

TESIS DOCTORAL



ESCUELA INTERNACIONAL DE DOCTORADO

Programa de Doctorado en Ciencias del Deporte

Determining the neuromuscular and energetic requirements of
loaded and unloaded sprint efforts through experimental
modeling: new integrated approaches

Autor:

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Directores:

Dr. D. Tomás T. Freitas

Dr. D. Pedro E. Alcaraz Ramón

Murcia, octubre de 2024

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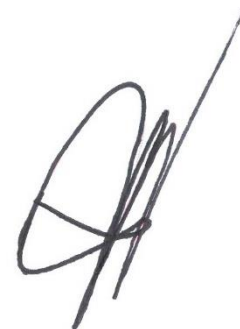
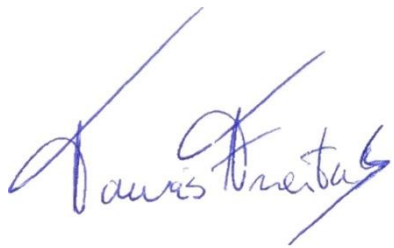
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Murcia, octubre de 2024

AUTORIZACIÓN DEL DIRECTOR DE LA TESIS PARA SU PRESENTACIÓN

El Dr. D. Tomás T. Freitas y el Dr. D. Pedro E. Alcaraz como Directores⁽¹⁾ de la Tesis Doctoral titulada “Determining the neuromuscular and energetic requirements of loaded and unloaded sprint efforts through experimental modeling: new integrated approaches” realizada por D. Gabriele Grassadonia en el Programa de Doctorado en Ciencias del Deporte, **autoriza su presentación a trámite** dado que reúne las condiciones necesarias para su defensa.

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⁽¹⁾ Si la Tesis está dirigida por más de un Director tienen que constar y firmar ambos.

ABSTRACT

Introduction. Sprinting is a critical component of performance in soccer, necessitating a comprehensive understanding of the neuromuscular and metabolic demands placed on athletes during high-intensity actions. Despite the widespread use of Global Positioning System (GPS) technology in monitoring these demands, discrepancies between GPS-derived data and physiological responses measured through electromyography (EMG) suggest that current methods may underestimate/overestimate the effective intensity of sprinting efforts. This Doctoral Thesis aims to bridge this gap by providing a detailed analysis of sprinting performance in elite youth soccer players, utilizing GPS and EMG methodologies. The research is structured around four interconnected studies, each contributing to a deeper understanding of the factors influencing sprint performance and offering practical applications for optimizing training in soccer.

Objective. The primary objective of this thesis is to evaluate the neuromuscular and metabolic demands of sprinting in soccer players using advanced assessment techniques. Specifically, the thesis aims to compare GPS and EMG-derived metrics in various sprinting conditions, analyze muscle activation patterns under different loading conditions, explore the utility of isometric and dynamic strength measures, and investigate the distinct demands of acceleration, high-speed running and deceleration.

Methodology. *Study 1* compares GPS and EMG methodologies for calculating metabolic power (MP) and energy cost (EC) during sprinting. Sixteen elite U17 soccer players participated in this study, performing submaximal runs and sprints while being monitored through portable GPS-IMU units and surface EMG. The findings reveal significant differences between the two methods, with EMG providing a more accurate representation of the energetic commitment required during sprints. *Study 2* examines muscle activation patterns and the effects of various resistance sprints. Seventeen elite U17 soccer players completed sprints under unloaded and loaded conditions, with parachute and sled weights ranging from 15 to 60 kg. The results demonstrate that increasing load alters muscle percentage recruitment, with external metrics underestimating the demands compared to internal metrics (EMG), particularly under heavier load conditions.

Results. The studies consistently demonstrate that EMG provides a more accurate

measure of the neuromuscular and metabolic demands of sprinting compared to GPS-IMU-derived metrics. This is particularly evident in conditions involving higher resistive loads and complex movement patterns such as high-intensity actions. The analysis covers critical insights into the specific neuromuscular requirements of different sprinting actions, offering practical applications for optimizing training methodologies and empowering coaches and researchers with new knowledge. **Conclusion.** This advances the field of sports science by offering a more detailed analysis of the neuromuscular and metabolic demands of typical movements in soccer (such as sprints). Integrating GPS and EMG technologies, alongside innovative assessment methods, provides a comprehensive framework for understanding and improving sprint performance in elite youth soccer players. The findings underscore the need for individualized training strategies that accurately reflect effective efforts, ultimately contributing to enhanced athletic performance.

KEY WORDS

Key words: energy cost, metabolic power, apparent efficiency, soccer players, sport performance.

THESAURUS TERMS: exercise physiology, movement physiology, muscle physiology

RESUMEN

Introducción. El sprint es un componente crítico del rendimiento en el fútbol, lo que exige una comprensión exhaustiva de las demandas neuromusculares y metabólicas impuestas a los atletas durante acciones de alta intensidad. A pesar del uso generalizado de la tecnología del Sistema de Posicionamiento Global (GPS) para monitorear estas demandas, las discrepancias entre los datos derivados del GPS y las respuestas fisiológicas medidas mediante electromiografía (EMG) sugieren que los métodos actuales pueden subestimar o sobreestimar la intensidad efectiva de los esfuerzos de sprint. Esta Tesis Doctoral tiene como objetivo reducir esta brecha proporcionando un análisis detallado del rendimiento en el sprint en jugadores juveniles de fútbol de élite, utilizando metodologías de GPS y EMG. La investigación se estructura en torno a cuatro estudios interconectados, cada uno contribuyendo a una comprensión más profunda de los factores que influyen en el rendimiento del sprint y ofreciendo aplicaciones prácticas para optimizar el entrenamiento en fútbol. **Objetivo.** El objetivo principal de esta tesis es evaluar las demandas neuromusculares y metabólicas del sprint en jugadores de fútbol utilizando técnicas avanzadas de evaluación. Específicamente, la tesis pretende comparar las métricas derivadas de GPS y EMG en diversas condiciones de sprint, analizar los patrones de activación muscular bajo diferentes condiciones de carga, explorar la utilidad de las medidas de fuerza isométrica y dinámica, e investigar las demandas específicas de la aceleración, la carrera de alta velocidad y la desaceleración. **Metodología.** *Estudio 1* compara las metodologías de GPS y EMG para calcular la potencia metabólica (PM) y el costo energético (CE) durante el sprint. Dieciséis jugadores de fútbol U17 de élite participaron en este estudio, realizando carreras submáximas y sprints mientras eran monitoreados mediante unidades portátiles GPS-IMU y EMG superficial. Los resultados revelan diferencias significativas entre los dos métodos, con el EMG proporcionando una representación más precisa del compromiso energético requerido durante los sprints. *Estudio 2* examina los patrones de activación muscular y los efectos de varios sprints de resistencia. Diecisiete

jugadores de fútbol U17 de élite completaron sprints bajo condiciones sin carga y con carga, utilizando paracaídas y trineos con pesos que oscilaban entre 15 y 60 kg. Los resultados demuestran que el aumento de la carga altera el porcentaje de reclutamiento muscular, con las métricas externas subestimando las demandas en comparación con las métricas internas (EMG), particularmente en condiciones de carga más pesada. **Resultados.** Los estudios demuestran consistentemente que el EMG proporciona una medida más precisa de las demandas neuromusculares y metabólicas del sprint en comparación con las métricas derivadas del GPS-IMU. Esto es particularmente evidente en condiciones que implican cargas resistivas más altas y patrones de movimiento complejos, como las acciones de alta intensidad. El análisis abarca ideas críticas sobre los requisitos neuromusculares específicos de las diferentes acciones de sprint, ofreciendo aplicaciones prácticas para optimizar las metodologías de entrenamiento y empoderando a los entrenadores e investigadores con nuevos conocimientos. **Conclusión.** Esta tesis avanza el campo de las ciencias del deporte al ofrecer un análisis más detallado de las demandas neuromusculares y metabólicas de los movimientos típicos en el fútbol (como sprints). La integración de tecnologías GPS y EMG, junto con métodos de evaluación innovadores, proporciona un marco integral para comprender y mejorar el rendimiento en el sprint en jugadores juveniles de fútbol de élite. Los hallazgos subrayan la necesidad de estrategias de entrenamiento individualizadas que reflejen con precisión los esfuerzos efectivos, contribuyendo en última instancia a un rendimiento atlético mejorado.

PALABRAS CLAVE

Palabras clave: coste energético, potencia metabólica, eficiencia aparente, futbolistas, rendimiento deportivo.

TERMINOS TESAURO: fisiología del ejercicio, fisiología del movimiento, fisiología muscular.

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"All those moments will be lost in time, like tears in rain."
Blade Runner (1982).

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ABBREVIATIONS

The abbreviations of the units from the International System Units are not included in the following list as there are internationally accepted standards for their use. In addition, no abbreviations universally used in statistics are presented in this section.

[La⁻]-b | Blood Lactate Concentration (expressed in mmol·L⁻¹)

ACC or **α** | Accelerations

ADP | Adenosine-di-phosphate

AI | Artificial Intelligence

AT | Achilles tendon

ATP | Adenosine triphosphate

BCoM or **CoM** | Body Center of Mass

BMI | Body Mass Index

CG | Control Group

CoD or **COD** | Changes of Direction

CONC | Concentric

CR | Constant Running

d | Distance

DEC or **d** | Decelerations

EC | Energy Cost

ECC | Eccentric

EC_r | Running Cost

EC_w | Walking Cost

ED | Equivalent Distance

EE | Elastic Energy

EG | Experimental Group

EGNOS | European Geostationary Navigation Overlay Service

EM | Equivalent Mass

EMG or **sEMG** | Electromyography (surface)

EMG/F | EMG/Force ratio

EMG_c | Concentric EMG

EMG_e | Eccentric EMG

EMG_{TOT_ecf} | Eccentric-Concentric-Flight phase

EPL | English Premier League

ES | Equivalent Slope

G | Glutes

GPE | Gravitational Potential Energy

GPS | Global Positioning Systems

H | Angular momentum

H | Hamstrings

HR | Heart Rate

HSR | High-Speed Running

I | Inertia

I or **Bi** | Inactive

IMU | Inertial Measurement Unit

KE | Kinetic Energy

KT | Multiplication Term

LR | Linear Runs

LSR | Linear Sprint Runs

m | Mass

ML | Muscle Load

MP | Metabolic Power

MTC | Muscle-tendon complex

MTU | Muscle-tendon unit

MVIC or **MVC** | Maximal Voluntary Isometric Contractions

NIRS | Near Infrared Spectroscopy

np or **Wnp** | Non-Possession (for Watt in Possession)

p or **Wp** | Ball Possession (for Watt in Possession)

PCr | Phosphocreatine

Pi | Inorganic phosphate

PRA | Muscle pre-activity of ground contact

PS | Parachute Sprint

Q | Quadriceps

r | Radius

RE | Rotational Energy

REC | Recruitment Phase

RMS | Root Mean Square

RPE | Rating of Perceived Exertion

SF or ***f*** | Stride Frequency

SL or ***l*** | Stride Length

SR | Shuttle Running

SS15 | Sled Sprint with 15 kg of additional load

SS30 | Sled Sprint with 30 kg of additional load

SS45 | Sled Sprint with 45 kg of additional load

SS60 | Sled Sprint with 60 kg of additional load

SSC | Stretch-shortening cycle

SSG | Small sided games

SSR | Shuttle Sprint Runs

StO₂ | Muscle tissue oxygen saturation

T | Total Time

T_c | Total Contact Time

TDC or **TD** | Total Distance Covered

TOT | Total Phase

UP | Unweighting Phase

US | Unloaded Sprint

v_{init} | Initial Running Speed

$\dot{V}O_{2max}$ or **$\dot{V}o_2$** or **O₂** | Oxygen Consumption (or Maximal)

V_x | Horizontal Speed

W or **W_{tot}**, **W_{ext}**, **W_{int}** | Work

WAAS | Wide Area Augmentation System

α_{max} | Maximal Voluntary Acceleration

τ | Torque

ω | Angular velocity

k | Radius of Gyration

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I – INTRODUCTION

I - INTRODUCTION

In modern sports, outcomes are often decided by the smallest of margins, with success and failure often quantified in seconds/minute increments or decrements (Henry, 1954; di Prampero et al., 1970; Drust et al., 2005; Cazzola et al., 2016; Ferretti et al., 2022; Harnish et al., 2024). Decisions made by an individual or a team can lead to winning a medal, scoring a goal, or conceding a goal, ultimately resulting in defeat or victory (Casanova et al., 2013), including emotional decisions that can be contagious for team success (Moll et al., 2010). Given the increasing importance of these margins and the critical role of sports development, highly scientific methods are being developed to assist players, managers, and sports scientists in analyzing performance (Drust et al., 2007; Dellal et al., 2012; Ade et al., 2016; Bourdon et al., 2017_{a,b}). Many team sports, including rugby, soccer, and basketball, are characterized by an "intermittent performance model" in which players repeatedly perform short bursts of activity involving acceleration, deceleration, changes of direction, and sprints interspersed with short periods of recovery (Little & Williams, 2005; Majumdar & Robergs, 2011; Nagasawa, 2013; Loturco et al., 2019; Loturco et al., 2021; Fornaziero et al., 2023; Pérez Armendáriz et al., 2024). A standard method for quantifying these high-intensity intermittent activities is to measure the distance covered at specific running speeds (Bradley et al., 2009; Dellal et al., 2010; Bradley et al., 2023). In addition, coaches should carefully consider the requirements for position changes to improve training design, paying particular attention to exercises replicating gameplay (Collet, 2013; Bortnik et al., 2024). Thus, understanding and optimizing these critical margins becomes imperative for competitive success across various sports. Consequently, refining these measurement techniques can significantly enhance training efficiency and athletic performance.

A variety of factors influence sports performance. Sports scientists are constantly trying to improve the performance of athletes and coaches by integrating knowledge and techniques from physiology, exercise science, biomechanics, and psychology (Stølen et al., 2005; Girard & Millet, 2009; Barnes et al., 2014). In addition to physiological, tactical, and cognitive skills, success in sports is also closely linked to physical performance (Casanova et al., 2013; Cazzola et al., 2016; Dambroz & Teoldo, 2023; Murphy et al., 2024). Accordingly, a multifaceted approach to athlete development, addressing physical and cognitive aspects, is essential. For example, players with low decision-making skills showed reduced tactical behavioral efficiency ($p = 0.002$) and maintained movement pace under physical fatigue (Dambroz & Teoldo, 2023). Time-motion analyses show that soccer players must perform various physical activities, including sprinting, turning, stopping, and jumping (Wisløff et al., 1998; Iaia et al., 2009; Paul et al., 2015; Hunter et al., 2015; Nakamura et al., 2017; Coutinho et al., 2019). *Soccer* is an intermittent, high-intensity sport that places significant physical demands on players (Åstrand et al., 1960a; Reilly, 1997; Bosco & Luhtanen, 1992; Colli et al., 2007). In light of these demands, targeted interventions to improve work/rest rates to specific performance models (Azzone & Lorenzon, 2019; Grassadonia et al., 2024). Studies show that soccer players can cover a total distance of approximately ~10 km during a match (Mohr et al., 2003). Around 30-60% of this time is spent in low-intensity activities such as walking, jogging, or running at low to medium speeds. High-intensity activities such as high-speed running ($>19.1 \text{ km} \cdot \text{h}^{-1}$) and sprinting ($>23 \text{ km} \cdot \text{h}^{-1}$) account for 6% and 4% of the total distance covered, respectively (Gregson et al., 2010). In addition, soccer matches require over 70% of maximal oxygen consumption ($\text{VO}_{2\text{max}}$), which underlines the need for high aerobic capacity (Reilly, 1997). Despite the predominantly aerobic nature of soccer, high blood lactate concentration levels $[\text{La-}]_{\text{b}}$, ranging from 2-14 $\text{mmol} \cdot \text{L}^{-1}$, during matches highlight the significant intermittent contributions of anaerobic energy sources (Åstrand et al., 1960a; Åstrand et al., 1963; Wisløff et al., 1998;

Krustrup et al., 2006; Santos-Silva et al., 2017; Fornaziero et al., 2023). Consequently, soccer players need to develop aerobic and anaerobic capacities to meet the demands of the sport over an entire season (Åstrand, 1986; Kalapotharakos et al., 2011; Evaggelos et al., 2012; Thorpe et al., 2015; Ferretti et al., 2022).

Effective training load monitoring is required to manage the high physical demands of training and competition and plan recovery. Such insights are indispensable for adjusting training regimens that optimize performance while minimizing injury risks. This is crucial for sport-specific adaptations and injury prevention strategies (Rogalski et al., 2013; Thornton et al., 2017; Savoia, 2019). Various physiological variables such as heart rate (HR), oxygen consumption ($\dot{V}O_2$), blood lactate concentration ($[La^-]$), and rating of perceived exertion (RPE) are used to assess physiological demands during matches and training and to determine training intensity (Åstrand & Saltin, 1961; Achten & Jeukendrup, 2003; Dellal et al., 2012; Castellano et al., 2015; Haugen & Buchheit, 2016; Coppalle et al., 2021). The physiological markers related to the analyzed players' characteristics must be accurate and useful (Gaesser & Brooks, 1975; Brueckner et al., 1991; di Prampero et al., 1993; Saunders et al., 2004; Burnley & Jones, 2007; Jones & Burnley, 2009; Fletcher et al., 2009). Although these variables are helpful, they have several limitations as performance in soccer is influenced by other factors, such as environmental factors and technical and tactical aspects (Bradley et al., 2011; Casamichana et al., 2013; Bradley et al., 2014; Bradley & Ade, 2018; Caldbeck & Dos'Santos, 2022; Silva et al., 2024). Advanced match analysis methods have recently become prevalent in soccer, including video-based time-motion analysis using semi-automatic cameras and Global Positioning Systems (GPS). These technologies support understanding performance dynamics, aiding in developing personalized training strategies. These systems enable sports scientists and coaches to continuously collect data on players' performance in matches and training, providing a deeper

comprehension of the interaction between different factors (Picerno, 2017; Cardinale & Varley, 2017; Bastida Castillo et al., 2018).

In a review by Polglaze et al. (2016), player tracking technology is an essential tool for comprehensively assessing physical exertion and energy expenditure in team sports. The underlying assumption is that displacement variables reflect many limitations in determining a correct energy cost when the activity is not performed at a constant speed in a straight line. Changes in speed and direction increase energy cost (EC) and should be considered when evaluating movement demands in team sports.

GPS enables precise location determination on the Earth's surface by using a network of satellites orbiting the planet. Initially designed for military applications, GPS technology has become widely used in various fields, including sports (Steede-Terry, 2000; Malone et al., 2017; Bastida Castillo et al., 2018). In recent years, GPS has become an essential tool in soccer, enabling tracking movement speed and distance covered during training sessions and matches (Aughey, 2011; Bastida Castillo et al., 2018). Numerous studies have evaluated the validity and reliability of GPS systems, particularly on the accuracy of physical data measurements. However, these assessments have predominantly been conducted on steady movements using devices with low GPS sampling frequencies (one measurement per second). Although high-frequency GPS systems (5 Hz and 10 Hz) have been validated for team sports, concerns remain regarding their validity and reliability when measuring high-speed linear sprints ($>20\text{-}30\text{ km}\cdot\text{h}^{-1}$) and lateral movements typical of soccer (Coutts & Duffield, 2010; Bastida Castillo et al., 2018; Padulo et al., 2019).

Given the importance of rapid acceleration, deceleration, and change of direction at different speeds and distances to soccer performance (Reilly et al., 2003), the use of GPS/video analysis systems with higher sampling frequencies is advantageous for the analysis of high-intensity sprinting activities during the game (Linke et al., 2018; Felipe et al., 2019; Pons et al., 2019; Pons et al., 2021). GPS technology provides practitioners with

important information about physical demands and enables the development of specific training programs personalized to each playing position (Svensson & Drust, 2005). It is essential to consider high-intensity runs and the ability to accelerate, decelerate, and change direction quickly across different speed and distance ranges, critical factors for optimal performance (Reilly et al., 2003; Tang et al., 2018).

To better understand effort and fatigue during soccer play and training, the concepts of EC and metabolic power (MP) performance proposed by Osgnach et al. (2010) and di Prampero et al. (2005) are crucial. This framework offers deeper insights into the energetics that underlie performance activities. The assessment of instantaneous MP based on actual models, including accelerations (ACC or α) and decelerations (DEC or d) in the different phases of the game, provides detailed insights into the "high intensity" of intermittent soccer activities (Osgnach et al., 2010). Accurately determining the physical demands of soccer matches is crucial for planning appropriate training and recovery phases to maximize performance (Bowen et al., 2016). Relying solely on external load metrics, such as total distance covered (TDC) and specific movement speeds, fails to capture the proper physiological response to the tasks performed (Osgnach et al., 2010; di Prampero et al., 2015). Therefore, Osgnach et al. (2010) proposed a new energetic model for soccer that accounts for ACC and DEC based on di Prampero et al. (2005) and Minetti et al. (2002). This model, based on the theory of "equivalent slope" (ES), assumes that accelerated running on flat terrain is mechanically equivalent to running uphill at a constant speed, with the *acceleration* rate determining the slope angle.

Minetti et al. (2002) quantified the EC of uphill running over a range of gradients, providing a basis for estimating the EC of ACC and DEC through the biomechanical equivalence model between constant running speed and terrain slope (Minetti et al., 2002; di Prampero et al., 2005; Osgnach et al., 2010). Using this approach, a soccer match's EC was 2-3 times higher than estimates based on speed and TDC alone (Osgnach et al., 2010).

This methodology allows coaches to estimate energetic demands during soccer-specific activities more accurately and may help determine internal/external load during training (Osgnach et al., 2010; Oxendale et al., 2017; Delaney et al., 2018).

Minetti & Pavei (2018) conducted experimental protocols to estimate the EC of variable speed locomotion and reviewed the complexity of design and management. Using the ES, such as the gradient of constant-speed locomotion metabolically equivalent to a progression of acceleration, was invaluable in estimating the cost of variable-speed gaits. However, extrapolating the experimental cost function to the gradient for a constant running speed leads to less reliable estimates when used with steep gradients. The aim was to extend the model so that it also works for deceleration and to revise the prediction equation so that it applies to much higher speed variations. Shuttle running over different distances (5 + 5 to 20 + 20 m) was analyzed using the new approach, and predictions were made regarding metabolic cost and efficiency that agreed well with the experimental data. Minetti & Pavei (2018) established a conceptual and computational framework to understand the metabolic demand of accelerated/decelerated running. This framework is based on the analogy of ES or the ultimate meaning of transportation cost. It is directly applicable to shuttle running in humans.

While there is limited data on actual changes in running cost (EC_r) in elite soccer players, preliminary evidence suggests that EC_r levels in elite youth soccer players fluctuate during the season (Buglione & di Prampero, 2012). Monitoring and possibly conditioning EC_r levels in soccer players seems advisable. However, such efforts should be based on a comprehensive understanding of EC levels specific to soccer players' training and playing conditions.

Studies by Minetti et al. (2002) and di Prampero et al. (2005) described in detail the inclusion of variable acceleration in the formulas for ES and EM (equivalent mass) to recalculate EC and MP. Consequently, reducing

average acceleration produces proportional energy cost reductions and vice versa. It is important to note that several factors influence the accuracy of EC estimation. The original concept of EC estimation was based on running on compact terrain, such as a treadmill (Minetti et al., 2002; di Prampero et al., 2005). However, running on grass surfaces increases EC by approximately 30% compared to dense terrain (Pinnington & Dawson, 2001).

Few studies have compared EC_r between natural and synthetic surfaces and found minimal differences (Sassi et al., 2011; Hughes et al., 2013). Fitness level may also affect EC_r , as the running economy improves with training (Beneke & Hütler, 2005; Iaia et al., 2009). Research on professional youth soccer players has shown that running EC_r increases by 14% from preseason to season (Buglione & di Prampero, 2012). Given these limitations, Osgnach et al. (2010) corrected the surface characteristics coefficient based on Pinnington & Dawson (2001) by applying a multiplication term of 1.29 ($KT = 1.29$) to account for the difference between running on treadmills and turf surfaces. However, this correction derived from recreational runners may not accurately represent elite soccer players due to differences in muscle fiber types, recruitment patterns, and metabolic adaptations. Therefore, the KT may not accurately represent the metabolic constant in elite soccer players (Savoia, 2019; Savoia et al., 2020). Consequently, the EC equation proposed by Osgnach et al. (2010) may not reflect the EC of exercising on a grass surface in elite soccer players. Consequently, the estimation of MP in elite soccer players using the Osgnach equation may be compromised. A paper proposed by Savoia et al. (2020) solves many of these issues.

In previous research, O_2 consumption measured during linear running at constant speed was found to be 73% of maximal O_2 consumption, confirming the aerobic nature of metabolic demand based on the measurement speed of EC used (Savoia, 2019; Savoia et al., 2020). Pinnington & Dawson (2001) and Rodio et al. (2004) found values of 4.64

and $5.70 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ respectively when running on natural grass in a group of recreational runners and sedentary men. In amateur soccer players, Sassi et al. (2011) reported an EC_r value of $4.20 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$, slightly lower than the value determined in the current study. Stevens et al. (2015) found that the EC_r value at a $10 \text{ km}\cdot\text{h}^{-1}$ running speed on artificial turf for non-elite soccer players is approximately $\sim 4.6 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$. These results differ from previous studies, likely due to differences in the player population (elite *vs.* non-elite), the playing surface (artificial *vs.* non-UEFA grass), and footwear use, all of which influence running mechanics and EC (di Prampero & Osgnach, 2018; Osgnach & di Prampero, 2018; Savoia et al., 2020; Riddick & Kuo, 2022). It is important to note that the reported EC_r value applies to elite players in a non-fatigued state. It is yet to be determined whether the EC_r value changes during play and training due to fatigue-related metabolic, biomechanical, and neuromuscular efficiency fluctuations (Diedrich & Warren, 1995; Hof et al., 2002; Delaney et al., 2018; Savoia et al., 2020; Riddick & Kuo, 2022).

Savoia et al. (2020) detected a new EC_r value of $4.66 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ had been determined in elite soccer players; a further aim was to incorporate and validate this result in a new MP algorithm containing a specific EC term. This algorithm was developed on elite soccer players on a UEFA elite turf pitch and with soccer-appropriate footwear to replicate best the factors considered important for determining the economy of movement in this population. This was facilitated by using the new constant term of EC_r and the regression prediction equation for the assessment of EC, using the average MP in a soccer-specific test by direct and indirect measurements of O_2 consumption using the approach of di Prampero et al. (2005) while modifying the energy cost equation of Minetti et al. (2002). The method has progressively evolved through the work of di Prampero et al. (2005) and Osgnach et al. (2010), together with the calculation of EC (Minetti et al., 2002). These approaches cannot be applied to other sports but only to soccer, which has a "predominantly horizontal" mode where running on flat terrain accounts for most of the energetic performance model.

The physical preparation of soccer players has become increasingly important and requires a high level of fitness to meet the constant and intermittent energy demands during a match (Iaia et al., 2009). Therefore, physical training must evolve to meet the growing demands of modern football. Modern match analysis highlights the importance of high-intensity actions such as sprinting, accelerating, decelerating, and covering long distances at high speeds (Carling et al., 2008). Various technologies have emerged in recent decades to assess these physical demands, encompassing general characteristics and high-intensity activities.

Investigating metabolic and mechanical demands in elite soccer has provided critical insights for optimizing training plans. Gaudino et al. (2014_{a,b}) highlight the discrepancies between running speed and MP in small-sided games and identify a systematic bias depending on the type of exercise, suggesting that traditional speed measurements may underestimate the energy demands of high-intensity activities. These biases are further explored in Gaudino et al. (2013_{a,b}), where training loads were monitored using running speed and MP data, highlighting the need for individualized training programs based on metabolic rather than purely mechanical parameters. These findings highlight the need for sports scientists to refine the monitoring of both metabolic and mechanical load during training to replicate the physiological demands of competitive matches better, as demonstrated in the extensive analysis of small-sided games (Gaudino et al., 2013_{a,b}; Gaudino et al., 2014_{a,b}). Coaches can ensure optimal performance throughout the season by aligning the training load with these insights. Integrating MP data alongside traditional metrics provides a more holistic view of an athlete's workload. This contributes to more effective training strategies aligned to elite soccer's energetic demands.

GPS technology has recently improved our understanding of the physical demands of soccer matches, providing detailed analysis of (i) movement categories based on speed, acceleration or power thresholds (Bradley et al., 2009); (ii) position-related differences in physical demands

(Licciardi et al., 2020); (iii) fatigue patterns during play (Mohr et al., 2003); and (iv) differences in physical demands between different soccer populations, such as adults versus youth (Buchheit et al., 2010) and males versus females (Bradley et al., 2014). Analyzing performance during a game is about the total distance covered and the intensity of the activities, which is usually classified using specific threshold models. In soccer, for example, although most activities are low-intensity, quickly running or high-intensity distances are meaningful physical performance indicators (Mohr et al., 2003). Differences in total distance between different levels of play or tactical roles in both female and male players may be due to different training programs and subsequent physiological adaptations (Licciardi et al., 2020; Savoia et al., 2020; Bradley, 2023; Bradley, 2023; Bradley, 2024; Grassadonia et al., 2024).

In soccer matches, training sessions, and small-sided games, rapid acceleration, deceleration, and multidirectional movements are crucial performance characteristics (Licciardi et al., 2020). The equation presented by Minetti et al. (2002), which underlies the model of Osgnach et al. (2010), does not accurately reflect the 'true EC' of accelerations and decelerations, as it only accounts for speed variations between $+4.5 \text{ m}\cdot\text{s}^{-2}$ and $-4.5 \text{ m}\cdot\text{s}^{-2}$. When running speeds exceed this range, the energy cost is not estimated, especially for highly eccentric deceleration. Therefore, Osgnach et al. (2010) suggested considering more significant deceleration rates ($-4 \text{ m}\cdot\text{s}^{-2}$ to $-6 \text{ m}\cdot\text{s}^{-2}$). In the context of accelerated and decelerated running using instantaneous MP in soccer, several conflicting views exist on the MP paradigm's application, efficacy, and utility (Buchheit et al., 2015a). Recent modifications by di Prampero et al. (2018) suggested replacing the EC of running at a constant speed with the effective cost of running (in non-constant) and walking (EC_w). However, this may still lead to underestimating MP in the non-walking phases. Therefore, a modified version of the Minetti et al. (2002) equation may provide more realistic estimates of MP, which is increasingly used in elite soccer training in current

software models. Nonetheless, its practical utility has gained recognition among practitioners (Colli, 2014; Kempton et al., 2015; Polglaze et al., 2017). Recent efforts by Martín García et al. (2018) have focused on quantifying the micro-cyclical structure and load of weekly elite soccer training alongside match data to guide training and facilitate compensatory training for non-playing players systematically (Bellistri, 2017; Hoppe et al., 2017; Polglaze & Hoppe, 2019). In addition, elite clubs across Europe have put this model into practice.

Researchers have also investigated acceleration distribution in different playing positions, considering the importance of sprints and acceleration/deceleration phases in soccer. Varley & Aughey (2013_{a,b}) found that the number of maximum accelerations was equal across most positions, with fullbacks showing a higher frequency of accelerations, likely due to their dual offensive and defensive roles. In this study, it was clear that players in all positions performed significantly more acceleration than sprinting. Acceleration and deceleration are, therefore, essential elements of the physical demands of soccer. A metabolic load is stressed during high-speed runs and whenever acceleration is high, even at low speeds (Osgnach et al., 2010). Before the study by Osgnach et al. (2010), the assessment of physical stress was limited to the total distance or the distances of the speed categories and the number of accelerations/decelerations (Castellano & Casamichana, 2013; Bellistri et al., 2017; Savoia et al., 2019). The new metabolic approach estimates total energy expenditure by considering speed and acceleration/deceleration during various match phases. This advance is crucial to assess soccer players' training and match loads.

Existing research on the physiology and biomechanics of running at constant speed confirms that the accurate calculation of energy expenditure in high-intensity intermittent sports, such as soccer, requires consideration of the non-steady locomotion phases, particularly acceleration and deceleration (Colli et al., 2007; Zadro et al., 2011; Buglione et al., 2013; Zamparo et al., 2016; Zamparo et al., 2019; Monte et al., 2020; Savoia et al.,

2020; Grassadonia et al., 2024). The EC of running at a constant speed independent of speed (up to a point often overestimated in the literature [Colli, unpublished]) provides an incomplete picture. For example, in a sprint, the instantaneous energy cost reaches a peak value of about $50 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ immediately after the start and gradually decreases within 30 meters to the value for a constant speed on flat terrain (in the exponential model proposed by di Prampero et al., 2005; which probably underestimates the effective cost of the action).

New metabolic approaches, such as those proposed by di Prampero et al. (2005) and applied by Osgnach et al. (2010), categorize exercise intensity based on power output: low power ($0\text{-}10 \text{ W}\cdot\text{kg}^{-1}$), medium power ($10\text{-}20 \text{ W}\cdot\text{kg}^{-1}$), high power ($20\text{-}35 \text{ W}\cdot\text{kg}^{-1}$), very high power ($35\text{-}55 \text{ W}\cdot\text{kg}^{-1}$) and maximal power ($>55 \text{ W}\cdot\text{kg}^{-1}$). In soccer, the threshold for high intensity is usually defined as $20 \text{ W}\cdot\text{kg}^{-1}$, corresponding to a VO_2 of about $57 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, the average $\text{VO}_{2\text{max}}$ of top players. The distance covered by the top players at high intensity was about 17-18% of TD at a speed threshold of $16 \text{ km}\cdot\text{h}^{-1}$, although they expended more than 42% of the total energy at high power ($>20 \text{ W}\cdot\text{kg}^{-1}$) [Osgnach et al., 2010]. This physiologically relevant parameter offers a promising approach for establishing individual, soccer-specific intensity thresholds for match analysis. However, further research is required to validate its effectiveness in categorizing match performance.

The studies conducted by Buglione & di Prampero (2013) and Stevens et al. (2015) show the method's limitations. It was observed that energy expenditure was overestimated when running at constant speed and underestimated during shuttle running, especially at high speeds and short distances (Buglione & di Prampero, 2012). Buchheit et al. (2016) also showed a significant underestimation of energy expenditure during soccer training with a ball using the MP model (Piras et al., 2017). However, these problems are due to some methodological errors (Colli, 2014; Osgnach et al., 2016; Savoia et al., 2020). Indeed, electromyography (EMG) reveals the actual

engagement by solving the problems exposed by Buccheit et al., (2014_{a,b,c}) and Piras et al. (2017) [Colli, unpublished; Grassadonia et al., 2024]. Brown et al. (2016) demonstrated the accuracy of GPS-based estimates for steady-state jogging and running. However, they also found significant underestimation for intermittent exercise patterns characteristic of soccer (Savoia et al., 2020).

These results raise concerns about the theoretical basis of the MP approach. Brown et al. (2016) point out that several assumptions may compromise its validity: 1) it equates accelerated running from a biomechanical perspective with running uphill at a constant speed, neglecting potential differences in body inclination or running economy (Ardigò et al., 2003); 2) it treats total body mass as a single unit, disregarding the differential contributions of the upper and lower limbs; and 3) it does not account for the directional changes and air resistance that occur when running on flat and non-flat terrain (Pugh, 1970). Despite these limitations, the MP approach remains the most commonly used method for estimating energy expenditure in intermittent high-intensity sports such as soccer. Future research should investigate alternative approaches and refine existing models to provide more accurate estimates considering these sports' particular demands (Ardigò et al., 2003; Saibene & Minetti, 2003).

Instead, approaches with EMG have always been separated regarding MP and EC. Nonetheless, bridging this gap could lead to a more comprehensive model of sports performance (Grassadonia et al., 2024). While the biomechanics of sprinting have been extensively studied (Mero et al., 1992), a complete model of soccer performance requires the inclusion of neuromuscular activation patterns during play (Mero et al., 1992; Montini et al., 2017; Grassadonia et al., 2024). This understanding can further inform performance optimization strategies in elite athletes. EMG analyses show that high-intensity actions such as sprinting, jumping, and rapid changes of direction (CoD) account for only a minimal part of overall playing effort (Montini et al., 2017). This is in line with the findings of Robineau et al.

(2012), which state that fatigue primarily originates centrally, reflected in reduced local muscular activity (e.g., quadriceps). However, this minimal contribution in terms of overall time is potentially crucial in determining critical match outcomes.

In sprint running, for example, the results of Mero & Komi (1987) showed a significant increase ($p < 0.001$) in PRA (pre-activity) and forces during the braking phase when running speed increased to supramaximal values. Moreover, these insights highlight the biomechanical adjustments required to maintain performance at higher speeds. The PRA ($p < 0.01$) correlated with the average resultant force during the braking phase. Relative PRA, expressed as a percentage of the maximum value during ipsilateral contact, remained relatively constant across all speeds (approximately 50 to 70%). During the propulsion phase of contact, integrated EMG activity and forces increased significantly ($p < 0.001$) up to the maximal running speed. In addition, post-contact activity and minimal activity increased significantly ($p < 0.001$) up to maximal running speeds, whereas during supramaximal running, integrated EMG activities were reduced during these phases. These results suggest that increased PRA is essential for increasing the muscle stiffness necessary to withstand the significant impact forces encountered during sprint running at the onset of ground contact. Hence, interventions to enhance and manage PRA may improve sprint performance (Kakehata et al., 2021).

Mero et al. (1992) then emphasized the importance of understanding the biomechanical factors influencing sprinting performance. They recognized the critical variables in long-distance running and sprinting, including reaction time, technique, EMG activity, force production, neural factors, and muscle structure. Although different methods were used in each study, the consistent results allowed clear conclusions to be drawn. Although elite athletes generally have short reaction times, these do not necessarily correlate with overall performance. The sprint technique was analyzed in detail in the acceleration, constant speed, and deceleration

phases. High power during the block start and acceleration phases is crucial for reaching top speed. In the constant speed phase, the preceding and during braking are crucial for maximizing explosive performance and efficient motion in the subsequent propulsion phase. Conversely, research on force production during sprint DEC still needs to be conducted (Harper et al., 2019; Harper, 2021; Harper et al., 2021; Harper et al., 2022). Addressing this gap could offer new insights into the underexplored phase of sprint DEC.

Takehata et al. (2021) emphasize the importance of a more even alternation of agonist-antagonist muscle activity and earlier activation of the rectus femoris in the ipsilateral leg compared to the contralateral biceps femoris for achieving a higher step frequency. This suggests that training interventions target unilateral muscle activity and coordinate bilateral muscle function to optimize athlete sprint performance.

A new approach to investigating the soccer performance model that incorporates neuromuscular activation during the game was proposed by Montini et al. (2017), who categorized the performance model into six groups. They exhibited over 60% of maximal muscle RMS (Root Mean Square) activation (4th, 5th, 6th class) and spent, on average, only 3% of total time in high-intensity muscle activity. One of the main reasons for this behavior could be the typical features of muscle activation in high-intensity muscle contractions. Therefore, this typical pattern of muscle effort should be considered when designing training sessions to resemble actual play. As Drust et al. (2007) described, soccer is characterized by "unorthodox patterns of movements" including bipodal actions and an uneven distribution of effort across the legs. Such patterns necessitate appropriate training protocols that reproduce match-specific demands. Montini et al. (2017) observed this phenomenon in the data recorded during the preliminary assessment, estimating that approximately 2.2% of the total time spent performing high of the total time was spent on high-intensity bipodal actions.

Enoka & Stuart (1992) emphasize the task-dependent nature of fatigue. Fatigue mechanisms are influenced by task characteristics such as activation patterns, motor control, intensity, duration, and contraction/execution velocity. Consequently, coaches and sports scientists should assess fatigue during competition and training exercises (e.g., small-sided games) and consider fatigue caused by resistance training. The activation patterns, duration and contraction velocities during resistance training differ significantly from those of competition, potentially leading to different fatigue pathways (Freitas et al., 2019; Matinlauri et al., 2019; Costantine et al., 2019).

While EMG approaches have traditionally been separated from analyses of metabolic power and energy cost (previous section), their integration provides a more holistic understanding of soccer performance. Future research should investigate the relationship between EMG activity, metabolic cost, and player performance in different match situations. In addition, training program optimization studies should be conducted to replicate the specific neuromuscular activation patterns observed in competition. By bridging the gap between metabolic and neuromuscular assessments, we can refine models of soccer performance and optimize training strategies for improved player performance. This integrative approach will enhance theoretical frameworks and practical applications in sports training.

