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Maximal fat oxidation impacts high-intensity running during soccer match: lessons from a retrospective study in elite soccer players

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Liste des abréviations

Anova : One-way analysis of variance
ATP : Adenosine Triphosphate
ATS : Acceleration Testing System
BMI : Body mass index
CD : Central defender
CHO : Carbohydrate
CM : Central midfielders
FB : Fullback
F_{0H} : Theoretical Horizontal Maximal Strength
F_{0V} : Theoretical Vertical Maximal Strength
FVP : Force velocity power profiles
GPS : Global Positioning System
HIR : High intensity
MFO : Maximal Fat Oxidation
PCr : Phosphocreatine
P_{maxH} : Theoretical Horizontal Maximal Power
P_{maxV} : Theoretical Vertical Maximal Power
S : Striker
SJ : Squat jump
SR : Sprint running
TD : Total distance
$\dot{V}CO2$: Carbon Dioxide Production
$\dot{V}O2$: Oxygen Consumption
$\dot{V}O2_{max}$: Maximal oxygen consumption
V_{0H} : Theoretical Horizontal Maximal Velocity
V_{0V} : Theoretical Vertical Maximal Velocity
W : Winger

Contexte du stage

Mon stage de Master 2 s'est déroulé entre le laboratoire M2S et le centre de formation du Stade Rennais FC à la Piverdière. J'ai ainsi travaillé sur différentes missions pour le Stade Rennais FC le lundi et le vendredi, encadré par Arthur Guillotel (Doctorant et Sport Scientist au Stade Rennais FC), alors que je travaillais au laboratoire M2S du mardi au vendredi, sous la supervision de mon tuteur Frédéric Derbré (Maître de conférences et chercheur au laboratoire M2S).

Au cours de mes missions au Stade Rennais, j'ai été amené à réaliser de nombreuses tâches courtes nécessitant un retour rapide pour le staff d'entrainement du centre de formation. J'ai ainsi participé au traitement quotidien et hebdomadaire des données GPS, des données technico-tactiques obtenues grâce à l'analyse vidéo, ainsi que des données issues de questionnaires psychologiques pour monitorer l'état de santé physique et psychologique des jeunes joueurs, tout en évaluant leurs performances en match. J'ai également accompagné le staff dans la mise en place de tests physiques sur les jeunes joueurs de la préformation. Des missions de plus long terme et de développement m'ont également été confiées. J'ai ainsi travaillé sur le calcul d'un score de performance issu du jeu Sorare. Pour ajuster ce score au ressenti des entraîneurs, j'ai modifié la pondération de la possession, qui surévaluait certains joueurs, notamment les défenseurs centraux, en raison du nombre élevé de passes vers l'avant qui ne font pas forcément avancer le jeu. J'ai également actualisé la méthode d'estimation du stade de maturité et de prédiction de la taille adulte en me basant sur la littérature scientifique. Bien que je n'aie pu ressortir de méthodes révolutionnaires récentes, j'ai identifié les méthodes qui sont les plus utilisées dans les clubs. Enfin, je suis actuellement investi dans la mise en place d'un algorithme de machine learning pour estimer le risque de blessure des joueurs à partir des différentes bases de données auxquelles j'ai accès.

Au laboratoire M2S, il m'a été demandé de réaliser un article scientifique à partir d'un ensemble de jeux de données qui avaient été collectés en collaboration par le laboratoire M2S et le Stade Rennais FC. Ce travail de recherche avait pour finalité 1) de déterminer si l'oxydation maximale lipidique des joueurs de football était une variable conditionnant en partie la performance physique des joueurs en match, et 2) d'observer le poids de cette oxydation maximale des lipides dans la performance physique en match comparativement aux autres qualités plus classiquement ciblées par les préparateurs physiques ($\dot{V}O2_{max}$, force, puissance). La finalité était d'ouvrir des perspectives très concrètes dans la planification de la préparation physique et la nutrition des joueurs de football (par exemple, intégration de blocs d'endurance fondamentale et de travail à jeun dans l'entraînement, périodisation glucidique). Cet article, rédigé en anglais, sera soumis à un journal scientifique cet été ou à la rentrée (*Scandinavian Journal of Sports Medicine ou Medicine & Science in Sports & Exercise*). Pour correspondre aux modalités de rendu, j'ai également écrit une revue de littérature en français, accessible en annexe.

Maximal fat oxidation impacts high-intensity running during soccer match: lessons from a retrospective study in elite soccer players.

Abstract

Purpose. Maximal fat oxidation rates (MFO) is considered an important determinant of athletic performance in endurance sport, but studies have rarely investigated this issue in soccer. This study examined the possible associations between maximal fat oxidation and match running performance in elite soccer players, and aimed to assess the importance of maximal fat oxidation in match performance compared to other physical qualities more traditionally targeted by physical trainers (e.g., $\dot{V}O2_{max}$, strength, power). **Methods.** During the pre-season training, 41 youth elite soccer players performed a maximal and fasted submaximal graded exercise test on a treadmill for the determination of peak oxygen uptake ($\dot{V}O2_{max}$) and MFO, respectively. Additionally, vertical and horizontal force-velocity-power profile were obtained for each soccer player. The match-running performance was measured by a global positioning system (GPS) over a competitive season. **Results.** Based on the weight of each variable obtained from 100 bootstraps on our regression trees, $\dot{V}O2_{max}$ was identified as the most important variable for estimating total distance, F_0 and P_{max} for estimating sprint distance, and MFO for estimating high-intensity running (> 15km/h). Players exhibiting $\dot{V}O2_{max}$ greater than 55.6 ml/min/kg covered more distance than others (P<0.05), and players with a MFO greater than 0.73 g/min covered more high-intensity distance (P<0.05). **Conclusion.** This study identifies a specific threshold of approximately 0.7 g/min for maximal fat oxidation, which could serve as a benchmark for physical staff in elite soccer clubs. This finding support that maximal fat oxidation play an important role in high-intensity running performance during soccer game. Optimizing physical performance and endurance in soccer requires a holistic training approach that targets lower limb explosiveness, aerobic power, and fat oxidation, recognizing the multifaceted nature of high-intensity effort.

Keywords: fat oxidation, exercise physiology, football, metabolic profile, anaerobic threshold

Introduction

Performance in soccer is influenced by various factors including technical, tactical, psychological, and physiological aspects (Stølen et al., 2005). Over the years, the sport has evolved; alongside its technical and tactical demands, soccer has become increasingly physically demanding (Bush et al., 2015; Lago-Peñas et al., 2023). Using tools such as video analysis, global positioning systems (GPS), and accelerometers, physical trainers and data scientists are now able to daily monitor the physical performance of players during training and competitive matches to maintain players' physical fitness throughout the competitive season (Rago et al., 2020).

In soccer, physical trainers propose personalized training programs that focus on developing the lower limbs muscle power and the ability to repeat high-intensity efforts throughout the match. Indeed, the frequency and intensity of these intense efforts tend to decrease towards the end of the match or following periods of maximum intensity (Dalen et al., 2016; Delaney et al., 2018; Izzo et al., 2020; Mohr et al., 2016, 2012). The decline in physical performance is multifactorial, but it is directly related to peripheral fatigue (Thomas et al., 2017). During brief and highly intense actions in a match, the degradation of phosphocreatine (PCr) coupled with muscle glycogenolysis are the primary sources of adenosine triphosphate (ATP) resynthesis. This results in the depletion of muscle PCr reserves and disturbances in the intracellular environment that may contribute to the onset of peripheral fatigue (Bangsbo et al., 2006; Vigh-Larsen et al., 2021). The regeneration of muscle PCr is directly dependent on the energy capacity of muscle mitochondrial respiration, which can supply the energy needed for this process during recovery phases in a match (Tomlin and Wenger, 2001). For these reasons, physical trainers prioritizes training sessions targeting the development of maximal oxygen consumption $\dot{V}O2_{max}$. Being associated to increased mitochondrial volume density and overall respiratory capacity (Furrer et al., 2023; Lundby and Jacobs, 2016), an increase in $\dot{V}O2_{max}$ improve time recovery between intense efforts by efficiently restoring muscle PCr and ATP stores from inorganic phosphate after exercise (Gharbi et al., 2015). As the match progresses and high-intensity actions demand maximal rates of glycogenolysis, the decline in glycogen levels also contribute to a deterioration in performance (below ~200 mmol-kg-1) (Vigh-Larsen et al., 2021), and is considered a key factor contributing to end-match fatigue (Mohr et al., 2022, 2016).

To minimize muscle glycogen depletion, athletic performance staffs implement training program and nutritional strategies to maximize muscle glycogen stores at the beginning of each match and to maintain the muscle fiber stores throughout the game. While it is very developed in endurance sports, the capacity of mitochondria to preferentially oxidize lipids during recovery and low-intensity efforts in a match is, paradoxically, rarely targeted in the physical training programs of soccer players. This metabolic adaptation to fuel availability allows to spare muscle glycogen stores for high-intensity exercises requiring maximal activation of the glycolytic system (Vigh-Larsen et al., 2021). The maximal whole-body capacity for fat oxidation during exercise (MFO) can be determined using the Fat_{max} test, indicating the highest rate of fat oxidation observed at various submaximal intensities (Achten et al., 2002; Maunder et al., 2018).

