fat and CHO 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 ($g \cdot min^{-1}$) and FATMAX (% $\dot{V}O_{2max}$) for each athlete:

$$\text{Fat oxidation } (g \cdot min^{-1}) = 1.718\dot{V}O_2 - 1.718\dot{V}CO_2$$

$$\text{CHO oxidation } (g \cdot min^{-1}) = 4.170\dot{V}CO_2 - 2.965\dot{V}O_2$$

Statistical analysis. Data analysis was performed using MINITAB 17. Data are expressed as mean, 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 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, FM, FATMAX, and $\dot{V}O_{2max}$. Bivariate correlation analysis between FFM and MFO was performed only when MFO was 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), whereas 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 $g \cdot min^{-1}$ and 10.2 ± 2.6 $mg \cdot kg \cdot FFM^{-1} \cdot min^{-1}$, respectively, occurring at a FATMAX of $49\% \pm 15\%$ $\dot{V}O_{2max}$. The lowest absolute MFO rate was 0.17 $g \cdot min^{-1}$, whereas the highest MFO rate measured was 1.27 $g \cdot min^{-1}$. A large range was also observed with fat oxidation rates when expressed relative to FFM (3.4–20.5 $mg \cdot kg \cdot FFM^{-1} \cdot min^{-1}$).

Sex differences. Of the 1121 athletes tested, 933 were male and 188 were female. On average, the male athletes were significantly heavier, had greater FFM, and had lower %BF (Table 3). Absolute rates of MFO ($g \cdot min^{-1}$) were significantly greater in the males compared with the female athletes (0.60 ± 0.18 and 0.50 ± 0.14 $g \cdot min^{-1}$, respectively). When expressed relative to FFM, maximal rates of fat oxidation were significantly higher in the female athletes compared with the males (11.0 ± 2.7 and 10.0 ± 2.7 $mg \cdot kg \cdot FFM^{-1} \cdot min^{-1}$, respectively).

Age differences. To determine whether the level of maturation affected fat oxidation, the athletes were grouped into two age categories: 18 yr or older (using the assumption that these individuals had reached Tanner stage 5) and younger than 18 yr. Of the 1121 athletes tested, 496 were 18 yr and older and 625 were less than 18 yr, the average age in these two groups was 23 ± 7 and 15 ± 1 yr, respectively. The 18-yr and older group was significantly heavier and had greater FFM compared with the <18-yr group. Absolute MFO rates were significantly greater in 18 yr and older. However, when expressed relative to FFM, recorded fat oxidation rates were higher in the <18-yr-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 that had $n > 40$ were included. 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 $g \cdot min^{-1}$; range 0.38–1.09 $g \cdot min^{-1}$) 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 $mg \cdot kg$ $FFM^{-1} \cdot min^{-1}$; range, 4.10–20.5 $mg \cdot kg$ $FFM^{-1} \cdot min^{-1}$). 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; $g \cdot min^{-1}$) or when scaled for FFM (MFO/FFM; $mg \cdot kg$ $FFM^{-1} \cdot min^{-1}$) as the dependant variable. With MFO as the dependant variable; FATMAX ($r = 0.20$, $P = 0.000$), $\dot{V}O_{2max}$ ($r = 0.20$, $P = 0.000$), %BF ($r = -0.09$, $P = 0.03$), fast duration ($r = 0.05$, $P = 0.02$), and FFM ($r = 0.55$, $P = 0.000$) 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 ($r = 0.36$, $P = 0.000$), $\dot{V}O_{2max}$ ($r = 0.17$, $P = 0.000$), body

TABLE 3. Athlete characteristics and fat metabolism grouped by sex and age.

Variable	Combined Group ($n = 1121$)	Males ($n = 933$)	Females ($n = 188$)	≥18 yr ($n = 496$)	<18 yr ($n = 625$)
Age (yr)	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)
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	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 ($g \cdot min^{-1}$)	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 ($mg \cdot kg$ $FFM^{-1} \cdot min^{-1}$)	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 (% $\dot{V}O_{2max}$)	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 presented as mean (range) for age (yr), body mass (kg), height (cm), body fat percent (%BF), fat free mass (FFM; kg), fat mass (FM; kg) maximal oxygen uptake ($\dot{V}O_{2max}$), absolute ($g \cdot min^{-1}$) and relative ($mg \cdot kg$ $FFM^{-1} \cdot min^{-1}$) MFO, and FATMAX ($\%\dot{V}O_{2max}$) for total athletes ($N = 1121$), males ($n = 933$), females ($n = 188$), ≥18 yr ($n = 496$), and <18 yr ($n = 625$).
*Significant difference ($P < 0.05$) from <18 yr.
**Significant difference ($P < 0.05$) from females.