Traditionally, research into MP and EC during sprinting has been conducted separately from EMG studies. However, EMG provides valuable insight into the neuromuscular basis of sprint performance. The literature extensively documents EMG activity patterns in the significant sprinting muscles. However, further research with highly trained athletes is needed to fully understand the coordinated function of multiple muscles during sprinting. In addition, the characteristics of skeletal muscle fibers play a role in identifying talent and training-related adaptations in sprinters. Optimal sprint performance requires a delicate balance between biomechanical

variables and external factors such as footwear, ground conditions, and air resistance (Mero & Komi, 1987; Mero et al., 1992). Even the evolution of equipment can influence the biomechanics and bioenergetics of running (Ortega et al., 2021; Rodrigo-Carranza et al., 2024; Mason et al., 2024). Future research efforts are warranted, particularly in the nervous system, muscle function, and force and power production during sprinting. By integrating these factors with measures of sprint economy and efficiency, we can gain a deeper understanding of sprint performance soon (Grassadonia et al., 2023; Grassadonia et al., 2024).

Van Hooren et al. (2019) assume that the dynamics of attractors play a complex role in human locomotion. These attractors can optimize energetic and mechanical efficiency (Selinger et al., 2015; Kung et al., 2018), minimize mechanical strain (Kung et al., 2018), maintain stability (Jordan et al., 2007), and improve the robustness of locomotion to internal (physiological) and external (environmental) perturbations (Santuz et al., 2018_{a,b}). A decrease in attractor stability and increased variability can trigger a spontaneous transition to another attractor. Human locomotion illustrates this by the transition from walking to running. As walking speed increases, the stability of the relationships in the walking phase decreases, and the out-of-phase joint coupling between the ankle, knee, and hip becomes more variable. This eventually leads to a self-organized transition to a more stable running gait at around $2 \text{ m}\cdot\text{s}^{-1}$, characterized by in-phase joint coupling (Diedrich & Warren, 1995; Lamothe et al., 2009; Kung et al., 2018; Carlsson et al., 2021). The use of attractor models to analyze physical data is becoming increasingly important, especially in technical-tactical metrics in match play. The tactical dimension of competition will likely exert a hierarchical influence on the physical responses captured by these metrics. Therefore, a deeper understanding of the technical and tactical implications is also necessary. This knowledge could provide insights into playing positions, optimal tactical systems against specific opponents, the effectiveness of a chosen playing philosophy, and the physical dimension to promote the

correct integration of the data and variables studied. However, some work, such as the data recorded by Haughen et al. (2019), suggests that the mechanical variables in sprinting are individual rather than sport-specific.

This dissertation investigated different approaches to understand the main mechanical and energetic needs and, consequently, make meaningful methodological choices. Furthermore, it helps to prevent recurrent running injuries at both high speeds/sprints and low speeds/distances and improves overall running performance. Muscle behavior, forces, and activation patterns during various exercises were examined to achieve these goals. This information can provide new insight into tissue strength modifications that may reduce the risk of injury and contribute to improved performance (Alt et al., 2022; King et al., 2022). In addition, the study investigated the relationship between running characteristics and relative cost and efficiency. *Running economy* is a key determinant of running performance and potentially influences injury risk, as more economical runners experience delayed fatigue (Verstegen et al., 2012). Quantifying and modifying the biomechanics of running and tissue loading in practice can reduce injury risk and improve running performance (Cappozzo, 1983; Marti et al., 1988; Threlkeld et al., 1989; Picerno et al., 2006; Filter et al., 2020). This thesis presents new perspectives for characterizing running activities, especially in soccer.

II – LITERATURE REVIEW

II - LITERATURE REVIEW

2.1. STRUCTURE OF THE REVIEW

This literature review aims to outline the scope and influence of physiological commitment in typical sports actions, such as sprints and jumps, with a specific focus on soccer. It is not intended to provide a comprehensive review of match/performance analysis approaches in soccer but to indicate the basic framework of precedent analysis with a new perspective. The aim is also to provide a solid context for assessing neuromuscular and energetic performance in soccer by determining the energy cost, metabolic power, apparent efficiency, EMG/Force ratio, etc. In addition, the review aims to determine and evaluate the appropriate concept and relationship between training load, physical analysis, and match performance variables in elite soccer.

The review includes an introduction to the scientific methods, research, and technologies in soccer, after which the main requests for match analysis are explained. For example, the applications in field sports and its future perspectives. The review will then define how primary performance markers can be analyzed and integrated into sports.

2.2. SOCCER COMPETITIVE DEMANDS

2.2.1. Soccer physical component's

Soccer is a complex, demanding team sport that requires a high level of multi-component tactical, technical, and physical skills to succeed. During a competitive match, a random combination of explosive and powerful activities and technical and tactical gestures are performed at irregular intervals over a 90-minute match (Dolci et al., 2020). This review presents a detailed analysis and current synthesis of the literature describing the activities and contribution of the energy system during soccer play to provide strength and conditioning coaches with a clear understanding of the physical needs of soccer players during competition.

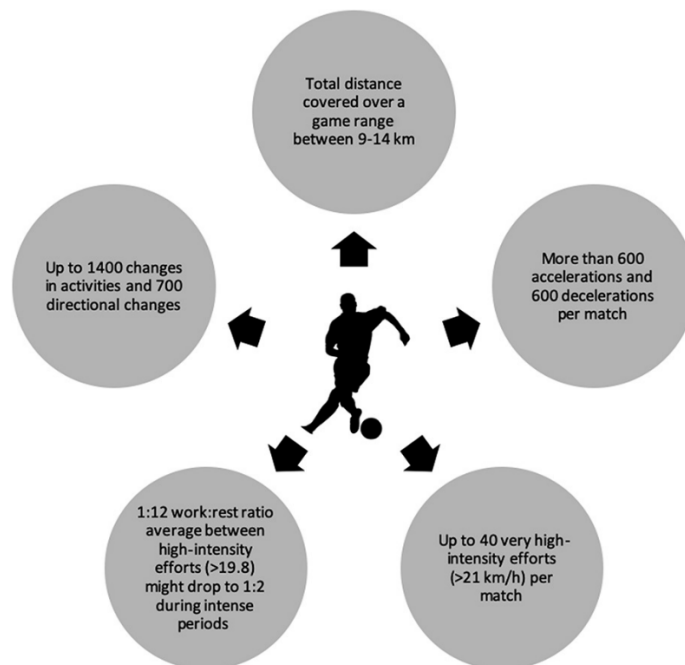


Figure 1. Overview of the activity of professional soccer players during a 90-minute game, with particular consideration of the high-intensity activity profile. Reproduced from Dolci et al. (2020).

The professional sports industry has started to use more scientific methods, research, and technology in its approaches to be more productive by quantifying the physical demands of soccer (Molinos, 2013; Collet, 2013). The technical and tactical aspects likely influence sports performance but also depend on mental and physical yield. The soccer player is less effective if all these aspects are not present (Paul et al., 2015). Players in team sports such as soccer often make ACC and DEC movements more energetically demanding than running at a constant speed (Stevens et al., 2015). In recent years, coaches have implemented portable devices to analyze players' characteristics (Grassadonia et al., 2024). Soccer team coaches constantly try to code player performance to quantify the micro-cycle structure and load of weekly elite soccer training and match play data (Gaudino et al., 2014; Hoppe et al., 2017). While primary data such as TDC and average speeds were collected in the past, correct comparison between two or more players was limited (Azzone & Lorenzon, 2019; Savoia et al., 2020). Therefore, new technologies, such as GPS and, more recently, portable sEMG, have enabled coaches to estimate high-quality and accurate metrics of player performance and identify markers of internal and external physical and physiological stress using different modeling systems (Randers et al., 2010; Buchheit et al., 2014; Montini et al., 2017; Hoppe et al., 2018; Grassadonia et al., 2024). In addition, the media also uses video analysis to provide viewers with a range of statistics that illustrate players' work rates (Halvorsen et al., 2013).

Soccer is constantly evolving, with tactical strategies and player roles adapting to the demands of the modern era. This evolution goes beyond formations and play styles and affects the physical demands placed on players in different positions. An essential aspect of this development is researchers' increasing use of data-driven approaches, which provide a deeper understanding of these changes. Bush et al. (2015) examine the evolution of match performance parameters in the English Premier League (EPL), which is at the forefront of tactical innovation, by analyzing data from seven seasons (from 2006-07 to 2012-13) to identify trends in physical

performance metrics across different playing positions. This research sheds light on how the physical demands of the game have changed, potentially revealing insights into player training strategies and tactical adaptations.

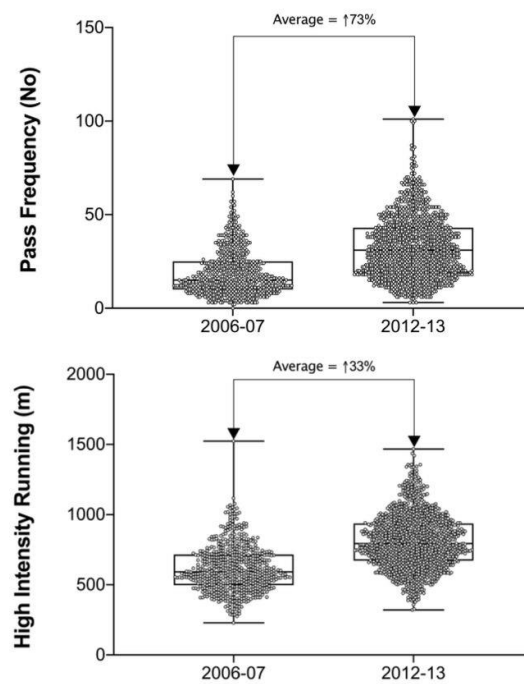


Figure 2. A central defensive role's physical and technical evolution across seven EPL seasons. Dots symbolize individual observations, and the center line of the box highlights the average. The whiskers denote the minimum and maximum values. Reproduced from Bush et al. (2015) and redrawn by Bradley (2022).

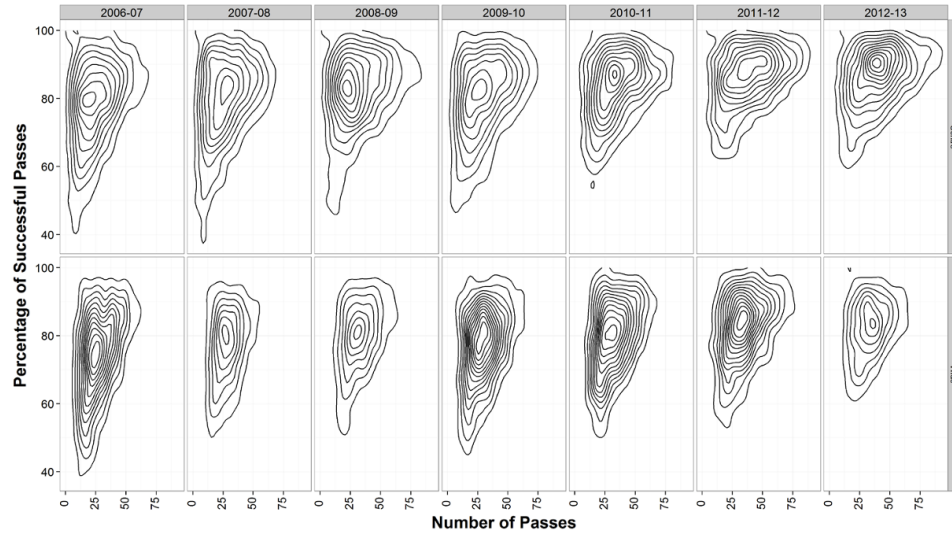


Figure 3. Two-dimensional kernel density plots represent the number of passes and the pass success rate of central (central defenders and central midfielders) and wide players in the EPL (full-backs and wide midfielders). The plot displays similar passes performed by wide players, while central players increase the number of passes over the seven seasons (plot width). Nevertheless, both wide and central players increased the success rate of passes (plot length). Reproduced from Bush et al. (2015).

Bush et al. (2015) show that players in wide and attacking positions increased the distance covered at high intensity and sprinting more than central defenders and central midfielders between 2006-07 and 2012-13. In contrast, central players were found to have increased the number of passes and pass ratio over the same period. These trends could be due to tactical changes, provide benchmark requirements for modern EPL players in each position, and can help with the recruitment and development of position-specific training.

To summarize, the findings of these observations reveals a league (EPL) that is evolving both physically and technically (Bush et al., 2015; Bradley et al., 2016; Bradley, 2022).

2.2.2. The FIFA World Cup Qatar 2022™: an attempt to quantify the "What," the "When," the "How," and the "Why."

For example, the FIFA World Cup Qatar 2022™ recently conducted a contextualized physical analysis to quantify the "what," "when," "how," and "why" of key performance attributes (Bradley, 2023). In particular, the aim of the study relative to the FIFA World Cup Qatar 2022™ is to examine distance at different speeds and phases of the game (Bradley, 2023). The game's physical demands have evolved significantly over the last decade, particularly in high intensity. This physical analysis combines physical metrics with FIFA's Enhanced Football Intelligence metrics to add much-needed context to the data. The results could provide valuable insights for practitioners and support the development of specific training drills that replicate aspects of the game.

In specific context, high intensity and sprint distances during FIFA World Cup Qatar 2022™ matches were highest for the USA and lowest for Costa Rica. Japan showed the most remarkable differences in total distance and distance covered at high intensity from match to match. Using quadrant plots, the USA, Iran, and Canada were categorized as teams with high volume and explosiveness during matches, while Costa Rica and Ecuador were the opposite (Bradley, 2023). The data shows that central and defensive midfielders covered the most total distance and central defenders covered the least total distance at the FIFA World Cup Qatar 2022™. Players in wide positions, such as wide midfielders and forwards, covered more distance at higher intensities than players in central positions, such as central defenders and midfielders. The quadrant diagrams illustrate that different positions occupy certain quadrants, but considerable differences exist between the individual positions (Bradley, 2023). Although most teams covered less total distance in the second half than in the first half, this varied for distances covered at higher intensity. In most positions, the total distance and the distance covered with higher intensity decreased in the second half. In the

second half, attacking midfielders showed the most significant decreases in high-intensity and sprint metrics. The teams covered similar total distances between World Cups, but distances covered at higher intensity were 16-19% greater in Qatar in 2022 than in Russia in 2018 (depending on match duration and substitutes) [Bradley, 2023].

Spain covered the major total distance with the ball, while Costa Rica and Japan covered the most distance without the ball. The USA covered the most kilometers with the ball at a higher intensity, and Saudi Arabia covered the most kilometers without the ball. Sprint distance was 6-19% higher in the FIFA World Cup™ final compared to other stages of the tournament. There was no correlation between the physical metrics and the percentage of wins achieved by teams at the FIFA World Cup Qatar 2022™. However, five quarter-finalists (Argentina, France, Brazil, England, and Portugal) covered significant sprinting distances with the ball. Central defenders and defensive midfielders cover around 70-85% of their high-intensity and sprint distances without the ball due to their specific roles (e.g., pressing, defensive recovery, and transitions). Midfielders and wingers cover around 60-70% of their high-intensity and sprint distances with the ball due to their offensive tasks (e.g., movement to receive the ball in space when pushing forward or in dangerous areas such as the final third). The physical performance of selected roles with and without the ball depends heavily on the quality and stylistic tendencies of the team in question (Bradley, 2023). Matches against teams with high or low physicality directly impact the total distance a team covers, as well as the distance they cover at higher intensity. High-intensity runs are closely related to phases of the game where the outcome is directly dependent on urgency (e.g., recovery phases in defense, movements in the final third). Moderate speed runs are more closely related to metrics related to the organization of attack and defense (e.g., build-up play, various pressing and blocking actions).

Case studies play a crucial role in unraveling the physical, technical, and tactical attributes of high-performance players. By using data in

conjunction with videos, practitioners can contextualize physical performances, empowering them to develop role-specific training drills that consider all aspects of the game. This approach ensures that the audience's expertise is at the forefront of performance improvement (Bradley, 2023).

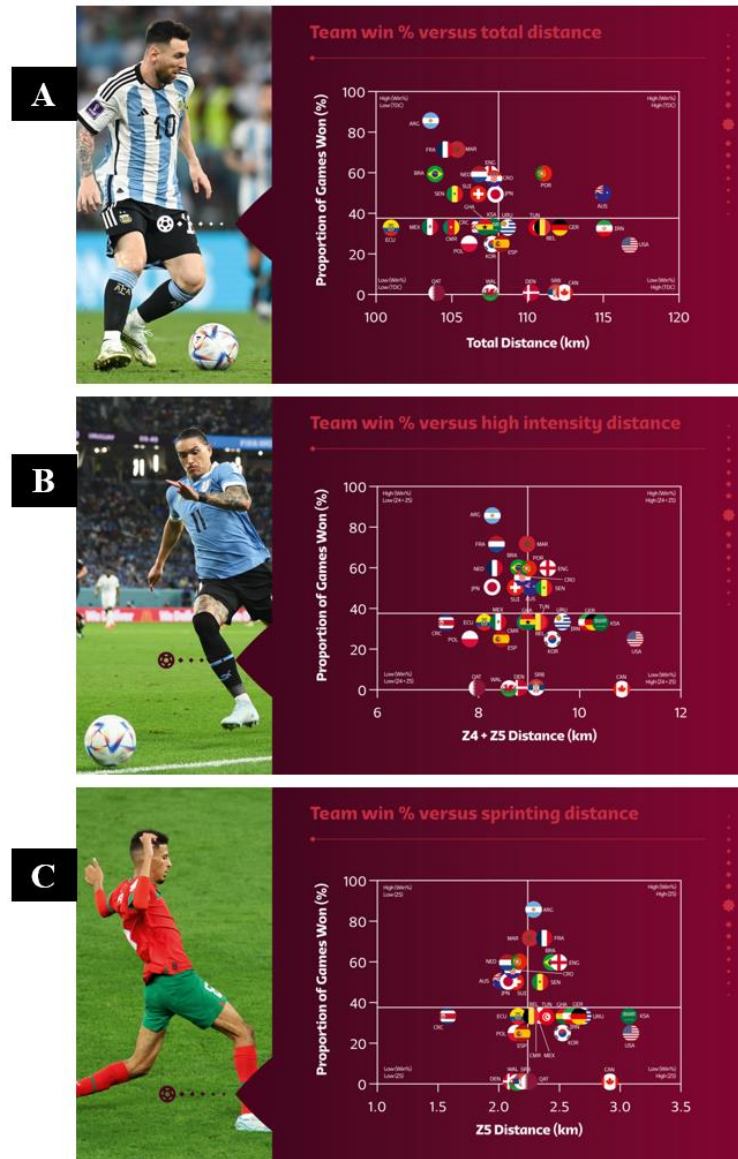


Figure 4 . A) Relation and comparison of team win (%) and total distance. B) Relation and comparison of team win (%) and high-intensity distance (Z4: 20-25 km·h⁻¹). C) Relation and comparison of team win (%) and sprinting distance (Z5: >25 km·h⁻¹). Reproduced from Bradley (2023).

2.3. STUDY OF HUMAN LOCOMOTION: HISTORICAL CONSIDERATIONS

Since the second half of the 19th century, a rich tapestry of studies has been woven in the field of biomechanics, exploring the energetics and mechanics of various forms of locomotion, including running (Marey & Demeny, 1885_{a,b}; Fenn, 1924; Furusawa et al., 1927; Fenn, 1930_{a,b}; Margaria et al., 1933; Hill, 1938; Margaria, 1938; Katz, 1939; Wilkie, 1949). These studies, conducted over a century, aimed to uncover the basic mechanisms of this natural form of locomotion. The historical context provides a backdrop that is an effective and crucial part of our current understanding, enlightening us about the evolution of biomechanics studies.

Fenn (1930_{a,b}) used the same method as Marey & Demeny in 1885_b (i.e., the moving image). In particular, Fenn (1930_{a,b}) adopted the Eastman Kodak Company, and in particular with the production of Eastman Teaching Medical Films, facilitated the involvement that was crucial in making accurate absolute measurements from the film, as it was necessary to run the runners behind a white wooden grid that formed a coordinate system with squares of 1 meter per side.

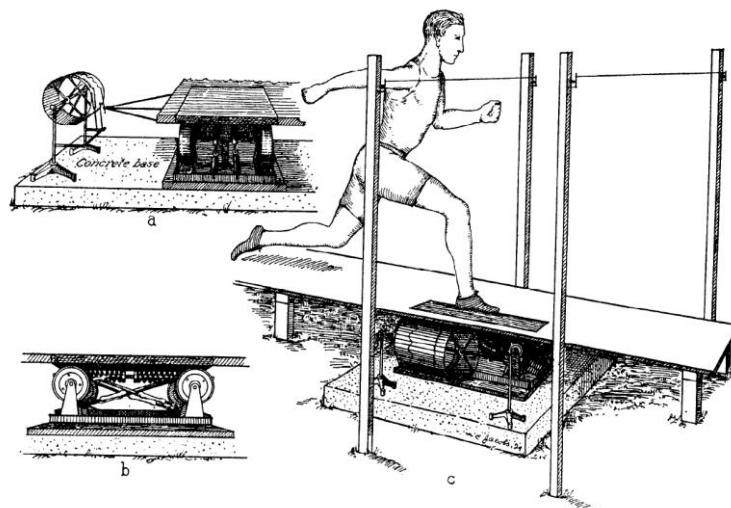


Figure 5. Arrangement of the apparatus for recording the forward components of the foot's pressure on the ground. Reproduced from Fenn (1930_b).

The direct method is based on measuring the horizontal pressure exerted by the foot when it touches the ground. A platform (*trottoir dynamique*) was built for a similar purpose by Amar (1916), who measured both horizontal (backward) and vertical pressure. This single diagrammatic recording shows that the foot pushes forward on the ground at the moment of touchdown and later, of course, also backward (Amar, 1923). Unfortunately, no information was given about the runner's speed or weight, so the change in energy cannot be determined. It should also be mentioned that Marey (1892) used a dynamo-graphic platform to measure the vertical pressure on the ground. Braune & Fischer (1899) calculated the direction and magnitude of foot pressure on the ground during walking from their moving images.

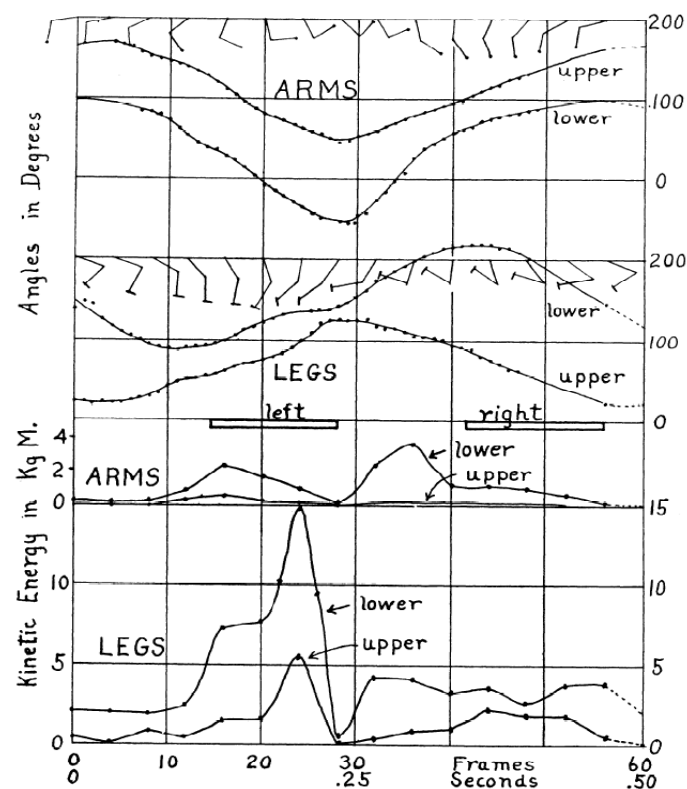


Figure 6. Shows the general arrangement used for this purpose in a case study of the runner in the kinetic energy and displacement curves. A telephoto lens was used for the recordings so that the camera could be placed 30 meters away from the runners. Reproduced from Fenn (1930_a).

Interest in running has led to a similar explosion of research and evaluation, fueled by technological and engineering advances such as faster cameras and marker systems that eliminate the need for manual digitization of video images. For example, growth in the field was also fueled by the vast increase in participants in long-distance running in the late 1960s and early 1970s (Novacheck, 1998).

The human body can be considered as a biological machine, that uses chemical energy to produce mechanical work (Margaria et al., 1963; di Prampero et al., 1970; Cavagna et al., 1971; Cavagna et al., 1976). As Rodolfo Margaria points out, *“The study of locomotion requires first the determination of the energy cost of exercise and then a detailed analysis of the mechanical work performed”* (Margaria, 1976). Other parameters are usually determined to evaluate human locomotion, such as cost, power, efficiency, etc.

However, the results of these studies also found direct practical applications. For example, they have been used to assess total metabolic energy expenditure and predict best performance. The movement strategies used in jumping, which hold significant historical relevance in human training and physiology, are also of great interest. This topic involves analyzing several factors that can also vary as the execution modes of these particular gestures change. The relationship between mechanics and energetics in a biological context, such as humans, is of great interest (Högberg, 1952; Bosco & Vittori, 1986; Peronnet & Thibault, 1989; Alexander, 1991; Grassadonia et al., 2024). This relationship is further complicated because concepts such as efficiency and energy cost, which have been extensively studied and are also the focus of current research, are also relevant to this relationship.

Instead, in the 1980s, to understand further peculiarities, the complex phenomenon that controls running speed was investigated with a new proposal that includes the relationship between running cycle and relative velocity performed at maximal and supra-maximal speed (Bosco & Vittori, 1986).

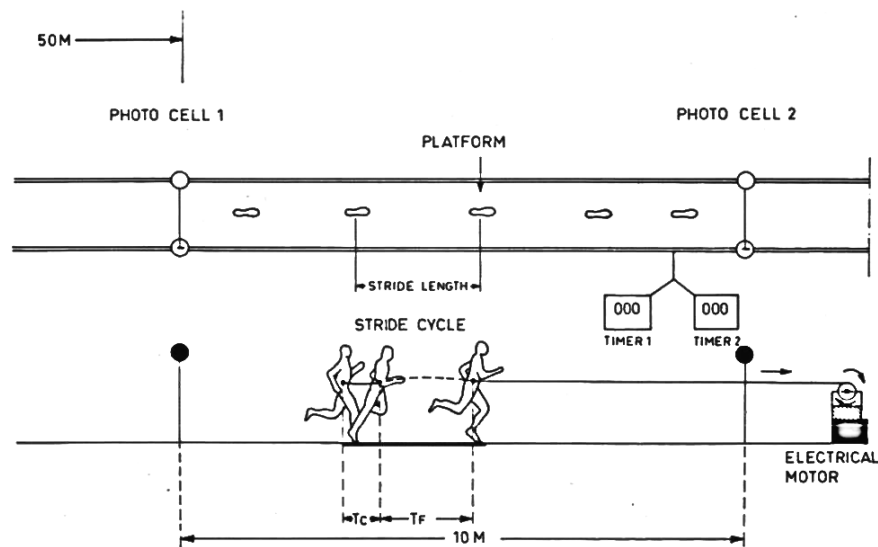


Figure 7. Schematic representation of the apparatus used. Reproduced from Bosco & Vittori, 1986.

Running speed is influenced by two mechanical parameters: stride length and stride frequency. These two parameters develop differently during running. The stride length flattens at higher running speeds while the stride frequency increases. This study shows how these two parameters develop differently at a supramaximal speed (artificially generated with a "towing system") than would be expected based on theoretical calculations. While the stride length increases in a specific way, the stride frequency surprisingly increases less than expected (Bosco & Vittori, 1986).

Bosco & Vittori (1986) investigate critical insights into the kinematic and kinetic variables that influence sprint performance, highlighting the distinctive mechanical demands imposed on athletes during different phases of high-speed running. Through a detailed analysis of stride length and stride frequency, the authors demonstrated that the ability to horizontal propulsive movements plays a decisive role in achieving supra-maximal speeds. Additionally, it underscored the importance of elastic energy storage and its contribution to enhancing sprint efficiency, particularly during the transition from acceleration to top-speed phases. This work laid

the foundation for subsequent research in sprint biomechanics, offering valuable implications for training methodologies and developing performance-enhancing strategies in elite athletes.

Horizontal sprint speed (v_x) is determined by the product of stride frequency (SF [contact + flight phases] or f [average stride frequency]) and stride length (SL [contact + flight phases] or l [average stride length]). Note that the time (T [total time] or T_c [contact time]) was represented in the following equations:

$$v = \frac{SL}{(T_c + T_f)} \quad or \quad v = f \cdot l \quad \text{[Speed Equations]}$$

$$SF = \frac{1}{(T_c + T_f)} \quad or \quad f = \frac{1}{T} \quad \text{[Frequency Equations]}$$

$$SL_c = v_x \cdot T_c \quad or \quad l = v \cdot \frac{1}{f} \quad \text{[Length Equations]}$$

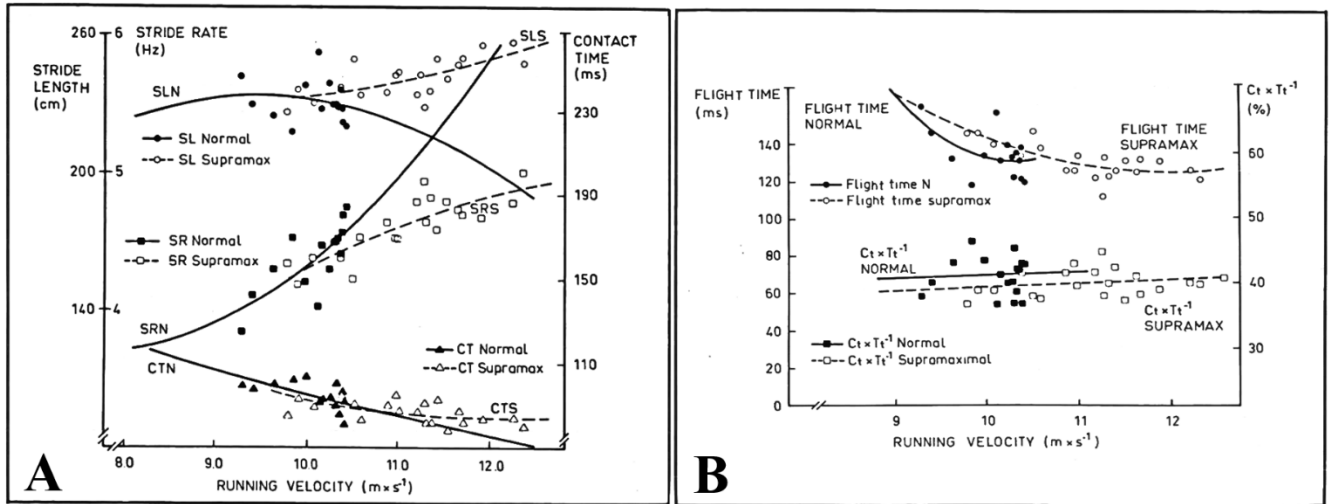


Figure 8.

A) Contact time, stride length, and stride rate are presented in the function of speed recorded during running performed in both normal and pulling conditions. Reproduced from Bosco & Vittori, 1986.

- i. Regression equation for contact time normal: $y = 268,49 - 23,21 x + 0,60 x^2$
- ii. Contact time supra-max.: $y = 111,25 + 39,79 x - 1,97 x^2$
- iii. Stride length normal: $y = -658,95 + 183,94 x - 9,47 x^2$
- iv. Stride length supra-max.: $y = 359,88 - 29,8 x + 1,72 x^2$
- v. Stride rate normal: $y = 15,24 - 2,72 x + 0,16 x^2$
- vi. Stride rate supra-max.: $y = -2,91 + 1,10 x - 0,04 x^2$

B) Flight time and the ratio Contact Time/Stride Cycle Total Time (C_t/T_t) are presented as a function of the speed recorded in both normal and pulling conditions. Reproduced from Bosco & Vittori, 1986.

- i. Regression equation for flight time normal: $y = -580,13 + 160,87 x - 8,9 x^2$
- ii. Flight time supra-max.: $y = 791,53 - 110,99 x + 4,62 x^2$
- iii. Ratio contact time/total time normal: $y = 192,24 - 30,38 x + 1,53 x^2$
- iv. Contact time/total time supra-max.: $y = -130,30 + 30,36 x - 1,35 x^2$

2.4. THE NOVEL APPLICATION OF GPS AND EMG IN MEASURING HUMAN LOCOMOTION

2.4.1. History and development of GPS technology

In 1997, the first attempt was to validate using commercially available GPS devices to measure human movement. The first participant in this study undertook several trials at different walking and running speeds, after which the data collected by the GPS was compared with a Swiss watch. The association between the GPS reading and chronometer was $r = 0.99$, with a constant disparity in the slope line. The initial study was very promising, but a gold standard was needed so scientists could validate and confirm GPS as a valid tool for measuring speed. The study was further hindered when the accuracy of satellite transmission was compromised by the United States Department of Defense (Schutz & Chambaz, 1997). However, in 2000s, this interference ended, which allowed the study to investigate how GPS could be used to measure the speed of objects.

The United States Department of Defense invests in GPS systems for military and navigation purposes. It has sent 32 operational satellites into orbit around the Earth, each equipped with an atomic clock (Larsson, 2003). Per period, the GPS signal receiver connected to the satellite synchronizes its clock with the atomic clock in the satellite. To calculate the distance from the satellite, the signal propagation time is multiplied by the speed of light. The exact position (altitude, latitude, and longitude) can be determined trigonometrically by calculating the distance to at least three satellites. Another satellite is required to calculate the fourth variable: time. In 1991, the United States Department of Defense considered selective availability with a system error inside, and it was not until 1999 that this error was corrected (Larsson, 2003).

Later tests showed that it was possible to correct the scrambled signals of GPS by calculating the second difference phase by using two

receivers positioned next to each other, thus reducing the three-dimensional error found in the first experiments (Witte & Wilson, 2005). This method was then used to measure the position and accelerometer data. The use of a high-precision GPS consistently led to high intra-individual variability. With the introduction of the European Geostationary Navigation Overlay Service (EGNOS) and the Wide Area Augmentation System (WAAS), the inaccuracies of GPS were further reduced, and significant improvements were achieved in the measurement of velocities and precise positions for straight-line tasks. After that, GPS systems sought to understand better the effectiveness of directional and speed changes (Aughey, 2011).

2.4.2. Reliability and validity of GPS systems in sport

Significant improvements were made in validating the use of GPS to measure the speeds and positions of individuals in a straight line, but significant challenges remained (Aughey, 2011). Determining the movement and speed of athletes making multiple CoD seemed difficult. In addition, the GPS had to withstand different conditions, such as humidity, heat, and other potential influences, before it could be successfully used in team sports. In 2003, the first commercially available GPS designed specifically for sports was introduced and compared to data collected with a computer-based system. A further comparison with a calibrated running wheel helped to confirm the use of GPS in measuring distance objects. Nevertheless, despite high correlations of over $r = 0.998$, an overestimation of 5% and a computer-based training of about 6% was found (Aughey & Falloon, 2010). Further validation of GPS for use in sport was undertaken in 2009-2010 when several studies were published using slightly different GPS technologies and methods. GPS technology has been used extensively to assess the physical demands of training and competition (Aughey, 2011). In particular, several studies have shown that GPS devices have sufficient

accuracy to monitor the actual demands of intermittent exercise and calculate MP during high-intensity activities (Rampinini et al., 2015). However, some concerns are associated with using GPS devices to measure high-speed events accurately. It has been shown that the sampling rate of the devices, as well as the speed, effort duration, and type of task, can affect accuracy (Coutts & Duffield, 2010; Colli, 2014; Bellistri, 2017).

For example, many studies have investigated and discussed the validity of determining the mechanical properties during acceleration when sprinting in a straight line. It was found that a higher sampling frequency for the GPS device is generally better for measuring the mechanical properties of sprint acceleration (Nagahara et al., 2016; Nagahara et al., 2017; Savoia et al., 2020). However, it should be noted that different uses may require different sampling frequencies and applied filters to correctly evaluate the data (Colli, 2014; Savoia et al., 2020).

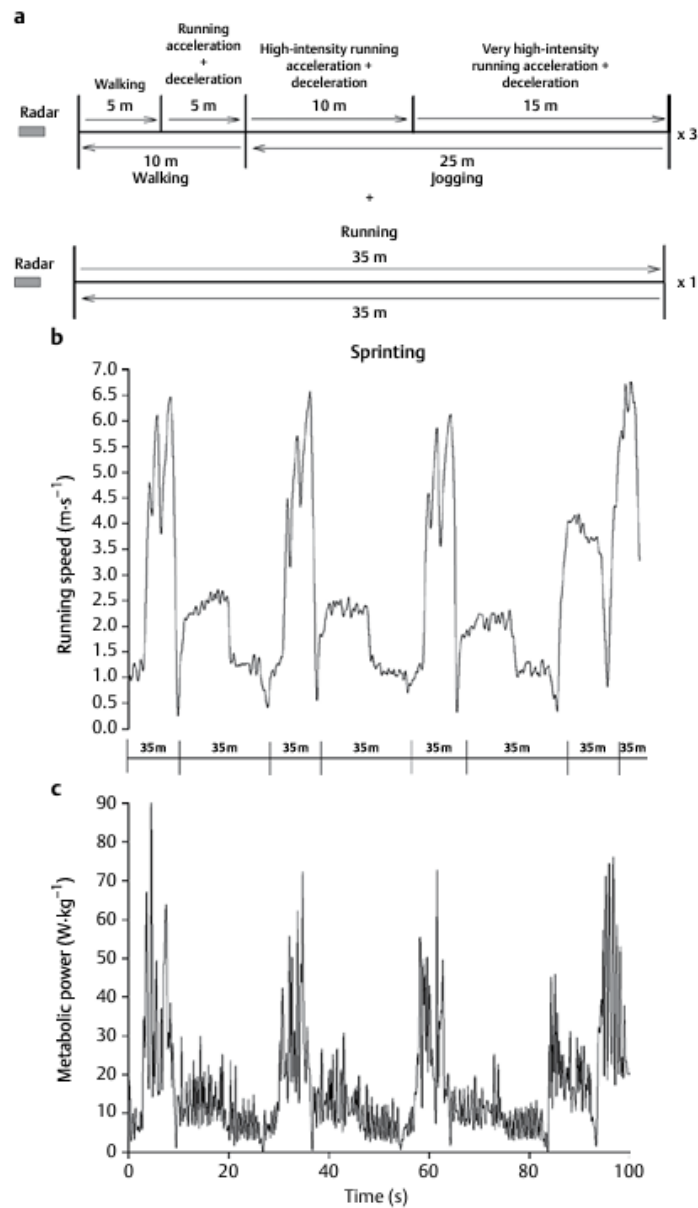


Figure 9. Schematic representation of the activities performed during each part of the intermittent shuttle run (panel a) and an example of the measurement of running speed (panel b) and the calculation of metabolic power (panel c) using the radar system. Reproduced from Rampinini et al. (2015).

2.4.3. Use of EMG: history and Recent Developments

Most research on soccer player performance has focused on metabolic demand, while few studies have focused on neuromuscular activation (Montini et al., 2017). One of the significant limitations in electromyographic studies of soccer player performance is the difficulty in recording EMG surface signals throughout the game. A previous investigation of muscle strength and activation during maximal voluntary isometric contractions (MVC) has shown that the neuromuscular performance of soccer players is severely impaired at the end of the match (Thorlund et al., 2009). Another previous study investigated the changes in hamstring muscle fatigue and central motor performance during a 90-minute simulated soccer match (Marshall et al., 2014). The authors reported an early decrease in hamstring torque development in the first half and a decrease in maximal activation of the biceps femoris in the second half, with measurements taken before, every 15 minutes during each half, and after the match. To gain insight into the neuromuscular demands of competitive soccer, Montini et al. (2017) investigated the activation profile of the leg muscles during a match. To this end, a continuous recording of the EMG surface signals of the vastus lateralis muscle was attempted and combined with an assessment of the post-match strength changes of the knee extensors. To the author's knowledge, this is the first study to continuously record EMG activation of the leg muscles during a 90-minute soccer match (Montini et al., 2017).