By more deeply profiling the physical capacities of soccer players, the development of new physiological parameters currently interests physical training staffs and can enhance physical training effectiveness through more personalized training programs. Van de Casteele and colleagues recently categorized soccer players based on their muscle fiber typologies by measuring the carnosine content in the soleus and medial gastrocnemius muscles using magnetic resonance imaging (Van de Casteele et al., 2024). Their analysis revealed that players classified as high fast-twitch skeletal muscle experienced a more pronounced decline in high-intensity actions towards the end of the match. These players could also be prone to earlier glycogen depletion, given the relationship between muscle glycogen concentration and fiber type(Vigh-Larsen et al., 2021). Other studies have directly profiled mitochondrial enzymes involved in fat oxidation in the skeletal muscle of soccer players using biopsies. While such approaches are highly interesting for scientists, they are less accessible for the professional soccer staffs (Mohr et al., 2016). In this context, classifying players based on carbohydrate and lipid metabolism profiles could provide a non-invasive and low cost-effective method to assess substrate utilization during matches.

Here, we hypothesized that soccer players with a higher MFO would be less prone to muscle glycogen depletion, thereby enabling them to repeat more high-intensity efforts. The present study was thus designed 1) to assess the physical and metabolic characteristics, as well as the GPS data describing the physical tasks' external intensity in young elite soccer players during an entire season 2) to explore the relative weight of MFO in matches GPS data compared to other main indicators of physical performance in soccer including $\dot{V}O2_{max}$, maximal power (P_{max}), and maximal strength (F_0).

Methods

Participants

41 young male elite soccer players (16.1± 1.2 years, 179±7 cm, 67±7 kg) were recruited from Stade Rennais FC academy (U16, U17, U19, reserve team). Each player received both written and verbal explanations of the study design and procedures, before signing the informed consent in their native language. The study was approved by the Rennes 2 University Ethics Approvals (Human Participants) Subcommittee. The participant's characteristics are shown in Table 1.

Table 1. Participant's physical characteristics (mean ± SD)

Age (years)	16.1 ± 1.3
Height (cm)	179 ± 7
Weight (kg)	67 ± 7
BMI (kg/m^2)	21.1 ± 1.6

General design

Metabolic and power data were collected during the pre-season and the start of the competitive season (September-October). All the players first completed an incremental exercise test on a treadmill to determine $\dot{V}O2_{max,}$ followed by a submaximal Fat_{max} test a few weeks later. Whole body rates of fat and CHO oxidation were calculated during the submaximal exercise test using indirect calorimetry. Additionally, the players performed a Squat Jump and a Sprinting test to determine vertical and horizontal force-velocity-power profile, respectively. Match running performance data were collected from official games throughout the 2022-2023 season, involving four teams (U16, U17, U19 and reserve teams).

Experimental design

$\dot{V}O2_{max}$ assessment

Incremental exercise tests were conducted in the Sports Medicine Department of Rennes Hospital on a running treadmill (H/P Cosmos Pulsar, H/P/COSMOS 3P, H/P/COSMOS Sports & Medical, Germany). Players performed an incremental running test until voluntary exhaustion to determine $\dot{V}O2_{max}$. The test started at an initial velocity of 9 km/h. From this point, the speed was increased by 1km/h every 2 minutes until reaching 13 km/h. Then, every stage increase of 1 km/h every minute without break between stages. The test ended when soccer players reached voluntary exhaustion. The highest value of $\dot{V}_{O2}$ was used provided two or more of the following criteria were met 1) an increase in $\dot{V}_{O2}$ <2.1 ml/min/kg with increasing workloads, 2) maximum HR within 10 bpm of age-predicted maximum HR (208-0.7 x age) and 3) RER exceeded 1.05. $\dot{V}_{O2}$ and $\dot{V}_{CO2}$ were continuously measured using an indirect calorimetry system (Oxycon device, Hoechberg, Germany).

Maximal fat oxidation assessment

At the beginning of the competitive season, a second visit to the "Movement, Sport and health Sciences" (M2S) laboratory was planned to perform submaximal metabolic tests on a treadmill, at running intensities corresponding to 50, 60 and 70% of the previously determined $\dot{V}O2_{max}$. The tests were carried out in a fasting state in the morning (between 7 a.m. and 9:30 a.m.). The $\dot{V}_{O2}$ and $\dot{V}_{CO2}$ were continuously monitored during the test using an indirect calorimetry system (Ultima CardiO2, Medgraphics, United Kingdom). Every stage was maintained for 6 minutes, and the last 60 seconds of each stage were used to calculate absolute rates of fat and carbohydrate oxidation (g/min) using stoichiometric equations (Equation 1 and 2) (Frayn, 1983), based on the assumption that the excretion of urinary nitrogen was negligible. Maximal fat oxidation (MFO) was considered as the highest value of fat oxidation among the three different running intensities.

Equation 1. Respiratory quotient

Carbohydrate oxidation :	$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2\ 6H_2O\ 36_{ATP}$
Fat oxidation :	$C_{16}H_{32}O_2 + 23O_2 \longrightarrow 16CO_2 + 16H_2O + 130_{ATP}$

Equation 2. Stoichiometric equations

CHO oxidation rate :	$1.67 \times \dot{V}O2$ (L/min) – $1.67 \times \dot{V}CO2$ (L/min)
Fat oxidation rate :	$4.55 \times \dot{V}O2$ (L/min) – $3.21 \times \dot{V}CO2$ (L/min)

Force-Velocity-Power (FVP) profiles

Horizontal PVP. All session began with a general warm up consisting of jogging and dynamic stretchings. Once the warm-up was completed, two maximal sprints were performed of 40 m, with the fastest sprint used for analyses. Running speed during the linear sprint was measured via a Stalker Acceleration Testing System (ATS) radar device (Stalker pro II, Applied Concepts, Dallas, TX, USA). The radar device was mounted on a tripod behind the starting line at a height of one meter, approximately corresponding to the height of participant's center of mass (Jiménez-Reyes et al., 2018). The radar device sampled velocity-time data at 46.9 Hz, and was operated remotely via connection to a laptop to minimize the possibility variability introduced by manual operation. Participants initiated the sprint from a standing position. All data were collected using Mtraining software (Mooky Stalker v3, France). Individual force–velocity relationships in sprinting were assessed using the Samozino's method (Morin and Samozino, 2016). The theoretical maximum values of force (F_{0H} in N/kg), velocity (V_{0H} in m/s), and power (P_{maxH} in W/kg) were calculated. F_{0H} and P_{maxH} were normalized to body mass.

Vertical PVP. All sessions began with 3 minutes of cycling at 1.5 W/kg body weight, followed by 10 squats, 10 left lunges, 10 right lunges and 10 repetitive squat jumps (SJ). Once the warm up was completed, players performed maximal SJ 1) without external loads, 2) with load at the Smith machine squat, and 3) with constant loads. For each loading condition, 2 SJ was performed, and the highest SJ was used for analyses. Jump height was measured with a valid optical measurement system (OptoJump Next Microgate, Bolzano, Italy). The values of force and velocity obtained during the trial with the highest jump height of each loading condition were modeled by least squares linear regressions to determine the individual vertical force-velocity profile (Jaric, 2015). F_{0V} represents the theoretical maximum force normalized to body mass, and P_{maxV} was calculated as $P_{max} = F_{0V}xV_{0V}/4$ and normalized to body mass.

Match running performance

Match running performance data from the 41 soccer players were collected during official games over the 2022-2023 season using GPS tracking system (McLloyd STv4, France and STATSports Apex, Northern Ireland). After the matches were recorded, the data were downloaded using McLloyd and STATSports software, then processed in RStudio (version 2023.12.1+402, RStudio Team, Boston, MA, USA). Only data from outfield players who were on the pitch for 90 min during at least 3 matches were retained, and covered distances were expressed per 90 minutes of playtime. On average, 7 matches per included player (n = 41) were analyzed, allowing performance in five playing positions to be profiled (central defenders (CD) n = 9 ; fullbacks (FB) n = 9 ; central midfielders (CM) n = 11 ; wingers (W) n = 7 ; strikers (S) n = 5).

The distances that players covered during the full game were split into the following running intensity categories: low speed running (0 – 14.9 km/h), moderate-speed running (15–19.9 km/h), high-speed running (20-24.9 km/h), and sprint running (>25 km/h) (Riboli et al., 2021; Van de Casteele et al., 2024). Total distance represented the summation of distances in all categories. High-intensity running consisted of the combined distance in moderate-speed running, high-speed running, and sprinting (> 15km/h) and very high intensity running consisted of the combined distance in high-speed running and sprinting (> 20 km/h).

Statistical analysis

Data are presented as mean ± SD. The Shapiro-Wilk test was used to assess normality, and Levene's test was employed to check if variances were equal across groups. One-way analysis of variance (ANOVA) was conducted to determine whether physical, anthropological, physiological and GPS data differed among playing positions. In cases of significant differences, Tukey's post hoc tests were applied to identify which positional groups differed. When the assumptions of normality or equal variances were violated, the Kruskal-Wallis rank sum test with Wilcoxon post hoc tests or Welch's ANOVA with Games-Howell post hoc tests were used, respectively. When comparing two groups, a Student t-test was performed. When the assumptions for the t-test were not met, either a Wilcoxon rank-sum test or a Welch's t-test was used instead.

We standardized our data on a match-by-match basis whenever possible. When a match includes at least three players, we use the match statistics to standardize our data as follows:

$$\frac{\mathrm{x} - \mu_{\mathrm{match}}}{\sigma_{\mathrm{match}}}$$

- x : Observation.
- σ : Mean of the match.
- μ: Standard deviation of the match data.

When the number of players for a match was insufficient (n < 3), we used the specific player’s data from their other matches for standardization as follows:

$$\frac{\mathrm{x} - \mu_{\mathrm{player}}}{\sigma_{\mathrm{player}}}$$

- x : Observation.
- σ : Mean of the player data.
- μ: Standard deviation of the player data.

