Observational Trial

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Sport-Specific Crossover Point Differences during a Maximal Oxygen Consumption Test

Joseph R. Stanzione,[1] George A. Brooks,[2] Michael L. Bruneau, Jr,[3] Duncan N. French,[4,5] Jennifer A. Nasser,[6] Sinclair A. Smith,[7] and Stella L. Volpe[8]

ABSTRACT

Introduction/Purpose: The crossover point occurs during exercise when one transitions energy substrates from fat to carbohydrate predominance. The crossover point varies in an intensity-dependent manner; however, less is known about its specificity in sports with varying metabolic demands. The purpose of our study was to determine if various sports yield differences in the time to crossover and heart rate and percentage of maximal oxygen consumption ($\dot{V}O_{2max}$) at crossover during a standardized exercise protocol. **Methods:** A total of 77 athletes (39 women, 38 men; 39.1 ± 10.4 yr of age) were measured for respiratory exchange ratio during a modified Taylor $\dot{V}O_{2max}$ treadmill test. Sports included running (n = 20), triathlon (n = 20), rowing (n = 20), and CrossFit (n = 17). A one-way ANOVA determined differences in time to crossover. A Kruskal–Wallis test was applied to determine differences between sport types for percent $\dot{V}O_{2max}$ and heart rate at crossover. Bonferroni correction procedures were used to control the family-wise error rate and maintain alpha levels at $P < 0.05$. **Results:** Average time to crossover for all athletes was 3:43 ± 1:12 min. Times to crossover for runners, triathletes, rowers, and CrossFit athletes were 4:16 ± 0:58, 3:28 ± 1:08, 4:00 ± 1:23, and 3:01 ± 0:58 min, respectively. Significant differences were observed between groups for time to crossover (P = 0.007) and percent $\dot{V}O_{2max}$ at crossover (P = 0.01). Pairwise analyses revealed that runners had a significantly longer time to crossover compared with CrossFit athletes (P = 0.009). Triathletes' percent $\dot{V}O_{2max}$ at crossover was significantly lower than rowers (P = 0.04) and runners (P = 0.04). **Conclusions:** We found significant differences in time to crossover between runners and CrossFit athletes, which suggests that substrate use may be dependent on sport type.

INTRODUCTION

The human oxidative energy system produces more energy than nonoxidative energy systems; therefore, it is an essential consideration when examining sports performance (1). During exercise, the oxidative system is characterized by an increase in oxygen uptake for the metabolism of energy substrates at a given exercise frequency, intensity, time, and type. To generate energy, the human body predominately relies on the macronutrients of fat and carbohydrate as substrates for oxidative phosphorylation. At the onset of exercise, there is a propensity for fat to be used as the predominant energy substrate (1). However, as exercise intensity increases, there is a shift in the propensity from predominantly fat to predominantly carbohydrate. This shift in fat to carbohydrate predominance can be quantified as the crossover point. Brooks and Mercier (1) first described the crossover point based on the principle that fat use is maximal at lower-intensity exercise and carbohydrate use is maximal at higher-intensity exercise.

It is understood that the tendency toward a substrate is highly dependent on the intensity of the exercise (2). In fact, van Loon and colleagues (3) confirmed this tendency in eight cyclists who were exposed to three 30-min stages of increasing intensities. The researchers noted that muscle glycogen and plasma glucose oxidation rates increased with every increment in exercise intensity, and subsequent whole-body fat oxidation declined at intensities reaching 75% maximal oxygen consumption ($\dot{V}O_{2max}$) (3).