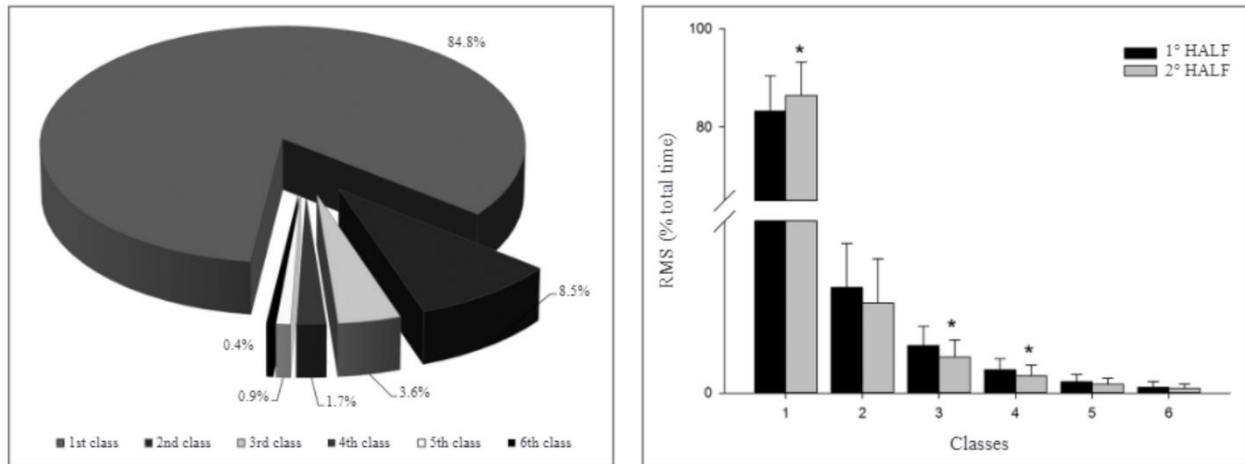


Figure 10. Left Panel: Temporal distribution of vastus lateralis RMS values expressed as %RMSmax in the six intensity classes (1°: 0-20% RMSmax; 2°: 20-40% RMSmax; 3°: 40-60% RMSmax; 4°: 60-80% RMSmax; 5°: 80-100% RMSmax; 6°: 100-120% RMSmax) during the 90-minute soccer match. Right Panel: Temporal distribution of the RMS values of the vastus lateralis, expressed as % RMSmax, in the six intensity classes determined in the first and second half. *Indicates a significant difference ($p < 0.05$) from the first half. Reproduced from Montini et al. (2017).

2.4.4. EMG main function

Muscle activity measured by electromyography (EMG) reflects the electrical action potential that results from muscle contraction and propagates within and on the surface of the muscle fibers. The changes in the action potential can be measured from the skin's surface using EMG electrodes that record the summed signal propagated from the active motor units. With increasing force, the recorded electrical activity increases as more muscle fibers are recruited and the firing frequency of the fibers increases. The EMG signal, therefore, reflects the amount of electrical activity recorded by the EMG electrodes. In clinical applications, surface EMG is used to study movement coordination and the role of different muscles in specific tasks by determining the level or absence of their electrical signal (De Luca, 1997). Since the contraction of skeletal muscles

causes physical activity (Pate et al., 1995), it is logical to measure the stress of physical activity by this outcome. The antigravity muscles, including the plantar flexors soleus and gastrocnemius, the knee extensors vastus lateralis, vastus medialis, and rectus femoris, the hip extensors hamstring and gluteal muscles, and the trunk extensors in the erector spinal muscle and other muscles, maintain the body in an upright posture during standing and provide movement during more intense physical activities (Panzer et al., 1995; Hof et al., 2002; Tikkanen et al., 2014). Conversely, many of these muscles are inactive when seated (Panzer et al., 1995; Tikkanen et al., 2013), suggesting that EMG can measure physical activity.

2.4.5. Reliability and validity of portable EMG systems in sport

The EMG shorts have undergone rigorous laboratory testing for validity, repeatability, and feasibility (Finni et al., 2007; Tikkanen et al., 2013; Pesola et al., 2022). The previous authors have demonstrated that they estimate energy expenditure accurately (Tikkanen et al., 2014; Grassadonia et al., 2024). To give strength to these considerations, in the laboratory measurements, the maximum voluntary contraction increased significantly after the measurement ($p < 0.001$), but the relationship between EMG and the force measured during the maximum voluntary contraction remained the same (Pesola et al., 2016).

The results with statistically significant differences from Barrera et al. (2022) show that the electrode area and the orientation to the muscle fibers influence signal quality and strength. These results suggest that the characteristics of the target muscle dictate the electrode size parameters to optimize the acquisition of surface electromyography signals.

However, this technology is still under development; it has already significantly impacted the technical characteristics (such as the size and shape of the textile surface electrodes) for electromyography in sports science and related research areas.

2.4.6. EMG textile electrodes

EMG measurement with portable and wearable textile electrodes has proven to be a feasible method to assess the presence and absence of muscle activity in muscle groups, which is relevant and applicable to sports and physical activity. Since the size of the conductive area and the distance between electrodes is more extensive for EMG textile electrodes sewn into the inside of shorts than for conventional bipolar electrodes, they provide data on the global muscle activity of the entire muscle groups on the thigh rather than measuring single muscles (Finni et al., 2007). Finni et al. (2007) showed that the signal, EMG, and intra-session repeatability recorded with these EMG shorts matched well with those of bipolar electrodes. However, using EMG shorts could improve inter-day reproducibility due to the large electrode area and lack of skin irritation (Finni et al., 2007). Tikkanen et al. (2014) have shown that EMG shorts can estimate energy expenditure and are more accurate than accelerometers and heart rates at low exercise and varying terrain when individual calibrations are performed.

Several physiological and methodological factors must be considered when interpreting the EMG signal measured in everyday life (Farina et al., 2004). The impedance between the skin and the electrode and the associated interindividual variability of the signal is usually reduced by normalizing the signal to that measured during maximal voluntary contraction to obtain the EMG activity relative to the maximal contraction of the muscle

(%EMG_{MVC}) [Burden, 2010]. The selection of the inactivity threshold used to separate gaps in the signal from physiological activity significantly impacts the results. Most recent studies have used an inactivity threshold of 2% of EMG_{MVC} (Kern et al., 2001; Harwood et al., 2008; Jakobi et al., 2008; Shirasawa et al., 2009; Harwood et al., 2011; Theou et al., 2013), but 10% of EMG_{MVC} has also been used (Howe, & Rafferty 2009). Klein et al. (2010) have shown that choosing a higher threshold decreases the duration of muscle activity in a curvilinear manner, as most bursts are of low intensity. In the studies where EMG shorts were used, a threshold was used that was individually lower than the muscle activity during standing (Tikkanen et al., 2013; Finni et al., 2014; Gao et al., 2016). This approach is advantageous because standing is defined as physical activity (Sedentary Behaviour Research Network 2012), and many daily activities are performed at an intensity of less than 2% of EMG_{MVC} (Okada, 1973; Panzer et al., 1995).

2.5. BIOMECHANICAL CONSIDERATIONS IN RUNNING

In running, the feet do not always land below the center of mass (CoM or BCoM, body center of mass) [e.g., CoD]. When we run slowly, this is more likely to be the case, but at high speeds, the feet land sideways (more or less parallel). So, the ground reaction force will accelerate us upwards and forwards, but it will also put us into a spin (creating a torque or moment of force - *Torque*: $\tau = F \cdot d$) [d : distance]. For a given angular velocity, the linear velocity of a point is greater the further it is from the center of rotation: $V = r\omega$ [r : radius]. When the legs accelerate, especially when the foot of the swinging leg contacts the ground, the upper limb is quickly extended. The increase in the angular velocity of the arm and the shift of its center of mass away from the shoulder (which causes a further increase in its velocity) leads to an increase in its angular momentum: $H = mk^2\omega$. The torque generated by the ground reaction force influences upward and forward acceleration and contributes to the rotational momentum of the runner's limbs. This angular momentum stabilizes the body and ensures proper directional control, particularly at high-speed running. When the lower limbs reach the end of their swing, the arms flex again, and their angular velocity decreases. The angular momentum of the limbs (upper and lower) is therefore equal and opposite to each other, partly because the runner would otherwise have difficulty maintaining a specific direction. When the foot of the swinging leg contacts the ground, the arms extend rapidly to counterbalance the rotational momentum generated by the legs. At speeds between 3.8 and $5.5 \text{ m}\cdot\text{s}^{-1}$, almost all of the rotational momentum generated by the legs is neutralized by that of the arms, and the contribution of the upper limbs increases with increasing speed. In fact, during fast running, the trunk rotates very little, which means that the upper limbs play a crucial role in its stabilization (Hinrichs, 1987_{a,b}; Bosch & Klomp, 2005; Bosch, 2015; Blazeovich, 2017). However, it is essential to clarify that this formula applies

specifically to a point mass rotating at a distance k (the radius of gyration) from the axis of rotation.

During running, the upper limbs flex to reduce their angular momentum and use the arms to counteract the rotations generated by the legs. The arms influence the legs because a non-optimal oscillation of the upper body also affects the lower body. Optimal oscillation involves the movement of the upper limbs in the sagittal plane in the opposite direction to the lower limbs. The angular momentum of the lower limbs and the torque generated by the ground reaction force change during the step, so the length of the lower limbs must also change. According to Newton's third law, the rotation of one body segment causes an opposite rotation in other body segments. This interconnectedness of the body's movements is a fascinating aspect of biomechanics that helps runners maintain balance and direction. For optimal running efficiency, the arms and legs must coordinate their movements to stabilize the trunk and minimize unnecessary rotational energy, particularly at higher speeds. For example, research has shown that upper limbs play a crucial role in stabilizing the trunk during fast running (Hinrichs, 1987^{a,b}; Blazevich, 2017). These principles underscore the need for precise arm and leg coordination to maintain running efficiency.

Rotational energy is a form of kinetic energy associated with the rotational motion of a rigid body. In the case of a rigid body with axisymmetric that rotates about the axis of symmetry, the rotational energy is proportional to the product of the body's moment of inertia (I) and its angular velocity (ω) when: $E (RE) = \frac{1}{2}I\omega^2$. The expression is similar to that of translational kinetic energy: $E (KE) = \frac{1}{2}mv^2$, but instead of the mass " m " the moment of inertia " I " appears (the property of bodies that counteracts rotational motion, just as mass counteracts translational motion), and instead of the linear velocity " v " the angular velocity " ω " appears. Substitution can quickly determine this: $I = mr^2$ and $\omega = v/r$. Note that these substitutions are typically used for circular motion for rigid bodies, so applying them to running biomechanics requires acknowledging that

running involves multi-segment rotational and translational movements, not simple circular paths. If a body of mass "m" changes its speed, its kinetic energy also changes. The work corresponds to this change in kinetic energy. Kinetic energy is, therefore, linked to the mass and speed of a moving body. The kinetic energy a body of mass "m" has in its falling motion equals its work when it stops. The kinetic energy depends on the reference inertial system. In a stationary reference system, the kinetic energy assumes a lower value than in a moving reference system. The additional kinetic energy corresponds to the kinetic energy of the translation of the mass "m" with the velocity "v" of the displacement of the reference inertial system.

In classical mechanics, the kinetic energy of a body of mass "m" is the work required to bring it from an initial velocity of zero to a final velocity "v", a function that depends on the square modulus of the velocity. This definition can be formalized thanks to the *theorem of living forces*, better known as the *theorem of kinetic energy*. The work done by the force when the body moves from an initial state to a final state is equal to the change in the body's kinetic energy:

$$W = \Delta KE = \frac{1}{2}m (v_f^2 - v_i^2)$$

This energy varies depending on the reference frame, and for a runner, it reflects the work required to bring the body from rest to a certain speed. The theorem of kinetic energy (also known as the *work-energy theorem*) formalizes this relationship, showing that the *work* (W) done by a force on the body corresponds to the change in its kinetic energy. The method of calculating W_{tot} results from an interpretation of *Köning's theorem* of mechanics, which states that the overall kinetic energy of a linked multi-segment system is the sum of the kinetic energy of the center of mass of the system (which is contained in W_{ext}) and the kinetic energy (translational and rotational energy) of the segments calculated from their relative speed to the center of mass of the system (which represents W_{int}) [Zamparo et al., 2016].

In summary, the ground reaction force generates torque $\tau = F \cdot d$ due to the foot landing away from the center of mass, contributing to rotational motion during running. This creates angular momentum $H = mk^2\omega$, where the *mass* and *radius* of gyration play a role in the velocity of rotating segments. When the foot contacts the ground, the arms extend to counterbalance this motion, by Newton's third law, stabilizing the upper body against rotational forces generated by the legs. The rotational kinetic energy associated with this motion can be described by $E(KE) = \frac{1}{2}I\omega^2$, where I is the moment of inertia and ω is the angular velocity. This is analogous to translational kinetic energy, $E(KE) = \frac{1}{2}mv^2$, with I playing the role of mass in rotational systems. As the mass of a segment increases or the angular velocity changes, the kinetic energy adjusts correspondingly, necessitating precise arm and leg coordination for optimal running efficiency (Hinrichs, 1987_{a,b}; Blazeovich, 2017).

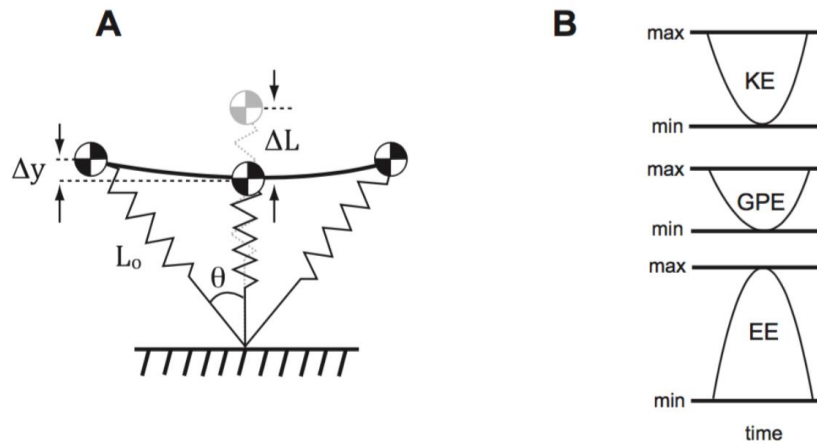


Figure 11. (A) Spring-mass model of human running. The model consists of a mass and a single-leg spring. This figure shows the model at the beginning of the stance phase (far left), in the middle (the leg spring is aligned vertically), and at the end of the stance phase (far right). The vertical displacement of the BCoM represents the spring's compression amount. (B) This figure illustrates the fluctuations in kinetic energy (KE), gravitational potential energy (GPE), and elastic energy (EE). During the first half of the stance, the KE and GPE of the BCoM compress the linear leg spring, and the EE is stored in the spring. In the second half of the stance, the linear leg spring rebounds and releases the EE, which is converted back into KE and GPE. Reproduced from Farley & González (1996) and modified by Monte (2020).

Despite the apparent simplicity of the spring-mass model of human running, this analogy presents a paradox (Monte, 2020). The model assumes that the linear spring is perfectly elastic, meaning that the same amount of mechanical energy is stored and returned during the stance phase of running (and thus no muscular work is required to maintain locomotion) [Farley & González (1996)]. Although this is not the case, it's crucial to understand that these elastic mechanisms, which we will explore further, play a significant role in reducing the energy cost of running in humans and other animals, and in influencing mechanical work production (Alexander, 1984).

Stretch-shortening cycle (SSC) can be well demonstrated by direct in vivo tendon force measurements, for example, during running at the level of a single muscle group. The technique used to obtain the force curves of the Achilles tendon (AT) force curves in **Figure 12**, a buckling transducer was implanted around the AT of a healthy person under local anesthesia (Komi, 2000).

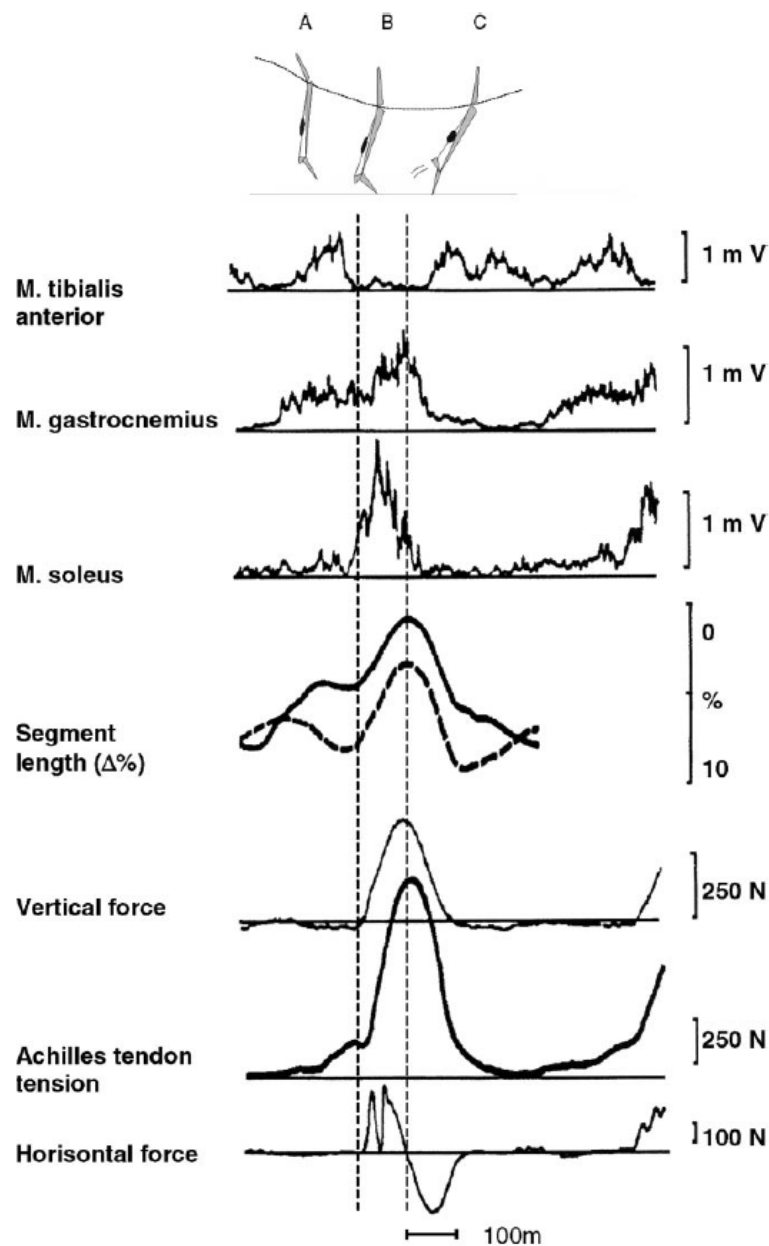


Figure 12. Demonstration of SSC for the triceps surae muscle during the (functional) ground contact phase of human running. Top: Schematic representation of the three phases of SSC. The remaining curves represent parameters in the following order (from top to bottom): Rectified surface EMG recordings of the tibialis anterior, gastrocnemius, and soleus muscles, segmental length changes of the two muscles (dashed "soleus, solid "gastrocnemius), vertical ground reaction force, directly recorded Achilles tendon force and horizontal ground reaction force. The vertical lines mark the beginning of the foot's contact (ball of the foot) on the force plate and the end of the eccentric phase. Reproduced from Komi (2000).

This type of muscle function sequence also includes the important features of pre-activation and variable activation. SSC muscle function has a well-known purpose: to improve performance during the final phase (concentric action) compared to isolated concentric action (Komi, 2000).

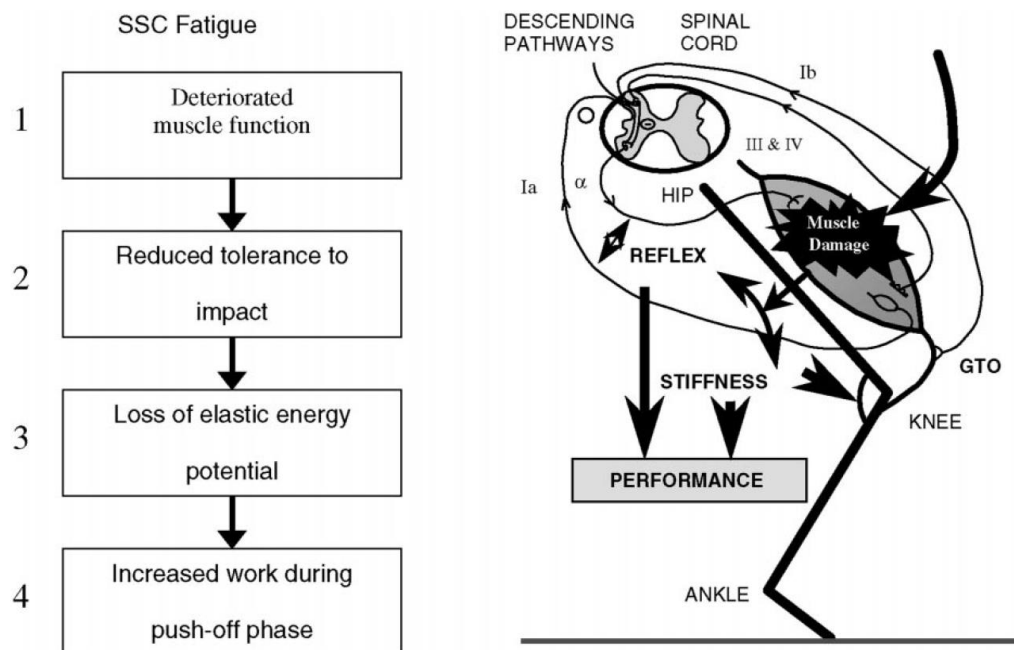


Figure 13. Proposed coupling between SSC exercise-induced muscle damage and reduced performance. Muscle damage alters stiffness regulation through changes in afferent inputs from the muscle spindle, Golgi tendon organ, and group III and IV afferent nerve endings. The events occur in the following order: 1. muscle damage decreases stretch-reflex sensitivity; 2. muscle (and joint) stiffness regulation is disrupted (reduced); 3. efficiency of SSC function (performance) decreases. The proposed mechanism may be even more evident in the triceps surae muscle than in the quadriceps group of the figure (based on Horita et al., 1999). Reproduced from Komi (2000).

The behavior of the muscle-tendon unit (MTU), fascicles, and Achilles tendon was investigated by Monte et al. (2020) during the absorption phase (in which the net ankle joint power is negative) and the propulsion phase (in which the net ankle joint power is positive) during stance. **Table I** shows the average MTU length, fascicle length, and tendon length during the absorption and propulsion phases, as well as the tendon strain (the

maximum value during the stance phase) and the tendon recoil (the maximum value during the propulsion phase). The velocities of the fascicle and tendon lengths were calculated by differentiating the lengths of each component concerning time in the stance phase. **Table I** reports the average values of muscle-tendon unit length, fascicle length, and tendon length during the absorption and propulsion phases and the values for tendon strain and recoil. These parameters increased significantly as a function of speed (main effect: $p < 0.001$), except gastrocnemius medialis fascicle length, which decreased as a function of speed during absorption and propulsion. Monte et al. (2020) found significant differences between the velocities for all muscle and tendon parameters investigated.

	10 km h ⁻¹	13 km h ⁻¹	16 km h ⁻¹
MTU length			
Absorption phase	47.41 ± 3.4	53.33 ± 3.9** [#]	58.87 ± 4.2*** [#]
Propulsive phase	44.32 ± 3.2	42.88 ± 2.7* [#]	40.04 ± 2.8*** [#]
Fascicle length			
Absorption phase	4.37 ± 1.01	4.28 ± 0.97* [#]	4.19 ± 0.83*** [#]
Propulsive phase	3.99 ± 0.98	3.81 ± 0.98* [#]	3.62 ± 0.98*** [#]
Tendon length			
Absorption phase	22.53 ± 2.2	23.78 ± 1.97* ^{##}	24.51 ± 1.89*** ^{##}
Propulsive phase	21.12 ± 1.9	20.02 ± 2.01* [#]	19.48 ± 1.88*** [#]
Tendon strain			
Absorption phase	1.10 ± 0.49	1.35 ± 0.52*** ^{##}	1.62 ± 0.57*** ^{##}
Tendon recoil			
Propulsive phase	0.89 ± 0.55	1.11 ± 0.48*** ^{##}	1.35 ± 0.51*** ^{##}

Tendon strain (the maximum value during the stance phase) and tendon recoil (the maximum value during the propulsive phase) are also reported. Data are means ± SD and are expressed in cm

Significant differences from 10 km h⁻¹ (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$); significant differences between 13 and 16 km h⁻¹ ([#] $P < 0.05$; ^{##} $P < 0.01$; ^{###} $P < 0.001$)

Table 1. Average MTU length, fascicle length, and tendon length during ground contact absorption and propulsive phases at 10, 13, and 16 km·h⁻¹.

The muscle activation patterns described by Mero and Komi (1987) show a difference in pre-activity prior to contact with the ground and differences, worthy of further investigation, between the eccentric and concentric phases. Furthermore, Mero & Komi (1987), found that the peak activity of the leg muscles, except the rectus femoralis, occurred as expected during the braking phase of the ipsi-lateral contact (**Figure 14**).

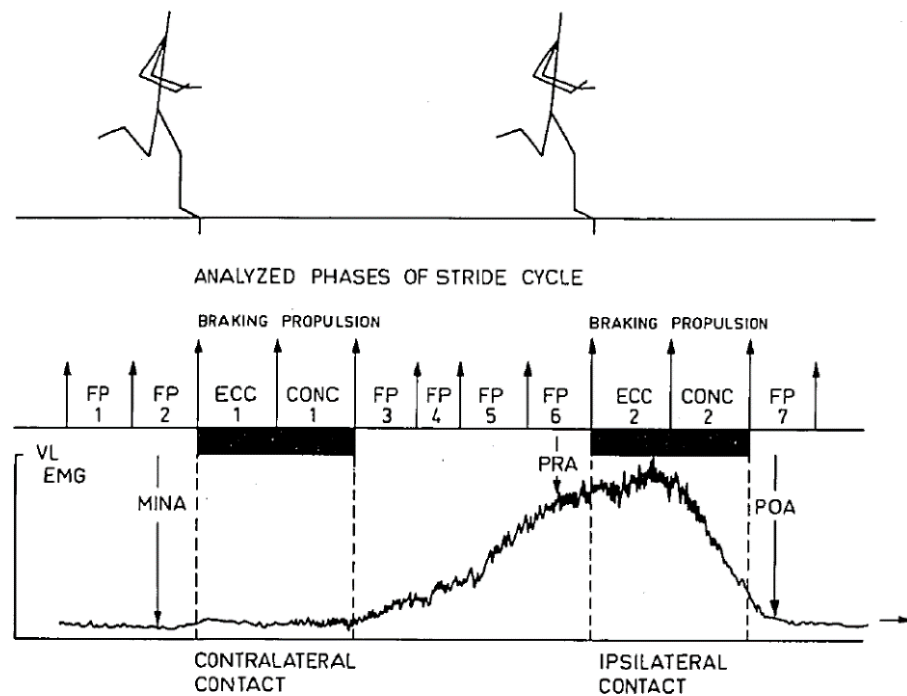


Figure 14. Analyzed phases of the rectified sEMG during the stride cycle. ECC: eccentric; CONC: concentric. Reproduced from Mero & Komi, 1987.

ELECTROMYOGRAPHIC ACTIVITY IN RUNNING

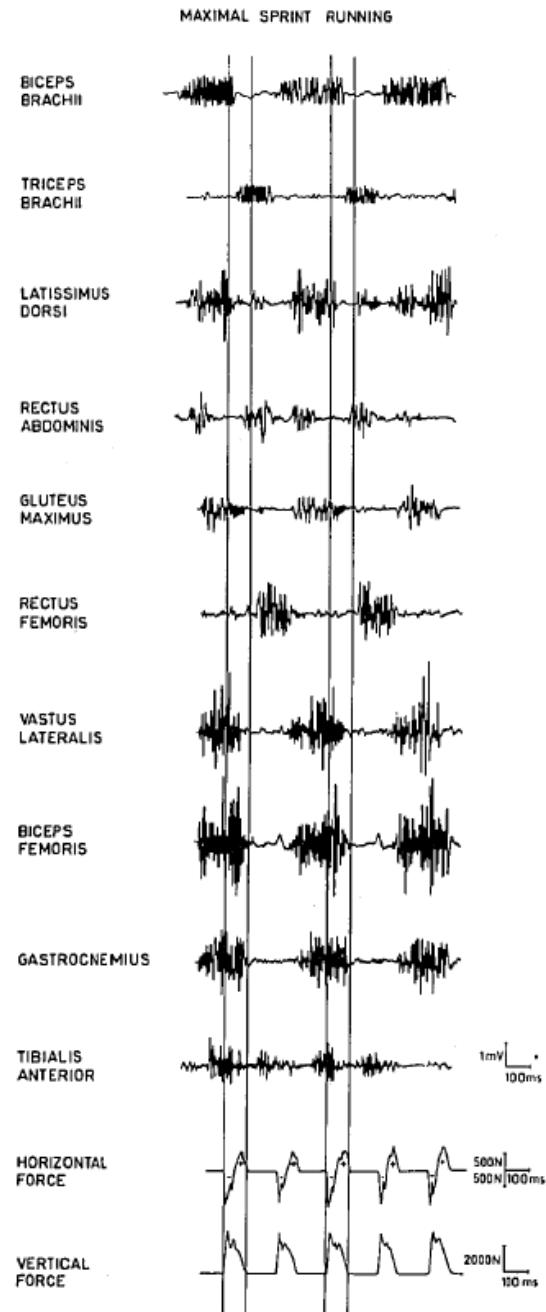


Figure 15. An example of the raw sEMG of the measured muscles during the stride at the maximum speed of a subject is shown together with the ground reaction forces. Reproduced from Mero & Komi, 1987.

From the preceding discussion, it is clear that the following three conditions for effective SSC action are: a well-timed pre-activation of the muscles prior to the eccentric phase, a short and fast eccentric phase, and an immediate transition (short delay) between lengthening (eccentric) and shortening (concentric phase). Instead, one needs to look for more “normal” activities such as running and hopping, where pre-activation conditions, faster stretching, and short transition time are well met (Cavagna et al., 1965; Cavagna et al., 1968_{a,b}; Asmussen & Bonde-Petersen, 1974_{a,b}; Asmussen et al., 1976; Komi & Bosco, 1978; Bosco, 1997). This could also apply to the possible contribution of the stretch reflex to SSC performance. In addition, the forces generated in the muscle-tendon complex (MTC) during these activities may have a typical form of a “bouncing ball” (Rook, 1996; Komi, 2000; Alexander, 2000; Komi & Ishikawa, 2007; Albracht & Arampatzis, 2013).

As suggested by Roberts & Azizi (2011), the functional role of tendons can be categorized according to the direction of energy flow, with three possible patterns (**Figure 16**): (A) energy from the body or a body segment is temporarily stored in tendons and then returned to the body; (B) mechanical energy produced by a muscle contraction is stored in a tendon and then released to increase the mechanical energy of the body or a body segment; and (C) energy from the body or a body segment is temporarily stored in a tendon and then released to do work on the muscle, which is actively lengthened to absorb energy (Kram & Taylor, 1990; Biewener & Roberts, 2000; Fletcher & MacIntosh, 2017; Burns et al., 2021; Riddick & Kuo, 2022; Garofolini et al., 2022).

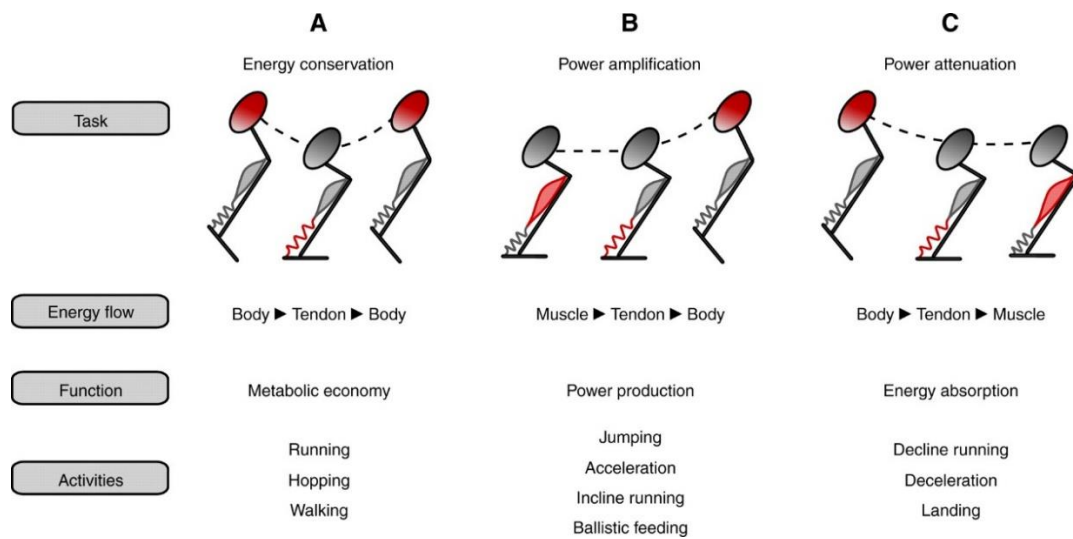


Figure 16. A schematic illustrating how the directional flow of energy in muscle-tendon systems determines mechanical function. (A) Mechanical energy is conserved (i.e., muscle work is reduced) when elastic structures store and recover cyclic changes in the body's mechanical energy or an appendage. (B) Tendons that are directly loaded by the work of muscle contraction can quickly release this energy to the body. Muscle power can be amplified if the energy is released faster than it is stored. (C) A rapid decrease in the body's mechanical energy or a limb can be temporarily stored as elastic strain energy, followed by the release of this strain energy to perform work on active muscles. This mechanism can potentially reduce the muscles' peak power output and thus act as a power damper. The figure in red shows the energy flow between the active muscle contraction, the strain energy of the tendon, and the kinetic/potential energy of the body.

2.6. HIGH-INTENSITY ACTIVITIES IN SOCCER

Match analyses reveal a key insight: top-level soccer players typically cover 9–14 km during a match, with 5-15% of playing time dedicated to high-intensity movements (Faude et al., 2012; Dolci et al., 2020). While sprinting activities only make up a small percentage of the total distance covered during matches, they are undeniably crucial in soccer. Faude et al. (2012) demonstrated this by showing that 83% of all goals (298 out of 360 goals) in the second half of the 2007/08 season in the German Bundesliga involved at least one powerful action by the scoring or assisting player. The straight sprint emerged as the most common powerful action in front of the goal for the scorer and the assistant, underscoring the significance of high-intensity running in soccer.

Bradley et al. (2009) detailed the effects of high-intensity running on soccer players in the English Premier League. The use of time-motion could help quantify the physiological needs of soccer players, providing a conceptual framework that can be used to measure the performance of specific training. Bradley et al. (2009) found that high running intensity in elite leagues such as the English Premier League imposes significant physiological demands on modern elite players, particularly central midfielders and defenders. The fact that the study was consistent with results found when studying players from other leagues (Hoppe et al., 2015; Chmura et al., 2018) proves that high-intensity running is one of the main determinants of soccer players' physiological and physical needs globally. Investigating how increased physical demands correlate with metabolic power and how players from different soccer leagues require different rates of metabolic features. High-intensity games and time spent in games are crucial, as they determine the amount and extent of energy elite players require. Despite the differences observed in high-intensity running between players of different positions, players must maintain the ability to perform these actions toward the end of the game. This suggests that elite players

participating in high-intensity running leagues such as the English Premier League still require the ability to perform at maximal metabolic power towards the end of their matches. Bradley et al. (2009) also found that the average recovery time during high-intensity running sessions in the EPL increased significantly for the entire match. The result was a distance deficit of approximately 30% during high-intensity runs, regardless of whether the team or player possessed the ball. During an average game, high-intensity activity decreases by about 50% after the first five minutes. The significance of this observation lies in the fact that during a soccer match, the moments in which players can show high-intensity running change at regular 5-minute intervals (Osgnach et al., 2010). Fatigue is a factor determining the level of high running intensity in soccer matches; this could result in a player not being able to continue playing at a high level if they do not have high metabolic recovery, thus compromising their contribution to the activity.

Furthermore, the potential of the MP model to evaluate the demands of team sports activities has sparked significant interest and debate in team sports research. Since the cost of acceleration depends on initial speed and the costs of acceleration and deceleration are not 'equal and opposite,' changes in speed must be considered when evaluating variable speed locomotion (Polglaze & Hoppe, 2019). This underscores the need for further research in this area to fully understand the implications and applications of the metabolic power model in assessing team sports activities.

To assist coaches in preparing for particularly demanding phases of play, implementing larger small sided games (SSG) formats is a valuable strategy to increase distance covered, speed, and metabolic power resulting from speed (Aasgaard & Kilding, 2020). Conversely, reducing the size of spaces may favor accelerations and decelerations and potentially increase the cognitive load associated with more ball touches and phases of tackling and 'fighting' in the game (Colli, unpublished; Grassadonia et al., 2024). It should be noted that MP is the product of two terms (*energy cost * speed*). If the distances are increased, it is conceivable that higher speeds are achieved,

but less demanding acceleration and deceleration occur (Colli, 2014; Sonderegger et al., 2016). Conversely, achieving high speeds is necessarily more complex and less likely if distances are decreased, but energy cost is higher on average. Therefore, MP remains the gold standard among the physical parameters that can be used for match analysis (and is only preferable to evaluating speed and distance) [di Prampero et al., 2005; Osgnach et al., 2010; Savoia et al., 2020; Grassadonia et al., 2024], must also be contextualized with other data to understand its effective properties.

2.7. FUTURE DEVELOPMENTS IN THE APPLICATION OF GPS AND EMG TO FIELD SPORTS

The future requirements for GPS technologies in sports will focus on several main areas (Aughey, 2011; Buchheit et al., 2014_{a,b,c}). Firstly, GPS will be used to explore the greater integration of movement data, particularly that associated with fitness, tactical, physiological, and strategic data. The second area will look at the application of GPS, specifically how GPS can be integrated with inertial sensor data. Thirdly, the future of GPS will involve further miniaturization with a possible increase in sampling rates to improve the accuracy and reliability of the data. Furthermore, considering each GPS device's many advantages and disadvantages, the extent of the differences between the systems will be evaluated, taking into account the effects of the pitch size of the distance and the variable of interest.

Textile EMG electrodes embedded in clothing enable the recording of muscle excitation in previously inaccessible environments; however, their ability to accurately and reliably measure EMG during dynamic tasks remains unexplored mainly (Colyer & McGuigan, 2018). Textile EMG electrodes generally provide comparable muscle excitation information and reproducibility to surface EMG during dynamic tasks. Textile EMG shorts could be a practical alternative to traditional laboratory-based methods and enable the collection of muscle arousal information in externally validated training environments (Colyer & McGuigan, 2018).

The combined use of technologies, such as GPS with textile EMG, is a potential game-changer in sports science. This integration can open up new scenarios for the accurate and ecological study of sports science (Colli, unpublished; Testa, 2022; Grassadonia et al., 2024).

2.8. TECHNOLOGY AND RECALCULATION AROUND THE CONCEPT OF METABOLIC POWER (MP), ENERGY COST (EC) AND APPARENT EFFICIENCY (AE) IN SOCCER

GPS, a practical device, enables the collection and analysis of movement data in soccer. It allows for the evaluation of players' key physical actions, such as the distances they cover, the time they spend running at high speed, and the number of changes in direction during a match (Akenhead et al., 2014). The concept of MP, when applied to soccer, has brought about a paradigm shift in the player-specific need for high-intensity activity. This revolutionary approach expands the performance vision with an energetic perspective that considers all kinematic aspects (speed and accelerations). To understand this, one must first grasp the concept of EC. Osgnach et al. (2010) calculated MP indirectly using a biomechanical strategy to utilize energy equivalence starting from the EC equation of Minetti et al. (2002).