After standardizing each variable for each player during each match, we calculated the mean of these values. This mean was then used for subsequent analyses. Throught this process, we can position, on average, each player relative to their teammates for a given variable.

To analyze the impact of various physiological variables on the measured GPS data, we used regression trees with the “Rpart” package in Rstudio and assessed their importance using 1000 bootstrap samples. This method aims to provide stable estimates of variable importance, expressed as mean ± SD. We used the following equation for this purpose:

$$I(X^m) = \sum_{t \in A} \Delta\hat{R}\ (d_m(t), t)$$

- A : Decision tree.
- t: A node in the tree.
- $\Delta\hat{R}$: Reducing prediction error.
- $d_m(t)$: The decision (or split) is made using the variable X^m at node t.

Then, we used a simplified regression tree model that consists of only one split. The results of this model are illustrated in our figures. The main split threshold of the tree was selected to segment individuals based on the physiological variable most associated with our GPS variable of interest. The effectiveness of this segmentation was evaluated using a Student t-test, with a significance threshold set at $p < 0.05$.

Results

Physical characteristics and running performance in official games among young elite soccer players

Player's physical capacities, according to their playing position are presented in the Table 2 and 3. Central players present significantly lower P_{maxH} and F_{0H} compared to side players ($p<0.05$, Table 2), while no significant differences were reported between the two groups concerning $\dot{V}O2_{max}$ and MFO. Further analysis by specific playing positions reveals that wingers exhibit significantly higher F_{0H} compared to strikers ($p<0.05$, Table 3). Match running performances accounting for actual playing times are detailed in Table 4 and 5. The analysis of physical performance metrics reveal significant positional differences among position. Side players have significantly greater high-speed running distance, sprint distance and very high-intensity running distance compared to central players ($p<0.05$). In contrast, central players cover more distance at low speed than side players ($p<0.05$). More specifically, wingers and fullbacks cover greater total distances at high speed and very high intensity compared to central defenders and central midfielders ($p<0.05$). Sprinting distances are significantly greater in fullbacks and wingers compared to central midfielders ($p<0.05$).

Table 2. Descriptive statistics of physical and metabolic performance and differences between players playing at central and side of the pitch.

	All Players (n=41)	Central Players (n= 25)	Side Players (n=16)
$\dot{V}O2_{max}$ (ml/min/kg)	57.1 ± 4.0	57.1 ± 4.5	57.1 ± 3.2
MFO (g/min)	0.66 ± 0.17	0.66 ± 0.17	0.65 ± 0.17
P_{maxH} (W/kg)	17.55 ± 2.15	17.03 ± 1.94*	18.36 ± 2.27*
F_{0H} (N/kg)	7.92 ± 0.99	7.72 ± 1.03*	8.23 ± 0.86*

Data are given as means ± SD. *: Significant differences when compared to central and side playing position ($p<0.05$, Student T-test).

Table 3. Descriptive statistics of physical and metabolic performance and differences between players at soccer specific playing positions.

	All (n=41)	CD (n = 9)	FB (n=9)	CM (n=11)	W (n=7)	S (n=5)
$\dot{V}O2_{max}$ (ml/min/kg)	57.1 ± 4	56.6 ± 6	56.7 ± 3.9	57.5 ± 3.3	57.6 ± 2.2	57.0 ± 4.6
MFO (g/min)	0.66 ± 0.17	0.61 ± 0.08	0.59 ± 0.18	0.69 ± 0.20	0.72 ± 0.13	0.72 ± 0.24
P_{maxH} (W/kg)	17.55 ± 2.15	17.42 ± 53	17.77 ± 1.90	17.14 ± 1.94	19.11 ± 2.63	16.10 ± 1.51
F_{0H} (N/kg)	7.92 ± 0.1	7.87 ± 1.30	7.95 ± 0.45	7.97 ± 0.72	8.58 ± 1.16^{S}	6.90 ± 0.77^{W}

Data are given as means ± SD. Superscripted letters indicate significant post-hoc differences when compared to specific playing position. CD: Central defenders, FB: Fullbacks, CM : Central midfielders, W: Wingers, S: Strikers.

Table 4. Descriptive statistics of match running and differences between players playing at central and side of the pitch

	All Players (n= 41)	Central Players (n=25)	Side Players (n=16)
Total Distance (m)	9,304 ± 598	9,366 ± 513	9,207 ± 318
Low Speed (m)	7,524 ± 422	7,651 ± 364*	7,326 ± 184*
Moderate Speed (m)	1,070 ± 232	1,119 ± 240	1000 ± 204
High Speed (m)	454 ± 125	405 ± 100*	531 ± 123*
High Intensity (m)	1,780 ± 351	1,714 ± 330	1,882 ± 369
Very High Intensity (m)	581 ± 188	500 ± 142*	706 ± 187*
Sprinting (m)	126 ± 74	95 ± 51*	175 ± 79*

Data per 90 minutes of match are given as means ± SD *: Significant differences when compared to central and side playing position ($p<0.05$, Student T-test).

Table 5. Descriptive statistics of match running performance and differences between players at soccer specific playing positions.

	All (n = 41)	CD (n = 9)	FB (n=9)	CM (n=11)	W (n=7)	S (n=5)
Total Distance (m)	9,304 ± 598	9,032 ± 457	9,264 ± 318	9,563 ± 475	9,531 ± 451	9,134 ± 1,07
Low Speed (m)	7,524 ± 422	7,457 ± 342	7,436 ± 184	7,830 ± 376	7,607 ± 181	7,184 ± 632
Moderate Speed (m)	1,070 ± 232	985 ± 138	976 ± 105	1,226 ± 246	1,123 ± 292	1,031 ± 295
High Speed (m)	454 ± 125	377 ± 67 ^{CB,W}	519 ± 114^{CB,CM}	378 ± 105^{FB,W}	515 ± 69^{CB,MC}	547 ± 142
High Intensity (m)	1,780 ± 351	1,575 ± 223	1,829 ± 295	1,733 ± 380	1,924 ± 309	1,950 ± 464
Very High Intensity (m)	581 ± 188	484 ± 117 ^{FB,W}	686 ± 191^{CB,CM}	442 ± 141^{FB,W}	658 ± 47^{CB,CM}	733 ± 193
Sprinting (m)	126 ± 74	107 ± 53	167 ± 89^{MC}	64 ± 39^{FB,W}	143 ± 26^{MC}	186 ± 68

Data are given as means ± SD. Superscripted letters indicate significant post-hoc differences when compared to specific playing position. CD: Central defenders, FB: Fullbacks, CM : Central midfielders, W: Wingers, S: Strikers.

Total match distance covered is mainly influenced by high maximal oxygen consumption ($\dot{V}O2_{max}$)

The contribution of various physiological factors to the total distance covered in a match is shown in Figure 1. This figure support that $\dot{V}O2_{max}$ has the most important contribution to estimating the total distance covered. The simplified decision tree provides a segmentation that is most discriminative at a threshold of 55.6 ml/min/kg. Players above this threshold cover, on average, a greater distance than those below it ($P<0.05$).