Within any specified activity, the level of training status and type of training will influence crossover point, likely because of

[1]Worldwide Sport Nutritional Supplements, Bohemia, NY; [2]Department of Integrative Biology, University of California, Berkeley, Berkeley, CA; [3]Department of Health Sciences, Drexel University, Philadelphia, PA; [4]School of Behavioral and Health Sciences, Australia Catholic University, Melbourne, AUSTRALIA; [5]School of Medical and Health Sciences, Edith Cowen University, Perth, AUSTRALIA; [6]Department of Nutrition Sciences, Drexel University, Philadelphia, PA; [7]Samson College of Health Sciences, University of the Sciences, Philadelphia, PA; and [8]Department of Human Nutrition, Foods, and Exercise, Virginia Polytechnic Institute and State University, Blacksburg, VA

Address for correspondence: Stella Lucia Volpe, Ph.D., R.D.N., ACSM-CEP, FACSM, Department of Human Nutrition, Foods, and Exercise, Virginia Polytechnic Institute and State University, 295 West Campus Drive (MC 0430), 338 Wallace Hall, Blacksburg, VA 24061 (E-mail: stellalv@vt.edu).

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the metabolic adaptations that take place after repeated exposure to the same activity (4). Other factors that can influence crossover point include exercise duration, diet, muscle glycogen content, and sex (5). Most would agree that competitive sports have varying degrees of exercise intensities; therefore, we would presume that substrate demand would vary between competitive sports. However, there have been few attempts to categorize crossover point for sport specificity. The purpose of our study was to analyze sport-specific differences in time to substrate crossover and heart rate and percent $\dot{V}O_{2max}$ at crossover point using respiratory exchange ratio (RER) during a $\dot{V}O_{2max}$ test.

METHODS

Data were obtained as a part of a larger ongoing study conducted in the Department of Nutrition Sciences at Drexel University between September 2013 and November 2019. This study is a cross-sectional analysis of exercise variables in a population of athletes 18 yr and older. The study includes two sessions where resting metabolic rate, body composition, energy expenditure, $\dot{V}O_{2max}$, and dietary parameters are collected. For the present study, we obtained data from a smaller subset of the data collected at the second session ($\dot{V}O_{2max}$ test) of the two-session design. We also collected body composition data using bioelectrical impedance analysis and dietary data from food frequency questionnaires as descriptive data.

Participants

Participants were recruited from Philadelphia-area gyms and sport programs. Participants qualified for the study if they were nonsmokers who exercised in their sport a minimum of 2 d per calendar week and were 18 yr and older. Participants were excluded if they had an uncontrolled chronic disease and/or were unable to participate in exercise, as determined by a physician. Participants analyzed in these analyses were master athletes who were operationally defined as those who were 26 yr and older. Master athletes were chosen because of equal representation between sport groups in this age range. Those included in our analyses identified as runners, triathletes, rowers, or CrossFit athletes. This study was reviewed and approved by the Institutional Review Board at Drexel University (No. 1304002037-R008). All participants provided written informed consent in accordance with the Declaration of Helsinki for all study procedures before enrollment.

Anthropometric and Body Composition Assessment

Height and body weight were measured using a Seca® 700 balance beam scale (Hamburg, Germany). Height and body weight were measured twice on a calibrated scale to ensure accuracy, and the average was taken to compute the actual value. Body mass index (BMI) was calculated from height and body weight measurements. Body composition was measured using an InBody© 520 bioelectrical impedance scale (InBody USA, Cerritos, CA). Metrics obtained from the body composition analyses were percent body fat (PBF), lean body mass (LBM), intracellular water content, extracellular water content, and total body water.

Dietary Information

To assess total energy and macronutrient intakes, each participant completed a self-administered 2005 Block Food Frequency Questionnaire (FFQ; Nutrition Quest©, Berkeley, CA) (6,7). The FFQ is a previously validated tool that produces data representative of yearly dietary consumption by asking questions about dietary habits and specific food consumption. The FFQ is a 110-food-item questionnaire developed based on foods reported in the National Health and Nutrition Examination Survey from 1999 to 2002. The FFQ performs comparably to 4-d diet records in predicting dietary intake (6). Completed questionnaires were sent to Nutrition Quest© for analysis and returned to the research team for interpretation and statistical analysis.

Indirect Calorimetry to Assess $\dot{V}O_{2MAX}$

For $\dot{V}O_{2max}$ testing, an Oxycon Mobile Device™ by Vyaire Medical™ (Yorba Linda, CA) and a laptop operating JLAB version 5.3x software (Erich Jaeger GmbH, Würzburg, Germany) were used to measure indirect calorimetry. Participants were also fitted with a Polar Electro© (model T31) heart rate monitor (Kempele, Finland) to analyze heart rate during the testing. The heart rate monitor was fitted directly on the skin and just below the sternum on the chest. Before testing, participants were instructed to fast for 6 h and abstained from exercise, caffeine, and alcohol for at least 12 h.