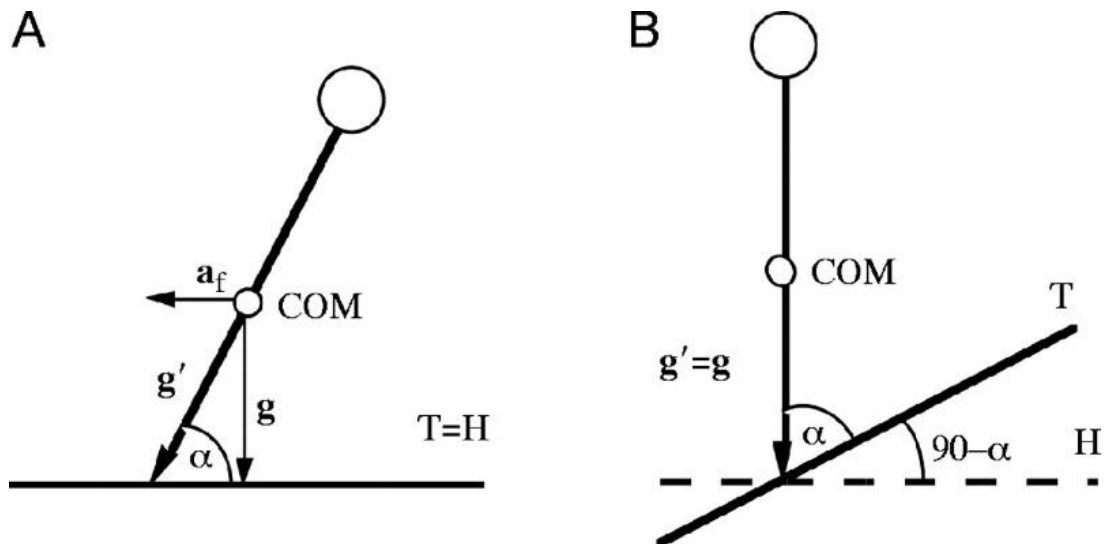


Figure 17. A: accelerated running on flat terrain; B: uphill running at constant speed. M , body mass; a_f , forward acceleration; g , acceleration of gravity; $g' = (a_f^2 + g^2)^{0.5}$, vectorial sum of a_f and g ; T , terrain; H , horizontal; α , angle between runner's body axis and T ; $90-\alpha$, angle between T and H (reproduced from di Prampero et al. 2005).

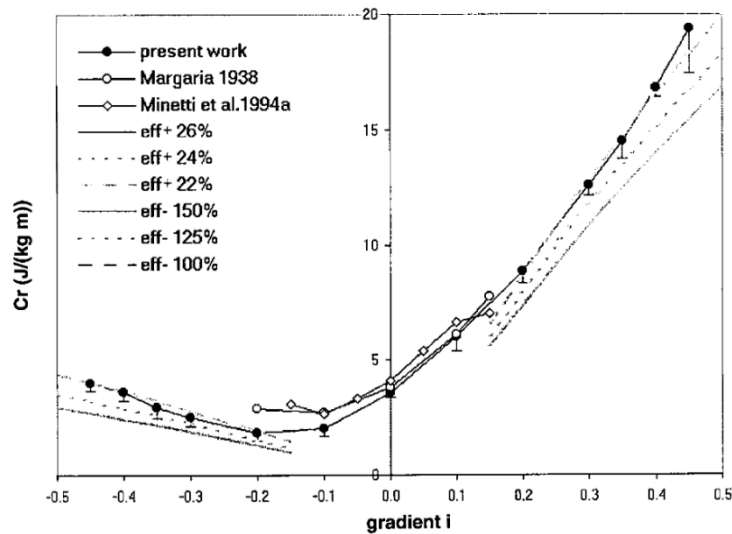


Figure 18. Metabolic energy cost of running (Cr) as a function of the gradient from the work by Margaria (1938; 1963) and Minetti et al. (1994). Average energy cost of running for each gradient have been reported. To accurately describe the relationship between Cr and the gradient i within the investigated range, 5th order polynomial regressions were performed, that yielded: $Cr_i = 155.4i^5 - 30.4i^4 - 43.3i^3 - 46.3i^2 + 19.5i + 3.6$ ($R^2 = 0.999$). Reproduced from Minetti et al. (2002).

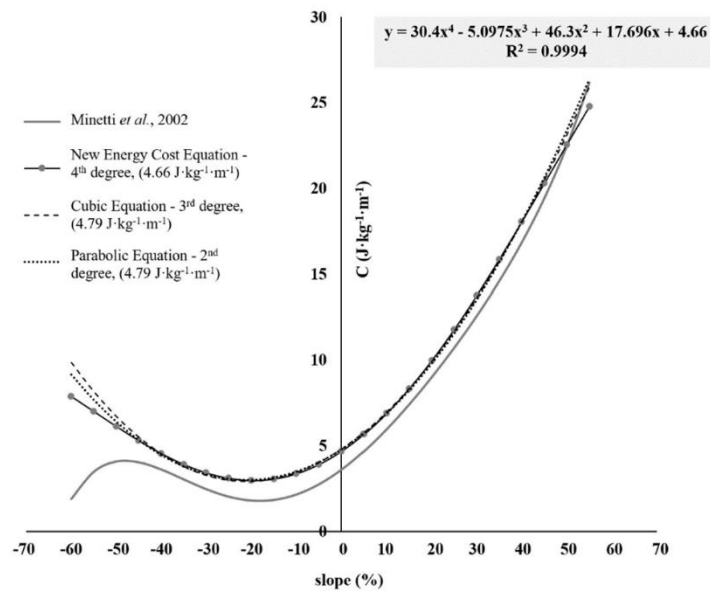


Figure 19. New energy cost paradigm (4th order polynomial) in terms of the C of running over grass in elite soccer as a gradient function with an initial Cr constant of 0% corresponding to $4.66 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$. Where $y =$ energy cost; $x =$ gradient (%): $y = 30.4x^4 - 5.0975x^3 + 46.3x^2 + 17.696x + 4.66$ (new energy cost equation). Reproduced from Savoia et al. (2020).

The EC of movement at constant speed, acceleration, deceleration, and combinations can be calculated. This allows the recalculation of MP. di Prampero et al. (2005) used the proposed innovative method to study 30 m sprints. This method used the polynomial formula 5th degree proposed by Minetti et al. (2002). In contrast, Osgnach et al. (2010) used the proposal of di Prampero et al. (2005) in conjunction with the equations of Minetti et al. (2002) and applied this model in the context of match analysis. Over time, numerous studies and reviews have proposed further modifications, including Savoia et al. (2020), which also examined a new formula for recalculating energy cost: a 4th degree polynomial that extends the previous ranges of the Minetti et al. (2002) formula.

Instead, Minetti et al. (2002) use the arrow in **Figure 18** to represent the gradient range ± 0.15 , within which the mechanical external work of walking (Minetti et al., 1993) and running (Minetti et al., 1994_a) is still contributed by a mixture of positive and negative work. For steeper positive gradients, the efficiency value of 0.25 implies that all of the work must be expended to lift the body: only positive work is performed in both gaits and the descent phase of the pendulum-like and bouncing ball (Cavagna et al., 1976) mechanisms of walking and running is lost. Similarly, the efficiency value of -1.2 for steeper negative gradients means that only negative work is performed in both gaits and that the ascending phase of the pendulum-like and bouncing ball (Cavagna et al., 1976) mechanisms of walking and running is lost. Since both mechanisms require both an ascending and a descending phase of the trajectory to recover the mechanical energy, this supports the concept (Minetti et al., 1994_b) that walking and running lose the pendulum-like and bouncing ball mechanisms, respectively, at gradients steeper than the ± 0.15 range. If this is so, and considering how close EC_w and EC_r are to each other on the steepest gradients, we wonder whether it is legitimate to speak of “walking” or “running” on the steepest slopes.

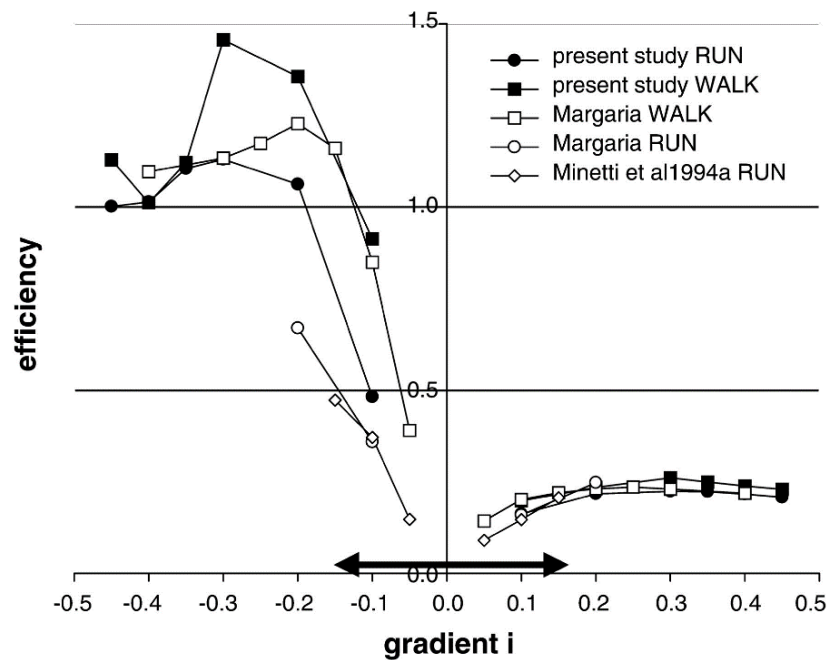


Figure 20. Mechanical efficiency of the work performed for the vertical displacement of the body during locomotion as a function of the gradient. The data come from Minetti et al. (2002), from Margaria (1938; 1963) and Minetti et al. (1994). The double arrow parallel to the x-axis defines the gradient range in which a combination of positive and negative work performs the external work of locomotion. Note that the scale on the y-axis indicates the absolute efficiency value: the sign should be negative for downhill locomotion and positive for uphill locomotion.

Zamparo et al. (2016) calculated the mechanical work during shuttle running (internal and external) using a motion capture system based on the changes in the mechanical energy of the body's center of mass, as previously proposed for linear running at constant speed, to measure the total mechanical work in shuttle runs over a distance of 5 + 5 m as the sum of the internal and external work. Furthermore, Zamparo et al. (2016) measured the energy cost of shuttle running (at maximum speed) to calculate the efficiency of this locomotion task. Shuttle running (SR) differs from running at constant running (CR) in that it includes acceleration and deceleration phases (and also changes of direction). The ability to perform rapid acceleration and deceleration actions in basketball, soccer, and futsal is one of the most critical skills to acquire and improve performance.

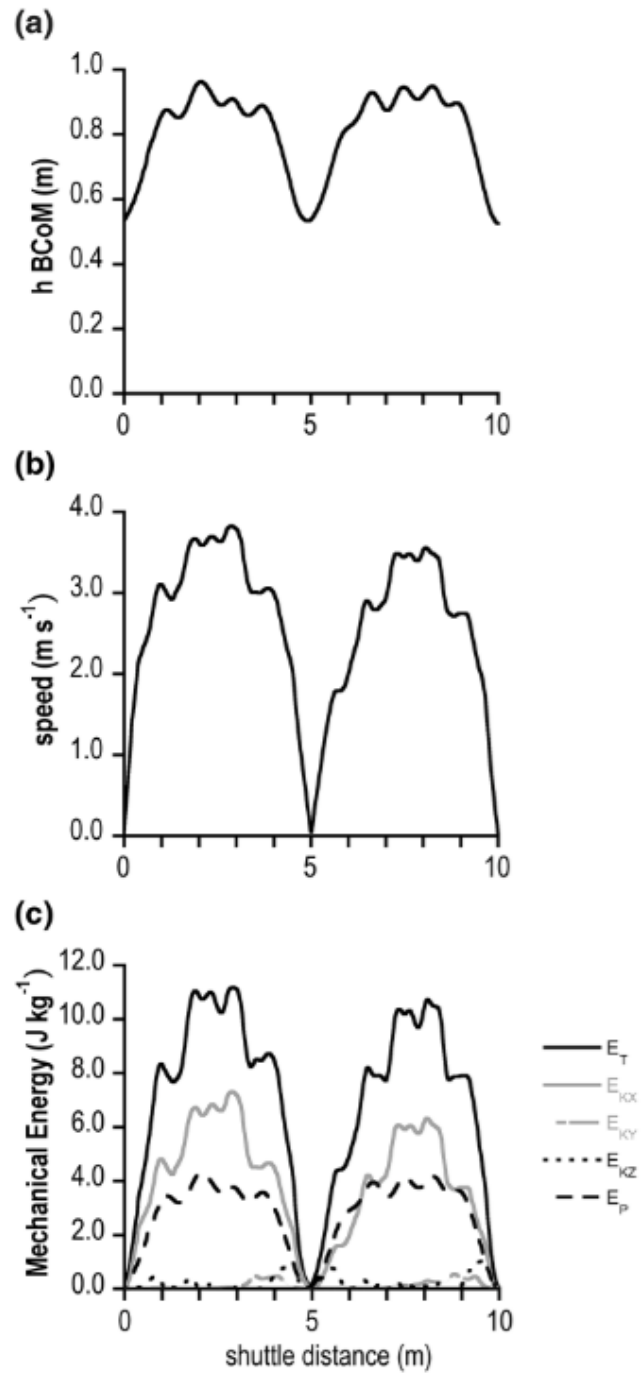


Figure 21. A Vertical displacement of the body's center of mass (hBCoM, m); b horizontal speed of the BCoM (speed, m·s⁻¹); and c time course of the BCoM kinetic (E_{KX} , E_{KY} , E_{KZ}), potential (E_P) and total (E_T) energy of the BCoM (J·kg⁻¹) as a function of the shuttle distance during a 5 + 5 m shuttle run. Reproduced from Zamparo et al., 2016.

Future studies on longer shuttle runs combining kinematic and metabolic data are needed to better understand the mechanics and energetics of shuttle running and its similarities/differences to linear running. These studies would be beneficial not only for coaches to improve the specificity of training sessions but also for exercise physiologists studying muscle behavior during unsteady locomotion (Zamparo et al., 2016).

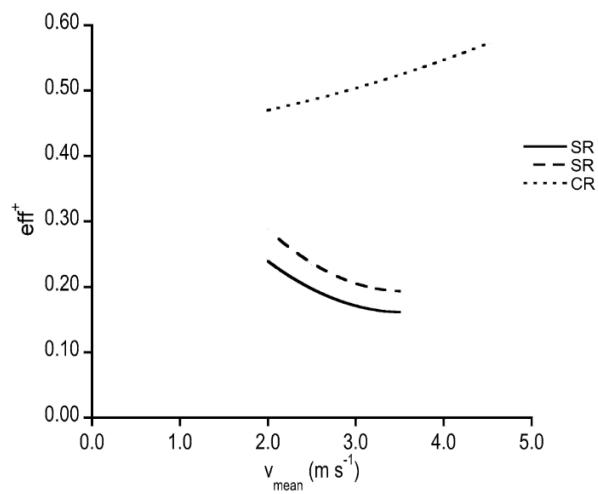


Figure 22. Mechanical efficiency as a function of the average shuttle speed (v_{mean} , m·s^{-1}). The dotted line represents the data of linear running at constant speed (redrawn from Cavagna and Kaneko 1977 by Zamparo et al., 2016), the continuous line the data calculated in this study for shuttle running (eff^+ , considering only positive work), and the dashed line the data for shuttle running considering also negative work. Reproduced from Zamparo et al., 2016.

The values obtained by Zamparo et al. (2019) of mechanical efficiency observed at the longer shuttle distance suggest a better exploitation of the elastic energy-saving mechanism (i.e., these values are close to those reported for linear running at constant speed). This mechanism seems impaired when the shuttle distance decreases (i.e., where accelerations and decelerations, e.g., non-steady conditions, play a more important role).

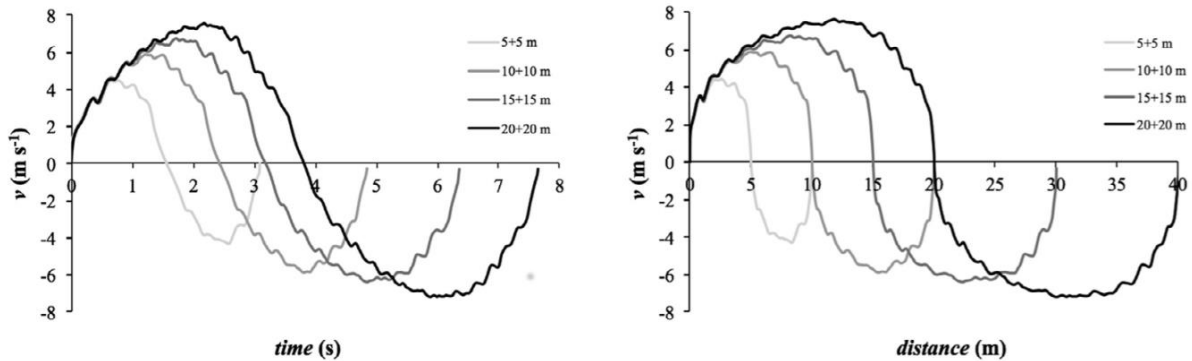


Figure 23. BCoM horizontal velocity (m·s⁻¹) as a function of shuttle time (s, left panel) or distance (m, right panel) for shuttles over different distances: 5 + 5 m (light gray line); 10 + 10 m (gray line); 15 + 15 m (dark gray line) and 20 + 20 m (black line). Reproduced from Zamparo et al., 2019.

Zamparo et al. (2019) investigate the mechanical work and efficiency of a shuttle running at different speeds and distances. Their study shows that both mechanical power and efficiency are potentially influenced by running speed and the length of SR, which has practical implications for training and performance optimization in sports with frequent CoD.

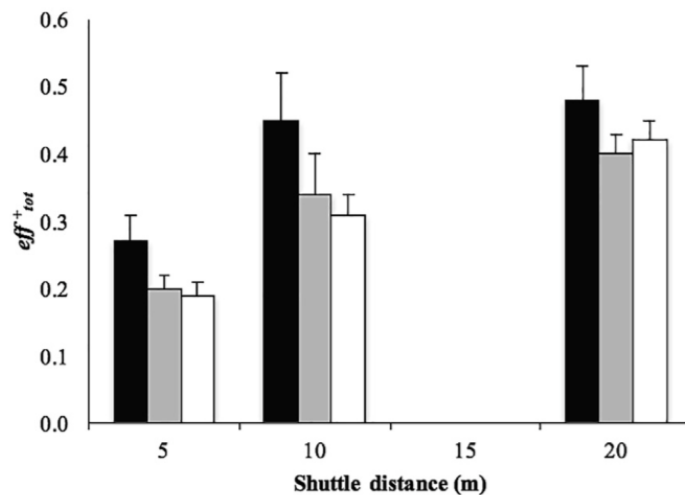


Figure 24. Mechanical efficiency as a function of shuttle distance at slow (black columns), moderate (gray columns), and maximum (white columns) speeds. Reproduced from Zamparo et al., 2019.

During a soccer match, the ACC phases lead to an average increase of 20% in the EC_r compared to the value observed at constant speed (Osgnach et al., 2010). This is an important basis for determining the overall energy consumption during the match. The aim of the study conducted by Buglione & di Prampero (2012) was to quantify the EC_r on flat terrain in professional soccer players before (July) and during (December) a competitive season. The EC_r was determined during a six-minute run at a constant speed ($10 \text{ km}\cdot\text{h}^{-1}$) on a treadmill with a portable gas analyzer (metabolimeter K4b², Cosmed, Italy). The study involved 40 professional Serie A soccer players, including 17 senior players (mean age 27 ± 4 years, mean body mass $75.8 \pm 5.6 \text{ kg}$) and 23 younger players (mean age 17.7 ± 0.6 years, mean body mass $71.4 \pm 6.3 \text{ kg}$). The measurements were taken before and during the season. The EC_r value of the senior players was $4.31 \pm 0.38 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ before the season and $5.12 \pm 0.43 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ during the season, which corresponds to an increase of 13.46%. In younger players, the values were $4.22 \pm 0.4 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ before the season and $4.48 \pm 0.31 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ during the season, which corresponds to an increase of 7.06%. The EC_r value in professional soccer players is higher than the value reported by various authors in middle and long-distance runners, increasing significantly during the season (Buglione & di Prampero, 2012). This increase is probably due to the constant acceleration and deceleration during matches, resulting in poorer running economy at constant speed. This is because the latter is not specific to the performance of soccer players (Buglione, 2010; Buglione & di Prampero, 2012; Buglione & di Prampero, 2013; Padulo et al., 2023).

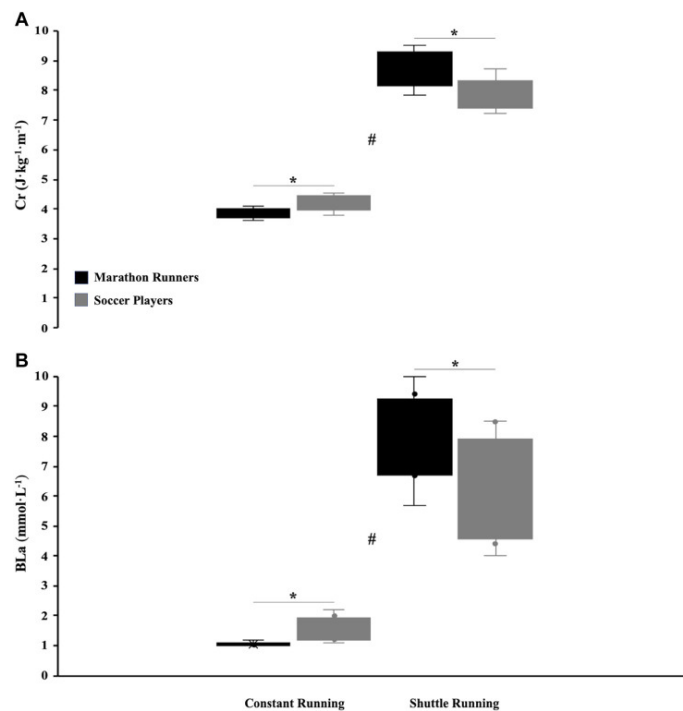


Figure 25. Energy cost (A) and blood lactate (B) between running conditions (# $p < 0.05$) and between soccer players and marathon runners (* $p < 0.05$). Reproduced from Padulo et al., 2023.

Buglione & di Prampero (2013) chose the intermittent SR in two modes: "continuous" and "intermittent". These two modes were selected because they are the most common practical version of the shuttle tests, with subjects randomly assigned to one of the two modes. In both cases, after covering the specified distance, which varied between 8.5 and 22 m, the subject stopped and resumed speed without any delay in the opposite sense. However, while in continuous mode, the duration of the test was 4–5 minutes without interruption; in intermittent mode, the subjects stopped for a brief pause (18–30 s) after 3, 4, or 6 runs, after which the test was resumed, using an energetic (via gas analyzer) and a kinetic approach (via video analysis and recalculation from di Prampero et al., 2005 with modifications), which were more congruent for the long shuttles (~20m) than for the shorter shuttles (~10m).

The metabolic cost of human running needs to be better explained, partly because the amount of work actively performed by the muscles is mainly unknown. Elastic series tissues such as tendons can conserve energy by working passively, but there are few direct measurements of the active and passive contributions to work during running. Indirect biomechanical measurements, however, can help estimate the relative contributions to overall metabolic cost. Riddick & Kuo (2022) developed a simple cost estimate for muscle work in humans running at moderate speeds (2.2 - 4.6 m·s⁻¹) based on measured joint mechanics and passive dissipation of soft tissue deformations and found that even when 50% of the work observed at the lower extremity joints is performed passively, active muscle work still accounts for 76% of the net energetic cost. Riddick & Kuo (2022) present a detailed analysis of mechanical work contributing to metabolic costs in **Figure 26**, which illustrates the relationship between the cost of work (expressed as a percentage of Net Metabolic Rate, %) and the cost coefficient, estimating muscle and muscle-tendon work and the efficiency limit in more and less elastic components. The center diagonal line represents the best estimate that mechanical work accounts for approximately 76% [61% to 106%] of the net metabolic cost of running, with uncertainty ranges indicating possible over- or underestimation. The shaded area indicates this range of estimates and suggests that variations in muscle properties could influence energy expenditure. For example, more elastic and efficient muscles (left side) lead to lower metabolic costs, while less elastic, less efficient muscles (right side) increase the cost. The authors conclude that mechanical work, particularly related to limb movement and center of mass, accounts for most energy costs, closely related to biomechanical efficiency. This insight highlights the crucial role of optimizing mechanical work to improve running economy, particularly by modulating muscle elasticity and energy efficiency. Up to 24% of this cost is offset by the energy lost during soft tissue deformation. The estimated cost of active labor can be adjusted based on multi-joint energy transfer, elasticity, and muscle

efficiency assumptions. However, even conservative assumptions yield at least 60% of the cost of active work. Passive elasticity can reduce the active work of running, but muscle work still explains most of the overall energy cost (Riddick & Kuo, 2022).

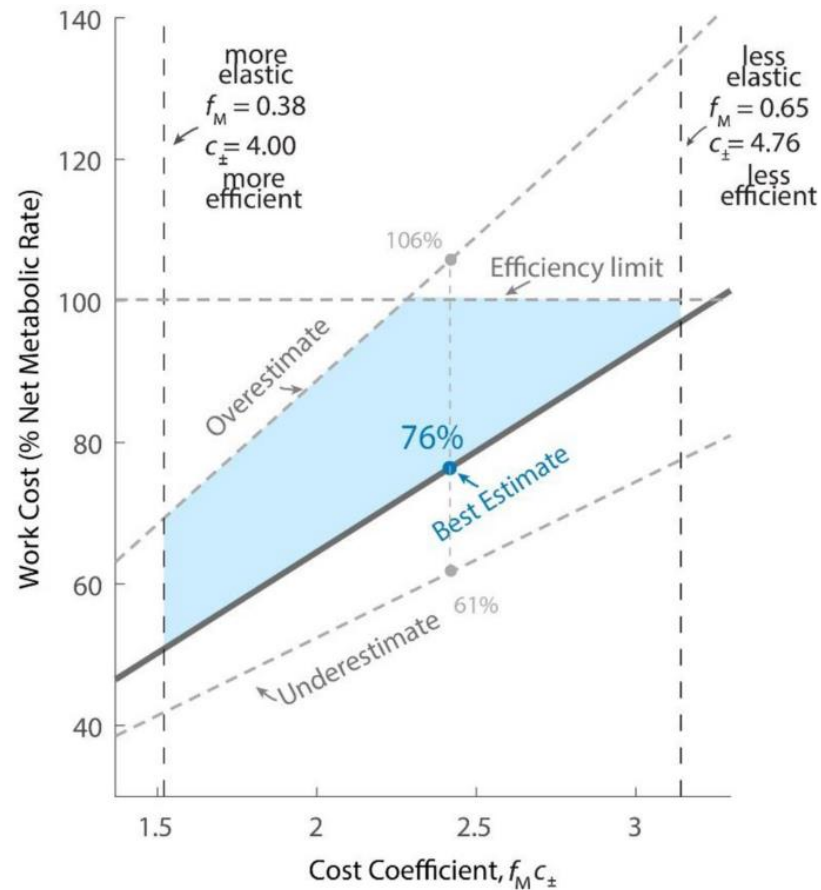


Figure 26. Average work cost as a function of cost coefficient for running speed at $3 \text{ m}\cdot\text{s}^{-1}$. Relative work cost is estimated metabolic cost of mechanical work divided by overall net metabolic cost. Cost coefficient is defined as fraction of work attributable to muscle from overall muscle–tendon work, multiplied by cost of active work. Boundaries are shown for extreme assumptions. Overestimate is for Independent Joints assumption, where muscles only act uniarticularly; underestimate is for Summed Bilateral joint assumption, where work can be transferred from one side of the body to the other. Left and right boundaries are for extremes in muscle work fraction, 38% and 65%, respectively, with constant cost of work. The proposed work estimate (Summed Ipsilateral joints), along with a muscle fraction of 50%, yields 76% of the metabolic cost of running is attributable to active work by muscle. For the same parameters, the Underestimate yields 61% and the Overestimate 106%. Reproduced from Riddick & Kuo, 2022.

An interesting future research direction could be to investigate the role of aspects of muscle (metabolism, muscle fiber type, pulmonary function) and efficiency (co-contraction, muscle sequencing, joint coordination) [Peyré-Tartaruga & Coertjens, 2018] to optimize and guide the methodological choice in running for soccer players and marathon runners. Note, however, that the optimization of EC during constant or SR is strictly related to the type of sport practiced (Buglione, 2010; Buglione & di Prampero, 2012; Buglione & di Prampero, 2013; Padulo et al., 2023).

Grassadonia & Monte (2020) have found a linear behavior in SR and in the distance of the thigh muscles (quadriceps, hamstrings, and glutes) at first approaches ($R^2 = 0.99$), with a shift in muscle predominance of the quadriceps at a shorter distance of about ~7.5 meters (< 7-8m) and hamstrings at a higher distance (> 7-8m).

During short and high-intensity activities, there are various methods to quantify physical exertion in team sports using positional data. The most common approach is to use distances at different speed zones. Recent studies have used ACC data for short and high-intensity actions. However, the decrease in acceleration with increasing initial running speed is not taken into account, leading to a bias. To address this, a novel methodological approach was developed, as seen in the works of Colli (2014) and Sonderegger et al. (2016). This approach removes the bias by calculating the percentage acceleration as the ratio between the maximum acceleration of the action ($\alpha_{max, \text{action}}$) and the maximum voluntary acceleration (α_{max}) that can be achieved at a given initial running speed (percentage acceleration [%] = $\alpha_{max, \text{action}} / \alpha_{max} * 100$). In addition, the percentage acceleration allows the identification of individual intensity thresholds specific to a given population or individual athlete.

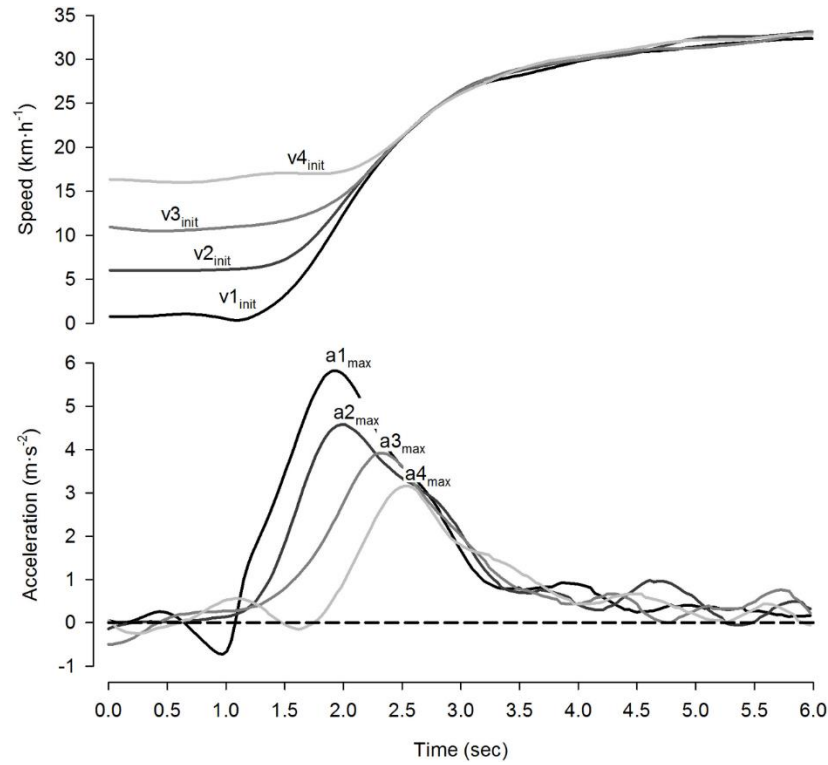


Figure 27. Speed (top) and acceleration (bottom) curves of the four sprints of a representative player. v_{1init} and a_{1max} : effective initial running speed (v_{init}) and maximal voluntary acceleration (a_{max}) from a standing position, respectively; v_{2init} and a_{2max} : v_{init} and a_{max} , trotting; v_{3init} and a_{3max} : v_{init} and a_{max} , jogging; and v_{4init} and a_{4max} : v_{init} and a_{max} , running. Reproduced from Sonderegger et al. (2016).

The new methodical approach evaluates the intensity of short movement sequences during training sessions or games based on percentage acceleration. The percentage acceleration is the ratio between the maximum acceleration of the action ($a_{max, action}$) and the maximum voluntary acceleration (a_{max}) that can be achieved for the respective v_{init} :

$$\text{Percentage acceleration [\%]} = \frac{a_{max \text{ of Action}}}{a_{max \text{ Relative Absolute}}} * 100$$

The percentage acceleration for each initial running speed is expressed as the percentage of a_{max} from that particular running speed.

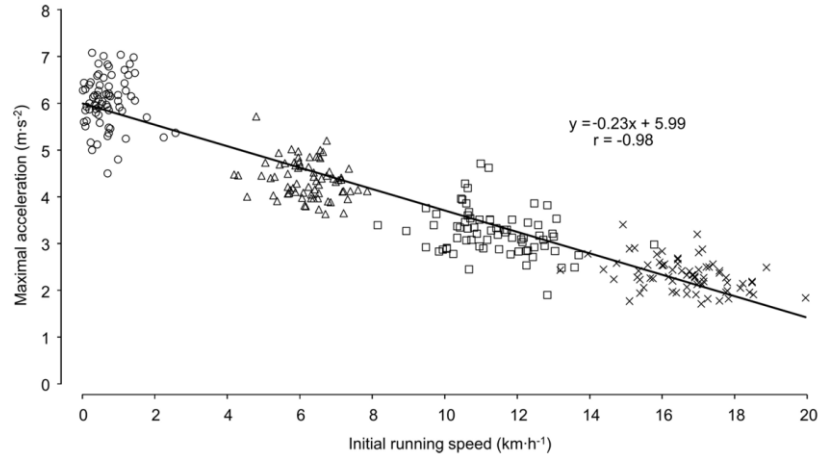


Figure 28. Maximal voluntary accelerations for standing (circles), trotting (triangles), jogging (squares), and running (crosses) of 72 highly trained male soccer players (under 18 league). Simple linear regression line with regression equation and Pearson's correlation coefficient r . Reproduced from Sonderegger et al. (2016).

The results of the investigation by Colli (2014) and Sonderegger et al. (2016) show a linear decrease in maximum voluntary acceleration when sprints are started with increasing initial speed. This demonstrates the importance of considering running speed before acceleration when measurements are used to assess the intensity of short locomotor actions. Nevertheless, most studies that have classified motor actions based on acceleration measurements have disregarded the initial running speed and used absolute acceleration thresholds. Therefore, these authors propose a new methodological approach based on quantifying motor actions using percentage acceleration instead of absolute acceleration values.

The method for calculating the high accelerations using the kinematic data from the official Serie A matches is based on the equation by Colli (2014) and Sonderegger et al. (2016) and was officially modified by Savoia et al. (2020):

$$\alpha_{max} \text{ (max acceleration): } -0.18 \text{ } (-0.17 \text{ to } -0.19) \cdot v_{init} + 5.91 \text{ (5.80 to 6.02)}$$

where α_{max} is expressed in $\text{m}\cdot\text{s}^{-2}$ and the v_{init} in $\text{km}\cdot\text{h}^{-1}$.

di Prampero & Osgnach (2018), in a recent review of the MP model in soccer, suggested the inclusion of walking phases [which are typically present in large proportions in the match; Bradley et al., 2013]. By including these energy cost estimates for walking (EC_w), which differ from those of running at constant speeds (EC_r), a new value for the constant term of the energy cost equation was proposed, namely $2.5 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$. **Figure 29** shows how this in-depth analysis can represent the different amounts of energy depending on the activities performed.

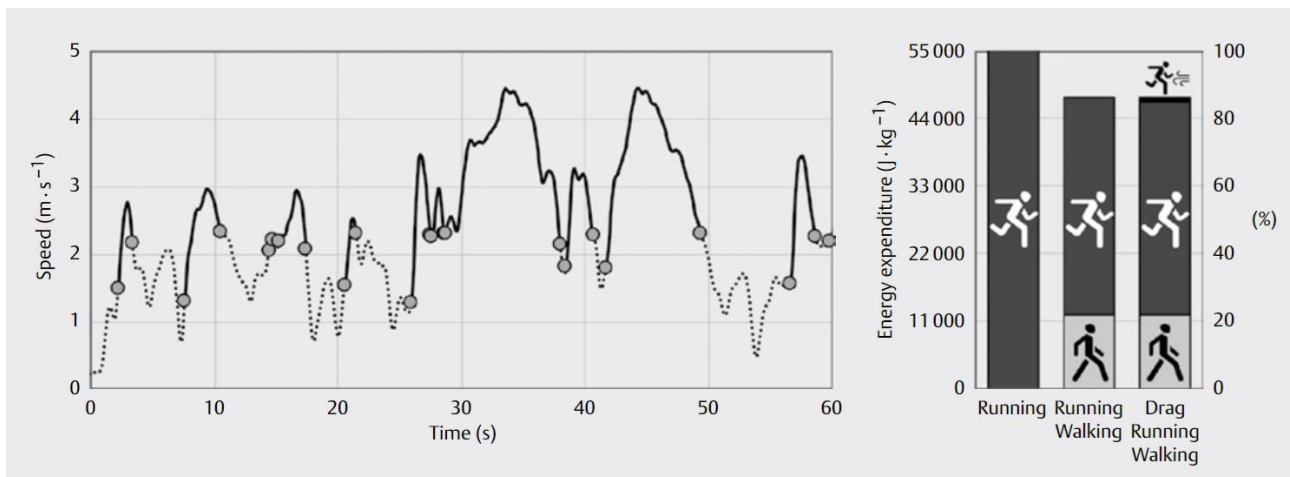


Figure 29. Left: the time course of the speed during 60 seconds of an actual match: broken line = walking; continuous lines = running. Open circles denote the transitions between the two gaits. Right: the left column = overall energy expenditure, as calculated neglecting energy cost differences between walking and running. The middle column = overall energy expenditure due to walking (white) or running (grey). The right column = the energy spent against the air resistance is indicated by the uppermost black part (reproduced from di Prampero et al., 2018).

Since such a model of MP, either in its original iteration or in its recently modified form (Osgnach et al., 2010; di Prampero et al., 2018), estimates the energy cost of activity, it is possible to express total energy expenditure as equivalent distance (ED) instead of TDC, as it depends both on TDC was performed. Although different players might have covered the

same TD, the use of ED allows the identification of different metabolic energy expenditures and, thus, an estimation of the “true” total energy expenditure independent of the actual distance covered (Savoia, 2019).

Recently, Minetti et al. (2018) updated the concept of equivalent slope on which the Osgnach et al. (2010) models are based by adding a deceleration component to his earlier model (Minetti et al., 2002) and revising the prediction equation so that it can be applied to much higher rates of speed change. The extension to a wider acceleration range benefits from recent metabolic results (Giovanelli et al., 2016) for running uphill at constant speed running up to $I = +0.84$ (where i is the gradient in terms of the tangent of the slope angle), which corresponds to level accelerations up to $8.24 \text{ m}\cdot\text{s}^{-2}$, according to the Equivalent Slope (ES) equation.

Buchheit et al. (2015a) indicate that when applying systems such as the ‘energetic approach’, it is easy for individuals to use GPS to estimate energy expenditure and determine MP from the ACC and DEC data of exercise. Sports scientists and coaches have found the importance of GPS invaluable due to its increased reliability and validity in recording the actions of athletes. Previous researchers such as Varley et al. (2012; 2017) and Stevens et al. (2014) have shown that GPS is a highly reliable tool at various sampling frequencies that coaches and other fitness personnel can use to assess external training loads. However, important caveats apply, as Buchheit et al. (2014a) found that the reliability of GPS tends to decrease at short distances (40 m) and quick movements ($19.8 \text{ km}\cdot\text{h}^{-1}$). Importantly, however, Dwyer & Gabbett (2012) found that higher-frequency GPS instruments were more reliable than lower-frequency GPS instruments, with frequencies between 10 and 15 Hz was classified as high frequency, while GPS with frequencies between 1 and 5 Hz was classified as low frequency (Johnston et al., 2012; Johnston et al., 2014). The classification of GPS into different frequencies is necessary as it helps to determine validity and reliability and, therefore, provides information on which GPS is most suitable under different conditions of sport data collection. Waldron et al.

(2011) showed that different GPS brands exhibit significant variability between and within the same brand of GPS devices. Molinos Domene (2013) emphasized the importance of obtaining accurate ACC and DEC values for the validity of distance covered and speed data. In soccer applications, both elements are essential for estimating and determining training intensity and volume where MP data is collected. Validating any GPS device prior to use when determining training load, particularly MP ensures calibration for the most common applications.

Witte & Wilson (2004; 2005) caution that GPS tends to underestimate the speed of shuttles, leading to a decrease in the accuracy of GPS instruments for rapid movements and small distances, even when done with a system with a lower sampling frequency. Similarly, Aughey (2011) reported that the accuracy of GPS deteriorates significantly when athletes make rapid changes in direction. This finding is increasingly reported, highlighting the need for caution when using GPS instruments due to potential inaccuracies in determining commuting speeds and distances. Buchheit et al. (2014a) also reported this notion, claiming that the reliability and accuracy of GPS devices between units are negatively affected by the multidirectional movements of athletes, a critical movement characteristic typical of all team sports. In addition, soccer stadiums and other specific environments have been found to affect the strength of signals received by the GPS device. Using GPS potentially reduces the number of available satellites and data transmission, leading to data loss. Ultimately, this reduces the reliability of the data, and therefore, great caution is required when using this collected data (Maddison & Ni Mhurchu, 2009). Other considerations that need to be taken into account are that the accuracy of the data depends on location and receiver density (Kao et al., 2013). Finally, while sampling rates of more than 10 Hz have further improved the reliability and validity of GPS data, other more technical aspects such as the antenna, the microprocessor, and its data processing algorithms, the positioning of the devices on the body, and the environmental conditions

have been shown to influence validity and reliability (Osgnach et al., 2016; Hoppe et al., 2017; Malone et al., 2017, Savoia, 2019).