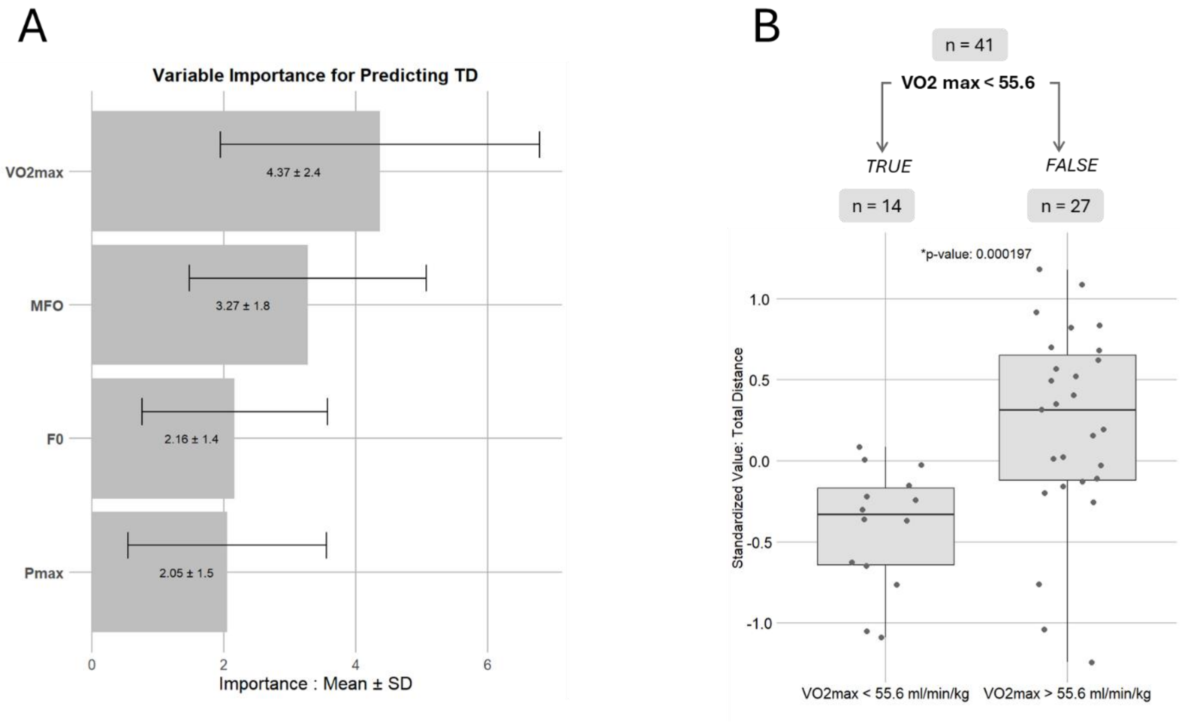
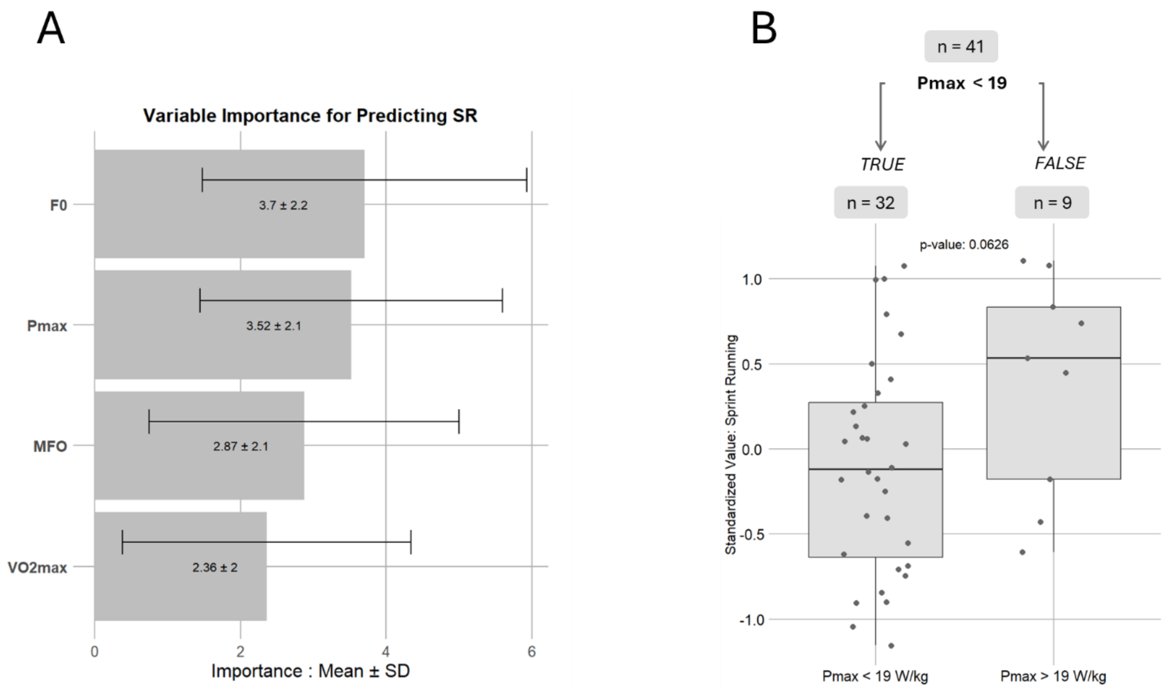


Figure 1: Variable Importances for Predicting Total Distance (TD) during matches and simplified Regression Tree Structure. *(A) Panel describing the relative importance of variables ($\dot{V}O2_{max}$, MFO, F_{0H}, P_{maxH}) for predicting the standardized value of total distance (mean±SD). These importance values were derived from 100 bootstrap samples to obtain the mean ± SD. (B) Simplified regression tree with a single split, identified as the most important, partitions the initial sample of 41 observations into two nodes based on the most discriminative variable regarding total distance. The boxplots show the distributions of standardized total distance values for each partition.*

Importance of lower limb power and strength in player's sprint performance during matches

The contribution of various physiological factors to the sprinting performance during matches is shown in Figure 2. F_{0H} and P_{maxH} are the most important factors for estimating sprint performance (Figure 2A). The simplified decision tree provides a segmentation based on P_{max}, which is most discriminative at a threshold of 19 W/kg. Players with higher P_{max} tend to have higher sprint performances (p=0.06, Figure 2B).



<u>Figure 2 : Variable Importances for Predicting Sprint Running (SR) during matches and Regression Tree Structure.</u> *(A) Panel describing the relative importance of variables (F_{0H}, P_{maxH}, MFO, $\dot{V}O2_{max}$) for predicting the standardized value of sprint running (mean± SD). These importance values were derived from 100 bootstrap samples to obtain the mean ± SD. (B) Simplified regression tree with a single split, identified as the most important, partitions the initial sample of 41 observations into two nodes based on the most discriminative variable regarding sprint running distance. The boxplots show the distributions of standardized sprint running values for each partition.*

High-intensity running covered is mainly influenced maximal fat oxidation (MFO)

The contribution of various physiological factors to high-intensity running (> 15 km/h) during matches is shown in Figure 3. MFO is the most important factor for estimating high intensity running (Figure 3A). The simplified decision tree provides a segmentation based on MFO, which is most discriminative at a threshold of 0.73 g/min. Players with higher MFO cover, on average, a greater distance at high intensity than those below this threshold (P<0.05) (Figure 3B).

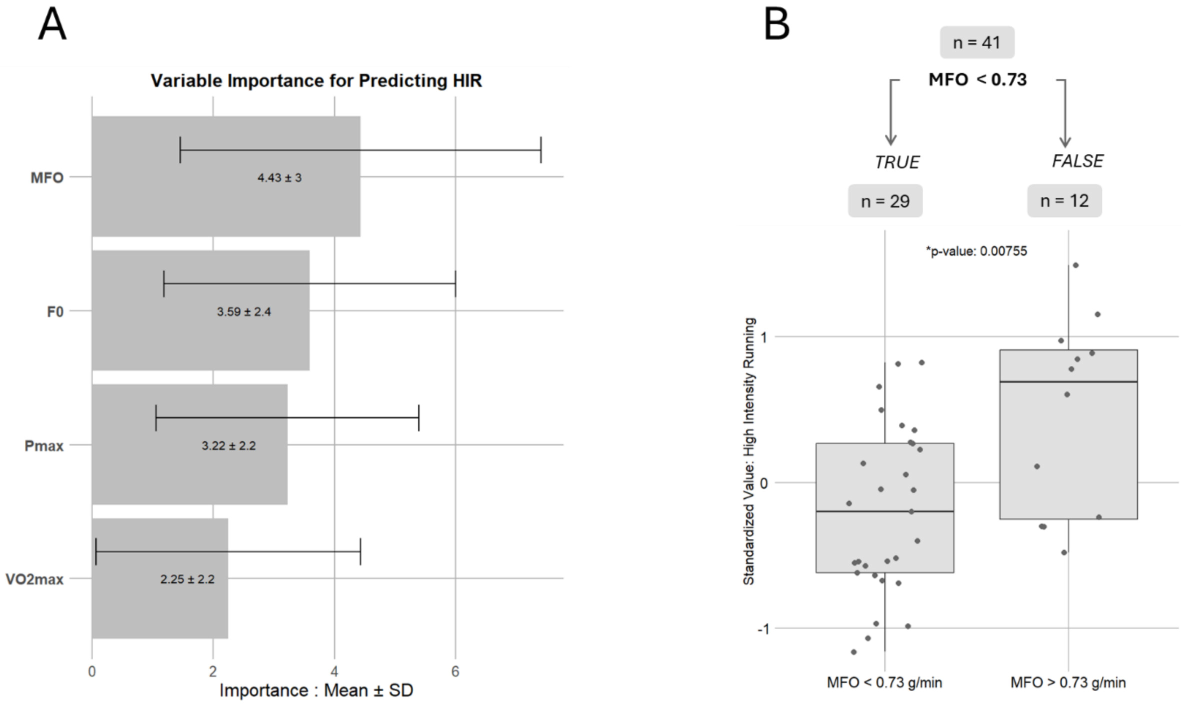


Figure 3 : Variable Importances for Predicting High Intensity Running (HIR) and Simplified Regression Tree Structure. *(A) Panel describing the relative importance of variables (MFO, F_{0H}, P_{maxH}, $\dot{V}O2_{max}$) for predicting the standardized value of high intensity running (mean±SD). These importance values were derived from 100 bootstrap samples to obtain the mean ± SD. (B) simplified regression tree with a single split, identified as the most important, partitions the initial sample of 41 observations into two nodes based on the most discriminative variable regarding HIR distance. The boxplots show the distributions of standardized high intensity running values for each partition.*

Discussion

The aim of the present study was to investigate the association between physical and metabolic characteristics of elite soccer players and match running performance during official matches. Unsurprisingly, $\dot{V}O2_{max}$ emerges as a significant determinant of the total distance covered during matches, whereas F_{0H} and P_{maxH} appears as key factors for sprint performance. Finally, our data highlight for the first time that maximal fat oxidation is the main physiological parameter associated to high-intensity running, suggesting the interest of including maximal fat oxidation testing in the profiling of elite soccer players.

$\dot{V}O2_{max}$ is considered the main physiological parameter to assess and monitor in soccer players to estimate their ability to repeat high-intensity running during matches. The data we obtained in our cohort of young male elite soccer players are consistent with previous studies reporting average $\dot{V}O2_{max}$ values in elite soccer players ranging between 55 and 65 ml/kg/min (Da Silva et al., 2011; Metaxas, 2021; Modric et al., 2020). The lack of significant differences in $\dot{V}O2_{max}$ among different playing positions confirms previous findings frequently reporting no significant differences in $\dot{V}O2_{max}$ values between playing positions in elite players (Al-Hazzaa et al., 2001; Modric et al., 2020; Slimani and Nikolaidis, 2018).

The average values of the horizontal FVP profile, including P_{maxH} and F_{0H}, are also consistent with previous studies conducted in young elite soccer players (Jiménez-Reyes et al., 2018), although slightly below those reported in elite professional soccer players (Haugen et al., 2020). We observed that central players exhibit lower P_{maxH} and F_{0H} compared to side players. These disparities among playing positions may be attributed to the specific physical demands and training associated with each position. Wide players often engage in intensive play phases, are typically selected based on sprint performance, and are developed by physical trainers to enhance this physical aspect (Ben Hassen et al., 2023) .