$\dot{V}O_{2max}$ testing was conducted using a modified Taylor protocol treadmill test (8). The modified Taylor protocol started with participants running at a speed of 7 mph for 2 min to warm-up. Afterward, the speed of the treadmill remained at 7 mph, and the incline of the treadmill increased by 1% grade every minute until the participant reached volitional exhaustion. If a maximum incline of 12% grade was attained, the incline remained at 12%, and the speed of the treadmill increased by 0.5 mph each minute until the participant signaled exhaustion. The test was concluded using the criteria of volitional exhaustion, which was determined exclusively by the participant's willingness to continue the test. Volitional exhaustion was communicated using verbal cues from the research team, as well as hand signals from the participants. After exhaustion, the speed of the treadmill was reduced to a 2.5-mph walking pace and returned to a flattened position for 2 min during the cool-down period. $\dot{V}O_{2max}$ values were also determined using the following observed criteria: a plateau in oxygen consumption after an increase in grade and a consistent heart rate at maximal exertion. After the $\dot{V}O_{2max}$ criteria were met, breath-by-breath data were averaged to 30-s intervals to determine the final $\dot{V}O_{2max}$ value. Crossover was determined using RER, which represents the ratio of the volume of carbon dioxide produced to the volume of oxygen consumed. Crossover was operationally defined as an RER that exceeded 0.85 with no return less than 0.85 for the remainder of the test. These criteria were chosen because others have reported that an RER of 0.85 is the point at which energy derived from carbohydrate and fat is about equal (9,10). At the crossover point, heart rate and $\dot{V}O_{2max}$ were also recorded and included in our statistical analyses.

Statistical Analyses

Sample size was determined *a priori* using G*Power software (version 3.1.9.3). An effect size of 0.48 was determined using a preliminary analysis of a similar data set (11). It was determined that to achieve 0.80 power at an alpha level of 0.05, a sample size of 52 individuals (13 per group) was

TABLE 1.
Demographic Information.

	All Athletes (n = 77)	Runners (n = 20)	Triathletes (n = 20)	Rowers (n = 20)	CrossFit Athletes (n = 17)
Age (yr)	39.1 ± 10.4	37.5 ± 9.7	36.6 ± 8.5	44.5 ± 13.3	39.1 ± 10.4
Height (cm)	173.7 ± 11.2	171.8 ± 10.8	175.9 ± 8.15	176.9 ± 12.2	169.6 ± 12.6
Weight (kg)	77.1 ± 16.7	71.9 ± 12.8	78.7 ± 17.7	81.1 ± 16.4	76.3 ± 19.6
BMI (kg·m^{-2})	25.4 ± 3.8	24.3 ± 3.4	25.3 ± 4.6	25.8 ± 3.9	26.2 ± 3.3
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	40.7 ± 10.7	41.3 ± 9.0	43.3 ± 9.5	37.8 ± 13.6	40.3 ± 10.1
PBF (%)	24.3 ± 8.8	25.1 ± 8.4	21.5 ± 8.2	26.8 ± 9.6	23.7 ± 8.8
LBM (kg)	54.9 ± 12.1	50.8 ± 11.0	57.5 ± 9.3	56.1 ± 14.0	55.4 ± 13.8

There were no significant differences between groups for all variables. Results are represented as means ± SD.

required. Descriptive statistics (mean ± SD) were used to determine average age, height, body weight, BMI, $\dot{V}O_{2max}$, PBF, LBM, energy intake, carbohydrate intake, protein intake, and fat intake. A one-way ANOVA was applied to delineate differences in time to crossover. A Kruskal–Wallis nonparametric test was applied to determine differences between sport types for percent $\dot{V}O_{2max}$ and heart rate at crossover. Bonferroni correction procedures were used to control the family-wise error rate and assess multiple comparisons. All statistical procedures were performed with the Statistical Package for the Social Sciences (SPSS) version 25.0 (IBM, Armonk, NY) with alpha levels set *a priori* to $P < 0.05$.