Osgnach et al. (2010) investigated the MP and EC imposed on elite players during a typical 90-minute soccer match and found that the average energy expenditure was $61.12 \pm 6.57 \text{ kJ} \cdot \text{kg}^{-1}$ ($14.60 \pm 1.57 \text{ kcal} \cdot \text{kg}^{-1}$) per player. The data also indicated that the total energy expended on high-intensity activities [high power] was more than 26% during a 90-minute match. The cumulative MP expended by athletes during high-intensity activities was significantly higher when a video motion analysis technique was used. When low-intensity running was considered, significantly lower athletes' metabolic power estimates were obtained. The video analysis method also provided additional parameters related to speed and distance covered that can be used by sports personnel to examine the player's profile.

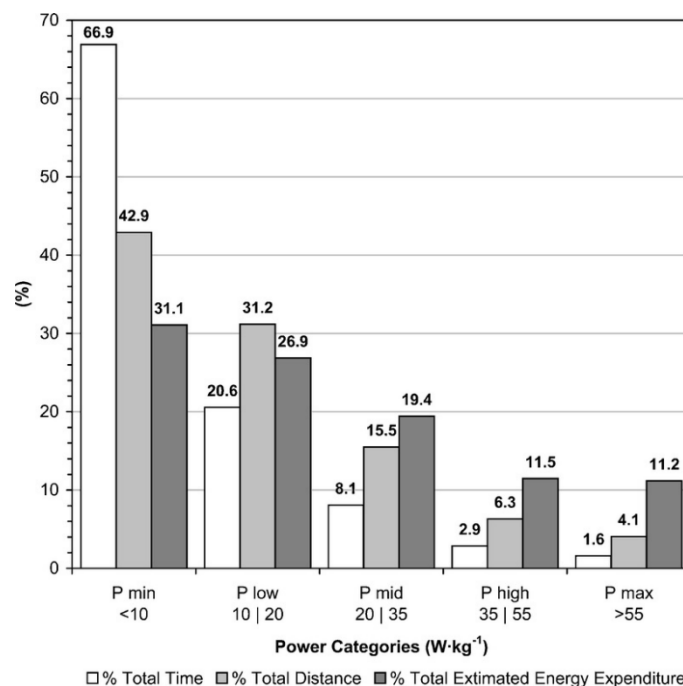


Figure 30. Time, distance and Estimated Energy Expenditure (EEE) [expressed in %], during the entire match in each power class. Reproduced from Osgnach et al. (2010).

Varley et al. (2017) investigated the match performances of elite players about the development of fatigue during soccer matches using a computerized time-motion analysis in which each player was filmed at close range. The data suggest that elite players play at high intensity (speeds of $14.3 \text{ km}\cdot\text{h}^{-1}$ or higher) for extended periods compared to non-elite players. In addition, elite players show better intermittent recovery than sub-elite professional players. The observations were made independent of the players playing positions. The results also support that player workload depends on playing positions, confirming that defenders covered the least distance and had the lowest running intensity during games (Bradley et al., 2010; Bradley et al., 2013; Varley et al., 2017). Vigne et al. (2010) asserted that when training elite players, one must improve their ability to perform high-intensity exercises and recover quickly from high-intensity training sessions. The observed differences in physical performance between elite players and players from lower leagues indicate the different physical activity and effort demands required for different intensities of play. High-intensity games require more energy from players to meet the increased physical demands. According to Vescovi & Favero (2014), the running intensity of players at all levels generally decreases towards the end of the game. This is important as it explains that soccer players tend to strain their physical abilities as the duration of the game increases. However, this physical demand should not be considered a representative model for all players, as different positions require different energy expenditures.

The indicators of high intensity should be interpreted with caution, and it is recommended that the match is observed repeatedly to establish meaningful profiles of players with high intensity both overall and concerning different positions. Differences between playing positions and relationships with explosive physical abilities suggest that MP analysis can provide new insights into the mechanics and energetics of soccer (Hoppe et al., 2017).

Savoia et al. (2020) provide a series of recommendations, including the use of an appropriate method to calculate MP during intermittent submaximal exercise, including the anaerobic component, and an appropriate experimental design by ensuring that the working protocol includes an appropriate population (elite soccer players), a specific terrain (natural grass) and appropriate footwear (soccer shoes) for the calculation of a specific EC. In addition, the performance model, such as the ratio of work-to-rest ratio and the different movement activities (e.g., sprinting, walking, jogging, high-speed running, CoD, etc.), must be appropriate for the activity, as the duration of pauses/recoveries plays a crucial role in the metabolic response in soccer. Moreover, applying the "MP" approach to video match and time-motion analysis using the same equations and algorithms used by GPS software to analyze training load represents the future of soccer. This would allow coaches and practitioners to evaluate each player's metabolic performance during each match and assist in studying trends related to loads during training and play. The uniformity and homologation of algorithms would be a real "game changer" for comparing training methods/philosophies (i.e., traditional, integrated, structured, tactical periodization, etc.) and similarities and/or differences between championships and competitions (in terms of the presence or absence of cup tournaments). Its usefulness could also extend to the aware choice of buying the appropriate players during the transfer window by helping to update databases useful for soccer scouting and match analysis. Moreover, the combination of the technical-tactical information, physical performance, and injury history allows a better understanding of the players' official performance parameters and current training load in their club by using an "integrated soccer language" (Azzone & Lorenzon, 2019; Savoia et al., 2020).

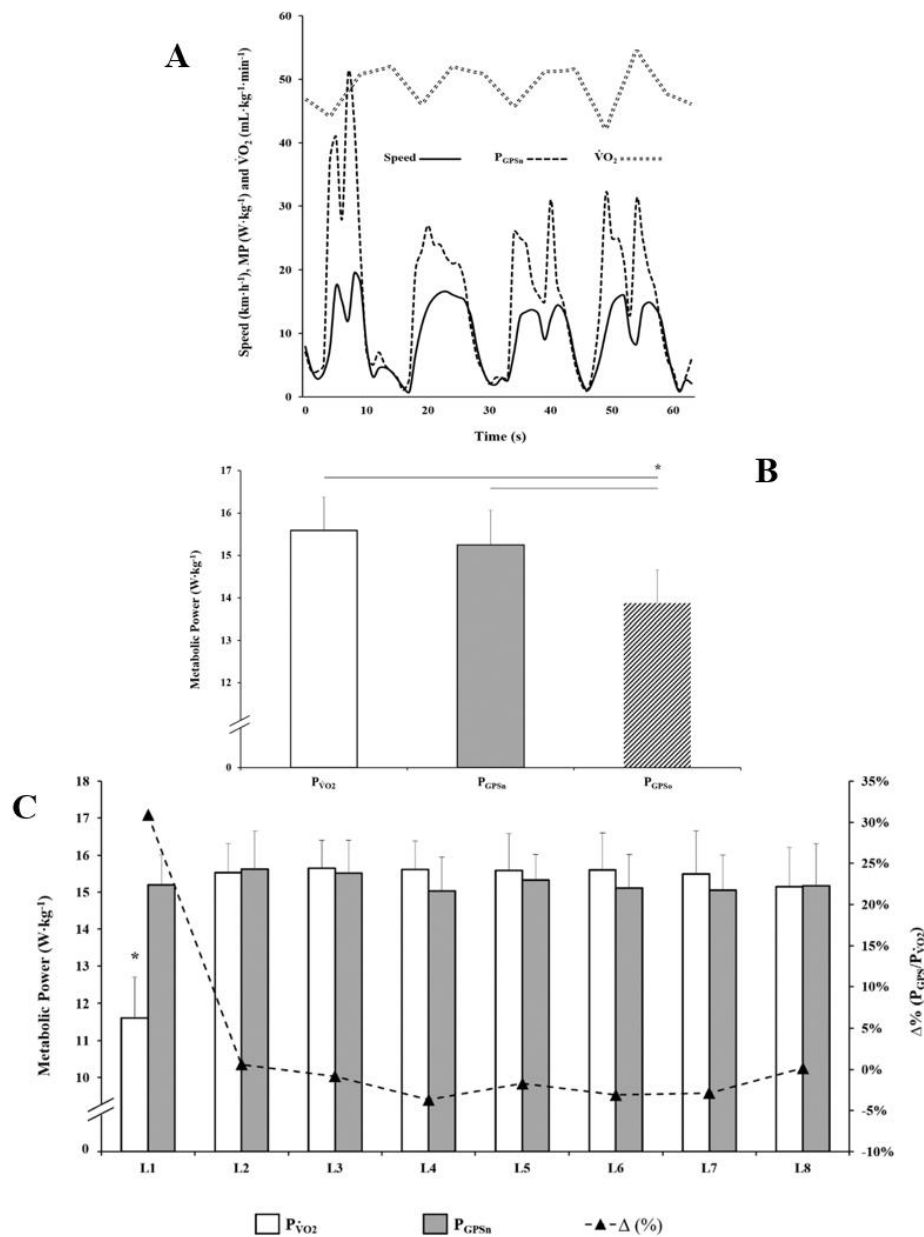


Figure 31. **A**) The oxygen uptake (VO₂), the speed and the metabolic power (P_{GPSn}) estimated from the movement requirements during one lap (1 minute) on the soccer-specific circuit of a representative player. **B**) Metabolic power derived from direct measurement (P_{VO2}) and indirect evaluation with two energy cost equations (P_{GPSn} and P_{GPSo}). Statistical significance is marked with “*” (p < 0.001), compared to the MP conditions. **C**) Metabolic power was assessed using either traditional calorimetry with oxygen uptake (P_{VO2}) or exercise-related metabolic power (P_{GPSn}) during the 8 rounds of soccer-specific laps (L1–L8). Statistical significance is indicated by “*” (p < 0.05). Reproduced from Savoia et al. (2020).

2.9. PERFORMANCE CHARACTERISTICS ACCORDING TO PLAYING POSITION IN SOCCER

Vigne et al. (2010) investigated the activities performed in different playing positions in Italian soccer matches. Differences were found between the two halves of a match, and it was shown that different situations require different efforts and different quantifications of activities. The study found that the average distance covered by the athletes was 121.0 ± 9.5 meters per minute, corresponding to approximately 10.94 kilometers in a 90-minute game and that metabolic requirements differed depending on the player. Similarly, Ade et al. (2014) found that a player covers an average of 10.80 kilometers in a 90-minute game. However, the recurring problem is correctly dividing these distances into different segments depending on the intensity of the activity. Ardigò et al. (2015) found that of the average 10.8 km covered by an athlete during a 90-minute game, 38% was covered by walking, 29.5% by jogging, 13% by running at a speed between 13 and 16 $\text{km}\cdot\text{h}^{-1}$, 9.8% by sprinting and the remaining 8.4% by running at a speed between 16 and 19 $\text{km}\cdot\text{h}^{-1}$. The authors concluded that the key to success in soccer was the ability to perform intense and brief efforts with minimal recovery periods. It was also reported that the ratio of work-recovery in a 90-minute game is approximately 1:8. These results are important to prepare soccer players for a 90-minute game to optimize their movements according to time. Significant differences between the first and second half of a soccer match were explained by the amount of time spent on low-intensity activities, which was higher in the second half than in the first half, possibly due to fatigue. Osgnach et al. (2016) also confirmed these observations and pointed out that the midfielders covered the greatest distance, closely followed by the forwards. The main reason for this observation was that midfielders are conduits between the offense and defense phases. Castellano et al. (2011) reported that midfielders are the most important members of team sports as they cover the greatest distance when the team has the ball. Haugen et al. (2014) indicate that the distances covered by top defenders and

forwards during a match are almost identical, with central defenders covering the least distance of all outfield players.

2.10. CONDITIONAL ASPECTS: THE EFFECTS OF ANAEROBIC AND AEROBIC PROCESSES

Stevens et al. (2015) provided evidence that professional soccer players engage in intermittent high-intensity running and efforts, and it was found that almost 98% of this running is under 10 seconds. Stevens et al. (2014) found that high-intensity runs in elite athletes were between 2.5 and 4 seconds and that midfielders cover the greatest distances during a game. Gaudino et al. (2013_{a,b}) found that anaerobic sources and processes provide low energy requirements during soccer competitions, with high anaerobic contributions observed in situations where players complete high-intensity runs (Aquino et al., 2016; Savoia et al., 2020). A study by Clemente et al. (2013) found that most high-intensity runs and efforts during a game took only 2 seconds and that only 10% of high-intensity running took up to 10 seconds or longer. Adenosine triphosphate (ATP) with muscle creatine phosphate (CP) is the major substrate for the highest-intensity bursts of players during a soccer match (Åstrand et al., 1960_{a,b}; Ferretti et al., 2022). ATP hydrolysis provides the free energy the contracting muscles use to generate work and heat (Åstrand, 1986). The indicated pathways ensure ATP resynthesis. ADP, adenosine-di-phosphate, Pi, inorganic phosphate, PCr, phosphocreatine (Margaria, 1944; Cerretelli et al., 1979; di Prampero, 1981; Ferretti et al., 2022).

Several researchers have shown that aerobic and glycolytic sources significantly contribute to the energy sources players require during games and exercise. Walker et al. (2016) found that aerobic energy sources have been shown to provide the energy required by athletes during repeated sprints using running ergometry. Ward-Smith & Radford (2000) showed that scaling the 15-minute observation to over 90 minutes indicated that field players can perform 10-s sprints with 18 times the total energy demand, which could be derived from either anaerobic or aerobic processes. There was a range of recovery times between high-intensity bursts of activity, and only 57% of all recoveries took less than 20 seconds, while only 3.5%

required more than 90 seconds or more. The importance of this study is that it has helped to illustrate that recovery time between bursts can significantly impact the energy system players use during high-intensity efforts. Waldron et al. (2011) showed that blood lactate accumulation and athlete performance were correlated and decreased performance during five 6-second maximal effort sprints when the recovery time was 60 seconds.

Ward-Smith & Radford (2000) analyzed elite athletes to study the kinetics of anaerobic metabolism and found that the results consisted of the measured running times and the calculated measurements. The model accurately tracked the time-distance progression during the game as if it were a 100-meter race. The results of this study provide strong support for the demonstration and use of the three-model equation of anaerobic metabolism, indicating that there are better models for demonstrating the energy requirements of athletes. Elite male sprinters illustrated several aspects of kinetic energy release during intense exercise. Sonderegger et al. (2016) further confirmed this claim by arguing that soccer players' performance is positively related to high-intensity activities. The study also suggests that speed endurance training is essential for improving the performance of competitive soccer players. According to Polglaze et al. (2016), speed endurance training is a form of near-maximal or maximal-intensity anaerobic training that can be categorized based on the recovery time between sprints performed. The primary goals of speed training are for athletes to develop the ability to sustain their maximal sprints and high-intensity activities for extended periods during games.

A fascinating study by Nagasawa (2013) aimed to investigate whether differences in aerobic capacity and training status affect muscle re-oxygenation after sprint exercise. It was hypothesized that the rate of muscle re-oxygenation after sprint exercise is slower in long-distance runners with a high aerobic capacity. Five male long-distance runners, 5 male sprinters, and 6 healthy male controls performed a 30-second sprint exercise on a cycle ergometer. Muscle tissue oxygen saturation (StO_2) in the vastus lateralis

muscles was measured by near-infrared spectroscopy. The re-oxygenation rate of the muscle after exercise was assessed at half the time required for the StO₂ recovery ($T_{1/2}$ StO₂). Aerobic capacity was determined by measuring maximal oxygen consumption ($\dot{V}O_2$ max). The $T_{1/2}$ StO₂ in the long-distance runners (25.0 ± 4.5 seconds) was significantly more than in the controls (15.9 ± 1.6 seconds; $p < 0.01$) and in the sprinters (18.0 ± 4.6 seconds; $p < 0.05$). In all subjects (distance runners, sprinters, and controls), $T_{1/2}$ StO₂ had a significant positive correlation with $\dot{V}O_2$ max ($r = 0.75$; $p < 0.01$) and was major in subjects with a higher $\dot{V}O_2$ max. These results suggest that aerobic capacity and training status influence re-oxygenation after sprint exercise and that subjects with higher aerobic capacity have delayed muscle re-oxygenation.

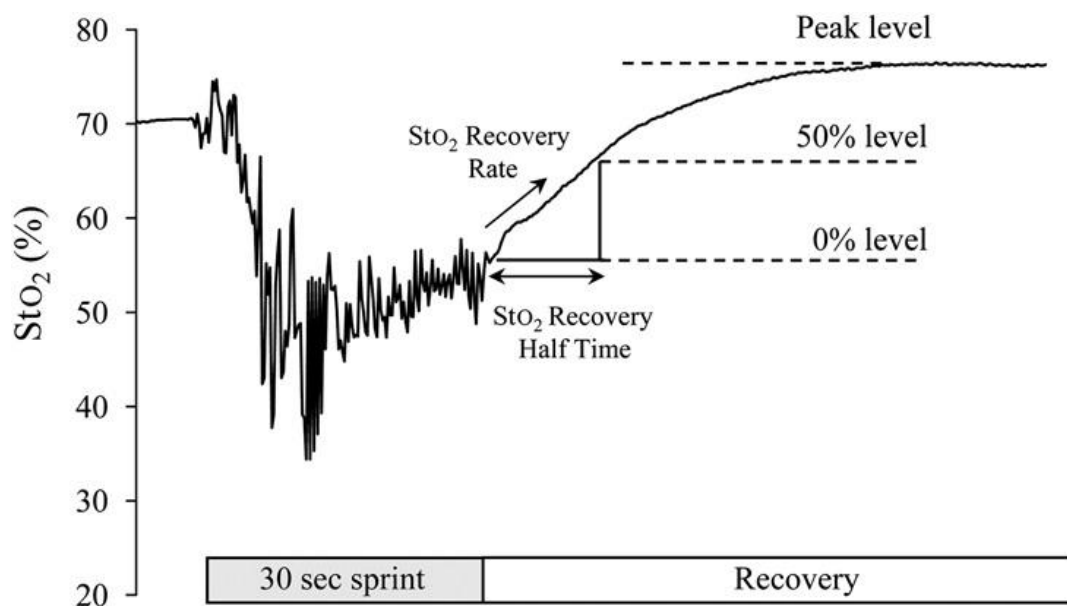


Figure 32. Method for assessing the time for recovery of 50% oxygen saturation in muscle tissue (StO₂) and the StO₂ recovery rate after sprint exercise.

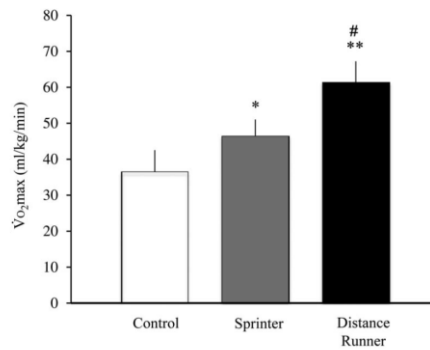


Figure 33. Maximum oxygen consumption ($\dot{V}O_{2\max}$) of controls, sprinters and long-distance runners. * $p < 0.05$, ** $p < 0.01$, significant difference to the control group. # $p < 0.05$, significant difference to the sprinter group.

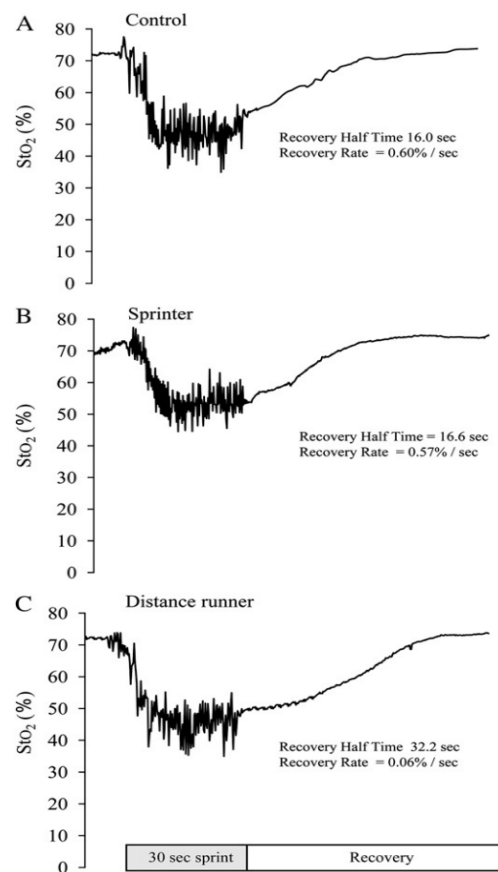


Figure 34. Typical changes in muscle tissue oxygen saturation (StO_2) at rest, during sprint exercise and in the recovery phase after exercise in control subjects (A), sprinters (B) and long-distance runners (C).

Fornaziero et al. (2023) investigated the acute reactions of participants to a soccer match using blood markers. Sixteen male U-18 elite soccer players were divided into two groups: the Experimental Group (EG, n = 10), which played a friendly match, and the Control Group (CG), which was not exposed to any physical exertion. Intravenous blood samples were collected from both groups at baseline, before, at half-time, and after the match. The blood analysis consisted of four groups: immunological (leukocytes, platelets, and cortisol), muscle damage (creatine kinase and lactate dehydrogenase), metabolic (lactate, glucose, erythrocytes, hematocrit, hemoglobin, and urea), and electrolytes (sodium, calcium, and potassium). *Edwards' training impulse* demonstrated that the first half was more demanding than the second half ($p = 0.020$). Significant changes between time points and groups were observed for leukocytes (pre-match: 6920 ± 1949 ; post-match: $13,890 \pm 3292$; $p \leq 0.05$) and cortisol (pre-match: 10.78 ± 3.63 ; post-match: 19.15 ± 7.40 ; $p \leq 0.05$). CK (pre-match: 516.50 ± 248.38 ; post-match: 713.70 ± 308.20 ; $p \leq 0.05$) and LDH (pre-match: 348.80 ± 36.49 ; post-match: 414.80 ± 26.55 ; $p \leq 0.05$) increased significantly in the EG, although there was no difference between the groups. Raised lactate (pre-match: 1.05 ± 0.32 ; post-match: 3.24 ± 1.60 ; $p \leq 0.05$) and glucose levels (pre-match: 72.54 ± 9.76 ; post-match: 101.42 ± 19.87 ; $p \leq 0.05$) between groups at half-time were also observed. These current results provide helpful information to understand better the demands of a soccer match regarding physiological effects.

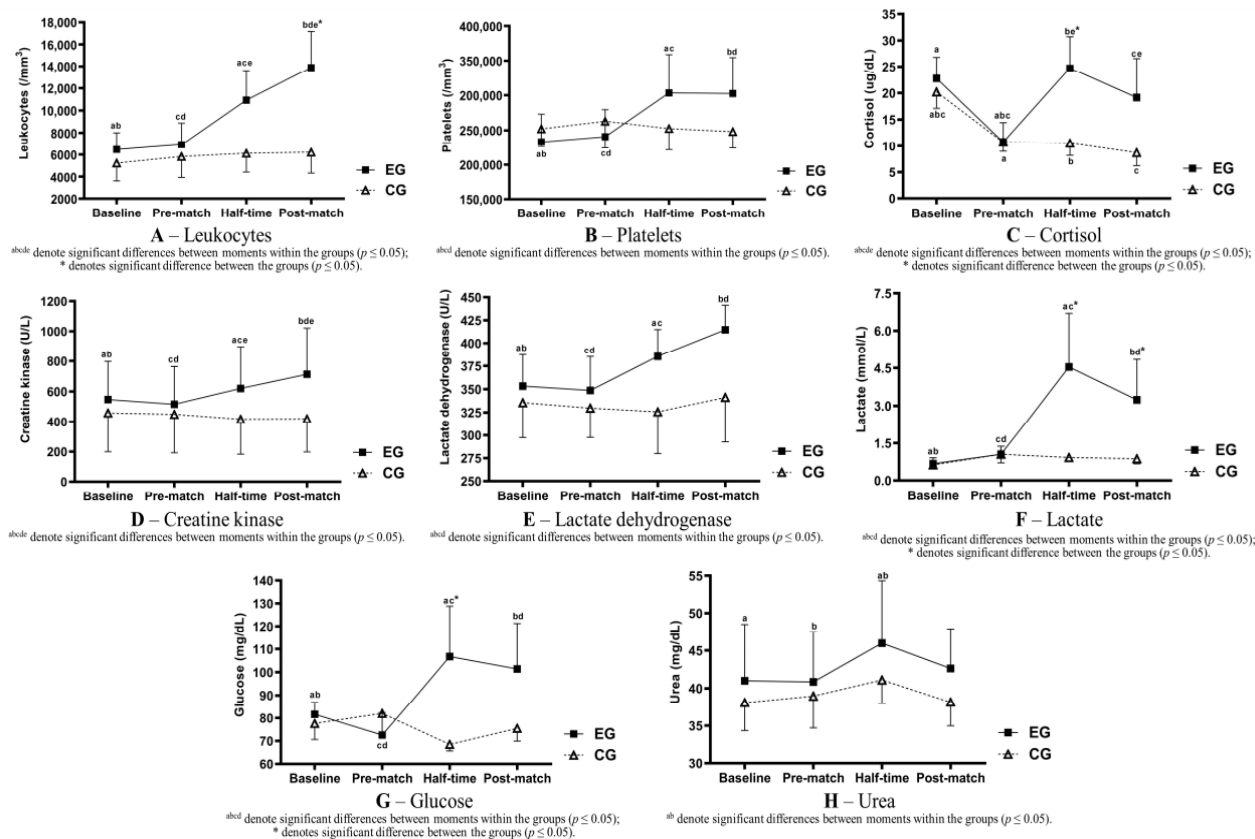


Figure 35. Behavior of blood markers after the soccer match (mean $\pm$ SD). abcde denote significant differences between moments within groups ($p \leq 0.05$); * denotes significant differences between groups ($p \leq 0.05$). Reproduced from Fornaziero et al. (2023).

2.11. FUNCTIONAL ASPECTS: FROM COST AND EFFICIENCY TO THE ROLE OF MOVEMENT COORDINATION

Coordination is an essential component of athletic performance and is crucial in optimizing energy expenditure and improving movement efficiency. Traditionally, sports science has focused on physiological variables such as cost and efficiency. However, the integrative nature of coordination — the ability to organize and control multiple body segments in response to environmental and task demands — provides an essential foundation for understanding the overall complexity of athletic performance (Newell, 1985; Newell, 1986). Coordination results from the athlete's interaction with his or her environment, characterized by action constraints and task demands (Bernstein, 1967; Newell, 1986).

Coordination is critical to the economy of movement by minimizing unnecessary muscular effort and thus reducing metabolic energy expenditure (Asami, 1976; Sparrow & Newell, 1998; Chardenon et al., 2002). Motor competence enables athletes to maintain high performance under dynamic conditions where the energy expended must be targeted to achieve successful outcomes, such as maintaining speed, controlling stability, or performing precise motor tasks (Guadagnoli & Lee, 2004; Renshaw et al., 2019). For example, visual control of tasks such as intercepting or catching a ball - a coordinated interplay of perception and action — has been shown to directly influence cognitive commitment and performance success (Chapman, 1968; Chardenon et al., 2002).

The constraints-led approach, which conceptualizes coordination as an emergent behavior influenced by task, environmental, and organismic constraints, has played an essential role in motor learning and performance (Renshaw et al., 2019; Gray, 2021; Gray, 2022; Gray & Sullivan, 2023). This approach is consistent with dynamic systems theory, in which coordination is understood as a self-organizing process that adapts to task-specific demands (Kelso, 2012). According to this model, coordination is not static

but flexible and subject to changes in environmental stimuli, making it crucial for athletes in complex, real-world environments (Gray, 2021).

However, coordination is about regulating movement and optimizing motor control in response to changing conditions. For example, Bernstein's (1967) seminal work on movement regulation shows how athletes dynamically reorganize their motor patterns to meet new challenges, often resulting in greater efficiency and efficacy. This dynamic process has been further explored in the context of skill acquisition, with different phases of learning, such as those proposed by Fitts & Posner (1967), involving the refinement of coordination as a key factor in the mastery of new motor skills. Recent work by Tenison & Anderson (2016) also emphasizes that skill acquisition is closely linked to developing coordination patterns that improve with practice.

Importantly, variability in coordination is a double-edged sword. While variability can provide the flexibility needed to adapt to novel or challenging situations, excessive variability can compromise performance precision and increase energy cost but change brief and long-term adaptations (Arieh et al., 2022_{a,b}). This was particularly evident in studies investigating the effects of pain on motor coordination. Here, changes in movement patterns often lead to increased energy expenditure and reduced performance accuracy (Arieh et al., 2022_{a,b}).

In addition to influencing movement efficiency, coordination plays a crucial role in improving the accuracy and precision of complex motor skills (Colli et al., 2009_{a,b}; Azzone, 2010; Cipriani, 2010). This can be seen in tasks such as kicking a ball, where energy efficiency correlates directly with limb coordination (Asami, 1976). In addition, the ability to make quick decisions in sports, which is highly dependent on coordinated motor actions, has been extensively modeled using models such as the recognition-driven decision model (Klein, 1993). The importance of coordination extends beyond motor efficiency to cognitive processes, with models of motor learning suggesting that coordination encompasses both perceptual and cognitive dimensions.

Gibson's (1966) ecological theory, which views perception as an active interaction process with the environment, has influenced how coordination is understood concerning environmental affordances. Coordination is thus not only about motor control in muscles but also about the brain's ability to integrate sensory information and predict the outcomes of motor actions (Gibson, 1966; Kimble et al., 1996; Newell et al., 2005; Reed, 2012).

From a practical perspective, the actual framework offers insights into how training environments can be structured to optimize coordination and motor learning (Guadagnoli & Lee, 2004; Edwards, 2010; Chow, 2013). By systematically increasing task difficulty and creating conditions that force athletes to reorganize their coordination patterns, it is possible to improve both motor efficiency and skill acquisition (Higgins & Spaeth, 1972; Edwards, 2010; Chow, 2013). The constraint-based approach further supports this by highlighting the role of task design in promoting adaptive and efficient motor behavior (Renshaw et al., 2019; Gray & Sullivan, 2023).

Energy cost and efficiency are critical to understanding sports performance. Coordination provides an integrative perspective that accounts for the complexity of motor behavior in dynamic environments. Coordination enables athletes to optimize their movements, reduce energy expenditure, and improve performance precision. By incorporating coordinative principles into training and performance analysis, sports scientists and coaches can better address the multifaceted nature of athletic performance (Glazier, 2017; Sands, 2017). Coordination is, therefore, not just a supporting element of motor performance but a fundamental component that underpins the efficiency and success of the movement itself (Posner, 1966; Bernstein, 1967; Farrow & Robertson, 2017; Otte et al., 2019; Wargel et al., 2023).

2.12. CONTRIBUTION: MATCH METABOLIC POWER ACROSS DIFFERENT PLAYING PHASES IN A YOUNG PROFESSIONAL SOCCER TEAM

The study by Licciardi et al. (2020) provides a comprehensive analysis of MP variations in young professional soccer players during competitive matches. Understanding these variations is crucial in the context of sports science, especially for the development of training programs that are finely tuned to soccer's specific demands. The study uses advanced tracking technology and metabolic calculations to analyze the physical demands of different phases of play, providing insights that can be directly applied to optimizing athletes' performance.

The study used GPS technology to track players' movements during official matches. This allowed for precise measurements such as distance covered, speed, and recalculation of MP (or W in this study). These variables were used to calculate the MP output of each player. The analysis focused on three different phases of the game: ball possession (p), non-possession (np), and inactive (i). Consideration of the different play phases is beneficial for designing more effective training protocols. Therefore, this study aimed to determine match body-mass normalized total metabolic power ($W \cdot kg^{-1}$) in the different phases of play using GPS devices in a young soccer team.

A total of 21 players (8 defenders, 8 midfielders, and 5 forwards; 16 ± 1 years, 67 ± 9 kg, and 1.77 ± 0.07 m) of a professional youth soccer team (under 17 years old) participating in the 2016-2017 national championship participated in this study during the mid-season. The inclusion criteria were high-level soccer training practice of ~ 5 years (5 ± 1 years) and ~ 8 hours of training per week in addition to weekly official play. Players were blinded to the aim of the study. The study results show significant differences in MP performance in the different play phases, summarized in **Table II** and **Table III**.

Table II shows the average metabolic powers over different outcomes and phases of play. Significant differences were observed as a function of both match results (main effect: $p = 0.003$ and $ES = 0.97$, moderate) and match phases ($p = 0.008$ and $ES = 0.67$, moderate). During victories and in comparison to defeats, Wp power resulted significantly lower and Bi power significantly higher. In contrast, Bi power was significantly lower in defeats compared to draws. Regardless of the match results, Wp and Wnp power were significantly higher than Bi power but did not differ significantly from each other.

Table III shows the average metabolic power values for the different playing positions and phases. Significant differences were found between the positions ($p = 0.03$ and $ES = 0.38$, small), playing phases ($p = 0.005$ and $ES = 0.58$, small), and interactions ($p = 0.03$ and $ES = 0.39$, small) were observed. The post-hoc test showed that: 1) Wp power resulted significantly lower in defenders compared to midfielders; 2) Wnp and Bi powers resulted significantly higher in defenders compared to forwards; and 3) Wp, Wnp and Bi power were significantly higher in midfielders compared to forwards. Regardless of playing position, Wp and Wnp powers resulted significantly higher than Bi's but did not differ significantly from each other.

	Wp ($W \cdot kg^{-1}$)	Wnp ($W \cdot kg^{-1}$)	Bi ($W \cdot kg^{-1}$)
Victories	12.91±1.62*	13.82±1.58	6.84±1.04*
Defeats	13.47±1.79	13.79±2.40	6.57±1.31^
Draws	13.29±1.31	14.77±2.17	6.73±0.85
WP: with ball possession; WnP: without ball possession, and Bi=all remaining time. *significant difference compared with defeats; ^significant difference compared with draws.			

Table 2. Metabolic Power Across Different Match Results. Reproduced from Licciardi et al., 2020.

	Wp (W·kg ⁻¹)	Wnp (W·kg ⁻¹)	Bi (W·kg ⁻¹)
Defenders	13.08±1.57*	14.08±1.57*	7.28±1.57*
Midfielders	13.47±7.46^	13.79±1.65^	7.46±1.17^
Forwards	13.05±1.41	12.81±1.75	6.99±1.00

WP: with ball possession; WnP: without ball possession; Bi: all remaining time.
 *Significant difference compared with midfielders and/or forwards; ^significant difference compared with forwards.

Table 3. Metabolic Power Across Different Playing Positions. Reproduced from Licciardi et al., 2020

Notably, the estimated MP during the match was found to be higher in Wp and Wnp (i.e., 'ball-active') than in Bi (**Table II**), a consistent finding from our previous research. In victories, compared to defeats, the average metabolic power was significantly lower in both match-phase independent and Wp match average metabolic power. In contrast, Bi power was notably higher (**Table II**, with unclear differences in draws and Wnp). These findings underscore the significant impact of physical performance on match outcomes, with victory potentially hinging on the ability to limit the demanding task of Wp.

Regarding the different playing positions, defenders showed a lower Wp power than midfielders but higher Wnp and Bi in MP than forwards (**Table III**). Midfielders showed higher MP than forwards in all phases of the game. It was observed that defenders and midfielders developed powers that were lower during the Wp than during the Wnp phase. In contrast, forwards developed higher power during Wp higher than during Wnp. These results help to describe the performance models of the different playing positions. Namely, defenders exert a high effort without the ball (to cover areas of the pitch, to mark, to reach the opponents), and midfielders exert a high effort in all phases of the game (to defend, to organize, and to

attack with or without the ball). Differently, forwards save some effort during all playing phases to – perhaps - prioritize more technical fundamentals (such as with the ball to assist and shoot).

Improving knowledge of specific situational variables and their possible influence on the tactical preparation of matches is a recognized and fundamental objective. In the present study, and at least at first sight, the behavior of metabolic powers during Wp and Wnp appeared very similar. Although the average differences between Wp and Wnp were not that big, their high variation indicated a high variability (**Table II**).

These results underscore the critical need for training programs targeting the ability to control efficiently, a crucial aspect of soccer. These findings' practical implications are significant for practitioners and researchers in sports science. The study's findings highlight the importance of designing training programs that address the specific metabolic demands of different phases of playing. This emphasis on specific metabolic demands can inform the development of more effective training plans that improve player performance and reduce injury risk. It also provides a solid foundation for future research that could examine the impact of these demands on athletes' long-term development and performance outcomes.

2.13. A NEW INTEGRATED APPROACH IN THE POSTURAL EVALUATION OF AN U16 ELITE SOCCER PLAYER: A CASE REPORT

Grassadonia et al. (2023) conducted a pioneering case study focusing on assessing posture in an elite U16 soccer player. This investigation is crucial in injury prevention and performance optimization as it presents an integrated approach combining different assessment tools to evaluate the athlete's postural alignment and functional abilities comprehensively. By integrating different assessment methods, this study attempts to overcome the limitations of traditional postural assessments and provide a more nuanced understanding of the factors contributing to athletic performance and injury risk.

The study used a multifaceted approach utilizing postural assessment tools, including Formetric®, stabilometry, baropodometry analysis, podal morphometry for static testing, and GPS-IMU for dynamic analysis. The player's movement patterns and biomechanical modeling were then used to integrate the data from these assessments to provide a detailed analysis of the player's body in different situations. This holistic approach allows for a more accurate diagnosis of potential postural problems and provides a basis for developing targeted interventions to correct these imbalances.

In soccer players, injuries to the external and internal oblique abdominal muscles, which work together to control trunk rotation and lateral trunk flexion, are less frequently described. Therefore, the central hypothesis of this case study is mainly aimed at drawing attention to the importance of a global postural assessment to identify the dysfunction in its entirety and define a targeted and effective rehabilitation approach. The subject was a 15-year-old (1.79 m and 59.5 ± 2.12 kg, with a BMI of 18.57 ± 0.66) elite U16 Italian championship soccer player who suffered from severe pain in the left parietal region during training in a pre-season tournament. After clinical suspicion, an ultrasound examination of the abdominal muscle

was performed, which revealed an injury to the distal third of the external left oblique muscle of the abdomen after an instrumental ultrasound examination. The mechanism of this rare injury, without contact during training in a pre-season competition, was a twisting-rotational movement during a friendly match.



Figure 36. Left Panel: Ultrasound examination of the abdominal wall carried out with a linear probe, where it shows physiological alteration of the distal third of the left external oblique muscle adjacent to the distal insertion on the iliac crest and iliac bone with fibrillar structure, an area diffusely hyper-echogenic with minimal surrounding fluid layer, consisting of a first-degree muscle distraction. Central Panel: pelvis radiograph imaging under load (acetabular space right ≈ 204.4 mm and acetabular space left ≈ 197.3 mm). Right Panel: Control ultrasound 14 days after the previous one, where the resolution of the altered echogenicity of the previously injured muscle is observed. Reproduced from Grassadonia et al., 2023.

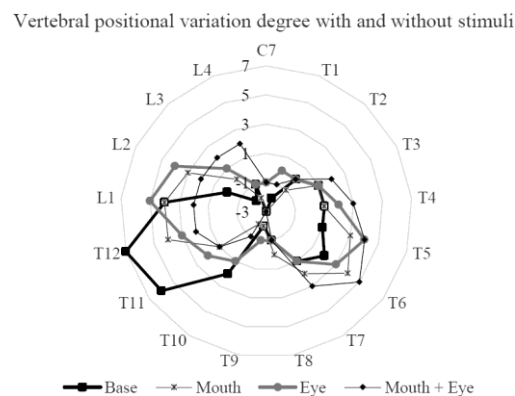


Figure 37. Kiviat chart with variables selected and comprised, ranking criteria signaled with the negative sign " - " for the vertebral rotations to the left side, while with the positive sign " + " to the right. The total sum of rotary degrees from C7 to L4 (both right and left) in "base" is 38° , "mouth correction" 36° , "eye correction" 32° , and "mouth and eye correction" 35° ; not showing the significative difference, despite noticeable quality differences. Reproduced from Grassadonia et al., 2023.