Very few studies previously assessed MFO in elite soccer players. The average values we obtained are in agreement with those reported in elite professional players and semi-professional players (Randell et al., 2019). Regarding running performance during official matches, our data are slightly below the normative values for European professional levels (Bradley et al., 2013; Riboli et al., 2021), but consistent with those reported for reserve or youth teams of professional European soccer clubs (Buchheit et al., 2014; Rago et al., 2017). Consistent with the literature, we observed that central players engage in fewer high-intensity runs compared to side players (Metaxas, 2021; Modric et al., 2021), but cover greater distances at lower speeds. These discrepancies may be attributed to various factors such as physical abilities, tactical roles, match scenarios, or playing styles (Bradley and Noakes, 2013; Morgans et al., 2024). Overall, all these findings support that our sample of 41 male soccer players can be considered a representative and validated population of elite level.

The energy used by soccer players is mainly produced by aerobic metabolism (Da Silva et al., 2011; Garcia-Tabar et al., 2019). Therefore, it is very important for players to develop maximal aerobic power, assessed by maximal oxygen uptake ($\dot{V}O2_{max}$). An increase in $\dot{V}O2_{max}$ helps recovery between intense efforts by effectively replenishing muscle PCr and ATP stores (Gharbi et al., 2015). Early and recent studies have highlighted a significant correlation between total distance, low-intensity running (<14.3 km/h), and $\dot{V}O2_{max}$ (Aquino et al., 2020; Bangsbo, 1994; Modric et al., 2021). Thus, a $\dot{V}O2_{max}$ >60 ml/kg/min is generally considered a threshold for possessing the physiological attributes necessary for success in men's elite soccer players (Reilly et al., 2000). Our results fit with these findings and confirm that $\dot{V}O2_{max}$ remains the main physiological parameters influencing the total distance covered during matches. Specifically, our statistical approach support that elite players with a $\dot{V}O2_{max}$ higher than 55.6 ml/kg/min covered significantly more distance than those with lower $\dot{V}O2_{max}$ levels. However, other studies also support that $\dot{V}O2_{max}$ should not be considered as the only discriminator of physical performance in sports strongly dependent of aerobic metabolism, including soccer (Da Silva et al., 2011; Hoff et al., 2002; Metaxas, 2021).

Power and speed abilities are obviously important in intense and decisive situations in elite soccer (Faude et al., 2012), and repeated sprint ability is one of the most important physical parameters conditioning physical performance in soccer matches (Da Silva et al., 2010). Positive correlations between maximal strength in half squat, maximal power in vertical jump with maximal speed, both in a straight line or with changes of direction, are clearly identified in elite athletes, including soccer players (Buchheit et al., 2014; Wisløff et al., 2004). These physical skills, estimated with the horizontal FVP profile (F_{0H} and P_{maxH}), show positive correlation with high intensity actions among women professional soccer players (Savolainen et al., 2023). Our results agree with these findings and confirm that in elite male young players, F_{0H} and P_{maxH} are important factors associated to the sprinting distance covered during official games. Furthermore, these results are notably consistent for maximal power when performing the same analysis with data from the vertical FVP (see Appendix 1 and 2), confirming the fact that P_{maxH} and P_{maxV} are key indicators of sprinting capacity during soccer matches. Finally, our data suggest that a value of horizontal P_{maxH} higher than 19 W/kg is a threshold that physical trainers could use to consider a soccer player as weak or strong on horizontal maximal power.

In endurance sports where glycogen availability is limited, MFO has indeed been well-established over decades with athletic performance (Frandsen et al., 2017; Maunder et al., 2018). However, in intermittent individual or team sports including soccer, the interest in such measurements is just emerging (Randell et al., 2019; Rømer et al., 2024), especially because the muscle glycogen depletion is now clearly considered as a limited factor of repeated sprint ability in soccer matches (Vigh-Larsen et al., 2021). As previously explained, training to improve the ability to repeat high-intensity efforts tends to only focus on $\dot{V}O2_{max}$ development. While this indicator is crucial for covering greater distances, $\dot{V}O2_{max}$ appears to be less significant for high-intensity running (Da Silva et al., 2010). Physiologically, high-intensity running during matches is generally well correlated with the anaerobic threshold, defined as the maximum intensity at which lactate production and elimination are balanced (Da Silva et al., 2010; Hoff et al., 2002). A high anaerobic threshold allows players to perform at very high intensities without lactate accumulation in the blood (Helgerud et al., 2001). Moderate and low-intensity runs have been significantly correlated with the aerobic threshold, which defines the players' efficiency at lower intensities (Da Silva et al., 2011). These measures provide different physiological information compared to MFO, but also offer more precise indications than $\dot{V}O2_{max}$ regarding exercise intensity during matches (Modric et al., 2021). In 2016, Mohr et al. first found that the activity of skeletal muscle enzymes involved in fat oxidation was correlated with high-intensity runs in soccer players (Mohr et al., 2016). These findings suggested the importance of muscle lipid metabolism in recovery and the ability to repeat intense efforts. While measuring the activity of these enzymes is not easily accessible to training staff, the Fat_{max} test used in this study offers a low-cost and non-invasive alternative for profiling players' substrate utilization. Among the different indicators measured, MFO emerged in our study as the most important for estimating the distance covered at high intensity (>15 km/h). More precisely, our data support that players with a MFO higher than 0.73 g/min covered more high-intensity distance than those with lower

MFO. For the first time, these results highlight the importance of fat oxidation capacity to perform moderate to high-intensity efforts during soccer matches (especially during recovery runs). These findings suggest that high fat oxidation could help to spare muscle glycogen for explosive and intense actions, which are crucial both offensively and defensively (Faude et al., 2012). To develop oxidation capacity and minimize muscle glycogen depletion, nutritional approach and training-based approaches constitute two main strategies that can be proposed to players. The nutritional approach involves supplementing the athlete with carbohydrates, with a periodized intake on match days being particularly relevant (Baker et al., 2015; Hulton et al., 2022). On the other hand, low-intensity exercise sessions increase the expression of membrane lipid transporters and mitochondrial transporters in skeletal muscle, leading to a preferential use of fatty acids and increasing the availability of intramuscular fatty acids. These effects are moreover optimized when training is performed with low carbohydrate availability (Marquet et al., 2016; Van Proeyen et al., 2011). Similarly to P_{maxH} for sprinting performance, the threshold of around 0.7 g/min we found in the present study could help physical trainers identify players who are weak or strong in MFO, and to personalize both nutritional and training program for each player.

Limitations of the present study

The most significant limitation of this study is that data were only retained if a player participated in a minimum of three full matches. Additionally, the elite players came from different age categories with varying physical demands. To level the playing field, we opted for a standardization method. However, when fewer than three players participated in a given match, individual standardization may have led to the loss of some information. Furthermore, MFO and $\dot{V}O2_{max}$ testing was conducted at the beginning of the season, while we observed the players throughout the entire season. As a result, it is possible that these indicators changed over the season.

Conclusion

To our knowledge, this study is the first to report an association between maximal fat oxidation and match running performance in elite soccer players. As supported by the literature, our findings confirm that while $\dot{V}O2_{max}$ and force-velocity-power profile are respectively crucial factors for total distance covered and sprint performance in a match, their importance diminishes when considering moderate-high-intensity running. Instead, MFO emerges as a critical determinant of performance for this type of efforts. Players with higher MFO values seem able to cover more distance at high intensities, emphasizing the importance of metabolic adaptations in sparing glycogen for intensive actions. In addition, this study provides a specific threshold of approximately 0.7 g/min for MFO, which could serve as a benchmark for physical staff in elite soccer clubs. The ability to repeat high-intensity efforts in soccer is multifaceted, involving both aerobic and anaerobic capacities. Training strategies should, therefore, incorporate a holistic approach, targeting lower limb muscle power, aerobic power, and MFO to optimize physical performance in elite soccer players.

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Appendix

Appendix 1. Descriptive statistics of vertical (Squat-Jump) force-velocity-power profile and differences between players playing at central and side of the pitch