RESULTS

Participant Characteristics

A total of 77 athletes were measured for RER during the $\dot{V}O_{2max}$ treadmill test (39 women, 38 men; 39.1 ± 10.4 yr of age). Athletes included 20 runners, 20 triathletes, 20 rowers, and 17 CrossFit athletes. Demographic and anthropometric information included age, height, body weight, BMI, $\dot{V}O_{2max}$, PBF, and LBM. A full description of the physical characteristics of the study sample can be found in Table 1. No significant differences were found among groups for any of the physical variables included in our analyses ($P > 0.05$).

Dietary Information

Results of the 2005 Block FFQ included energy, carbohydrate, protein, and fat intakes. These data are a representation of 66 athletes because of missing dietary information from 2 rowers and 9 CrossFit athletes. The findings from the FFQ can be found in Table 2. No significant differences among groups were found for any of the dietary variables of the Block FFQ for the current analysis ($P > 0.05$).

Crossover Point

The crossover point was operationally defined as the point at which RER exceeded 0.85 with no return less than 0.85 for the remainder of the test. There was a significant difference between groups for time to crossover point: runners (4:16 ± 0:58 min), triathletes (3:28 ± 1:08 min), rowers (4:00 ± 1:23 min), and CrossFit athletes (3:01 ± 0:58 min; $F_{3,73} = 4.39$, $P = 0.007$; Table 3, Fig. 1). *Post hoc* analyses of pairwise comparisons revealed that runners had a significantly longer time to crossover point than CrossFit athletes (4:16 ± 0:58 vs 3:01 ± 0:58 min; $P = 0.009$). For percentage of $\dot{V}O_{2max}$ at crossover point, there were significant differences among groups: runners (73.0% ± 13.1%), triathletes (57.5% ± 20.6%), rowers (71.9% ± 17.2%), and CrossFit athletes (60.2% ± 22.4%; $F_{3,73} = 3.57$, $P = 0.01$; Fig. 2). *Post hoc* analyses of pairwise comparisons revealed that triathletes'

TABLE 2.
Dietary Information.

	All Athletes (n = 66)	Runners (n = 20)	Triathletes (n = 20)	Rowers (n = 18)	CrossFit Athletes (n = 8)
Energy (kcal·d^{-1})	1899.0 ± 885.7	1965.0 ± 761.3	2147.3 ± 1208.4	1723.7 ± 702.1	1507.2 ± 327.4
Carbohydrate (g·d^{-1})	212.3 ± 125.2	227.3 ± 104.7	249.6 ± 177.7	176.7 ± 78.0	161.2 ± 66.3
Protein (g·d^{-1})	74.6 ± 30.7	73.0 ± 28.7	82.7 ± 34.4	73.4 ± 34.2	61.2 ± 8.0
Fat (g·d^{-1})	79.4 ± 32.6	78.8 ± 28.6	85.7 ± 42.4	77.5 ± 30.7	69.5 ± 14.5

There were no significant differences between groups for all variables. Results are represented as means ± SD. The sample size is lower for dietary data because dietary data were missing for two rowers and nine CrossFit athletes.

TABLE 3.
Time to Crossover in All Athletes.

Sport (*n*)	Time to Crossover (min)	% $\dot{V}O_{2max}$ at Crossover (%)	Heart Rate at Crossover (bpm)
All Athletes (77)	3:43 ± 1:12[a]	65.9 ± 19.4[a]	137.3 ± 20.6
Runners (20)	4:16 ± 0:58[b]	73.0 ± 13.1	141.7 ± 15.1
Triathletes (20)	3:28 ± 1:08	57.5 ± 20.6	126.9 ± 26.7
Rowers (20)	4:00 ± 1:23	71.9 ± 17.2	138.5 ± 20.6
CrossFit athletes (17)	3:01 ± 0:58	60.2 ± 22.4	141.7 ± 15.1

[a] Significant main-effect difference between all sport groups ($P = 0.009$).
[b] Runners' time to crossover was significantly higher than CrossFit athletes ($P = 0.009$).

percent $\dot{V}O_{2max}$ at crossover was significantly lower than rowers ($P = 0.04$) and runners ($P = 0.04$). No significant differences between groups were observed for heart rate at crossover ($P = 0.06$).