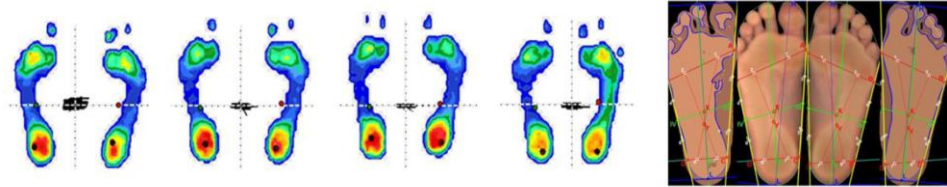


Figure 38. Left Panel: Baropodometry and Stabilometry in bipodal position with four different conditions from left to right: "base", only "mouth correction", only "eye correction" and both "mouth and eye correction". Right Panel: Podalic morphometry. The plantar morphometry is present in central images and laterally in contact morphometry. Podalic morphometry mean difference on the left foot is 12%, while on the right foot is 11.8%, which indicates a good structural condition. Reproduced from Grassadonia et al., 2023.

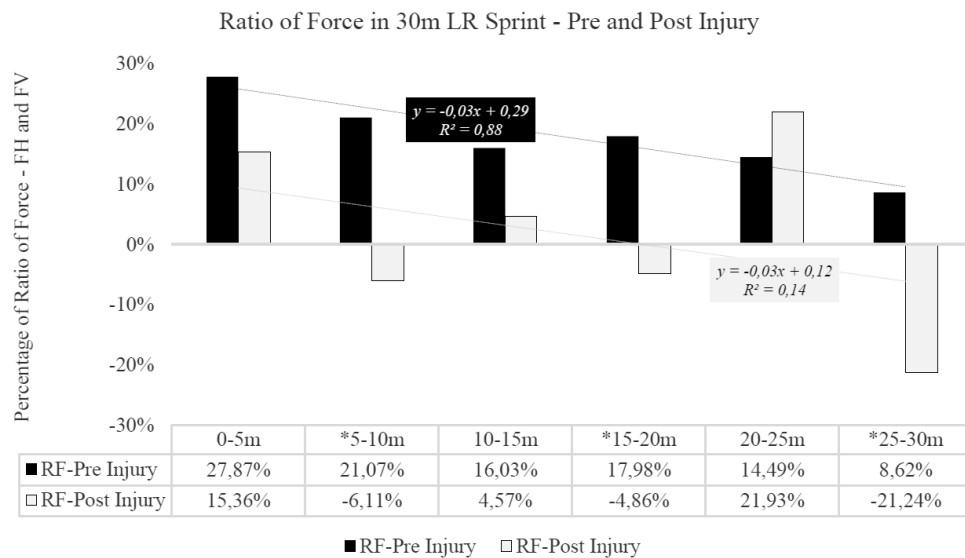


Figure 39. Ratio of Force (RF), horizontal and vertical force, in 30m on LR (Linear Runs) each 5 meters, pre and post injury, with relative correlations. *Statistically significant differences. Reproduced from Grassadonia et al., 2023.

Elite athletes who practice sports requiring high-intensity, multidirectional, and multivariable movements can often have postural problems that sometimes develop into pathologies. An exercise or treatment must be prescribed based on the specific need. It should be based on biomechanical factors resulting from tests and other assessments related to the sport. The corrections studied instead involved static tests, such as raster

stereography, stabilometry, and baropodometry, a gauze used as thickness to correct the mouth, and a 1400 Gauss magnet to correct the left eye. Several sport-specific requirements can affect this relationship. A typical example is the specific movements of multiplanar, locomotor, and torsional-rotational single-leg actions for many sports (one of them is soccer, as in our case); this is one of the main reasons for the great importance of multivariability of training stimuli to improve "motor skills" at younger ages. An integrated system with a complete rehabilitation approach can allow athletes to recover first with optimal results.

Effective injury management in sports involves not only understanding the causes of injury but also following methodological indications for proper recovery. Neglecting the postural conditions that can lead to injury can be detrimental. Therefore, it's crucial to manage the stages of return to sport and pay attention to correct timing.

A multimodal approach such as ours has helped us better study and understand the different motor behaviors and negative adaptations that could cause and respond to the injury mechanisms. A more global approach naturally opens and lends itself to more in-depth studies that need to be conducted to understand more and find new markers that are better explanatory and suitable than those already in use. Complete and integrated profiling of the subjects to postural evaluation, especially athletes, should be a practice recommended to coaches and physical trainers as well as medical staff to create a '*roadmap*' aimed at individualizing training methods to optimize movement strategies and prevent injuries as much as possible or recover better from them.

Our study has important implications for both clinical practice and sports science research. It suggests that a more holistic approach to postural assessment could lead to more effective injury prevention strategies, particularly in young athletes. Identifying specific postural weaknesses and understanding their biomechanical implications is crucial. This understanding guides the development of targeted intervention programs

that can correct these problems before they lead to injury. From a research perspective, our study contributes to the growing body of evidence supporting the use of integrated assessment tools in sports science. It highlights the need for further research into the long-term effects of postural damage on athletic performance and injury risk, particularly in elite youth athletes. In summary, our integrated approach to postural assessment provides a valuable framework for both practitioners and researchers, emphasizing the importance of considering the athlete's biomechanics as a whole.

2.14. STATEMENT OF THE PROBLEM: CONCLUSION AND FUTURE PERSPECTIVES

MP, EC, AE, etc. can potentially provide new solutions and a more comprehensive measure of the intensity, volume, density, etc., for the variable of speed locomotion, allowing for better monitoring of training and competition efforts (Polglaze et al., 2019; Monte et al., 2020; Savoia et al., 2020; Grassadonia et al., 2024). Practitioners and researchers should select the most relevant duration-specific period and microtechnology-derived variable for their specific needs when prescribing conditioning exercises and training intensity (Whitehead et al., 2018). Nevertheless, experienced individuals must perform the analysis to identify the peak demands of the match further. Using microtechnology alongside video analysis would provide coaches with more detailed information about the technical-tactical and physical demands during the match. In modern sports, these variables are essential not only for coaches and athletes but also for sports scientist and doctors. It has been shown that an athlete's energy expenditure is influenced by several factors, including the intensity of the game, the level of play (elite or less demanding games), and the amount of activity during a game, such as high-intensity running or low-focus running. Consequently, the need to accurately measure the level of energy expenditure has become more important in recent years. As a result, several methods have been developed to help regulate energy requirements and effort levels during different games. Methods used to measure athletes' performance to obtain data for calculating energy include multi-camera analysis, time-motion analysis, video-motion analysis, and, most importantly, the use of GPS. However, the validity and reliability of these techniques are a constant point of contention between various researchers and sports science technicians and scientists. Therefore, several experiments have been conducted to determine the validity and reliability of these techniques. Although research on the use of GPS in sports is extensive and comprehensive, much remains to be done to obtain the data required to calculate the energy requirements

of athletes in individual and team sports, mainly about using GPS as an analytical tool. The validity of these tools needs to be further investigated to ensure their accuracy and improve sports science support for athletes and coaches (Savoia, 2019).

In a recent paper, Harper et al. (2021) asked themselves what has evolved in soccer and what needs to evolve soon and identified 4 key points to watch out for in this decade (from 2020 to 2030). The exercise/player profile has the greatest influence on physical preparation and performance by:

1. *Raising the 'ceiling'*: advanced, field-based profiling identifies individualized, specific training needs so that the 'ceiling' for each high-intensity motor skill can be raised through individualized training. Raising the 'ceiling' will improve players' ability to repeat and recover from dense, high-intensity running workloads.
2. *Braking performance skills*: developing and refining deceleration metrics and designing appropriate training interventions will improve braking performance skills, enabling game-specific speed abilities and reducing susceptibility to fatigue and injury.
3. *Precise monitoring*: small embedded micro-technologies will enable advanced, precise physiological and mechanical insights into high-intensity locomotor performance. When analyzed with machine learning algorithms, this data should provide information that more accurately supports the decision-making processes of coaches, sports scientists, and medical professionals.
4. *Precise loading*: new technologies will make it possible to precisely load the specific force-velocity components required for each high-intensity motor skill. For example, wearable electronic systems can create player-specific acceleration, deceleration, and high-speed running (HSR) training targets with assistance and resistance.

In summary, the future challenge will increasingly prioritize "individualization". The movement profile is an essential topic that can help us manage the complexity of future game requirements.

Although significant progress has been made in understanding the mechanical and energetic demands of sprinting, mainly through studies exploring the interplay between muscle activation patterns, MP and EC under different situations, there remain critical gaps in the literature that warrant further investigation. Study 1 aimed to analyze submaximal running efforts and sprints, focusing on EMG activity-to-force ratios and neuromuscular profiling using GPS-IMU and EMG data. While it provided valuable insight into training goals based on neuromuscular demands, it focused primarily on linear sprints without comprehensively examining sprint effort at different resistance levels. In contrast, Study 2 addressed this limitation by examining variations in muscle activation and energetic demands under different loading conditions, comparing sprinting with and unloaded sprinting using novel GPS-EMG methods.

Despite these contributions, both studies still need to be answered, particularly regarding the generalizability of the results across different sprinting modalities and the precise interplay between muscle coordination, MP, and EC during dynamic, high-intensity movements. Furthermore, while innovative, the exclusive use of GPS and EMG data may overlook the complexity of muscle efficiency and coordination under variable, real-world conditions. Therefore, this research addresses these gaps by investigating how different sprinting conditions and resistances affect muscular activation and energetics. The ultimate goal is to provide insights that could revolutionize training methodologies, optimizing performance efficiency and energy expenditure in different athletic contexts.

The thesis aims to use GPS-IMU and EMG to identify the key neuromuscular and metabolic markers in the biomechanical and bioenergetic properties during typical soccer actions and to fill the gaps exposed by previous scientific literature. Furthermore, it will determine if changes in these parameters can be observed in specific scenarios and movement patterns to assess the effectiveness of new physiology models under varying conditions in elite youth soccer players.

III – HYPOTHESIS

III - HYPOTHESIS

Summary of the hypothesis of this thesis are:

1. The first study aimed to investigate EMG activity and EMG/F ratio during different submaximal and maximal runs and to examine the differences between GPS-IMU and EMG technologies in calculating MP and EC during constant running and sprinting efforts. In addition, the current results show a linear increase in the EMG/F ratio during sprints up to a breakpoint (i.e., observed at 30 m) when a change in the overall trend is observed (i.e., when considering the entire 50 m). In addition, differences were hypothesized and found between the MP and EC calculated using the GPS-IMU and EMG at certain splits, suggesting that these technologies cannot be used interchangeably to determine these metrics (Study 1).

2. The aim of the second study, which builds on established assumptions in the scientific community, is to evaluate muscle engagement during loaded sprints with increasing loads in resisted sprints in the sled conditions (i.e., SS15, SS30, SS45 and SS60 corresponding to 15, 30, 45 and 60 kg of additional mass) and parachute (PS). This study employs a novel approach recently employed in previous research in unloaded sprinting, setting it apart from conventional methods (Study 2).

This thesis's challenge is to determine the keys to sports performance markers through experimental modeling with new integrated approaches.

IV – OBJECTIVES

IV - OBJECTIVES

The achieved objectives for the realization of the aims will be pursued through several specific sub-objectives, which are outlined as follows:

General Objective:

The primary goal of this thesis is to pioneer a new model of key markers (e.g.: metabolic power, energy cost, apparent efficiency and EMG/Force ratio) to determine common motor actions typical of athletic demands such as sprinting in elite youth soccer players.

Specific Objectives:

Study 1

1. Analyze submaximal running efforts at different constant speeds to investigate possible different mechanical–energetic demands compared to sprinting;
2. Investigate the behavior of the EMG activity-force (EMG/F) ratio during linear sprints over 30 m and 50 m and the corresponding 5 m sections;
3. Determine the sprint's EC and MP obtained by GPS-IMU and EMG by creating an ad hoc neuromuscular profile using muscle activation patterns.

Study 2

1. Analyze the variations in muscle activation patterns during sprints under different loading conditions with the respective different technical and temporal characteristics;
2. Investigate and compare the MP and EC determined by the GPS and EMG in each sprint condition;

3. Investigate the AE (i.e., a performance marker previously used in the literature during sprint efforts with resistance using parachutes and sleds).

V – GENERAL OVERVIEW OF THE STUDIES

V - GENERAL OVERVIEW OF THE STUDIES

STUDY N° 1:

COMPARISON OF METABOLIC POWER AND ENERGY COST OF SUBMAXIMAL AND SPRINT RUNNING EFFORTS USING DIFFERENT METHODS IN ELITE YOUTH SOCCER PLAYERS: A NOVEL ENERGETIC APPROACH

Abstract

Sprinting is a decisive action in soccer that is considerably taxing from a neuromuscular and energetic perspective. This study compared different calculation methods for the metabolic power (MP) and energy cost (EC) of sprinting using global positioning system (GPS) metrics and electromyography (EMG), with the aim of identifying potential differences in performance markers. Sixteen elite U17 male soccer players (age: 16.4 ± 0.5 years; body mass: 64.6 ± 4.4 kg; and height: 177.4 ± 4.3 cm) participated in the study and completed four different submaximal constant running efforts followed by sprinting actions while using portable GPS-IMU units and surface EMG. GPS-derived MP was determined based on GPS velocity, and the EMG-MP and EC were calculated based on individual profiles plotting the MP of the GPS and all EMG signals acquired. The goodness of fit of the linear regressions was assessed by the coefficient of determination (R^2), and a repeated measures ANOVA was used to detect changes. A linear trend was found in EMG activity during submaximal speed runs ($R^2 = 1$), but when the sprint effort was considered, the trend became exponential ($R^2 = 0.89$). The EMG/force ratio displayed two different trends: linear up to a 30

m sprint ($R^2 = 0.99$) and polynomial up to a 50 m sprint ($R^2 = 0.96$). Statistically significant differences between the GPS and EMG were observed for MP splits at 0–5 m, 5–10 m, 25–30 m, 30–35 m, and 35–40 m and for EC splits at 5–10 m, 25–30 m, 30–35 m, and 35–40 m ($p \leq 0.05$). Therefore, the determination of the MP and EC based on GPS technology underestimated the neuromuscular and metabolic engagement during the sprinting efforts. Thus, the EMG-derived method seems to be more accurate for calculating the MP and EC in this type of action.

STUDY N° 2:

ENERGETIC AND NEUROMUSCULAR DEMANDS OF UNRESISTED, PARACHUTE- AND SLED-RESISTED SPRINTS IN YOUTH SOCCER PLAYERS: DIFFERENCES BETWEEN TWO NOVEL DETERMINATION METHODS

Abstract

The aim of this study was to analyze the differences in terms of: 1) muscle activation patterns; 2) metabolic power (MP) and energy cost (EC) estimated via two determination methods (i.e., Global Positioning System [GPS] and electromyography-based [EMG]); and 3) the apparent efficiency (AE), of 30-meter linear sprints in seventeen elite U17 male soccer players performed under different conditions (i.e., unloaded sprint [US], parachute sprint [PS] and four incremental sled loads [SS15, SS30, SS45, SS60, corresponding to 15, 30, 45 and 60 kg of additional mass]). In a single testing session, each participant executed six trials (one attempt per sprint type). The results indicated that increasing sled loads led to a linear increase in the relative contribution of the quadriceps ($R^2 = 0.98$) and gluteus ($R^2 = 0.94$) and a linear decrease in hamstring recruitment ($R^2 = 0.99$). MP during US was significantly different from SS15, SS30, SS45, and SS60, as determined by the GPS and EMG approaches (p -values ranging from 0.01 to 0.001). Regarding

EC, significant differences were found among US and all sled conditions (i.e., SS15, SS30, SS45, and SS60) using the GPS and EMG methods (all $p \leq 0.001$). Moreover, MP and EC determined via GPS were significantly lower in all sled conditions when compared to EMG (all $p \leq 0.001$). AE was significantly higher in US when compared to the loaded sprinting conditions (all $p \leq 0.001$). In conclusion, muscle activation patterns, MP and EC, and AE changed as a function of load in sled-resisted sprinting. Furthermore, GPS-derived MP and EC seemed to underestimate the actual neuromuscular and metabolic demands imposed on youth soccer players compared to EMG.

VI – STUDY 1

VI - STUDY 1

6.1. INTRODUCTION

The energy cost (EC) and kinematics of various forms of locomotion (e.g., running) have been analyzed in numerous investigations [Minetti et al., 1994_{a,b}; Minetti et al., 2002; Zamparo et al., 2016; Minetti & Pavei, 2018; Van Hooren et al., 2019; Zamparo et al., 2019] with the aim of elucidating the main mechanisms of different movements. These studies have practical applications and allow for evaluating the metabolic energy expenditure or predicting the “ideal” performance (Furusawa et al., 1927; Fenn, 1930_{a,b}; Hill, 1938; Margaria, 1938; Margaria et al., 1963; Margaria, 1970) based on the relationship between mechanics and energetics (Marey & Demeny, 1885; Cavagna & Kaneko, 1977; Pinnington & Dawson, 2001; Colli et al., 2007; di Prampero et al., 2015; Zamparo et al., 2019), which is one of the most crucial and extensively researched domains of human movement (Deutsch, 1952; Cavagna et al., 1971; Cavagna & Kaneko, 1977; Minetti et al., 2002; di Prampero et al., 2005; Buglione & di Prampero, 2013; Zamparo et al., 2016; Piras et al., 2017; Monte & Zamparo, 2019; Pavei et al., 2019; Monte et al., 2020).

For example, di Prampero et al. (2005) estimated the EC of the first 30 m of a sprint running from a standing position to overcome the challenges of directly measuring effort during dynamic actions. In brief, the method relied on the equivalence between acceleration on flat ground and ascent at constant speed, with an equivalent slope defined by forward acceleration. Since the EC of constant speed on a varied range of slopes is well known (Margaria et al., 1963; Minetti et al., 1994_{a,b}; Minetti, 1998; Minetti et al., 2002; Minetti & Pavei, 2018), estimating the EC of the run is possible when the equivalence between forward acceleration and the slope is known. Therefore, di Prampero et al.’s (2005) model has been suggested to redefine

the concept of “high intensity”. Nevertheless, despite the new possibilities that arise from this approach (di Prampero et al., 2005) in terms of workload quantification and physical performance evaluation during training and competition (Colli et al., 2007; Osgnach et al., 2010; Buglione & di Prampero, 2012; Osgnach et al., 2016; Licciardi et al., 2020; Savoia et al., 2020; Spyrou et al., 2023), more evidence is still needed to determine the feasibility of EC estimation in applied scenarios.

Some researchers tried to evaluate neuromuscular and metabolic engagement during training and match events by using portable technology to understand muscle activation thresholds. A first attempt to characterize the profile of neuromuscular activation during a soccer match was proposed by Montini et al. (2017), with the intention to integrate, in competition, more traditional laboratory-based approaches (e.g., electromyography [EMG]) to help better understand the physiological demands of competitive soccer. The authors analyzed different intensity zones to create a relative performance model and suggested that this approach could be used to improve the understanding of the physiological requirements of competitive soccer (Montini et al., 2017). However, the EC and metabolic power (MP) calculated by EMG were not determined; thus, additional research is still necessary to consolidate measurements of economy and neuromuscular activation during performance activities that involve high-intensity running. This type of methodological approach is important for practitioners since, by using portable technologies, it is possible to collect data on more ecologically valid conditions than in laboratory settings.

The literature has explored the behavior of EMG during sprints and submaximal runs since Mero & Komi (1987); however, to the authors’ knowledge, it has not been utilized for the calculation of the MP and EC until Colli’s work (unpublished data retrieved from *laltrametodologia.com*). Thus, this remains a topic that needs further investigation to better understand the main mechanistic–energetic needs and, consequently, make

meaningful methodological choices. Currently, there are numerous existing studies evaluating MP and energy expenditure, utilizing global positioning systems (GPS) and inertial measurement units (IMU) [Piras et al., 2017; Licciardi et al., 2020; Savoia et al., 2020; Savoia et al., 2021; Ju et al., 2022; Rodriguez-Barbero et al., 2023; di Prampero & Osgnach, 2023_{a,b}; Van Hooren et al., 2024_{a,b}], but there is a complete absence of studies calculating these parameters from EMG technology. Analyzing submaximal and maximal sprint behavior with the aim of determining the MP and EC calculated by EMG and the EMG and force relationship could help clarify actual metabolic and neuromuscular engagement during linear running actions. The comparison of two distinct technologies (i.e., EMG and GPS-IMU) has the potential to provide precise estimates of relative effort for actions such as sprints, yielding hypothetical benefits.

Therefore, the aims of this study were to (1) analyze submaximal running efforts at various constant speeds to investigate possible differing mechanical–energetic demands when compared to sprinting; (2) examine the behavior of the EMG activity-to-force ratio (EMG/F) in linear sprints over 30 m and 50 m and their corresponding 5 m sections; and (3) determine the EC and MP of sprinting assessed by GPS-IMU and EMG by creating an ad hoc neuromuscular profile utilizing muscle activation patterns. The present study may have significant implications for the establishment and structuring of training objectives.

6.2. MATERIALS AND METHODS

6.2.1. Study design

A cross-sectional study design was used (**Figure 40**). Data were collected during the 2020/2021 competitive season, during the months of September through November, with players from the under-17 (U17) age category of a professional soccer club academy. To avoid a potential source of bias, de-identified data were analyzed by a researcher not directly involved in data collection. After a careful theoretical explanation accompanied by a practical demonstration, players completed four different submaximal constant running efforts followed by sprinting actions while using portable GPS-IMU units and surface EMG. All athlete measures were taken in a single testing session for each player during the pre-season period. The warm-up included mobility and running-based exercises for a duration of ~15 min. All warm-up exercises had been previously used by all the players, as they were applied in daily training

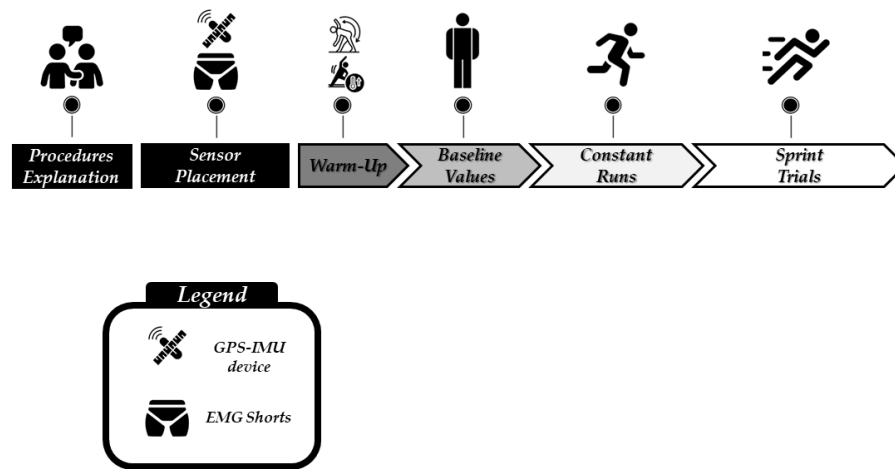


Figure 40. Overview of the study design.

6.2.2. Participants

A convenience sample of sixteen U17 football players (age: 16.4 ± 0.5 years; body mass: 64.6 ± 4.4 kg; height: 177.4 ± 4.3 cm; and BMI: 20.5 ± 1.3) of the “Elite Italian Championship” volunteered to participate in this study. A normal team practice and competition schedule, consisting of at least four training sessions and one match per week, was maintained during the investigation period. Only players who were free from recent injuries or medical conditions that could limit their maximum effort were included in the study. Detailed information regarding all testing and training procedures was provided to the subjects and their legal guardians before the latter signed a written informed consent. The Local Human Subjects Ethics Committee approved the study in compliance with the Declaration of Helsinki.

6.2.3. Procedures

6.2.3.1. *Constant Running and Sprint Testing*

Four incremental constant ($C_{1,2,3,4}$) running speeds (over 50 m, at theoretical required times of ~22.5, ~15, ~11.3, and ~9 s in “C₁”, “C₂”, “C₃”, and “C₄”, respectively) and a sprint effort (where only the split of the maximum speed phase was taken) were used for the construction of an individual profile (detailed below; coded with “S₅”). Timing adherence was manually controlled using stopwatches during the constant runs in the trials. All tests were conducted on the training and match field, and each player was given the appropriate technical clothing to maintain their running characteristics (ecological field test). As mentioned, the players started by performing the constant runs with the objective of having an approximate constant difference between runs rather than a set datum (impossible for a field test that does not take place on an ergometer); thus, they were asked to maintain the same running characteristics during each trial. After the constant runs and a rest period (2 min), the players performed a total of three all-out sprints over 50 m. To establish the zone of maximum sprinting speed, a plateau with a delta of no more than 3 km·h⁻¹ in the GPS data was selected to objectively determine when athletes reached their peak speed. A 5 min passive rest period was provided between trials to minimize fatigue effects on performance. Participants were encouraged to perform each sprint trial as fast as possible.

6.2.3.2. *Electromyography Recording and Analysis*

During the trials, EMG shorts equipped with textile electrodes (Myonear Pro, Myontec, Kuopio, Finland) were used to collect muscle

activation data (**Figure 41**). The conductive electrodes and the associated wires were integrated into the fabric. These electrodes covered three main muscle groups, bilaterally, with 6 differential EMG biosignal channels: quadriceps, hamstrings, and glutes. Two sizes of shorts were available (medium and large), and the best fit was chosen for each participant. The proper size of the shorts is essential to establish necessary contact between electrodes and skin and to minimize or avoid any movement artifacts during dynamic activities (Colyer & McGuigan, 2018). Additionally, a small amount of water was applied to the electrodes before the participant put on the shorts to ensure adequate signal conduction, as previously recommended (Finni et al., 2007). EMG signals were transmitted to a laptop and analyzed and collected at 1000 Hz with the Myontec “Muscle Monitor” software version 3.1.0.4 (Myontec Ltd., Kuopio, Finland). Textile electrodes embedded in shorts appeared to provide comparable lower limb muscle activation data to traditional surface EMG (Colyer & McGuigan, 2018). Each trial was firstly filtered with a second-order Butterworth band pass (a bandwidth of 40–200 Hz, derived through an exploration of the frequency domain with a signal voltage and –3 dB cutoff frequency) filter, before being rectified and averaged over 100 Hz. In accordance with Kyröläinen et al. (2005), who criticized the use of voluntary maximum isometric contractions (MVICs) for evaluating neuromuscular activation during running, the EMG data were normalized using the peak EMG activity (EMG_{peak}) detected during the sprint, thus allowing for greater repeatability of the measurements. In addition, the EMG signals during the runs were segmented into subphases to enable a detailed analysis not only of the overall trend (total EMG recording [EMG_{TOT_ecf}], comprehensive of ground contact, eccentric and concentric, and of the flight phases) but also of the characteristics of each phase (i.e., eccentric [EMG_e], concentric [EMG_c], and flight phase) utilizing the LagalaColli software (version 1.0.2.218, Spinitalia S.R.L., Rome, Italy). The EMG/F ratio was determined with an arbitrary unit, consisting of the ratio of the normalized EMG signal with peak values and

expressing it as a percentage and the resulting force (in $\text{N}\cdot\text{kg}^{-1}$), which was calculated by integrating the accelerations from the three axes (x, y, and z) using IMU technology.

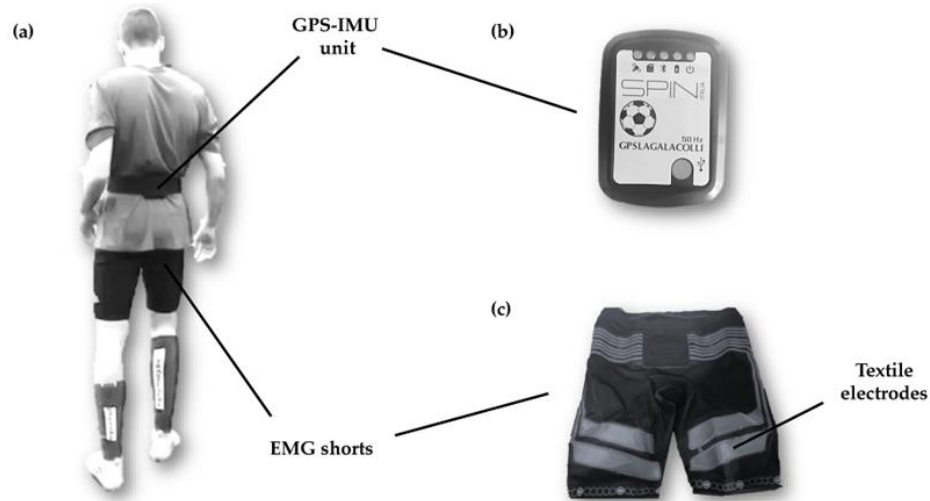


Figure 41. (a) Back view of the sensor placement; (b) GPS unit; (c) EMG shorts equipped with textile electrodes with 6 differential EMG biosignal channels.

6.2.3.3. *Ad Hoc Profiling and Metabolic Power Calculation*

Prior to the sprint analysis, an individual linear profile (including slope and intercept) was constructed for each athlete by plotting the MP of the GPS and muscle load (ML) from all the EMG signals acquired. The profile was individualized and made it possible to recalculate the MP from the EMG by a simple method that consisted of multiplying by the slope and then adding intercept (MP Equation). Then, the EC was calculated by dividing the obtained value of MP by the speed achieved (EC Equation).

$$MP_{EMG} = (ML_{EMG} * SLOPE) + INTERCEPT$$

$$EC_{EMG} = \frac{MP_{EMG}}{SPEED_{IMU}}$$

The EMG data were integrated with GPS-IMU signals to permit us to temporally and kinematically differentiate phases. Sprint analyses were conducted utilizing personalized spreadsheets. The GPS MP was based on the GPS velocity, and the integrated GPS-IMU velocity was utilized to determine the EMG MP. The GPS data were recorded at 50 Hz and the IMU at 100 Hz in accordance with the manufacturer's instructions.

6.2.4. Statistical Analysis

Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) software, version 25.0 (Chicago, IL, USA), Microsoft Excel 2019 (Redmond, WA, USA), and the free Statistical Software Jamovi 2.3.28. Data are presented as means and standard deviations. The goodness of fit of the linear regressions was assessed by the coefficient of determination (R^2) and the confidence interval (CI, set at 95%). The Shapiro–Wilk test was used to verify if the values were normally distributed, and the Wilcoxon signed rank nonparametric test was used for data not normally distributed. A repeated measures ANOVA was used to detect changes, with a two-sample F-test for variances. The effect size (ES, Cohen's d) of the intervention was calculated using Cohen's guidelines (Cohen, 1988; Cohen, 1992). The threshold values for the ES were small (≥ 0.2), medium (≥ 0.5), and large (≥ 0.8). For all procedures, a level of $p \leq 0.05$ was selected to indicate statistical significance.

6.3. RESULTS

During the experimental period, no injuries were sustained by any of the players, and the compliance with the assessments and degree to which the participants adhered to the study protocol and accepted the interventions and assessments were maximal, as there were no dropouts. Regarding the study results, these include the EMG signal and speed mean values, detected with the EMG signal in a bipodal static ($2.4 \pm 0.6\%$ relative to the EMG_{peak}) and obtained during the four incremental constant running and sprint efforts over 50 m. The first constant running (C_1) exercise was completed at $6.9 \pm 0.8 \text{ km}\cdot\text{h}^{-1}$, with an EMG_e of $16.2 \pm 8.3\%$, an EMG_c of $14.0 \pm 3.8\%$, and an EMG_{TOT_ecf} of $13.9 \pm 5.3\%$. In the second constant running (C_2) exercise, the speed was $10.2 \pm 0.8 \text{ km}\cdot\text{h}^{-1}$ with an EMG_e of $21.6 \pm 11.8\%$, an EMG_c of $17.7 \pm 6.4\%$, and an EMG_{TOT_ecf} of $18.5 \pm 8.3\%$. C_3 was completed at $13.3 \pm 1.5 \text{ km}\cdot\text{h}^{-1}$, with EMG_e , EMG_c , and EMG_{TOT_ecf} values of $27.4 \pm 11.8\%$, $23.0 \pm 5.9\%$, and $23.1 \pm 7.8\%$, respectively. Finally, the speed reached in C_4 was $17.4 \pm 1.3 \text{ km}\cdot\text{h}^{-1}$, with an EMG_e of $33.1 \pm 8.7\%$, an EMG_c of $30.4 \pm 12.6\%$, and EMG_{TOT_ecf} of $28.6 \pm 8.0\%$. Regarding the sprint effort (S_5), the speed achieved was $27.3 \pm 1.8 \text{ km}\cdot\text{h}^{-1}$, the EMG_e was $62.3 \pm 8.6\%$, the EMG_c was $57.4 \pm 8.6\%$, and the EMG_{TOT_ecf} $63.1 \pm 8.7\%$. **Figure 42** displays the corresponding total EMG patterns in relation to running speed.

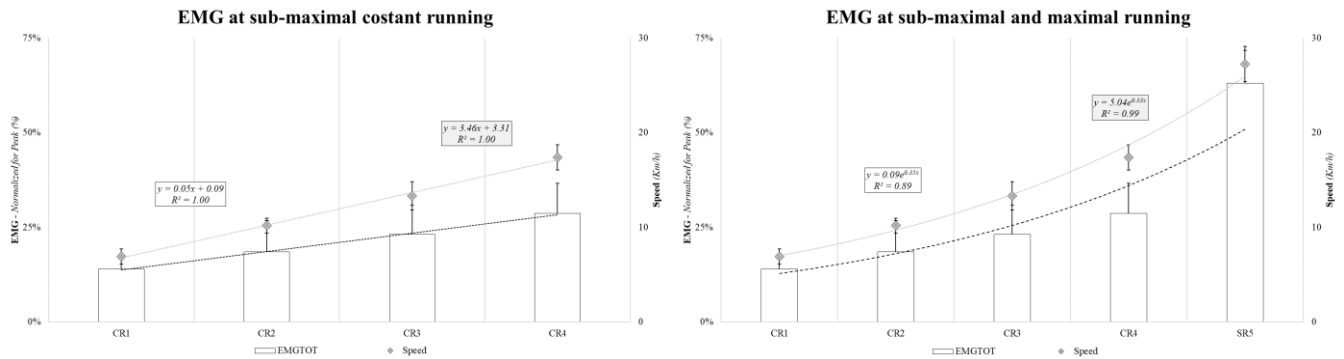


Figure 42. EMG at four different submaximal running speeds (left panel) and with sprint efforts (right panel).

During sprinting, the EMG/F ratio data were processed for each 5 m interval (**Figure 43**) and presented a double behavior interpolated with two types of fit. The EMG/F ratio was linear up to 30 m ($R^2 = 0.99$) and polynomial (fourth degree) up to the completion of 50 m ($R^2 = 0.96$).

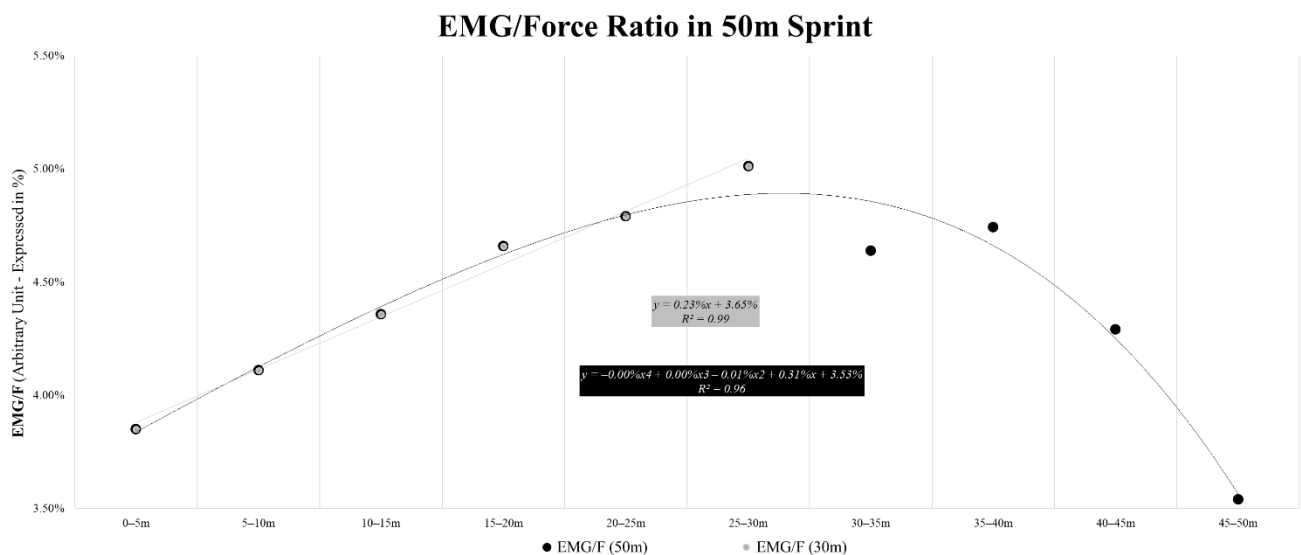


Figure 43. Linear (gray) and curvilinear (polynomial, in black) fits of the EMG/F ratio over 50 m sprints.

Comparisons of the MP for the different split distances obtained with the GPS and EMG are presented in **Figure 44**. The data were not normally distributed at 20–25 m and 35–40 m distances. In the 0–5 m and 5–10 m splits, the MP calculated with the GPS was significantly higher than with EMG (0–5 m: $p = 0.03$, $F = 1.13$, $ES = 0.81$; 5–10 m: $p = 0.02$, $F = 1.67$, $ES = 0.89$). Conversely, in the 10–15 m and 15–20 m ranges, no significant differences were observed between both methods (10–15 m: $p = 0.31$, $F = 1.42$, $ES = 0.37$; 15–20 m: $p = 0.58$, $F = 1.76$, $ES = 0.20$; 20–25 m: $p = 0.39$, $F = 1.66$, $ES = 0.10$). In the 20–25 m, 25–30 m, 30–35 m, and 35–40 m splits, the MP was significantly lower when determined via the GPS rather than EMG (20–25 m: $p = 0.01$, $F = 1.66$, $ES = 0.31$; 25–30 m: $p \leq 0.001$, $F = 1.17$, $ES = 1.42$; 30–35 m: $p = 0.002$, $F = 0.48$; $ES = 1.19$; and 35–40 m: $p = 0.02$, $F = 1.15$, $ES = 0.98$). Lastly, no differences between the MP determined via the GPS and EMG were found in the 40–45 m ($p = 0.14$; $F = 0.94$, $ES = 0.54$) and 45–50 m splits ($p = 0.53$; $F = 1.38$, $ES = 0.22$). **Table SI** (in Supplementary) illustrates the values obtained after adjustments, applying the nonparametric statistical test.

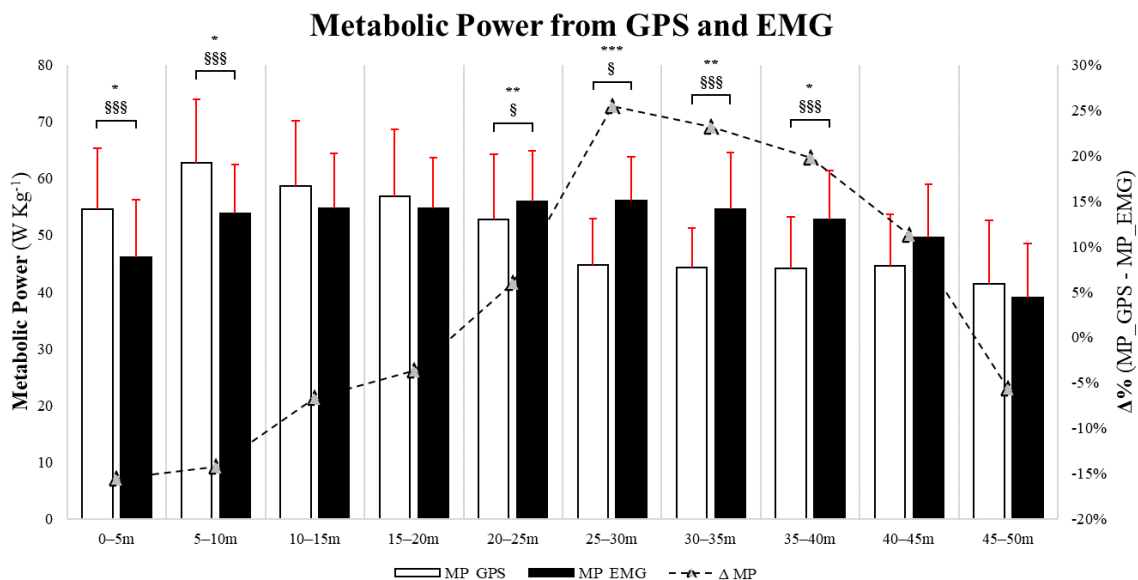


Figure 44. Metabolic power calculated via GPS and EMG methods during the linear 50 m sprint. * p -value ≤ 0.05 , ** $p \leq 0.01$, *** $p \leq 0.001$; § $ES \geq 0.20$, §§ $ES \geq 0.50$, §§§ $ES \geq 0.80$.