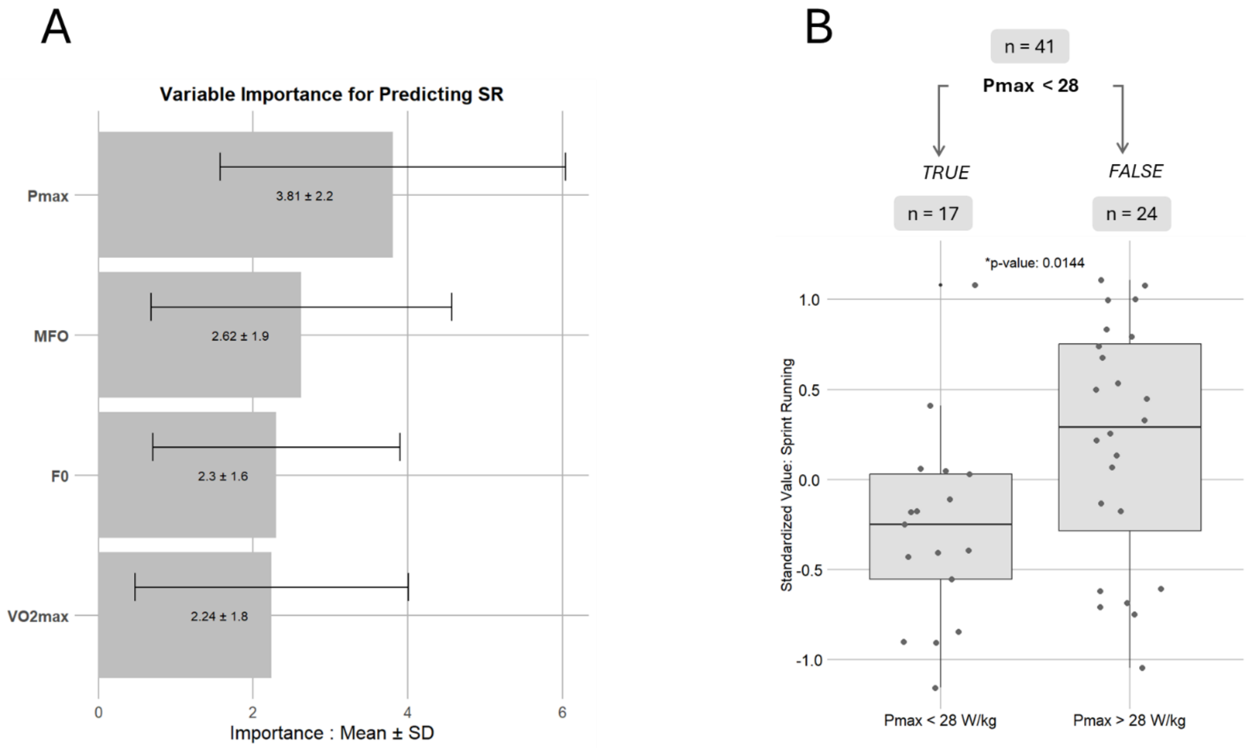
	All Players (n=41)	Central Players (n= 25)	Side Players (n=16)
P_{maxV} (W/kg)	29.2 ± 5.8	28.2 ± 4.1	30.8 ± 7.7
F_{0V} (N/kg)	29.9 ± 4.5	30.9 ± 4.7	28.4 ± 3.7

Data are given as Means ± SD.

Appendix 2. Descriptive statistics of vertical (Squat-Jump) force-velocity-power profile and differences between players at soccer specific playing positions.

	All (n=41)	CB (n = 9)	FB (n=9)	CM (n=11)	W (n=7)	S (n=5)
P_{maxV} (W/kg)	29.2 ± 5.8	29.8 ± 4.9	28.4 ± 4	27.1 ± 2.9	33.7 ± 10.3	27.9 ± 4.7
F_{0V} (N/kg)	29.9 ± 4.5	31.9 ± 3.4	28.4 ± 2.8	30.5 ± 5.4	28.3 ± 4.8	30 ± 5.7

Data are given as means ± SD. CD: Central defenders, FB: Fullbacks, CM : Central midfielders, W: Wingers, S: Strikers.



Appendix 3 : Variable Importances for Predicting Sprint Running (SR) and Regression Tree Structure. *(A) Panel describing the relative importance of variables (F_{0V}, P_{maxV}, MFO, $\dot{V}O2_{max}$) for predicting the standardized value of sprint running (mean± SD).). These importance values were derived from 100 bootstrap samples to obtain the mean ± SD. (B) Simplified regression tree with a single split, identified as the most important, partitions the initial sample of 41 observations into two nodes based on the most discriminative variable regarding Sprint Running distance. The boxplots show the distributions of standardized SR values for each partition.*

Appendix 4. Literature review

Liste des abréviations

ADP : Adénosine diphosphate

AGL : Acide gras libre

ATP : Adénosine triphosphate

CP : Créatine phosphate

FVP : Profil Force Vitesse

GPS : Global positioning system

OLM : Oxydation lipidique maximale

O2 : oxygène

QR : Quotient respiratoire

$\dot{V}CO2$ **:** Production de dioxyde de carbone

V_{MA} : Vitesse maximale aérobie

V_{max} : Vitesse maximale anaérobie

$\dot{V}O2$ **:** consommation d'oxygène

$\dot{V}O2_{max}$ **:** Consommation maximale d'oxygène

V_{res} : Vitesse de réserve anaérobie

I. Quantification de l’activité externe et interne du joueur de football

A. Monitoring de l’activité en match: outils et variables

Les activités de course associées à d'autres actions spécifiques du football, comme les tacles, les dribbles, représentent la charge externe mesurable d'un joueur pendant les matchs. L’augmentation de la demande physique et des courses à haute intensité ces dernières années suscite l’intérêt et encourage le développement de méthodes pour mesurer cette activité pendant les matchs (Bush et al., 2015). Différents outils sont utilisés pour surveiller cette activité externe. L'analyse vidéo est couramment utilisée par les entraîneurs (Cuevas et al., 2020), mais ces dernières années, c’est le système de navigation par satellites, « Global Positionning System » (GPS) qui est devenu populaire (Rago et al., 2020). Le GPS permet de mesurer la position, la vitesse, la distance parcourue, la durée du déplacement d'un joueur et sa précision dépend de l’environnement, de son emplacement sur le joueur. Depuis 2015, la FIFA autorise l'utilisation des dispositifs GPS lors des matchs officiels, ce qui a conduit à de nombreuses études visant à mieux comprendre les caractéristiques physiologiques nécessaires pour atteindre les meilleures performances (Tierney et al., 2016). Les nouveaux dispositifs GPS avec une fréquence d'acquisition de 10 Hz ou plus offrent une meilleure validité et fiabilité par rapport aux dispositifs moins performants (1-5 Hz) (Scott et al., 2016).

Ces systèmes permettent de recueillir différentes variables intéressantes dans la caractérisation de l'activité externe, telles que la distance parcourue à différents seuils de vitesse. Cependant, les seuils de vitesse sont généralement déterminés de manière arbitraire, ce qui sous-estime l'activité à haute intensité (Abbott et al., 2018; Hunter et al., 2014). Par conséquent, certains auteurs recommandent l'utilisation de seuils d'intensité individualisés basés sur différentes métriques telles que la vitesse maximale anaérobie (V_{MAX}), la vitesse maximale aérobie (V_{MA}) et la vitesse de réserve anaérobie (V_{RES}) (Abbott et al., 2018; Hunter et al., 2014; Rago et al., 2020). L'utilisation de seuils arbitraires pour définir l'intensité ne tient pas compte des spécificités de chaque joueur. C'est pourquoi il peut être intéressant de se référer à des seuils individualisés, mais il est également important de combiner les méthodes. Par exemple, estimer et isoler la V_{MAX} ne permet pas de connaître la capacité du joueur à maintenir une vitesse élevée sur une période prolongée. De même, la V_{MA} ne permet pas d'évaluer la capacité du joueur à accélérer sur de courtes périodes. L'utilisation combinée de V_{MAX}, V_{MA} et V_{RES} semble donc plus pertinente que l'utilisation isolée de V_{MAX} et V_{MA} (Hunter et al., 2014; Rago et al., 2020).

Pour disposer d’une vision complète de l'activité externe, ces variables demeurent toutefois insuffisantes. En effet, cette méthode ne prend pas en compte le fait que même à des vitesses absolues faibles, l'accélération et donc la demande métabolique peuvent être importantes. C'est pourquoi l'utilisation combinée des accéléromètres avec les GPS est plus généralement utilisée par les staffs (Akenhead et al., 2013). Grâce à la fréquence d'acquisition plus élevée des accéléromètres intégrés aux GPS, les mesures d'accélérations sont plus fiables que les données GPS. Les valeurs minimales couramment utilisées pour l'accélération ou la décélération varient généralement de 1 m/s^2 (faible) à 3 m/s^2 (élevée) (Akenhead et al., 2016; Hunter et al., 2014; Osgnach et al., 2010). Au-delà de ces valeurs d'accélération et de décélération, certains auteurs définissent un indicateur appelé « Player Load », qui correspond généralement à la somme des accélérations selon les 3 axes au carré (Akenhead et al., 2016.; Dalen et al., 2016).

En associant les données d'accélération et de vitesse, on peut également obtenir la puissance métabolique ou la distance parcourue à charge métabolique élevée (Osgnach et al., 2010). La puissance métabolique décrit la quantité d'énergie nécessaire pour maintenir un niveau musculaire constant d'adénosine triphosphate (ATP). Cette approche est basée sur l'extrapolation de la charge externe à la charge interne. En 2009, Osgnach et al. ont utilisé cette notion pour créer un indicateur qui estime la distance qu'un joueur aurait parcourue s'il avait couru à une vitesse constante pendant tout le match, en se basant sur la dépense énergétique réelle mesurée. Cet indicateur est obtenu en calculant le rapport entre cette distance estimée et la distance réellement parcourue par le joueur. Plus cet indice est élevé, plus cela signifie qu'il y a eu des épisodes de fortes accélérations qui ont engendré une dépense énergétique supérieure à celle d'une course à vitesse constante (Di Prampero and Osgnach, 2018). Selon certaines recherches, les variables basées sur la puissance métabolique pourraient être plus appropriées pour déterminer les mouvements à haute intensité que celles basées sur la vitesse (Gaudino et al., 2014). Cependant, la validité scientifique de ces méthodes doit encore être prouvée (Rago et al., 2020).

Bien que l'ensemble de ces outils et variables représente de manière précise l'activité externe, il est difficile d'identifier clairement le coût physiologique de l’activité des joueurs sans informations sur la charge interne. La charge interne fait référence au stress physiologique et psychologique et peut être évaluée de manière subjective et objective. Les mesures objectives les plus fréquemment utilisées comprennent des indicateurs physiologiques tels que la fréquence cardiaque, la lactatémie ou la consommation d'oxygène. Quant aux mesures subjectives, elles incluent des évaluations de la perception de l'effort ainsi que des questionnaires portant sur le côté psychologique (Dolci et al., 2020).