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 (yr)	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)
$\dot{V}O_{2max}$ (mL·kg^{-1}·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·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·kg FFM^{-1}·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 (% $\dot{V}O_{2max}$)	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 presented as mean (range) for age (yr), body mass (kg), height (cm), body fat percent (%BF), fat free mass (FFM; kg), fat mass (FM; kg) maximal oxygen uptake ($\dot{V}O_{2max}$), absolute (g·min^{-1}) and relative (mg·kg FFM^{-1}·min^{-1}) MFO, and FATMAX (%$\dot{V}O_{2max}$) for athletes competing in different sports. Mean values that do not share a letter are significantly different.
*Includes data from Rugby League, Rugby Union, and Aussie Football League athletes.

mass (r = −.23, P = 0.02), %BF (r = 0.19, P = 0.000), and fast duration (r = 0.06, P = 0.05) 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 recognize the individual differences among the sample population. The range of oxidation rates observed in the present study is similar to what have been previously 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 with the group average observed in our athletes (mean ± SE = 0.46 ± 0.01 g·min^{-1} and mean ± SD = 0.59 ± 0.18 g·min^{-1}, respectively).

Fat oxidation rates in different sports. Because of 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 with others. For example, the MFO values of rugby players were ~0.23 g·min^{-1} higher than those of 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 interindividual differences within a sport exist. This is interesting when considering a sport like golf, which is an individual, nonpositional sport, where we reported MFO values 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 $\dot{V}O_{2max}$, %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, $\dot{V}O_{2max}$, gender, and FM. Possible explanations for the potential relationship between these variables and fat oxidation are discussed in the following sections.

$\dot{V}O_{2max}$ and MFO rates. In 2003, Achten and Jeukendrup (3) reported significantly higher MFO in athletes when the group was spilt into individuals who had a $\dot{V}O_{2max}$ higher or lower than the group mean (0.56 ± 0.14 vs 0.48 ± 0.15 g·min^{-1}, respectively). Our findings support this observation by finding a significant positive correlation between MFO and $\dot{V}O_{2max}$. More recently, a strong positive correlation was found between MFO and $\dot{V}O_{2max}$ 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 MFO rates. In the present study, the body composition of the athletes (in terms of %BF and FFM) ranged significantly because of 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 et al. (14) found greater intramuscular triglyceride content and oxidative capacity of skeletal muscle in trained individuals compared with 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 MFO rates. In the present study, all athletes were tested in the fasted state, defined as ≥5 h after any food or fluid consumption that contained calories. Bivariate analysis on our data found a significant but weak correlation between fasting duration and MFO rates. This is unsurprising as Montain et al. (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 before a FATMAX test, MFO rates have been reported to be suppressed by 28% compared with no CHO ingestion (2).

Habitual diet. Our data set have 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 that 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-wk period subjects consumed a low-CHO diet (21% CHO and 62% fat) or a low-fat diet (65% CHO and 20% fat) while following the same training protocol. After the 7-wk period, subjects completed a steady-state exercise bout during which substrate metabolism was measured. Helge et al. (16) found that the RER was significantly lower (indicative of higher fat utilization) 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 with a moderate CHO diet (68% CHO and 22% fat). Stoa et al. (32) supported this finding more recently by observing a 31% decrease in fat oxidation rates when a 1-d CHO rich diet was consumed (62.6% CHO, 20.1%, protein, and 12.4% fat) compared with a diet that was rich in fat (26.8% CHO, 23.2% protein, and 47.1% fat). However, it should be noted that these aforementioned studies administered extreme diets, for example, high CHO and high/negligible fat. Using a different approach, Robinson et al. (28) found a significant positive correlation between 24-h habitual fat intake (% 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 article, the genetic factors that contribute to metabolism, especially that of endogenous fat and CHO, warrant mention. Recently, Roke et al. (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 precursor 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 interindividual variation in fatty acid levels (22). Similarly, Sarzynski et al. (30) demonstrated that several single nucleotide polymorphisms were responsible for more than 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 personalized 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 individualized strategies may be advantageous to aid the athletes' specific goals, i.e., body fat loss, weight maintenance, and performance. However, long-term studies are required to determine the implications of this approach for body composition, training, and performance-oriented outcomes.

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 categorized 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, $\dot{V}O_{2max}$,

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.

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 the American College of Sports Medicine. 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(1 Suppl):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 WH3rd, 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 Metab*. 2016;41(7):791–4.
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 (1985)*. 1996;80(1):133–9.