DISCUSSION

The primary purpose of our study was to examine if different sport types would yield differences in time to crossover, heart rate, and percentage of $\dot{V}O_{2max}$ at crossover point during a standardized exercise protocol. We found that when athletes of a different sport type were exposed to a standardized protocol, they expressed differences in their time spent transitioning from fat to carbohydrate. In addition, we noted that crossover point occurred at different percentages of $\dot{V}O_{2max}$. Although differences in fuel use existed for time and percentage of $\dot{V}O_{2max}$, crossover point differences were not identifiable from heart rate, which is somewhat surprising because heart rate has been previously linked to $\dot{V}O_{2max}$ (12).

All athletes rely on substrates for the production of energy during exercise, but it seems that exposure to repetitive bouts of the same sport promotes a metabolic adaptation. For instance, researchers have previously shown that, based on training status, athletes exhibit higher control over substrate use (13). Bergouignan and colleagues (13) measured metabolic flexibility, defined as "the body's ability to adapt fuel oxidation to changing fuel availability and energy demand." These researchers reported that physical activity level increased variances in nonprotein respiratory quotients across all participants (13). Their findings suggest that those with a higher level of activity may have a higher metabolic flexibility and therefore may have a greater affinity for fluctuation between substrate sources. Moreover, their findings support an assumption of our central hypothesis that sport type, or repeated exposure to a sport, can elicit meaningful metabolic changes. Our study is in close alignment with others who have measured crossover point. Notably, Pettigrew (14) measured crossover point and found that average percent $\dot{V}O_{2max}$ at crossover was 55%, with a range of 32% to 78% of $\dot{V}O_{2max}$. These data are in similar to the triathletes in our study who had the closest $\dot{V}O_{2max}$ (43.3 ± 9.5 $mL \cdot kg^{-1} \cdot min^{-1}$) compared with the group in the Pettigrew et al. study (47 $mL \cdot kg^{-1} \cdot min^{-1}$) (14).

It has previously been shown that exercise intensity level is positively correlated with RER, suggesting that a higher exercise intensity elicits an earlier use of carbohydrate and thus an earlier crossover point. Peric and colleagues (15) demonstrated this finding by examining the contributions of fat and carbohydrates through progressive exercise intensities. They reported that, at anaerobic threshold (~58% $\dot{V}O_{2max}$), there

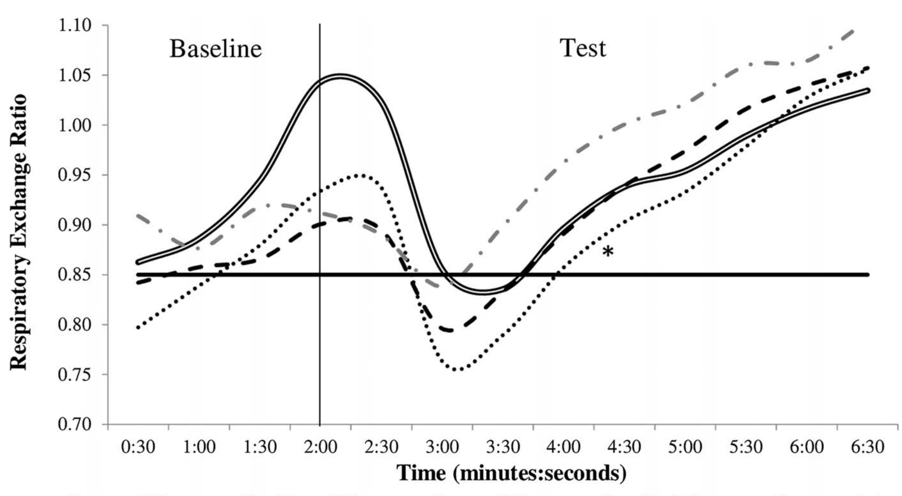

Figure 1: Crossover point differences between sport types during $\dot{V}O_{2max}$ testing. *Runners had significantly longer time to crossover than CrossFit athletes ($P = 0.009$).