B. Caractérisation de l’activité externe dans un match de football

À partir des différents outils énumérés précédemment, il est possible de caractériser de manière précise l'activité externe des joueurs. Le football est un sport intermittent où les joueurs alternent entre la réalisation de mouvements explosifs variés de manière répétée, tels que les sauts, les accélérations et les changements de direction, et des périodes de récupération à faible intensité (Dolci et al., 2020). Environ 150 à 250 actions à haute intensité sont effectuées par les joueurs (Mohr et al., 2003), avec une fréquence de course à une vitesse supérieure à 20 km/h toutes les 72 secondes, et une distance parcourue d'environ 9 à 14 km en 90 minutes (Bradley et al., 2009; Modric et al., 2021). Cependant, des différences importantes existent en fonction du poste de jeu. Des études ont montré que les milieux centraux parcourent une plus grande distance que les autres postes tandis que les défenseurs centraux parcourent la plus petite distance (Bradley et al., 2009; Modric et al., 2023).

En ce qui concerne la distance parcourue à haute intensité, les joueurs évoluant sur les côtés du terrain (défenseurs latéraux et excentrés offensifs) réalisent davantage de performances que les joueurs placés dans l'axe du terrain (Metaxas, 2021; Modric et al., 2023). Cela peut être dû aux compétences physiques, mais également et surtout au rôle tactique de ces joueurs, au scénario du match, ou encore au style de jeu de l'équipe et des adversaires (Bradley and Noakes, 2013). La majorité de la distance parcourue se fait à faible intensité (Mohr et al., 2003), mais avec l'évolution tactique du football, la proportion d'actions à haute intensité et le nombre de sprints ont augmenté dans le football européen (Barnes et al., 2014). La performance en sprint des joueurs a également augmenté (Haugen et al., 2014), et l'importance de ces sprints est mise en avant dans une étude (Faude et al., 2012), où les sprints représentent les actions les plus décisives menant à un but. La capacité d'accélération, qui exprime la faculté à décélérer, à accélérer et à changer de direction, est une composante distincte de la vitesse maximale de sprint et constitue également un déterminant de la performance (Haugen et al., 2014). En raison de la fatigue, ces actions à haute intensité diminuent au cours du match. Il est donc essentiel de bénéficier de ces qualités de vitesse et d'explosivité du début à la fin du match. Pour cela, la capacité à récupérer et à reproduire ces efforts intenses apparaît comme une composante essentielle d'un sport intermittent comme le football (Mohr et al., 2003).

C. Quantification de l'intensité et de la fatigue en match

En sport, la fatigue peut être définie comme l'incapacité à maintenir la puissance requise (Edwards, 1983). Dans le football, cette puissance se réfère à la capacité de répéter les efforts intenses tout au long du match. Des études ont montré une diminution significative de la distance parcourue à haute intensité lors des 15 dernières minutes de jeu (Mohr et al., 2005). Les données provenant des accéléromètres soutiennent ces observations, indiquant une détérioration progressive de la capacité d'accélération et de décélération au cours du match (Akenhead et al., 2013).

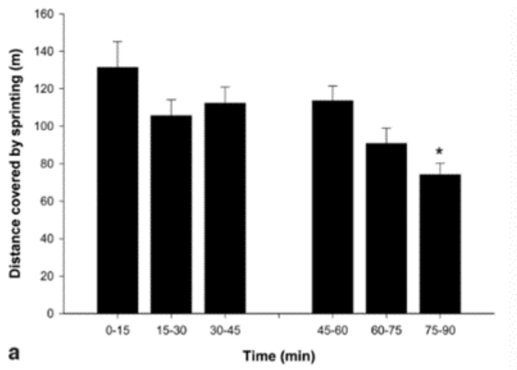


figure 1 :Distance parcourue en sprintant pendant des périodes de 15 minutes (Mohr et al, 2005).

Les données disponibles d'accéléromètre et de GPS mettent en évidence l'apparition de la fatigue en deuxième mi-temps, en particulier lors du dernier quart d'heure. De plus, une diminution significative de l'intensité des courses a été constatée après une phase de jeu très intense (Bradley and Noakes, 2013; Mohr et al., 2012, 2003). La fatigue peut également se manifester par des périodes de récupération plus longues pendant le match, ce qui augmente le temps consacré aux activités à faible intensité (Carling et al., 2008). Cependant, d'autres facteurs situationnels tels que la physionomie du match, les consignes tactiques et le niveau de l'adversité influencent ce déclin de la performance (Bradley and Noakes, 2013; Carling et al., 2008). En conclusion, on distingue principalement deux types de fatigue, 1) une temporaire qui survient après une période de jeu intense, et 2) la fatigue qui s'installe vers la fin du match. Pour développer des stratégies visant à éviter cette fatigue, il est essentiel de comprendre les mécanismes physiologiques qui sous-tendent la performance physique et qui contribuent à cette fatigue pendant le match.

II. Adaptations physiologiques nécessaires pour mettre de l'intensité et limiter la fatigue en match

A. L'explosivité au service de l'intensité en match

La vitesse maximale en sprint et la capacité à accélérer et à changer de direction sont des éléments essentiels dans les situations décisives du football. Plusieurs études ont montré des corrélations positives entre la force maximale en demi-squat, la puissance musculaire en saut vertical et la vitesse maximale, que ce soit en ligne droite ou avec des changements de direction (Buchheit et al., 2014; Wisløff et al., 2004). Ainsi, la force et la puissance musculaires maximales jouent un rôle crucial dans la performance des sprints à différentes distances et dans les changements brusques de direction. Ces qualités de force et de puissance sont étroitement liées, et la capacité à générer une puissance musculaire importante dépend du niveau de force de l'athlète (Cormie et al.,2011). Des études de Samozino et al. (2012, 2014) ont introduit des méthodes de terrain pour évaluer les profils force-vitesse (PFV), permettant d'améliorer la compréhension de cette performance en saut vertical, en sprint et d'estimer ces qualités de force et de puissance. Ces méthodes permettent de calculer les principaux paramètres mécaniques à partir de mesures de base telles que la masse corporelle, la longueur des membres inférieurs, la hauteur de saut et les données de temps-distance ou de vitesse-temps (Morin and Samozino, 2016). La performance en saut et en sprint dépend principalement de la capacité des systèmes neuromusculaires et ostéoarticulaires à générer des niveaux élevés de force, à appliquer efficacement cette force au sol et à produire cette force à des vitesses de contraction élevées. Cependant, il est essentiel d'avoir à disposition, les substrats nécessaires à l'activité (Hoff and Helgerud, 2004).

Pour les efforts courts et intenses, l' adénosine diphosphate (ADP) et la créatine phosphate (CP) sont utilisées pour resynthétiser rapidement l'ATP nécessaire à la contraction musculaire intense (Vigh-Larsen et al., 2021). Au cours d'un match de football, on observe une diminution de la CP musculaire et des perturbations dans l'environnement cellulaire, qui contribuent à la fatigue (Krustrup et al., 2006; Mohr et al., 2003; Tornero-Aguilera et al., 2022; Vigh-Larsen et al., 2021). Pour les efforts intenses légèrement plus longs, le métabolisme anaérobie lactique est impliqué, avec la dégradation du glycogène et du glucose. Cette voie métabolique entraîne la formation de lactate, qu'on retrouve en grande quantité au football avec des valeurs pouvant dépasser 10 mmol/L (Krustrup et al., 2006; Mohr et al., 2003). Lorsqu'un joueur est capable de produire une intensité maximale lors d'actions brèves, l'objectif suivant est de maintenir ce niveau élevé d'intensité en préservant les réserves de substrats énergétiques afin de contrer les mécanismes physiologiques de la fatigue.

B. Limiter la fatigue et la réduction de l'intensité en match

D'un point de vue physiologique, la fatigue peut être causée par des facteurs centraux liés au système nerveux central et périphériques dus à des changements musculaires (Tornero-Aguilera et al., 2022). Dans le football, on observe une diminution de la capacité à répéter les efforts intenses au fil du match, avec une baisse de la performance physique en fin de match et après des périodes de jeu intenses. Le métabolisme des substrats énergétiques joue un rôle clé dans l'apparition de la fatigue.

La régénération de la CP musculaire dépend directement de la capacité énergétique de la respiration mitochondriale, qui peut fournir l'énergie nécessaire pour ce processus pendant les phases de récupération d'un match. Pour cette raison, les préparateurs physiques priorisent l'entraînement physique visant à améliorer la $\dot{V}O2_{max}$. Une augmentation de la $\dot{V}O2_{max}$ aide à améliorer la récupération entre les efforts intenses en restaurant efficacement les réserves de CP et d'ATP à partir du phosphate inorganique après l'exercice (Gharbi et al., 2015). Une $\dot{V}O2_{max}$ plus élevé est également associé à une densité de volume mitochondrial accrue et à une capacité respiratoire globale améliorée (Furrer et al., 2023; Lundby and Jacobs, 2016). La capillarisation musculaire, qui permet l'approvisionnement en oxygène des fibres musculaires, joue un rôle crucial dans la performance en endurance. Les athlètes d'endurance ont une meilleure capillarisation, associée à une $\dot{V}O2_{max}$ plus élevée (Van Der Zwaard et al., 2021). Selon Mohr et ses collaborateurs (Mohr et al., 2016), la capillarisation musculaire est essentielle pour les joueurs pendant les moments les plus intenses du match et contribue à résister à la fatigue après ces efforts. De plus, les réserves de glycogène musculaire sont également un facteur clé pour la capacité à répéter les efforts intenses.