The EC estimated through the GPS and EMG is displayed in **Figure 45**. The data were not normally distributed at the distances 15–20 m, 20–25 m, 25–30 m, 30–35 m, and 35–40 m. No differences were found between both approaches in the 0–5 m split ($p = 0.30$, $F = 0.68$, $ES = 0.38$), which contrasts with the 5–10 m split, in which the EC determined via the GPS was significantly greater ($p = 0.001$, $F = 1.03$, $ES = 1.33$). In the 10–15 m ($p = 0.09$, $F = 1.03$, $ES = 0.63$), 15–20 m ($p = 0.09$, $F = 1.32$, $ES = 0.40$), and 20–25 m ($p = 0.54$, $F = 1.66$, $ES = 0.20$) ranges, no differences in EC were identified. Regarding the 25–30 m ($p = 0.02$; $F = 0.96$, $ES = 1.35$), 30–35 m ($p = 0.003$, $F = 0.61$, $ES = 0.95$), and 35–40 m ($p = 0.05$, $F = 1.14$, $ES = 0.76$) ranges, the EC estimated through EMG was significantly higher. Finally, in the 40–45 m ($p = 0.30$, $F = 1.57$, $ES = 0.37$) and 45–50 m splits ($p = 0.12$, $F = 2.78$, $ES = 0.56$), no differences were observed in the EC estimated with the GPS and EMG. **Table SII** (in Supplementary) illustrates the values obtained after adjustments, applying the nonparametric statistical test.

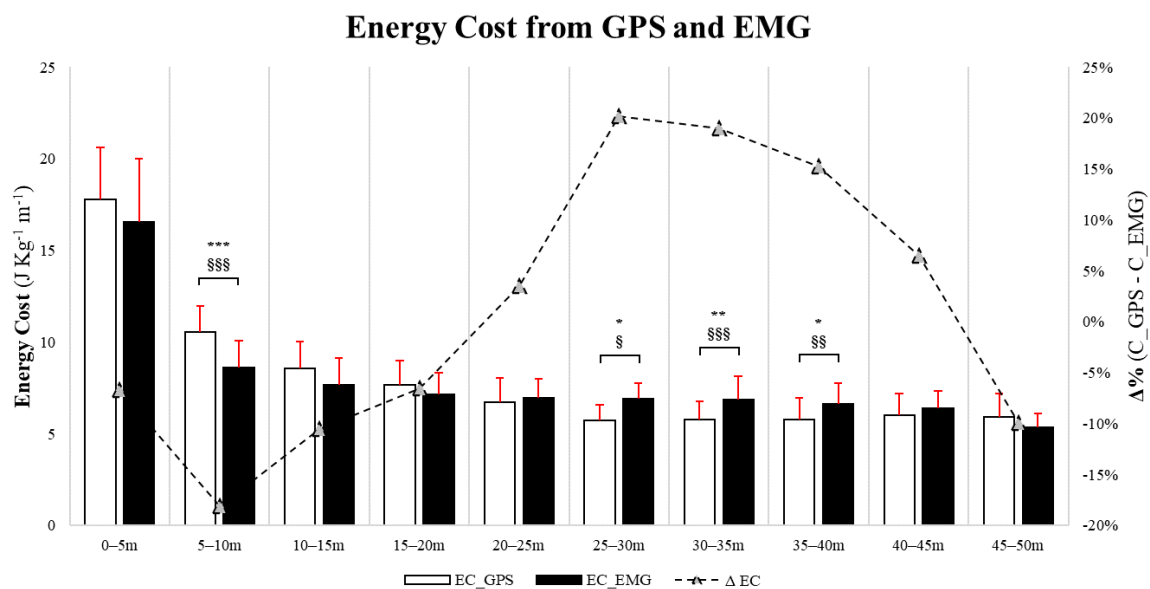


Figure 45. Energy cost calculated via GPS and EMG methods during the linear 50 m sprint. * p -value ≤ 0.05 , ** $p \leq 0.01$, *** $p \leq 0.001$; § $ES \geq 0.20$, §§ $ES \geq 0.50$, §§§ $ES \geq 0.80$.

6.4. DISCUSSION

The present study aimed to investigate the EMG activity and the EMG/F ratio during different submaximal and maximal runs and to study the differences between GPS-IMU and EMG technologies in the calculation of the MP and EC during constant running and sprinting efforts. The main findings indicate a linear increase in EMG values with running speed during the submaximal runs, which becomes exponential when considering the inclusion of sprinting. Moreover, the current results demonstrate the existence of a linear increase in the EMG/F ratio in sprints up to a breaking point (i.e., observed at 30 m) when an alteration in the overall trend is observed (i.e., considering the whole 50 m). In addition, differences were found at certain splits between the MP and EC calculated from the GPS-IMU and EMG, which indicates that these technologies cannot be used interchangeably to determine these metrics. Taking this into account, the present findings suggest that EMG seems to be a more precise technology for accurately estimating the MP and EC, showing a higher EC for sprinting, especially at greater speeds.

Notably, in the constant-speed runs, the EMG activity increased linearly with increasing speed. However, when also considering the sprint actions, the best-fitting trend becomes exponential (**Figure 42**). This might have an important implication for the study of the metabolic engagement of running efforts, as it supports the idea that sprint situations may cause an important increase in the energy expenditure of soccer players (Mero & Komi, 1987; Kyröläinen et al., 2005; Sonderegger et al., 2017; Hoppe et al., 2017). However, it should be considered that the present study did not specifically consider the EC of acceleration, high-speed running, and deceleration efforts, although from previous studies (Margaria, 1938; Minetti et al., 2002; di Prampero et al., 2005; Savoia et al., 2020), we could already hypothesize significant differences between these types of actions.

From a coaching perspective, the results herein could be used to determine the effective energetic and neuromuscular engagement needed for different types of actions and better understand performance models to develop the best training methodologies.

Another important parameter to be considered when investigating the interaction between external and internal loads during actions such as linear sprinting is the EMG/F ratio (Bosco, 1997; Grant & Habes, 1997; Hautier et al., 2000; Madeleine et al., 2001; Oksanen et al., 2008). The current data highlight that this ratio appears to linearly increase until a ‘breakpoint’, where a decrease occurs (i.e., at 30 m, as evidenced by the data interpolation in **Figure 43**), which may have significant practical applications. In brief, it indicates that the expression of neuromuscular parameters likely varies across different distances and sports contexts, providing practitioners with an ideal range of distances that could be used in sprint training. For example, for youth soccer players, from an energetic and neuromuscular perspective, it may not be optimal to perform linear sprints greater than 30 m due to the observed decline in EMG/F. In our analyzed sample, there appears to be difficulty in maintaining the neuromuscular engagement characteristics indicated by the EMG/F marker over longer distances. This may be due to poor sprinting habits for longer distances, particularly under static start conditions. Future studies should verify the behavior of this parameter in other populations of athletes (e.g., sprinters), assuming that the drop in the EMG/F ratio should be postponed as much as possible for those who must perform linear sprints.

Finally, based on the construction of an ad hoc profile that allowed for the calculation of the MP and EC from EMG, it appears that the GPS-IMU approach may systematically underestimate the actual cost of sprinting in a statistically significant manner, especially for sprint actions between 25 and 40 m, when compared to EMG. This may be explained, at least in part, by the fact that at higher speeds, acceleration rates are considerably lower (Sonderegger et al., 2016; Polglaze et al., 2016) but more costly; hence, the

GPS-IMU may not be the most appropriate approach to quantify energy expenditure. Of note, EMG technology seems to display different MP and EC engagement with a much more “curvilinear pattern” (i.e., a fourth-degree polynomial relationship) during sprints, thus emphasizing a different, realistically more accurate engagement in some splits. These considerations could be useful for coaches and physical trainers to understand actual energy engagement and neuromuscular parameters in soccer, knowing more about its limitations and potential (Polglaze et al., 2016; Hoppe et al., 2018). However, further research is required to determine the practical applications of this area of study in different populations with different purposes. In accordance with Van Hooren et al. (2019), the calculation of the markers would be important for optimizing energetic and mechanical efficiency, possibly minimizing injury occurrence resulting from internal (i.e., physiology) and external (i.e., environment) sources. All these findings seem to be important in characterizing sprint action. The MP and EC analyses using EMG in comparison to the GPS may provide more precise results for evaluating neuromuscular and metabolic activity. This approach can be advantageous for optimizing mechanical–energetic requirements and warrants further investigation, including cognitive engagement during exercises involving a ball.

This study has several limitations that should be considered when interpreting the results. Firstly, the cross-sectional design used prevents us from drawing any causal inferences regarding the examined variables. Secondly, only isolated and “decontextualized” linear sprints without a ball were assessed when it is known that, in soccer, most physical capacities are expressed along with technical–tactical elements with the ball (Licciardi et al., 2020; Ju et al., 2022). Thus, the data here should not be directly extrapolated to sprinting during soccer matchplay. Thirdly, other important running-based actions, such as accelerations and decelerations, were not assessed and compared in detail. Additionally, the EC and MP were

estimated through a GPS-IMU and EMG, and the use of a portable gas analyzer could have enhanced the study's accuracy, providing practical assistance and a better understanding when comparing data. This was demonstrated by Savoia et al. (2020) when comparing the GPS algorithm based upon di Prampero's theoretical model in elite soccer players with a measure obtained with a portable gas analyzer. Nevertheless, the methodological approach here is more practical and easier to apply in real-world contexts, which is an important point worth highlighting. Further research is necessary to determine whether and how the current findings may be affected by training adaptations.

The outcomes of this study may be useful for strength and conditioning coaches to plan their sessions more effectively. Our data examined the EC of running at different speeds and identified the EMG trends indicative of actual neuromuscular demands. The analysis of an internal-to-external load ratio, such as the EMG/F ratio, may be useful in determining appropriate distances for training. In addition, the differences between the MP and EC calculated by the GPS-IMU and EMG suggested an important underestimation of the actual demands of high-speed actions by the former (which must be considered when developing training exercises). However, it is important to note that the current data were collected from a sample of U17 soccer players from a Mediterranean context and that the generalization of the results to other populations should be made cautiously. Further research should be conducted to investigate these aspects and potential disparities in game scenarios.

6.5. CONCLUSIONS

In summary, this study presents a new perspective for characterizing running activities in soccer, utilizing parameters such as the EMG/F ratio and using the MP and EC calculated from EMG, and just a GPS-IMU. Defining and characterizing the specifics of physical engagement are strategic factors for designing a novel approach (Rumpf et al., 2016; Matusiński et al., 2022; Zabaloy et al., 2022) to study neuromuscular and metabolic activity to continue development (Minetti et al., 2002; Sonderegger et al., 2016; Polglaze et al., 2016; Savoia et al., 2020). Although additional research is necessary, these indicators appear suitable for accurately studying workload, improving performance, examining the dose–response relationship of exercise, and identifying the onset and modification of fatigue during competitions. In the future, a GPS-IMU and EMG should be validated against direct measures of energy expenditure, both external and internal, to determine their relationship with direct measures of fitness and performance.

6.6. SUPPLEMENTARY FILES

MP											
<i>Splits</i>	<i>Mean MP_GPS</i>	<i>SD MP_GPS</i>	<i>Mean MP_EMG</i>	<i>SD MP_EMG</i>	<i>CV (%) MP_GPS</i>	<i>CV (%) MP_EMG</i>	<i>p-value</i>	<i>ES</i>	<i>F</i>	<i>CI (95%, lower)</i>	<i>CI (95%, upper)</i>
<i>0-5m</i>	54.58	10.80	46.07	10.15	19.79%	22.04%	0.029*	0.81§§§	1.13	2.54	14.465
<i>5-10m</i>	62.77	11.23	53.81	8.70	17.89%	16.16%	0.017*	0.89§§§	1.67	2.56	15.381
<i>10-15m</i>	58.61	11.57	54.70	9.70	19.74%	17.74%	0.308	0.37§	1.42	-4.65	12.478
<i>15-20m</i>	56.88	11.83	54.78	8.91	20.80%	16.27%	0.575	0.20§	1.76	-3.89	8.086
<i>20-25m</i>	52.73	11.53	55.89	8.94	21.86%	16.00%	0.01**	0.31§	1.66	-11.72	4.195
<i>25-30m</i>	44.67	8.31	56.07	7.70	18.60%	13.73%	0.000***	1.42§§§	1.17	-15.88	-6.901
<i>30-35m</i>	44.25	6.97	54.51	10.04	15.75%	18.42%	0.002**	1.19§§§	0.48	-14.54	-5.982
<i>35-40m</i>	44.08	9.17	52.79	8.56	20.81%	16.22%	0.015*	0.98§§§	1.15	-14.59	-2.23
<i>40-45m</i>	44.53	9.17	49.58	9.46	20.59%	19.08%	0.136	0.54§§	0.94	-10.6	0.519
<i>45-50m</i>	41.35	11.20	39.02	9.54	27.08%	24.46%	0.532	0.22§	1.38	-2.67	7.318

Table S1. Metabolic Power outcomes and statistical analysis results for the different splits. CV = Coefficient of Variation; EC = Energy cost; ES = Effect size; SD = Standard deviation; * p-value≤0.05, ** p ≤ 0.01, *** p ≤ 0.001; §§ ES ≥ 0.20, §§ ES ≥ 0.50, §§§§ ES ≥ 0.80.

EC											
<i>Splits</i>	<i>Mean EC_GPS</i>	<i>SD EC_GPS</i>	<i>Mean EC_EMG</i>	<i>SD EC_EMG</i>	<i>CV (%) EC_GPS</i>	<i>CV (%) EC_EMG</i>	<i>p-value</i>	<i>ES</i>	<i>F</i>	<i>CI (95%, lower)</i>	<i>CI (95%, upper)</i>
<i>0-5m</i>	17.76	2.85	16.57	3.46	16.04%	20.87%	0.296	0.38§	0.68	-1.23	3.62
<i>5-10m</i>	10.54	1.45	8.64	1.42	13.71%	16.49%	0.001***	1.33§§§	1.03	0.84	2.97
<i>10-15m</i>	8.59	1.45	7.69	1.43	16.89%	18.59%	0.087	0.63§§	1.03	-0.30	2.10
<i>15-20m</i>	7.67	1.33	7.17	1.16	17.32%	16.11%	0.085	0.40§	1.32	-0.50	1.38
<i>20-25m</i>	6.72	1.33	6.95	1.03	19.84%	14.86%	0.542	0.20§	1.66	-1.32	0.69
<i>25-30m</i>	5.73	0.85	6.89	0.86	14.76%	12.52%	0.02*	1.35§§§	0.96	-1.76	-0.55
<i>30-35m</i>	5.78	1.00	6.87	1.29	17.38%	18.71%	0.003**	0.95§§§	0.61	-1.58	-0.61
<i>35-40m</i>	5.76	1.19	6.64	1.12	20.69%	16.80%	0.048*	0.76§§	1.14	-1.57	0.08
<i>40-45m</i>	6.02	1.16	6.41	0.92	19.20%	14.39%	0.298	0.37§	1.57	-1.04	0.26
<i>45-50m</i>	5.94	1.28	5.35	0.77	21.56%	14.36%	0.124	0.56§§	2.78	-0.15	1.33

Table S2. Energy Cost outcomes and statistical analysis results for the different splits. * p-value≤0.05, ** p ≤ 0.01, *** p ≤ 0.001; § ES ≥ 0.20, §§ ES ≥ 0.50, §§§ ES ≥ 0.80.

VII – STUDY 2

VII - STUDY 2

7.1. INTRODUCTION

Achieving high acceleration rates and top speeds in sprinting efforts is a key factor in team-sports (Zatsiorsky, 2000; Zafeiridis et al., 2005; Alcaraz et al., 2008; Alcaraz et al., 2009; Zabaloy et al., 2020; Sinclair et al., 2021). Therefore, training strategies to improve this type of action have been increasingly developed in recent years (Alcaraz et al., 2018; Zabaloy et al., 2022; Zagatto et al., 2022; Zisi et al., 2022; Zabaloy et al., 2023). For example, loaded sled towing has been used as a common method for resistance sprint training (Lockie et al., 2003; Linthorne & Cooper, 2013; Martínez - Valencia et al., 2014; Martínez-Serrano et al., 2021), usually prescribed based on a percentage of body mass or velocity loss (i.e., percentage of velocity loss relative to the maximum speed achieved (Zabaloy et al., 2023; Grazioli et al., 2023_{a,b}). Sled towing has been found to increase ground contact time, trunk angle, hip flexion (Zabaloy et al., 2023; Cronin et al., 2008; Pareja-Blanco et al., 2022; Pareja-Blanco et al., 2021), and shoulder range of motion due to added resistance (Alcaraz et al., 2008; Alcaraz et al., 2009; Pareja-Blanco et al., 2021; Hinrichs, 1987; Hinrichs et al., 1987) in a load-dependent manner (i.e., the greater the load, the greater the kinematic changes). To replicate sprint mechanics with an additional load (i.e., as a secondary training method (Zabaloy et al., 2022), programs primarily use lighter loads, as heavier loads can lead to acute changes in running form and disrupt normal acceleration kinematics (Alcaraz et al., 2008; Alcaraz et al., 2009; Zabaloy et al., 2023; Seitz et al., 2014). Therefore, appropriate load control helps achieve training specificity regarding movement patterns and speed (Bosch & Klomp, 2005; Bosch, 2015; Alcaraz et al., 2014). When it comes to short to long-term adaptations to sled towing shown this method to improve short-

distance sprint performance (e.g., acceleration and transition phases) and change of direction (COD) ability [McMorrow et al., 2019]. Sprint training without resistance, in turn, improves performance in the maximal speed phase; thus, it appears that each phase of sprint running requires a specific training approach (Bosco & Vittori, 1986; Péronnet & Thibault, 1989; Lacour, 1996; Verkhoshanky, 1996; Savoia et al., 2020; Buglione & di Prampero, 2012).

Notably, most research on sprinting (loaded and unloaded) has predominantly focused on its neuromuscular determinants, while relatively little attention has been devoted to examining the energetic demands associated with these efforts. In this regard, di Prampero et al. [2005] used the study by Minetti et al. [2002] to estimate the energy cost (EC) and metabolic power (MP) of running using a biomechanical equivalence. This approach redefined ‘high-intensity’ and offered new possibilities for quantifying workload and assessing physical performance in training and competition. However, this approach has yet to be applied in studies using sprints with resistance (e.g., sleds, parachutes, etc.) as the biomechanical and physiological differences from the original model may lead to discrepancies. Understanding the energetic demands of loaded sprinting could enable practitioners to optimize application of this method by determining, for example, the most appropriate timing for its use (such as during specific phases of the competitive season or within a weekly microcycle). In this context, a recently proposed model (Grassadonia et al., 2024) based on Colli [unpublished], could be reapplied to address this issue and allow the study the MP and EC of sprinting with an overload when compared to without external resistance.

Another parameter not studied in sprinting with resistance is apparent efficiency (AE). This metric corresponds to the ratio between total work and EC. The AE is based on various assumptions and tools (Asmussen & Bonde-Petersen, 1974; Kaneko, 1990; Alexander, 1991; Kyröläinen et al., 1995; Monte et al., 2020), with the concept of estimating total mechanical

work being controversial (Zatsiorsky, 2000; Hinrichs, 1987; Hinrichs et al., 1987; Monte et al., 2020; Willems et al., 1995). The sum of internal and external work represents the total work (mechanical and metabolic) performed to move the body over a given distance (Willems et al., 1995; Farris & Sawicki, 2012; Voigt et al., 1995). Therefore, previous studies have performed a kinematic-biomechanical analysis rather than a muscle-tendon analysis (Kaneko, 1990; Kyröläinen et al., 1995; Monte et al., 2020) and have not investigated AE during high-intensity actions such as loaded and unloaded sprinting. Considering that AE is derived from different modalities and movement patterns that are still unexplored, it is necessary to analyze this parameter during loaded and unloaded sprinting.

Hence, based on all of the above, the study aims to: 1) analyze the variations in muscle activation patterns (assessed as changes in relative contribution of the quadriceps, glutes and hamstring muscles) during sprints under different loading conditions; 2) investigate and compare the MP and EC of loaded and unloaded sprinting through the use of two novel methods (based on Global Positioning System [GPS] and electromyography [EMG] measures) [Grassadonia et al., 2024]; and 3) evaluate the AE of resisted sprint efforts. The hypotheses were that the relative muscle contribution would change as a load function, that MP and EC would be underestimated if determined using GPS technology, and that AE would be lower in resisted sprints compared to unloaded sprints.

7.2. MATERIALS AND METHODS

7.2.1. Study Design

A comparative cross-sectional study was designed and implemented with a convenience sample being recruited for the research. During the 2021/2022 preseason (i.e., July), data was collected from players of the same soccer club and category (under seventeen, U17) who were available to participate in the study. All measurements were performed during a single test session per player. The experimental procedures consisting on participants first completing four constant incremental runs over 50 meters to establish an ad-hoc running profile (Grassadonia et al., 2024). Sprints over 30-m were then performed under different loading conditions: unloaded sprint (US), parachute sprint (PS), and sled sprints with loads of 15, 30, 45, and 60 kg (SS15, SS30, SS45, and SS60, respectively). During the weeks before the study, all participants were submitted, in multiple occasions, to parachute and sled sprinting stimulus to become familiarized with these specific methods. On the testing day, before data collection, a warm-up consisting of mobility and athletic running exercises was completed for approximately 15 minutes. The players were familiar with all the exercises suggested during the warm-up as they were regularly included in the daily training practices. Before starting trials, there was a theoretical explanation and a practical demonstration.

7.2.2. Participants

A total of seventeen elite U17 male soccer players (body mass = 69.1 kg $\pm$ 5.7; height = 177.7 cm $\pm$ 4.7; body mass index = 21.9 $\pm$ 2 kg·m⁻²) competing in the Italian Championship volunteered to participate in this

study. Data were collected using the GPS-Inertial Measurement Unit (IMU) units Spinalia v2 (100 Hz) and the EMG system Myontec M-Body 3 (sampling at 1000 Hz and, subsequently, resampled to 100 Hz). Only players with no recent injuries or health problems that could limit their maximum effort were included in the study. Subjects and their legal guardians were informed in detail about all testing and training procedures, and the latter signed a written informed consent form. The local Human Subjects Ethics Committee approved the study in accordance with the Declaration of Helsinki.

7.2.3. Procedures

All tests were conducted on the same training and playing field (home field), without changing the grass pitch, and each player was provided with technical clothing suitable for the tests that did not impair their running characteristics. The players first performed a series of constant runs to meet the required theoretical standards (Grassadonia et al., 2024). Each player completed a maximal sprint over 30 meters following the continuous runs. Each participant executed six trials, one attempt per sprint type. Players were instructed to perform all-out efforts in each trial and could repeat the sprint if unsatisfied with their first attempt. To minimize the effects of fatigue on performance, a five-minute rest period was allowed between trials. Participants were verbally encouraged during the tests to complete each trial as quickly as possible to achieve the best possible results.

Constant Running Testing. Four incremental constant running speeds over 50 m were conducted, with required times of ~22.5, ~15, ~11.3, and ~9 seconds. A US test was then performed, using only the maximum speed reached (as registered by the GPS device) to create an individual profile, as

detailed by Grassadonia et al. [2024] and explained below (see *Ad-hoc Profiling* section).

Unresisted Sprint (US). The US protocol involved athletes performing a maximal sprint over 30-m without any external resistance. Athletes were instructed to sprint with maximal effort from a stationary position, covering the designated distance in the shortest time possible (Grassadonia et al., 2023; Grassadonia et al., 2024). The distance on the field was fixed using metric tape and cones to ensure the perfect visibility for the players (this was maintained for all sprint tests). In the absence of photocells or a radar gun, sprint performance was determined as the maximal instantaneous velocity recorded by the GPS device during the trial. The US represented the benchmark value for all other sprint conditions for all variables assessed (i.e., muscle activation, MP, EC and AE).

Parachute Sprint (PS). The PS required athletes to sprint while dragging a parachute (142 × 142 cm parachute size) attached to their waist to ensure the resistance aligned with the body's center of mass. This added resistance created drag, challenging the athletes' ability to maintain speed. Athletes performed maximal sprints over a specified distance 30-m with the parachute deployed. The PS test is frequently employed to assess an athlete's ability to generate sprinting under resisted conditions, emphasizing a scenario where athletes encounter external resistance by air (Alcaraz et al., 2008). In the present study, we ensured consistency using all players' identical field positions and parachutes. This approach was crucial in minimizing variables, as air resistance can be unpredictable and difficult to control in field test situations (Pugh, 1970). Nevertheless, during the month of July, 2021, the average wind velocity was fairly constant for the time of day of the testing sessions (~16h15) across the different days of data collection, ranging from ~17.5 km·h⁻¹ to 18.7 km·h⁻¹ (data retrieved from weatherspark.com). As for the US, sprint performance was determined as the maximal instantaneous velocity recorded by the GPS device.

Sled Sprint (SS). In the SS protocol, athletes sprint while towing a sled loaded with various additional loads (i.e., 15 kg, ~22% of body mass [$21.86 \pm 1.89\%$]; 30 kg, ~44% of body mass [$43.72 \pm 3.77\%$]; 45 kg, ~66% of body mass [$65.57 \pm 5.66\%$]; 60 kg, ~87% of body mass [$87.43 \pm 7.54\%$]). The order of the loads used (i.e., SS15, SS30, SS45 and SS60) was randomized for each participant. Despite the well-established limitations of using absolute loads, rather than relative loads (Zabaloy et al., 2023), the former were utilized due to the limited time available for conducting the tests. This approach allowed for more efficient data collection under the given time constraints. The sled was attached via a harness around the trunk and shoulders to distribute the load on the upper body. Athletes performed maximal sprints over the designated distance (i.e., 30-m) with the peak velocity registered by the GPS to be considered for analysis. GPS and EMG data were recorded and analyzed.

EMG recording and analysis. During the experimental trials, the players incorporated textile electrodes into EMG shorts (Myonear Pro, Myontec, Kuopio, Finland). The electrodes, endowed with conductive properties, and their associated wiring were seamlessly integrated into the fabric. These electrodes covered, globally, three major muscle groups on both sides and formed six differential EMG biosignal channels specifically targeting the quadriceps (Q), hamstrings (H), and glutes (G). The total muscle load, the sum of all EMG signals, was also recorded and considered for the analysis. Two different sizes of shorts (i.e., M and L) were provided, with participants being individually fitted with the most suitable size. The correct fit of the shorts proved to be a crucial factor as it allowed the necessary contact between the electrodes and the skin. This precaution reduced potential movement artifacts during the dynamic activities (Colyer & McGuigan, 2018). Before participants wore the shorts, a small amount of water was carefully applied to the electrodes to improve signal conduction, a technique recommended in previous research (Finni et al., 2007). The resulting EMG signals were transmitted and analyzed on a laptop. They

were recorded at 1000 Hz and analyzed using Myontec “Muscle Monitor” software version 3.1.0.4 (Kuopio, Finland). The textile electrodes embedded in the shorts were comparable to conventional surface EMG methods in recording lower limb muscle excitation data (Colyer & McGuigan, 2018). Each trial was first processed using a second-order Butterworth bandpass filter (with a bandwidth of 40-200 Hz determined by frequency domain examination and a signal voltage at a -3dB cut-off frequency). The filtered signals were then rectified and averaged at 100 Hz. The relative contribution of the Q, H and G to the whole recorded EMG signals during the US was used as a reference benchmark for all comparisons with the loaded sprints.

GPS and IMU recording and analysis. Integrating EMG data with GPS signals enabled a temporal and kinematic differentiation of the phases. Sprint analyses were performed with personalized spreadsheets. GPS movement patterns were determined based on GPS data (e.g., via di Prampero’s model [2005]), while integrated GPS-IMU data were used to determine EMG movement patterns (e.g., obtaining the EC_EMG from MP_EMG/Speed_IMU). According to the manufacturer’s instructions, the GPS data were recorded at 50 Hz and the IMU data at 100 Hz (Spinitalia S.R.L., Rome, Italy) [Padulo et al., 2019].

Ad-hoc Profiling. The profiling was performed before the sprint trials, utilizing an individualized linear profile for each athlete. This profile included slope and intercept and was constructed by plotting GPS MP and muscle load from all EMG signals acquired. A new, simple method was used to recalculate MP and EC from the EMG to ensure accuracy during the profiling (Colli, unpublished), as Grassadonia et al. [2024] explained.

Apparent Efficiency (AE). AE was calculated from the Total Work/EC ratio (both expressed in $\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) [Monte et al., 2020]. This was done since, to calculate efficiency, the metabolic and mechanical demands must be expressed in the same units. External work was calculated by first using triaxial integration of acceleration (x, y, z) multiplied by speed to obtain mechanical power. Then, the mechanical power was multiplied and

normalized by the time unit (correct condition so that the comparison is not affected by the duration), thus obtaining the external work. Regarding internal work, MP (obtained by EMG) was also used, multiplied, and normalized by the unit of time. Once the internal and external work were obtained, they were summed to obtain the total work. Then, the total work was divided by the net EC. Finally, EC_EMG and MP_EMG were used instead of GPS markers due to their higher accuracy, as demonstrated by Grassadonia et al. [2024]. GPS-IMU was only used to estimate external work. A clarifying equation follows:

Apparent Efficiency Calculation

$$AE = \frac{[(\text{Mechanical Power} * \text{Time Unit}) + (\text{Metabolic Power} * \text{Time Unit})]}{\text{Energy Cost}}$$

7.2.4. Statistical Analysis

Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) software, version 25.0 (Chicago, Illinois, USA), Microsoft Excel 2019 (Redmond, Washington State, USA), and Statistical Software Jamovi, version 2.3.28. Data are presented as means and standard deviations. In agreement with previously published studies (Grazioli et al., 2023_{a,b}), the velocity loss percentage (%) and intra-trial differences on a test of GPS and IMU were used to check the speed loss concerning the US. The coefficient of determination (R²) was used to assess the goodness of fit of the linear regressions (e.g., in relative muscle contribution and AE). The Kolmogorov-Smirnov test was used to verify if the values followed a normal distribution, while the Wilcoxon Signed Rank test was used for non-normally distributed data. A 2x6 repeated measures ANOVA with determination method (GPS-IMU, EMG) and loading condition (US, PS, SS15, SS30, SS45, and SS60) as factors were used to examine differences in

MP and EC. When significant method*loading interactions were found, pairwise comparisons with Tukey post-hoc analysis were conducted to confirm all statistical differences. Partial eta squared (η^2p) with threshold values fixed for small ($\eta^2p \geq 0.01$), medium ($\eta^2p \geq 0.06$), and large ($\eta^2p \geq 0.14$) was used to measure the effect size (ES) of the different variables in the ANOVA models and *Cohen's d* ES with the corresponding 95% confidence intervals were calculated for pairwise comparisons. Threshold values fixed for *Cohen's d* ES were considered small (≥ 0.2), medium (≥ 0.5), and large (≥ 0.8). A significance level of $p \leq 0.05$ for all procedures to determine statistical significance.

7.3. RESULTS

Figure 46 displays the comparison of MP determined by GPS and EMG data across the different loading conditions. Significant effects for method ($p \leq 0.001$; $\eta^2p = 0.53$) and load ($p \leq 0.001$; $\eta^2p = 0.78$) were found. When comparing the US with sleds, significant differences were found with GPS and EMG data (p ranging from 0.01 to 0.001 and ES ranging from 0.4 for the US to 1.1-2.1 in SS) but not in the PS ($p = 0.305$). Moreover, a significant method*load interaction was observed ($p \leq 0.001$, $\eta^2p = 0.78$). In the US condition, there were significant differences ($\Delta 11.2\%$; $p \leq 0.01$; ES = 0.4 [0.2;0.6]) between MP_GPS and MP_EMG. In the PS condition, MP_GPS and MP_EMG were not significantly different ($\Delta 8.4\%$; $p = 0.305$; ES = 0.3 [0.1;0.5]). Notably, in the SS15 ($\Delta -39.6\%$; $p \leq 0.001$; ES = 1.1 [0.9;1.4]), SS30 ($\Delta -73.0\%$; $p \leq 0.001$; ES = 1.6 [1.3;1.9]), SS45 ($\Delta -127.4\%$; $p \leq 0.001$; ES = 2.0 [1.6;2.3]) and SS60 ($\Delta -165.3\%$; $p \leq 0.001$; ES = 2.1 [1.7;2.4]) conditions, the MP_GPS values were significantly lower than MP_EMG.

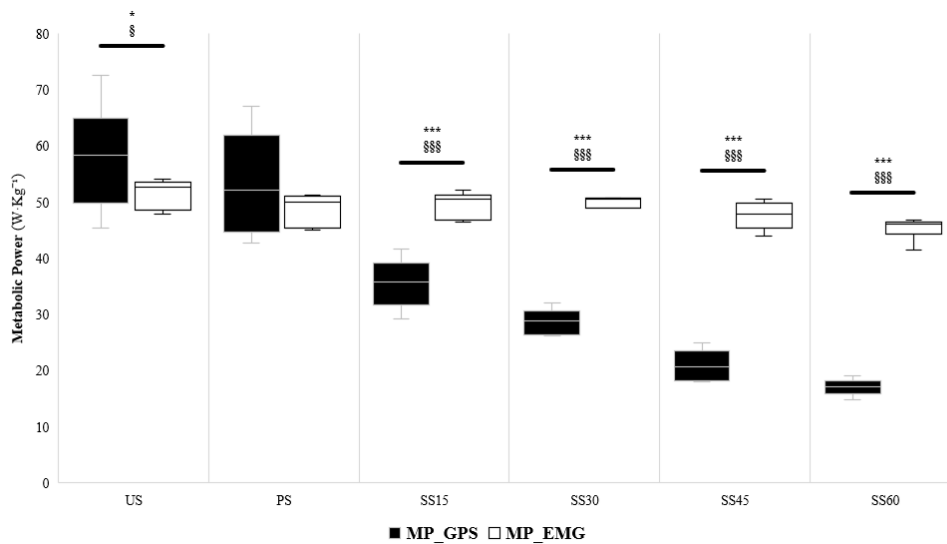


Figure 46. Comparison of the Metabolic Power determined through the GPS and EMG approaches in the different loading conditions. * p -value ≤ 0.05 , ** $p \leq 0.01$, *** $p \leq 0.001$; § ES ≥ 0.20 , §§ ES ≥ 0.50 , §§§ ES ≥ 0.80 .

Figure 47 shows the EC values obtained from both GPS and EMG approaches in all loading conditions. A significant effect for method ($p \leq 0.001$; $\eta^2 p = 0.57$) and load ($p \leq 0.001$; $\eta^2 p = 0.22$) was found. When comparing the US with the loaded sprints, significant differences were found with the GPS and EMG methods in all sled conditions (i.e., SS15, SS30, SS45, and SS60, all $p \leq 0.001$; d ranging from 0.4 with $p = 0.002$ to 0.9-1.8 in sleds) but not in the PS ($p = 0.102$). Moreover, a significant method*load interaction was observed ($p \leq 0.001$, $\eta^2 p = 0.73$). In the US condition, significant differences were found between approaches ($\Delta 12.9\%$; $p = 0.002$; ES = 0.4 [0.2;0.6]). Conversely, no significant differences were identified in the PS between EC_GPS and EC_EMG ($\Delta 10.7\%$; $p = 0.102$; ES = 0.3 [0.1;0.5]). Large significant differences were detected in the SS15 ($\Delta -38.8\%$; $p \leq 0.001$; ES = 0.9 [0.7;1.1]), SS30 ($\Delta -77.5\%$; $p \leq 0.001$; ES = 1.2 [0.9;1.4]) and SS45 ($\Delta -132.4\%$; $p \leq 0.001$; ES = 1.4 [1.2;1.7]) and SS60 ($\Delta -168.46\%$; $p \leq 0.001$; ES = 1.8 [1.5;2.1]) conditions, where the EC_GPS was lower than EC_EMG.

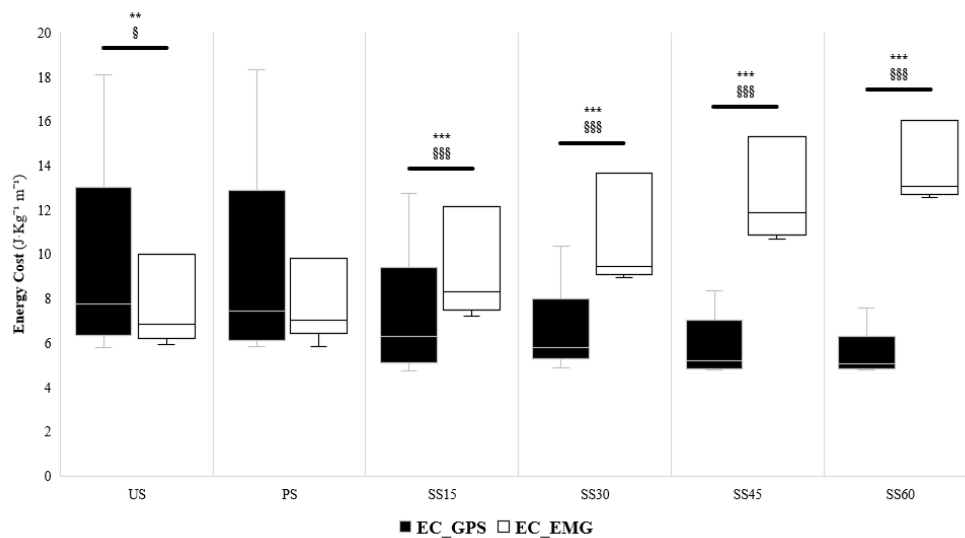


Figure 47. Comparison of the Energy Cost determined through the GPS and EMG approaches in the different loading conditions. * p -value ≤ 0.05 , ** $p \leq 0.01$, *** $p \leq 0.001$; § ES ≥ 0.20 , §§ ES ≥ 0.50 , §§§ ES ≥ 0.80 .

Figure 48 depicts the relative muscle contribution of the Q, H and G (in percentage of the total muscle load detected) in the different sprinting conditions. The muscle's relative contribution, expressed in percentage, shows statistically significant differences that grow with increasing overload (**Figure 48A** and **48B**). A linear increase was observed in the Q and G activation as load increased ($R^2 = 0.98$ and $R^2 = 0.94$, respectively); conversely, a linear decline was found with increasing loads in the H activity ($R^2 = 0.99$) (**Figure 48A**). **Figure 48B** details the relative contributions of the Q, H, and G in terms of muscle activation. Considering the US and the PS conditions, significant differences were found in the Q ($p = 0.011$; ES = 0.3 [0.1;0.5]) but not in the H ($p = 0.569$; ES = 0.1 [0.1;0.3]), and G ($p = 0.095$; ES = 0.2 [0.0;0.4]). Regarding SS15, no significant changes were found for the Q ($p = 0.148$; ES = 0.1 [0.1;0.3]), but a significantly greater and lower EMG activity was observed for the G ($p \leq 0.001$; ES = 0.4 [0.2;0.6]) and H ($p \leq 0.001$; ES = 0.5 [0.3;0.7]), respectively. In the SS30, no significant differences were reported in the relative contribution of the Q ($p = 0.004$; ES = 0.3 [0.1;0.5]), but significantly lower and higher relative muscle activations were registered for the H ($p \leq 0.001$; ES = 0.7 [0.5;0.9]) and the G ($p \leq 0.001$; ES = 0.4 [0.2;0.6]), respectively. In the SS45 condition, significantly different muscle activation patterns concerning the US were found in all three muscles assessed: Q ($p \leq 0.001$; ES = 0.5 [0.3;0.7]), H ($p \leq 0.001$; ES = 1.0 [0.8;1.3]) and G ($p \leq 0.001$; ES = 0.5 [0.2;0.7]). Lastly, for the SS60, the results followed the same trend as in the previous conditions with significantly higher contributions of the Q ($p \leq 0.001$; ES = 0.8 [0.6;1.0]) and G ($p \leq 0.001$; ES = 0.5 [0.3;0.7]) and significantly lower for the H ($p \leq 0.001$; ES = 1.5 [1.2;1.8]).