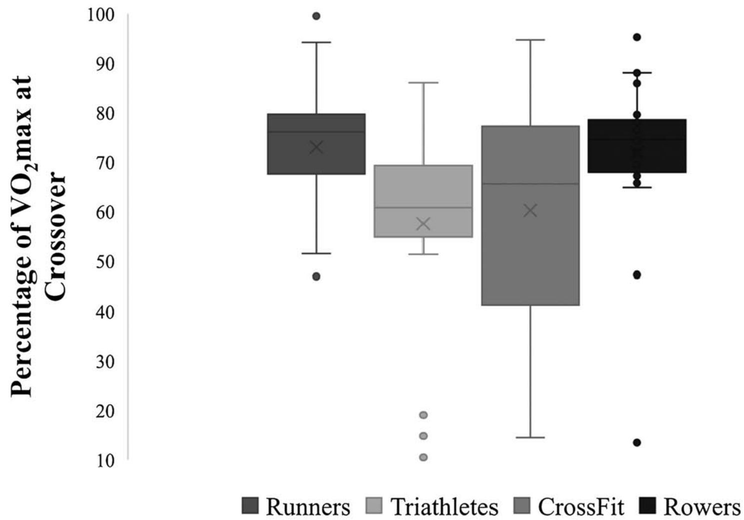

Figure 2: Differences in percentage of $\dot{V}O_{2max}$ at crossover point between sport types. Data points represented by dots indicate outliers within sport group. Triathletes' percent $\dot{V}O_{2max}$ at crossover was significantly lower than runners (P = 0.04) and rowers (P = 0.04).

was a progressive decrease in total fat oxidation and an increase in carbohydrate utilization in both athletes and nonathletes (15). These researchers also reported that at intensities of 87% $\dot{V}O_{2max}$, fat oxidation is minimal and carbohydrate use contributes to almost the entirety of energy production (15). Romijn and colleagues (16) examined a group of endurance-trained cyclists and measured them using stable isotopes during varying degrees of exercise intensities. They reported that plasma glucose tissue uptake and muscle glycogen oxidation increased in relation to exercise intensity (16). They also reported that peripheral lipolysis was maximal at the lowest exercise intensities, and fatty acids released into plasma decreased with increasing exercise intensities (16). In addition, athletes exercising at lower intensities have a higher propensity to use fat for fuel. Notably, Goedecke et al. (17) studied a group of endurance-trained cyclists, who represented a population participating in low to moderate exercise intensities. They reported that metabolic equivalents per day (indicative of exercise volume) were negatively correlated with RER (17). Therefore, the more these endurance athletes engaged in daily activity, the higher reliance they had on fat as an energy substrate. These studies align with ours and suggest that sports, of varying degrees of intensity and duration, elicit different energy substrate demands. Our findings also suggest that CrossFit athletes and those who participate in higher-intensity activities for shorter durations have a higher use of carbohydrate as a fuel source, whereas runners have a higher use of fat as a fuel source. However, previous researchers have not considered sport type and how repeated exposure to a sport type can dictate a propensity toward certain fuel sources.

Although our study is the first to analyze differences in sport types, there have been previous attempts to denote differences between sport modalities. Knechtle et al. (18) analyzed two sport types in endurance-trained athletes. They exposed the participants to a 30-min treadmill protocol and an identical 30-min cycling protocol at 55%, 65%, and 75% $\dot{V}O_{2peak}$ (18). Most notably, these researchers reported that participants had significantly higher fat oxidation at all exercise intensities during running compared with cycling (18). In addition, Achten et al. (2) studied 12 moderately trained men to determine the intensity that exercise elicits for maximal fat oxidation. They confirmed that running, compared with cycling, elicited a higher rate of fat oxidation, indicating that sport type can dictate fuel use, even within the same individuals (2).