Lorsque l'exercice se prolonge et lors des phases de basse intensité, le métabolisme oxydatif des glucides et des lipides contribue fortement à la production d'ATP. Les réserves de glycogène musculaire sont limitées et vers la fin du match, la diminution du glycogène musculaire entraîne une altération des performances et est largement reconnue comme un facteur contribuant à l'apparition de la fatigue (Mohr et al., 2016; Vigh-Larsen et al., 2021). Lorsque les réserves de glycogène diminuent, l'organisme dégrade le glucose sanguin pour fournir de l'énergie. La baisse de glucose sanguin est un facteur de fatigue chez les athlètes lors d'exercices prolongés. Au football, une hypoglycémie légère à modérée est observée lors des matchs avec prolongation (Mohr et al., 2023). La glycémie est essentielle pour le fonctionnement cérébral et la fatigue causée par une baisse de glycémie est d'origine centrale, en raison d'une réduction de l'apport énergétique au cerveau (Nybo et al., 2004). Le manque de glycogène affecte le métabolisme musculaire, entraînant à la fois une fatigue périphérique et centrale qui s'influencent mutuellement (Nybo et al, 2004). Différents processus sont mis en place pour atténuer cette fatigue. Pendant le match, la concentration d'acides gras libres (AGL) augmente progressivement, favorisée par les périodes de repos et d'intensité faible. Les changements hormonaux, tels que la diminution de l'insuline et l'augmentation des catécholamines, stimulent la libération d'AGL dans le sang (Mohr et al., 2022). Les mitochondries des muscles sollicités utilisent ces AGL pour produire de l'énergie, notamment pendant les périodes de récupération à faible intensité. Cela compense la déplétion du glycogène musculaire et maintient un taux élevé de glucose sanguin. La $\dot{V}O2_{max}$ est couramment utilisée pour évaluer la puissance aérobie des footballeurs, mais il est crucial de considérer la capacité oxydative musculaire et l'utilisation des lipides comme source d'énergie. Cette utilisation des lipides peut retarder l'apparition de la fatigue en préservant le glycogène. Étant donné que la contribution relative des lipides et des glucides varie d'un joueur à l'autre, certains peuvent être plus sujets à la fatigue précoce en raison d'une déplétion plus rapide des réserves de glycogène. Ainsi, étudier le métabolisme de chaque joueur de manière individuelle, en évaluant leur préférence en matière de sources d'énergie à différentes intensités d'effort, serait bénéfique (Randell et al., 2019). Cela permettrait d'adapter leur alimentation et leur entraînement pour optimiser les performances et réduire la fatigue.

III. Liens entre Profil Glucido-Lipidique, Capacité d'oxydation lipidique et Capacité à répéter les efforts intenses?

A. Profil Glucido-Lipidique

L'oxydation des lipides augmente des basses aux moyennes intensités, puis diminue aux intensités plus élevées. La cinétique d'oxydation des lipides peut donc être représentée en fonction de l'intensité de l'exercice sous la forme d'un U inversé (Chenevière et al., 2013). Cette forme implique une zone d'intensité d'exercice pour laquelle l'oxydation des lipides est maximale, appelée «OLM». Elle est définie comme la « V_{fatmax} » et oscille entre 40 et 70% de la $\dot{V}O2_{max}$ (Chenevière et al., 2013). Le test permettant d'obtenir ces valeurs et donc le profil glucido-lipidique des athlètes en fonction de l'intensité de l'exercice se nomme « Fat_{max} test » et doit être réalisé à jeun (Chenevière et al., 2013 ; Maunder et al., 2018). Ce test a été mis au point afin de comprendre la relation entre l'intensité de l'exercice et le taux d'oxydation des lipides (Achten et al., 2002). Avant de réaliser ce test, il faut effectuer un test incrémental maximal pour obtenir une valeur de $\dot{V}O2_{max}$ (Maunder et al., 2018). Le test Fat_{max} est ensuite réalisé avec des paliers à une intensité de 40, 50, 60 ou 70% de la $\dot{V}O2_{max}$. La seule étude effectuée sur des footballeurs professionnels rapporte une vitesse maximale où l'oxydation lipidique est maximale d'environ 50% de la $\dot{V}O2_{max}$ (Randell et al., 2019). Pour des sujets sains modérément entraînés en endurance, il a été montré que des paliers de 3 minutes étaient suffisants (Achten et al., 2002). Cependant, chez des athlètes non spécialisés en endurance, augmenter ce temps de palier permet d'augmenter la fiabilité des données (Maunder et al., 2018). À l'aide d'un système de calorimétrie indirecte, la production de dioxyde de carbone ($\dot{V}CO2$), la consommation d'oxygène ($\dot{V}O2$) et donc le quotient respiratoire (QR) sont enregistrés lors de la dernière minute de chaque palier. L'estimation des débits d'oxydation des substrats par le biais de la calorimétrie indirecte est basée sur l'hypothèse que la $\dot{V}O2$ et la $\dot{V}CO2$ mesurées au niveau de la bouche reflètent la consommation d'oxygène (O2) et la production de dioxyde de carbone (CO2) au niveau des tissus, et donc que le QR mesuré au niveau de la bouche équivaut au QR cellulaire. Le taux d'oxydation des glucides et des lipides est alors calculé à partir d'équations stœchiométriques (Frayn, 1983), en supposant que l'excrétion d'azote urinaire est négligeable. La contribution relative des glucides et des lipides à la dépense énergétique totale peut également être calculée à partir des facteurs d'Atwater, avec 9 kcal/min pour les lipides et 4 kcal/min pour les glucides (Brooks et Mercier., 1994).

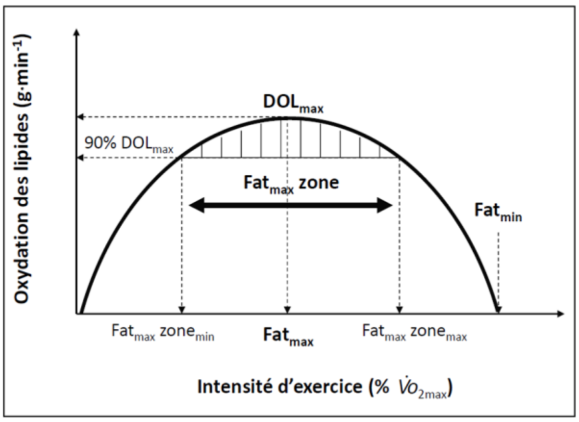


figure 2 :Représentation schématique de la cinétique d'oxydation des lipides en fonction de l'intensité de l'exercice (Cheneviere et al, 2013)

B. Capacité d'oxydation lipidique et performance physique

Si un athlète utilise davantage l'oxydation lipidique pour soutenir son métabolisme, cela lui permet de réduire le besoin d'oxydation des glucides à une intensité donnée et à limiter l'épuisement du glycogène musculaire. Cette oxydation lipidique maximale (OLM) est nettement supérieure chez les personnes entraînées par rapport aux personnes non entraînées (Nordby et al., 2006). Pour les sports de longue durée où la disponibilité des glucides est limitée, il semble évident que l'OLM est liée à la performance sportive (Maunder et al., 2018). Une étude récente portant sur 64 triathlètes a montré une corrélation faible mais significative entre l'OLM et la performance sportive, mesurée par le temps de course (Frandsen et al., 2017). Cependant, les recherches sur cette relation pour les sports collectifs intermittents, tels que le football, sont beaucoup plus rares. Étant donné l'importance de la déplétion du glycogène en tant que facteur limitant de la performance, travailler sur cette capacité d'oxydation pour limiter l'apparition de la fatigue en match semble pertinent.

C. Stratégies d'épargne du glycogène musculaire

Pour minimiser l'épuisement des réserves de glycogène pendant un match et retarder l'apparition de la fatigue, deux stratégies principales peuvent être adoptées, une approche nutritionnelle et une approche basée sur l'entraînement. L'approche nutritionnelle consiste généralement à supplémenter quotidiennement l'athlète en glucides (Collins et al., 2021). Cependant, de nombreuses études montrent la pertinence d'une approche périodisée de l'apport en glucides les jours de match (Baker et al., 2015; Hulton et al., 2022).

La seconde approche, basée sur l'entraînement, vise à augmenter l'oxydation des lipides pendant l'exercice ou à augmenter la resynthèse du glycogène pendant la récupération. À long terme, l'entraînement continu d'intensité modérée est une solution pour augmenter le taux d'oxydation des lipides (Talanian et al., 2010) . Les améliorations de l'OLM par l'entraînement sont le résultat d'adaptations liées à la lipolyse du tissu adipeux, au transport des AGL vers les muscles, à l'assimilation des AGL par les muscles, à la dégradation des triglycérides musculaires et/ou à l'absorption mitochondriale des acides gras (Spriet, 2014). Différents types d'entraînement par intervalles à haute intensité ou de sprint peuvent également stimuler des adaptations favorables à plusieurs étapes du processus d'oxydation des graisses (Mohr et al., 2022). D'autre part, les séances de faible intensité augmentent l'expression des transporteurs de lipides membranaires et des transporteurs mitochondriaux, ce qui conduit à une utilisation préférentielle des acides gras et augmente la disponibilité des acides gras intramusculaires. Ces effets sont optimisés lorsque l'entraînement est réalisé avec une faible disponibilité en glucides (Van Proeyen et al., 2011). Le développement de l'oxydation lipidique par l'entraînement a montré de nombreux bienfaits, mais ces avantages sont principalement observés chez les populations sédentaires ou en situation d'obésité. Il existe très peu d'informations concernant les athlètes entraînés et encore moins concernant les joueurs de football.

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