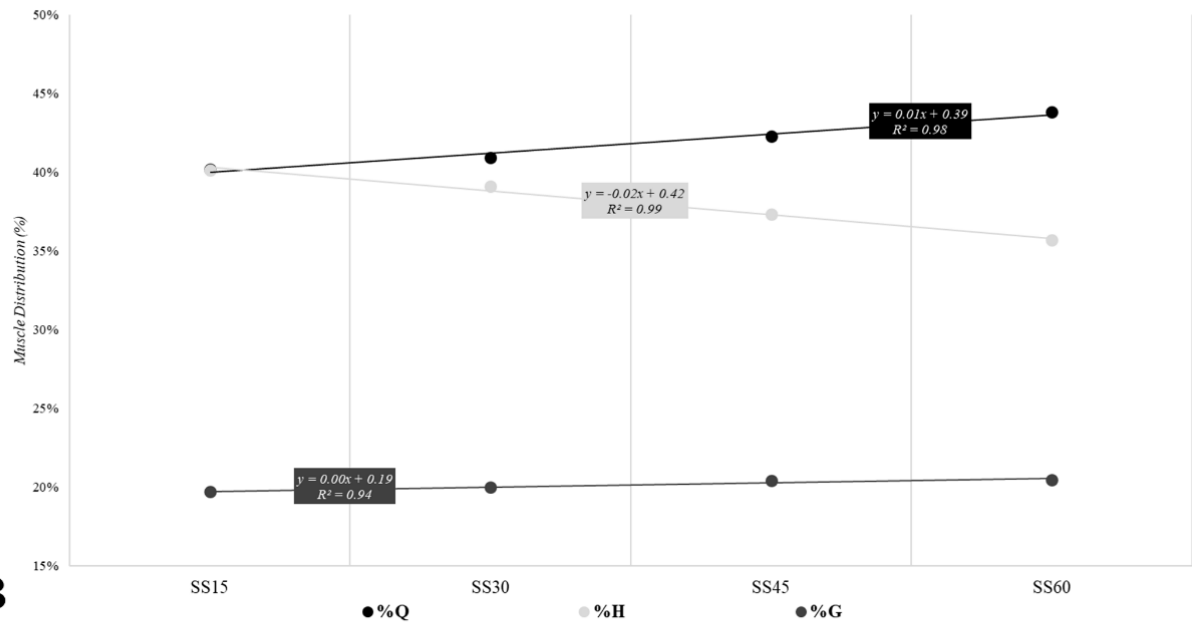
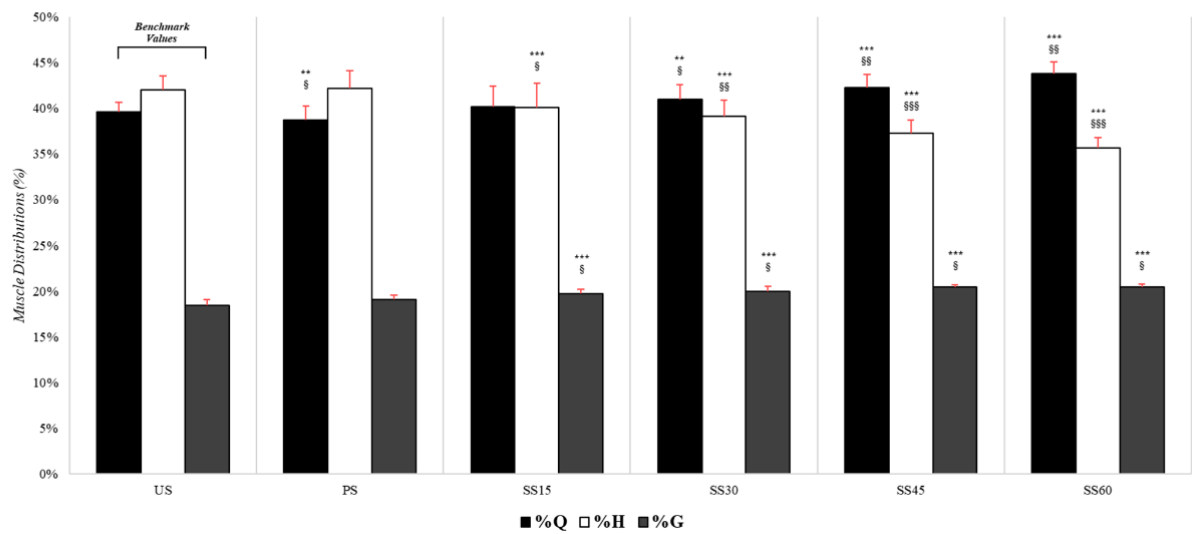
A**B**

Figure 48.. Linear regressions of the relative contribution of the quadriceps, hamstrings, and gluteus muscles as a function of sled load (A). Comparison of the muscle distribution in each loading condition (B). *p-value $\leq$ 0.05, **p $\leq$ 0.01, ***p $\leq$ 0.001; § ES $\geq$ 0.20, §§ ES $\geq$ 0.50, §§§ ES $\geq$ 0.80

Table IV presents the AE's descriptive data, and **Figure 49** displays the linear regression ($R^2 = 0.99$) obtained when plotting AE from the different sprinting conditions. A statistically higher AE_US was found when compared to AE_PS ($p \leq 0.001$; ES = 0.5 [0.3;0.7]). Likewise, statistically significant differences were found when comparing the former with AE_SS15 ($p \leq 0.001$; ES = 1.8 [1.5;2.1]), AE_SS30 ($p \leq 0.001$; ES = 2.4 [2.0;2.7]), AE_SS45 ($p \leq 0.001$; ES = 2.8 [2.4;3.2]); and AE_SS60 ($p \leq 0.001$; ES = 3.2 [2.7;3.6]).

	Apparent Efficiency (Arbitrary unit)
US	1.14 ± 0.24
PS	1.08 ± 0.23
SS15	0.90 ± 0.22
SS30	0.76 ± 0.19
SS45	0.60 ± 0.14
SS60	0.50 ± 0.12

PS: Parachute Sprinting; SS: Sled Sprinting; US: Unloaded Sprinting.

Table 4. Descriptive data on the Apparent Efficiency in the different sprinting conditions

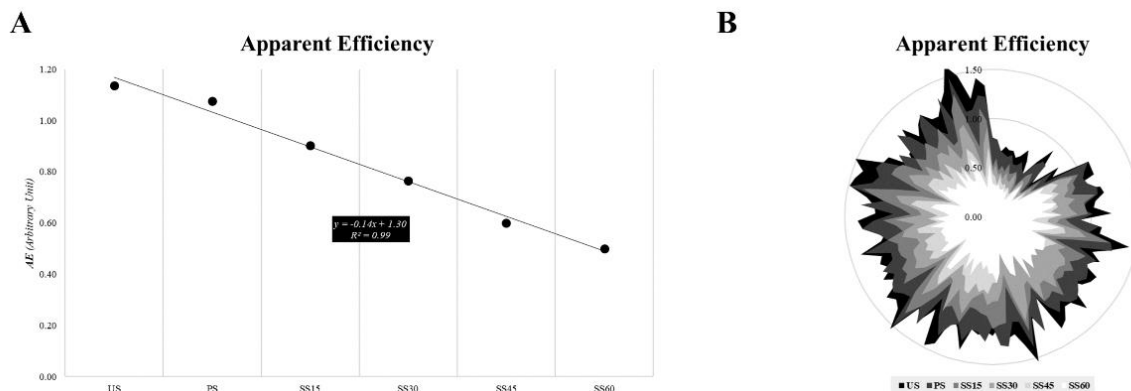


Figure 48. Linear regression of the Apparent Efficiency as a function of sled load (A) and qualitative trend states comparison at each 5m split for a single player (B).

7.4. DISCUSSION

Sprinting is essential to many sporting activities, making it crucial to study the muscle engagement and the metabolic and energetic requirements of different sprints (Alcaraz et al., 2008; Zabaloy et al., 2023; Bosch & Klomp, 2005; Bosch, 2015; Colyer et al., 2018_{a,b}; Priyantono et al., 2023). As such, in the current research, alterations in the relative muscle contribution of the Q, H, and G, as well as the EC, MP, and AE were assessed during resisted sprint efforts using a novel approach recently employed in unloaded sprinting (Grassadonia et al., 2024). The main findings were that: 1) a greater relative contribution of the Q and G were observed with increasing loads in resisted sprints; in contrast, lower activations of the H were noted; 2) changes in EC and MP were observed in the sled conditions (i.e., SS15, SS30, SS45 and SS60), with the GPS-derived calculations significantly underestimating these metrics when compared to the EMG-derived values; 3) an almost perfectly linear decrement in AE was observed when the imposed external resistance increased ($R^2 = 0.99$).

Regarding muscle recruitment during resisted sprints, the present findings indicated that PS did not result in different activation patterns of the Q, H, and G compared to the US condition. This outcome was somehow expected, as the parachute introduces only a minimal overload, seemingly insufficient to markedly alter muscle activation. In contrast, when sleds were used, the activation of the Q significantly increased as a function of load as opposed to the H, in which the relative contribution decreased linearly (**Figure 48A**). Thus, H showed an inverse behaviour to Q, which increased and became the primary active muscle as more load was added (due to increased knee flexion and reduced leg stiffness with higher loads [Zabaloy et al., 2022]). These findings align with those by Zabaloy et al. (2020) and van den Tillaar (2021_a) that also reported significant lower and higher H and Q EMG activity, respectively, with increasing loads in resisted sprinting. These alterations are partially explained by the acute changes in

running mechanics that occur in loaded sprints (Zabaloy et al., 2022; Pareja-Blanco et al., 2022) that eventually change muscle recruitment. Therefore, based on the reported disruptions in muscle activity, stiffness, and running kinematics (e.g., reduced stride length, different trunk or lower limb angles) when heavier sled loads are used (e.g., above 30% velocity loss) [Zabaloy et al., 2022; Pareja-Blanco et al., 2022], it has been suggested that players may not be “sprinting” but instead, “strength training” (Zabaloy et al., 2023). In this regard, SS may presumably have a lower transfer to high-speed actions (e.g., maximum velocity phase of sprinting) being, instead, better suited to improve acceleration capabilities (Zabaloy et al., 2023; Pareja-Blanco et al., 2022; Pareja-Blanco et al., 2021; van den Tillaar, 2021_b; van den Tillaar et al., 2021). Altogether, the present findings indicate that PS appears to cause fewer changes in muscle activation patterns compared to SS in youth soccer players. Using the former may be advantageous when the goal is to replicate US conditions with a slight overload. However, practitioners should be aware that, with PS, controlling training load is challenging, more complex, and less controllable (e.g., depends on air resistance and environmental conditions), especially during the acceleration as opposed to the maximum velocity phase (Alcaraz et al., 2008). Further research is needed to confirm these findings and to fully understand the mechanisms behind the broader effects of PS and SS.

Notably, when sleds were used (i.e., SS15, SS30, SS45, and SS60), the MP derived from EMG differed significantly from that derived from GPS, which was not the case in the PS condition. As the load on the sled increased, GPS data produced a larger error in estimating MP due to GPS calculations being based on acceleration data, which may not provide an estimate of effective energy input in these conditions (Savoia et al., 2020; Osgnach et al., 2010; Sonderegger et al., 2016; Piras et al., 2017; Licciardi et al., 2020). The present findings indicated that the MP derived from the EMG remained practically constant while the GPS-derived calculation decreased. Thus, with increasing loads, a greater divergence of the data obtained from GPS

and EMG was noted (e.g., **Figure 46**). This may be explained by the fact that MP is the product of EC and speed, and, as EC increases with sled load (**Figure 47**), but the speed decreases, the MP remains stable when derived from EMG (despite being attained in entirely different ways). This indicates that MP derived from the external load data (as GPS) might underestimate the effort during the loaded sprint. Therefore, researchers and physical trainers should be cautious and aware when prescribing sprint runs with specialized modalities (e.g., sleds) and use the MP and EC obtained from EMG (rather than GPS-IMU) to assess its effective neuromuscular and energetic commitment. Another aspect worth highlighting is that the variability among GPS splits was greater than that of the EMG, which is essential from a qualitative perspective (Grassadonia et al., 2024). Thus, when evaluating actions against resistance, using EMG to determine the actual neuromuscular and metabolic demands properly would be desirable.

Finally, regarding AE, a linear decay ($R^2 = 0.99$) was observed with the addition of loads during the sprints (**Figure 49A** and **49B**), which is a clear indication of the effects of the external resistance on efficiency. In a previous study, Monte et al. (2020) analyzed AE during dynamic efforts such as constant running at different speeds and concluded that the “apparent” running efficiency increased with increasing constant speed (10, 13, and 16 km·h⁻¹). However, direct comparisons with the present findings are impossible to draw since, to date, no study has investigated AE in resisted sprinting (to the authors’ knowledge). The results of Zabaloy et al. (2022) indicate that, as load increased, the ability to store and release elastic energy (hence, to “recycle” mechanical work) was significantly compromised. The authors noted significantly lower leg stiffness values when external resistance increased, which suggested that stretch-shortening cycle function was impaired under heavier-sled load conditions. For all of the above, determining AE could prove very useful in practice as it provides an appropriate response to the effect of different external resistance during sprints. From an applied perspective, practitioners should keep in mind that

if the goal is to develop maximum speed capabilities (with short, reactive, and forceful ground contacts with optimal utilization of the stretch-shortening cycle is key) [Bosco & Vittori, 1986; Douglas et al., 2018; Douglas et al., 2020; Mero et al., 1992], sled towing should be used with caution (Zabaloy et al., 2022).

This study has limitations that must be considered when interpreting the results. In particular, the mechanical-energetic engagement (Bezodis et al., 2019; Jarvis et al., 2017; Malone et al., 2017; Novacheck, 1998; Winwood et al., 2016) was evaluated against the same absolute loads which does not account for variability in athletes' anthropometric characteristics or performance (i.e., velocity and force production) [Zatsiorsky, 2000; Sinclair et al., 2021; Zabaloy et al., 2023; Priyantono et al., 2023]. However, this decision was made in conjunction with the team's coaching staff since it was the most time-efficient manner to implement this study during the preseason (despite acknowledging that using load thresholds relative to the athletes' body mass or speed loss could have improved the study's accuracy and allowed further comparison of data among individuals). Also, even though the average wind velocity was fairly constant across the different days of data collection, it is essential to recognize that slight variations in climatic conditions could have influenced PS performance. Finally, the methodological approach used to obtain the AE data limits the comparison with the few previous studies that have analyzed this variable (Minetti et al., 2002; Asmussen & Bonde-Petersen, 1974; Kaneko, 1990; Alexander, 1991; Kyröläinen et al., 1995; Monte et al., 2020; Zamparo et al., 2016). Further research is needed to determine if and how training adjustments can influence the current results. Nevertheless, the present research represents the first attempt in the literature to capture these data in resisted sprinting (e.g., EC, MP, AE) and offers a new perspective on sprint evaluation.

7.5. CONCLUSIONS

The present findings may help strength and conditioning coaches plan their training sessions more effectively. Firstly, the current results support that muscle activation patterns change as a function of load in sprinting. Thus, coaches should be aware that, as load increases, so does the activation of the Q and G as opposed to the H, that become less determinant under heavier loading. Secondly, practitioners must acknowledge that PS may be preferred when the goal is to replicate US conditions with a slight over-load, without major disruptions in running mechanics and alterations in muscle involvement. Thirdly, the current data demonstrate that GPS-derived MP and EC underestimate the neuromuscular and metabolic demands imposed on youth soccer players, particularly under heavier load conditions (i.e., > SS15). Therefore, EMG-derived calculations are recommended to better understand the EC and MP of loaded sprinting actions. Finally, coaches and physical trainers should consider the decreased AE and increased EC associated with augmented loads. Future research should investigate parameters such as muscle load and relative recruitment of each muscle group detected, as well as speed, MP, and EC analysis when applying different training methods. These modalities of sprint development, including US, PS, and SS protocols, provide valuable insight into an athlete's sprinting abilities under various conditions and provide essential data for optimizing training programs and improving performance.

VIII – DISCUSSION

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The integration of GPS and EMG technologies has brought about a revolutionary change in the study of human performance in sports. These tools have provided unprecedented insights into the physical and physiological demands of high-intensity activities such as sprinting, jumping, and other sport-specific movements (Grassadonia et al., 2024). They have enabled more accurate assessments of key markers such as MP and EC, which are critical to understanding performance dynamics and optimizing training methods.

One of the most important developments in sports science has been the widespread use of EMG to assess neuromuscular activation during dynamic activities. Studies such as that by Montini et al. (2017) have shown that continuous recording of EMG signals in athletes, particularly during activities such as sprinting and competitive games, provides crucial insights into muscle activation patterns that were previously inaccessible.

The literature consistently shows that muscle activation patterns vary depending on the type of activity, intensity, and external load. For example, Bosco & Vittori (1986) highlighted the importance of improving during maximal effort sprints in sprinting. These findings were later extended by Komi (2000), who showed that pre-activation, a rapid eccentric phase, and a quick transition into concentric movement are crucial for maintaining optimal performance in SSC-based movements such as sprinting and jumping.

However, despite these advances, there are still limitations to the continuous and practical use of EMG in the field, particularly in competitive environments where movement artifacts and external conditions can compromise electrode placement and signal reliability (Farina et al., 2004; Pesola et al., 2022). Nevertheless, recent developments in wearable EMG

technologies, as described by Finni et al. (2007), offer promising solutions that allow for more consistent data acquisition during dynamic and complex movement patterns.

di Prampero et al. (2005) introduced the concept of MP by recalculating with biomechanical equivalence, marking a significant paradigm shift in the quantification of physical exertion in team sports. Traditionally, the physical demands of soccer and similar sports were assessed using time-motion analysis, which measured variables such as total distance covered and running speed. However, these measurements often do not consider the significant metabolic demands of acceleration and deceleration, which are key components of high-intensity sports such as soccer (Osgnach et al., 2010).

By combining GPS data with biomechanical models, di Prampero and colleagues could more accurately estimate the energy cost of these movements. A study by Savoia et al. (2020) expanded on this work by validating GPS-based measures of MP during high-intensity running activities. These studies confirmed that GPS is a reliable tool for tracking external workloads and estimating the energy expenditure required to perform accelerating and decelerating actions in team sports.

However, despite its widespread use, GPS-based assessment of MP has notable limitations, particularly in capturing internal physiological workload. Stevens et al. (2014) found that while GPS accurately measures speed, distance, and acceleration, it does not directly measure the muscular and neuromuscular responses that produce those movements. The actual limitation might be much more pronounced for para-isometric movements between GPS and EMG rather than only for movements with high rates of dynamism (Colli, unpublished; Grassadonia et al., 2024). This has increased interest in combining GPS with other technologies, such as EMG, to develop a more holistic understanding of athlete performance.

Integrating GPS and EMG technologies represents a powerful approach to understanding the external and internal stresses to which

athletes are subjected. The synergy between these tools provides a more comprehensive performance analysis, allowing coaches and sports scientists to design training programs more effectively. As Aughey (2011) points out, while GPS is ideal for tracking the physical demands of field sports, it needs to be complemented by neuromuscular assessments, such as those provided by EMG, to gain insight into how muscles respond to different training stimuli (Montini et al., 2017; Grassadonia et al., 2024).

Recent studies have emphasized the importance of combining GPS and EMG to overcome the limitations associated with each tool individually. For example, Nagahara et al. (2016) have shown that using GPS to measure external load provides a partial picture of performance. By integrating EMG, researchers can track how muscle activation patterns change in response to fatigue or different external loads (Colli, unpublished; Grassadonia et al., 2024). This provides valuable data for injury prevention strategies and training adaptations (Montini et al., 2017; Grassadonia et al., 2024). This combination is particularly relevant in sprints with resistance, where the external load significantly alters metabolic and neuromuscular demands.

Although GPS and EMG have made significant progress in sports science, limitations remain. For example, there are issues with accuracy when GPS devices are used in environments with signal interference (Witte & Wilson, 2004). Similarly, although EMG provides valuable data on muscle activation, it is susceptible to factors such as electrode placement, skin impedance, and movement artifacts (Finni et al., 2007; Pesola et al., 2022).

The primary objective of this thesis was to develop an innovative model to determine key performance markers such as metabolic power (MP), energy cost (EC), apparent efficiency (AE), and EMG/Force ratio (EMG/F). These markers were analyzed within typical movements in elite youth soccer players, such as sprinting, using integrated technological approaches with GPS-IMU, and electromyography (EMG). To explore the application of these approaches comprehensively, we examined the impact

on different movement patterns. The findings contribute significantly to understanding mechanical-energetic demands, muscle activation patterns, and training optimization with performance settings.

The first study examined EMG activity during submaximal and maximal running efforts. Furthermore, it explored the behavior of speed and force, particularly in sprinting performance. A fundamental discovery was the linear increase in the EMG/F ratio during the sprints until a breakpoint was identified at 30 meters. Beyond this breakpoint, the relationship between EMG activity and force began to plateau, indicating a shift in neuromuscular engagement as the sprint progressed.

Additionally, the study found significant differences between MP and EC values calculated using GPS-IMU versus EMG technology. The discrepancies between these technologies suggest they cannot be used interchangeably when measuring MP and EC. Precisely, the EMG data captured muscle activation patterns, leading to a more accurate estimation of neuromuscular demands. Developing an individual profile for recalculating MP and EC by EMG is important, as it can better inform training programs to optimize sprint performance. The creation of such a profile provides a foundation for understanding how energetic and neuromuscular workloads interact during high-intensity running. A novel energetic approach from the EMG-derived method is more accurate for calculating the MP and EC.

Building on the foundational findings of the first study, the second study evaluated muscle engagement under various resisted sprint conditions, including sled sprints (SS15, SS30, SS45, SS60) and parachute sprints (PS). This work builds on earlier studies but introduces a novel approach by examining muscle activation and AE during different types of sprints. One of the primary findings was that increasing the external load in resisted sprints significantly altered muscle activation patterns and the corresponding mechanical demands. Specifically, higher loads induced different muscle pattern activation, as evidenced by the behavior of EMG

percentage distribution in different muscle groups (e.g., linearly increasing quadriceps recruitment at the expense of hamstrings). Building upon these findings, we can further evaluate the practical implications for training design and performance enhancement.

Interestingly, using different types of resistance sprints resulted in varying muscle engagement, MP, EC, and AE levels. There are statistically significant differences between GPS-IMU and EMG, which increase as the external resistance increases, which makes the GPS-IMU technology that only evaluates the external load of little use in correctly detecting the actual commitment of such actions. These findings have significant practical implications for training design, suggesting that the type of resistance training must be carefully chosen based on the specific performance outcomes being targeted, whether that be maximal strength, speed, or endurance.

Developing a novel model to calculate MP, EC, AE, and EMG/F ratios marks a significant advance and opens new perspectives for analyzing sprint mechanics. However, the observed discrepancies between GPS-IMU and EMG-derived metrics highlight a fundamental limitation in external load measurements on athletes during high-intensity actions such as sprints, especially under resistance conditions (e.g., PS and SSs). This highlights the importance of integrating multiple data sources to create a more comprehensive picture of sports performance. In future work, refinement of this model to include additional physiological markers such as oxygen consumption, heart rate variability, lactate accumulation, etc., could improve accuracy and applicability in training and competition contexts.

In addition, questions such as the following arise: Could chronic exposure to high-resistance sprinting increase the risk of muscle imbalances or overuse injuries? Answering this question requires a deeper investigation into the neuromuscular trade-offs that occur during different resistance

sprinting protocols. There is also a need to investigate how these adaptations affect sprint mechanics and injury risk over time.

Moreover, the concept of a breakpoint in the EMG/F ratio during sprinting presents an unexplored opportunity for further investigation in other sports. The plateau observed after 30 meters suggests a shift in neuromuscular engagement that could be related to the onset of fatigue or changes in motor unit recruitment strategies. Investigating the mechanisms underlying this shift — whether metabolic, neural, or mechanical — could provide new insights into how athletes manage fatigue during high-intensity efforts. Furthermore, investigating how different training interventions influence this breakpoint could lead to developing targeted strategies to delay fatigue and maintain maximal performance over longer distances.

IX – CONCLUSIONS

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9.1. GENERAL CONCLUSIONS

The hypotheses conducted in this thesis successfully contributes to the understanding of key markers involved in motor actions typical of athletic demands, particularly sprinting in elite youth soccer players. By introducing a novel model that integrates MP, EC, AE, and EMG/F, this work establishes a framework that can be used in both practical and theoretical applications for performance analysis and training optimization. The results provide essential insights into the physiological and biomechanical demands of sprinting and emphasize the crucial role of neuromuscular coordination in sports performance. Furthermore, integrating GPS-IMU technology with EMG measurements enables a more precise assessment of sprint mechanics and provides coaches and sports scientists with a comprehensive tool to evaluate athletic performance. Overall, this thesis contributes to a deeper understanding of the energetic and mechanical complexity of sprinting and provides practical implications for developing more effective training methods tailored to the specific demands of elite youth athletes.

Coordination and cognitive engagement have emerged as critical factors affecting the efficiency and cost of sprinting that need to be investigated soon. The integration of EMG with GPS-IMU, a precise and advanced method, provides a detailed understanding of muscle activation patterns, particularly lower limb muscles, during the acceleration, deceleration, and maximum speed phases of sprinting. This facilitates the identification of potential muscular imbalances or inefficiencies and offers a

diagnostic tool for the development of team and individual training programs.

Moreover, the application of MP and EC models represents a significant advance in quantifying the physiological demands of sprinting. It goes beyond only using traditional measures such as time and distance. To address external and internal loads, the proposed new model allows for a more accurate estimation of energetic and neuromuscular demands on athletes, which can be further optimized for training plans. The results emphasize the importance of balancing the ratio between work and cost with relative efficiency, thus providing a basis for developing targeted interventions to improve athletes' capacities.

The practical application of GPS-IMU technology offers new opportunities for field-based sprint analysis, particularly in a competitive context. Proper monitoring of ACC, DEC, and HSR provides a deep understanding of athlete performance under competitive conditions. This technology can be further refined to monitor load management, injury prevention, and recovery strategies. Combining these technologies in a cohesive framework improves the accuracy and reliability of performance assessment and ensures that the data collected can be used directly to optimize training and performance.

Furthermore, this thesis opens up several avenues for future research. Longitudinal studies are still needed to investigate changes in muscle-tendon stiffness and architecture, motor control, and muscle fiber recruitment patterns, which could further elucidate the mechanisms underlying sprint performance in technical-tactical contexts (e.g., SSG, match, etc.). Examining these factors concerning age, maturation, and training experience would provide valuable insight into the scope of developing age-appropriate training protocols that maximize physical development while minimizing injury risk.

In conclusion, integrating advanced biomechanical and physiological models combined with state-of-the-art technological tools provides the basis

for a new approach to performance analysis. The insights acquired from this thesis contribute to the existing knowledge of sprint mechanics and have wide-reaching implications for applied sports science and training methodology. This work highlights the need for individualized training approaches as part of a comprehensive understanding of the multifactorial nature of running performance.

9.2. SPECIFIC CONCLUSIONS

Study 1:

- The analysis of submaximal running effort at different constant speeds revealed crucial differences compared to sprinting (linear *versus* exponential trend).
- The results showed that the EMG/F ratio varied significantly across sprint distances, with different neuromuscular profiles emerging for 30 m and 50 m sprints and for the corresponding 5 m sections.
- Integrating GPS-IMU and EMG data provided a robust approach for calculating EC and MP. It led to the development of a detailed neuromuscular profile that can be used to optimize training and performance.

Study 2:

- Different loading conditions influence muscle activation patterns during sprinting. In particular, Q and G increase linearly with heavy loads in sleds, while H decreases linearly.
- The study examined the variations of MP and EC in each sprint condition and showed that load significantly alters both parameters. GPS and EMG technologies proved essential in capturing these complex interactions, enabling a comprehensive comparison between loaded and unloaded sprints and providing valuable evidence for applying resistance training in elite youth soccer.
- The study found that AE decreased under resistance conditions, supporting the hypothesis that higher resistance leads to lower efficiency during sprinting.

X - LIMITATIONS



X - LIMITATIONS

Study 1 has several limitations that should be considered when interpreting the results. First, the cross-sectional design prevents us from drawing causal inferences about the variables studied. Second, only isolated and “decontextualized” linear sprints without the ball were examined. However, it is known that in soccer, most physical skills are expressed with the ball, along with technical and tactical elements. Therefore, the data here should not be extrapolated directly to sprinting during a soccer match. Thirdly, other necessary running actions, such as accelerations and decelerations, were not assessed and compared in detail. In addition, EC and MP were estimated using a GPS-IMU and EMG. Using a portable gas analyzer could have improved the study’s accuracy and provided practical help and a better understanding when comparing the GPS algorithm based on di Prampero’s theoretical model in elite soccer players with measurement using a portable gas analyzer. Nevertheless, the methodological approach used here is more practical and easier to apply in real-world contexts, which is crucial to emphasize. Further research is needed to determine how training adjustments influence current findings.

Study 2 has limitations that need to be considered when interpreting the results. Specifically, mechanical-energetic engagement was assessed using the same absolute loads, which does not account for variability in athletes’ anthropometric characteristics or performance (i.e., speed and force production). However, this decision was made in conjunction with the team’s coaching staff, as this was the most time-efficient manner to conduct this study in the preseason (although the use of load thresholds related to athletes’ body mass or speed loss could have improved the accuracy of the study and allowed for further comparison of data between individuals).

Even if the average wind speed was relatively constant on the different days of data collection, it must be recognized that slight variations in climatic conditions could have influenced the performance of the PS. Finally, the methodological approach used to obtain the AE data limits comparison with the few previous studies that have analyzed this variable. Further investigation is needed to determine if and how training adaptations may influence the current results. Nonetheless, study 2 represents the first attempt in the literature to collect this data during sprinting with resistance (e.g., EC, MP, AE) and provides a new perspective for evaluating sprinting.

XI - PRATICAL APPLICATIONS

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The outcomes of Study 1 have many potential practical applications to significantly advance the field of sports science, particularly for strength and conditioning coaches. Our data, which examined the EC of running at different speeds and identified the EMG trends indicative of actual neuromuscular demands, could revolutionize the planning of training sessions. Analyzing a ratio between internal and external load, such as the EMG/F ratio, could be crucial in determining appropriate training distances. The differences between the MP and EC calculated by GPS-IMU and EMG suggest that the former significantly underestimates the actual demands of high-speed actions. This finding could change the development of training exercises. However, it is important to note that the current data were collected on a sample of U17 soccer players from a Mediterranean context and that generalizing the results to other populations should be cautiously made. Study 1 underscores the need for further research and explore potential differences in match scenarios. It presents a fresh perspective for characterizing running activities in soccer, using parameters such as EMG/F ratio, MP, and EC calculated from EMG and only one GPS-IMU. Defining and characterizing the specificities of physical engagement are strategic factors for developing a novel approach to studying neuromuscular and metabolic activity. Although further research is needed, these indicators seem promising for accurately examining workload, improving performance, examining the dose-response relationship of training, and detecting the onset and change of fatigue during competition. The call for further research invites the scientific community to contribute to advancing this field. In the future, GPS-IMU and EMG should be validated against direct measures of energy expenditure, both external and internal, to determine their relationship to direct measures of fitness and performance.

Instead, the findings of Study 2 will help strength and conditioning coaches plan their training sessions more effectively. First, the current results support that muscle activation patterns change depending on the load during sprinting. Thus, coaches should be aware that as load increases, the activation of Q and G increases in contrast to H, which are less determinant at higher loads. Second, practitioners must recognize that PS is preferable if the goal is to replicate US conditions with a slight overload without significant disruption to running mechanics and changes in muscle involvement. Third, the current data indicate that GPS-derived MP and EC underestimate the neuromuscular and metabolic demands on youth soccer players, particularly under heavier loading conditions (i.e., > SS15). Therefore, EMG-derived calculations are recommended to better understand the EC and MP of loaded sprint actions. Finally, coaches and physical trainers should consider the decreased AE and increased EC associated with increased loads. Future research should investigate parameters such as muscle loading and relative recruitment of each muscle group assessed, as well as analyzing speed, MP, and EC when using different training methods. These modalities of sprint development, including US, PS, and SS protocols, provide valuable insight into an athlete's sprinting abilities under different conditions and provide important data for optimizing training programs and improving performance.

XII - FUTURE RESEARCH LINES

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The thesis aimed further to define the concept of training load in soccer. The starting point must be the soccer-specific investigation of the movement and the peculiarities needed with current technology. This allows us to indirectly measure the essential physiological variables to guide training and provide a deeper understanding of the physical aspects required during a match. EC is an index that summarizes the physiological and technical demands by explaining how sport-specific training can modify some parameters closely related to player efficiency. Studying this value in soccer players is a fundamental way to apply a value to mathematical models and equations that consider daily activities, such as accelerations, decelerations, and changes of direction. This further leads to the economy running at a constant speed in the opposite direction.

For example, the study by Hamad et al. (2024) offers critical insights into the comparative effectiveness of uphill-downhill sprinting and sprinting with resistance to improve sprint performance. Although both methods may be efficacy, future research should aim to elucidate further the underlying biomechanical and physiological mechanisms that contribute to these performance improvements. Understanding the different adaptations induced by uphill and downhill sprinting could lead to tailored training protocols that optimize specific performance parameters such as acceleration, deceleration, top speed, and fatigue resistance. Future research could also consider the practical application of these findings in different sports and populations. For instance, how these sprint training methods affect athletes could be investigated. This approach, which accounts for individual variability in response to sprint training, could promote personalized athletic development strategies and ultimately contribute to improved sports performance.

Applying the 'metabolic power' approach analysis to determine effective engagement represents the future of soccer and team sports, as it provides the ability to evaluate player profiles and examine training and match tendencies. Knowledge of algorithms would be a real game changer when comparing training methods/philosophies (i.e., traditional, tactical periodization) and different championship competitions (similarities and differences in the presence or absence of cup tournaments). Continuing the discussion, the usefulness would also refer to the selection of players during the transfer window by updating the valuable database for soccer scouting, match analysis, and transfer dynamics, integrating the technical-tactical information, physical performance and injury history, looking for the fundamental pillars for understanding official performance parameters together with the training loads, through the same 'integrated soccer language' (Azzone & Lorenzon, 2019).

Despite some limitations, the information we have can significantly enhance our understanding of the current activity in soccer and the concept of intensity. This provides a gateway to a more comprehensive analysis and observation. The practical application of these models is crucial for the daily analysis of training sessions, both with and without the ball. For instance, the advent of video tracking systems in stadiums and the ability to monitor players during their weekly microcycles with high-frequency GPS have sparked a new interest in comparing and periodizing training among professionals in this field (Minetti et al., 2013; Savoia, 2019). A modern data scientist who wants to understand the game better cannot separate the purely physical data (effect) from the technical-tactical aspect (cause) during the match. Soccer is a situational sport where performance is mainly influenced by the need for strategic and tactical developments on the pitch, which may also require moments of pause/rest between high-intensity actions. The ultimate aim of this thesis was to examine exactly how the system of play can influence performance and how the latter is not necessarily related to the outcome. Furthermore, as the data from the

training sessions were available, it was necessary to investigate how the intensity of the exercises with the ball correlated more strongly with some of the physical parameters analyzed during the competition than the 'dry activity' (without the ball) [Azzone & Lorenzon, 2019; Savoia, 2019]. Proof that specificity correlates more strongly with the game than physical activity, which has more general characteristics.

Future research should prioritize the application of machine learning and data mining to large datasets to refine predictive models of player performance and injury prevention. These tools could offer unparalleled insights into individualizing training and rehabilitation programs. This will help to ensure that not only "static information" is associated with the physical data, such as role, a system of play, result, percentage of possession and relative zones, etc., but also "dynamic information," such as the flow of tactical adjustments. This would lead to the understanding and explanation of the observed physical data according to the specific moment/action in the game and help summarize the information that helps choose a winning game strategy for the coaches.

Recently, several sports scientists and technology companies have developed equations that attempt to combine various spatial, temporal, and positional factors that influence the difficulty of a pass in the context of a soccer match. These include performance characteristics such as the distribution of opponents, the time it takes to complete the pass, and the main distances between the ball, teammates, and opponents, including the ball's trajectories, etc. These equations are complex and include several variables that can be adjusted or weighted depending on the perceived importance of each factor in the analysis model. They use efficiency indices and artificial intelligence-driven systems to automatically calculate various technical and performance-related parameters directly from the game material. Using artificial intelligence systems to analyze opponents could provide necessary training and match preparation feedback. Understanding

future opponents' tendencies and physical requirements will allow teams to adapt their strategies and focus on precisely what is needed. The following is a clarifying equation (example regarding *coefficient of passing difficulty* [C-PASS]), unpublished and generated by AI (Artificial Intelligence) for educational purposes only:

$$C_p = \alpha \cdot \left(\frac{A_k}{A} + b^2 \cdot \frac{T_r}{T} \right) \cdot c \cdot \frac{D_{pass}}{D_{p-e}} + d \cdot e \cdot m \cdot \frac{D_{b-te}}{D_{o-m_{x1}}} \cdot \frac{D_{b-te}}{D_{o-m_{x2}}}$$

Where:

C_p : Coefficient of passing difficulty (C-PASS), indicating the complexity of completing a specific pass.

α : A normalization constant or weight associated with the area of the k-regions, indicating the influence of the space opponents cover on the pass's difficulty.

A_k : Area of the k-regions influenced by opponents, where opponents' presence may obstruct the pass.

A : The total area considered in the analysis is often the entire playing field or a defined zone.

b : A constant related to the temporal aspect of the pass, modulating the importance of time in the equation.

T_r : Time required for the ball to reach the receiving player, reflecting the speed and trajectory of the pass.

T : Total time available to execute the pass within the game context.

c : A scaling factor associated with the distance of the pass, adjusting how much distance impacts the pass difficulty.

D_{pass} : The distance covered by the ball during the pass directly affects the complexity of the play.

D_{p-e} : Distance between the ball's initial and final position, representing the pass's straight-line distance.

d : A constant related to the ball's trajectory relative to opponents, influencing the perceived difficulty based on how the ball must navigate around or over defenders.

e : A significant factor that represents additional external conditions, such as pressure from opponents, that can impact the pass.

m : A multiplicative factor related to the number and proximity of opponents to the pass trajectory.

D_{b-te} : Distance between the ball's trajectory and the closest teammate, essential for determining the feasibility of the pass.

$D_{o-m_{x1}}$ and $D_{o-m_{x2}}$: Distances between the ball's trajectory and the areas occupied by opponents in different spatial dimensions, helping to assess how likely the pass is to be intercepted or obstructed.

One could consider percentage thresholds to divide the difficulty ranges (e.g., difficult passages if the C-PASS score is above 66%; medium passages if the C-PASS score is between 33-66%; and easy passages if the C-PASS score is less than 33%).

The synthesis of findings from these studies contributes to developing a new model for understanding and optimizing key performance markers in soccer performance. This thesis offers a more comprehensive approach to assessing and enhancing athletic performance by integrating technologies such as GPS-IMU and EMG and identifying novel markers and established metrics that provide new insights into high-intensity movements and the mechanical and energetic properties demands (Delaney et al., 2018; Grassadonia et al., 2024). These findings significantly affect performance optimization in elite athletes and clinical rehabilitation, offering potential pathways for more targeted and effective interventions. This thesis successfully establishes a framework for future research and practical application in sports science. Refining the understanding of how mechanical and energetic factors interact during sports activities sets the stage for more precise training and rehabilitation protocols that can lead to improved performance outcomes.

Future investigations could focus on coding and improving performance in specific ball training (e.g., SSG) and match contexts by integrating GPS-IMU with EMG. Furthermore, adding a gas analyzer (metabolimeter) to GPS-IMU and EMG could be helpful in further studying and verifying the EC and other related physiological variables. However, other technologies, such as NIRS (Near Infrared Spectroscopy), can improve the comprehensive performance model and/or individual capacity (e.g., work/rest ratio parameters).

Summarizing the results of this research, it is clear that the complexity of sports performance improvement goes beyond isolated training methods

and that there is a need to develop more specific models for the effective coding of mechanical-energetic engagement. Integrating different approaches is crucial for optimizing outcomes across performance dimensions through appropriate comparisons. As outlined in this *Thesis*, the convergence of traditional and new models underscores the need for a multifaceted strategy that recognizes athletic development's dynamic and individualized nature. To move from the insights of the past to future applications, research should continue to explore these intersections with the aim of refining and expanding our understanding of how best to support athletes to achieve maximum performance potential while maintaining long-term health and well-being (Smith & Pell, 2003; Ioannidis, 2005; Jones & Wallace, 2005; Cushion et al., 2012; Greenhalgh et al., 2014).

XIII - BIBLIOGRAPHICAL REFERENCES

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