Our results also revealed that crossover point occurs at different percentages of each sport's $\dot{V}O_{2max}$. Specifically, triathletes and CrossFit athletes transitioned to using carbohydrate at lower exercise intensities relative to their $\dot{V}O_{2max}$ compared with runners and rowers. Therefore, the stimuli of exercise intensity that elicits a transition to higher carbohydrate use is lower for these athletes compared with runners and rowers. These results are consistent with other studies that examined differences in fat oxidation levels between sports (19). Randell and colleagues (20) measured FAT_{max}, defined as the exercise intensity at which the maximal fat oxidation was observed, and found that FAT_{max} varied significantly between athletes participating in different sports and also between those in the same sport. It should be noted that FAT_{max} testing is designed to identify the maximal fat oxidation of an athlete. We did not use this method because it is not as useful to represent the balance between carbohydrate and fat as is submaximal testing.

It is important to highlight that there were no significant differences between dietary intakes in the athletes in our study. This finding implies that athletes' dietary patterns do not differ despite the metabolic demands of their respective sports. Hence, this suggests that, even though there are metabolic differences between these athletes, they do not differ in their fueling approaches to exercise. This has important implications, implying that the metabolic requirements of athletes need to be differentiated from their specific sport's metabolic demands.

Our study was not without limitations. Our results constituted a sample of four different sports; however, three of these would likely be classified as endurance-type activities, whereas the other represents an activity with relatively high intensities. To strengthen our design, it would have been beneficial to represent a greater diversity of sports types and activity intensities. In addition, our study operates on the assumption that athletes of a certain intensity level predominantly train in a similar fashion; however, it is not safe to assume that CrossFit athletes, for instance, do not participate in any endurance training. Moreover, although we analyzed typical dietary intake, we did not control for diet before administration of the $\dot{V}O_{2max}$ test. It has been reported that diet in the weeks leading up to, or as early as 1 d before, testing can have an impact on substrate use (19,21). Standardizing a diet at least 24 h before the test would have helped with accurate translation of the findings. In addition, we analyzed athletes for substrate use during a $\dot{V}O_{2max}$ test, a relatively high-intensity test that may not be representative of the intensity of the exercise in which endurance athletes participate. It would therefore have been more valuable to include a variety of treadmill protocols that may have better represented the progression of exercise intensities performed for each of the individual sport types.

To the best of our knowledge, this is the first study to analyze crossover point differences between various sport types. Our results support the notion that there are sport-specific differences in metabolic adjustments among sports. We theorize that this may be due to metabolic changes that occur as a result of repeated exposure to a sport type. Based on our results, it is clear that sports, specifically those of a polarizing nature—low to moderate intensity versus high intensity—have different metabolic demands that manifest themselves through metabolic adaptations toward specific substrates. For instance, we found significant differences in the transition from fat to carbohydrate substrate predominance across all sport types. More specifically, CrossFit athletes had an earlier use of carbohydrate, whereas runners had a longer duration of fat oxidation during a $\dot{V}O_{2max}$ test. This is highlighted in Fig. 1, which demonstrates that, after the start of the test, runners were the last group to reach an RER >0.85. In addition, the level of intensity that elicited this transition was significantly different between sport types. This is highlighted in Fig. 2, which demonstrates that, on average, triathletes had a significantly lower percent $\dot{V}O_{2max}$ at the crossover point compared with runners and rowers. Therefore, the use of certain substrates at relative intensities may be dependent on the specific type of sport or exercise in which the athlete engages as part of their training program. This is valuable for understanding the optimization of sport performance considering sport specificity. Based on the information herein, we hypothesize that dietary considerations for specific training methods should be a focus of athletes because, if they can improve the efficiency of their metabolism for their sport, they may be able to improve their performance outcomes. This has practical implications for those participating in different modes of exercise and how their bodies metabolically respond to the exercise stimuli. Furthermore, our results may imply inherent differences in how athletes of different sport modalities have sport-specific nutritional needs. Nonetheless, our results have yet to be elucidated. Further analyses should consider alterations in substrate use through dietary and training approaches, and how they influence performance outcomes for different sport modalities.

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