Training Load, Fatigue and Post-Match Recovery in Italian Serie A Youth Soccer Players

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Abstract

Monitoring training load and its responses is a fundamental component of the training process. For sports scientists and coaches working with adolescent soccer players, a key challenge lies in balancing training stress with adequate recovery to promote performance and development, while minimising maladaptation and injury risk. The aim of this thesis was to investigate the training load, acute fatigue and post-match recovery responses in Italian Serie A youth soccer players.

Study 1 (Chapter 3) quantified external and internal load across a competitive season in 90 high-level youth players (under-19, under-17, under-16, under-15). External load was measured via duration and global navigation satellite systems (GNSS), while internal load was assessed using heart rate (HR) and rating of perceived exertion (RPE). Under-19 and under-17 players exhibited higher training frequency, greater weekly accumulated external and sRPE-training load (sRPE-TL), and more pronounced daily load fluctuations across the microcycle compared to their younger counterparts ($p < 0.05$). In contrast, weekly accumulated HR internal loads were higher in under-15 players ($p < 0.05$). Match day (MD) session imposed the highest load across the microcycle ($p < 0.05$). These findings highlight the importance of monitoring the training process using a combination of external and internal load measures.

Study 2 (Chapter 4) determined the reliability and sensitivity to change of physical performance tests used for assessing post-match fatigue and recovery. Eighteen high-level youth players completed the isometric posterior chain (IPC) and the countermovement jump (CMJ) tests across four testing sessions. IPC and CMJ measures demonstrated acceptable levels of absolute reliability with coefficients of variation (CVs), ranging from 1.5 to 8.8%, and *moderate* to *excellent* levels of relative reliability, with intraclass correlation coefficients (ICCs), from 0.70 to 0.98. IPC peak force and torque, CMJ reactive strength index (RSI) modified, CMJ eccentric forces (mean breaking force, mean deceleration force, peak force, force at zero velocity) and CMJ mean power measures had post-match changes greater than their typical error (TE), demonstrating acceptable sensitivity in detecting performance changes at post-match. These measures may be more suitable for monitoring acute changes in physical performance at post-match.

Study 3 (Chapter 5) described the time course of recovery post-match and examined the effects of manipulating training volume 48 h following match-play. Forty-eight high-level youth players were assessed using physical performance tests (IPC and CMJ) and

perceptual measures (muscle soreness and fatigue via visual analogue scales (VAS)) before (pre) and after (0.5 h post, 48 h post, 72 h post) an 80-minute match. At 48 h post-match, players were randomly assigned to a complete training (CT; $n = 26$) or a reduced training (RT; $n = 22$) group. Acute fatigue was evident with significant impairments at 0.5 h post-match ($p < 0.05$). At 48 h post-match, CMJ and perceptual fatigue returned to baseline ($p > 0.05$), whereas IPC and perception of muscle soreness were not fully recovered ($p < 0.05$), highlighting variations in recovery responses. CT players experienced higher training loads on MD+2 compared to RT ($p < 0.05$). A significant time x group interaction was observed for CMJ and IPC measures ($p < 0.05$), with reductions in physical performance observed in the CT group from 48 h to 72 h post-match ($p < 0.05$). A high-intensity training session administered on MD+2 may negatively influence performance recovery, whilst a moderate-intensity session may support the recovery process without further impairment of performance.

Study 4 (Chapter 6) characterised the acute fatigue responses to a typical training session combining physical performance, metabolic and perceptual measures in 13 high-level youth players. Pre- and post-training assessments included physical performance tests (IPC and CMJ), metabolomics analysis (via capillary blood sample) and perceptual measures (muscle soreness and fatigue via VAS). Physical performance and perceptual measures showed no changes post-training ($p > 0.05$), except for significant reductions in CMJ force at zero velocity, eccentric and concentric peak force ($p < 0.05$). Metabolomics revealed significant post-training alterations in 21 metabolites ($p < 0.05$), including increased metabolite concentrations related to carbohydrate, amino acid and lipid metabolisms. Although a moderate-intensity training session elicited minimal acute changes in physical performance and perceptual fatigue measures, it induced significant perturbations in the serum metabolome, particularly in energy metabolism pathways.

In summary, this thesis provides novel insights into training load, acute responses to training and match-play, and post-match recovery profiles of Italian Serie A youth soccer players. These findings offer practical recommendations for sport scientists and coaches seeking to optimise physical performance monitoring and refine training and recovery strategies in high-level adolescent soccer players.

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Declaration

I declare that the work within this thesis, unless otherwise stated, is entirely my own. All attempts have been made to ensure that the work of others who have contributed to this thesis breaches no copyright laws and is appropriately cited and referenced within the thesis.

Publications

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List of Abbreviations

Δ	Mean change
ANOVA	Analysis of variance
AROM	Athlete-reported outcome measure
ATP	Adenosine triphosphate
AU	Arbitrary unit
Ca^{2+}	Calcium
CI	Confidence interval
CK	Creatine kinase
CMJ	Countermovement jump
COD	Change of direction
CT	Complete training
CWI	Cold water immersion
CWT	Contrast water immersion
CR	Category ratio
CV	Coefficient of variation
DOMS	Delayed onset of muscle soreness
EIMD	Exercise-induced muscle damage
GNSS	Global navigation satellite systems
^{1}H-NMR	Proton nuclear magnetic resonance
HR	Heart rate
HR_{avg}	Average heart rate
HR_{max}	Maximal heart rate
HR_{peak}	Peak heart rate
HSR	High-speed running
ICC	Intraclass correlation coefficient
IPC	Isometric posterior chain
IMU	Inertial measurement units
MD	Match day
MIP	Maximal intensity period
MS	Mass spectrometry
NMR	Nuclear magnetic resonance
PCA	Principal component analysis

PQN	Probabilistic quotient normalisation
RFPM	Remote food photographic method
RPE	Rating of perceived exertion
RSI	Reactive strength index
RT	Reduced training
SPR	Sprinting running
sRPE	Session rating of perceived exertion
sRPE-TL	Session rating of perceived exertion training load
SD	Standard deviation
SSC	Stretch-shortening cycle
TE	Typical error
TRIMP	Training impulse
TWI	Thermoneutral water immersion
VAS	Visual analogue scale
VO_{2max}	Maximal oxygen consumption

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1.1 Background

Soccer, or association football, is the most popular sport in the world. Professional clubs invest substantial resources in their youth academies to identify and develop talented players through structured developmental programs (Ford et al., 2020). In Europe, high-level youth soccer players participate in specialised training and competitive matches, including national and international tournaments (e.g., national championships and UEFA Youth League). To increase their chances of success, youth players are required to train and compete at high intensities, continuously developing the technical, tactical, physical and psychological components needed to excel at the professional level (Bowen et al., 2017). Training to enhance physical performance in youth soccer players is a longitudinal process that requires planning, monitoring and manipulation of the training stimulus, incorporating the different characteristics of match demands and appreciation of growth and maturation processes (McBurnie et al., 2021). The cumulative training loads, combined with additional commitments such as school and national team, place significant stress on their developing bodies (Johnson et al., 2022). Consequently, a critical challenge for coaches and sports scientists working with adolescent players is to balance training stress and recovery to facilitate positive adaptations that enhance performance while minimising injury risk (Kellmann et al., 2018; Murray, 2017). Over the last decade, there has been an increased interest in applied soccer science research that investigates key areas of youth physical development, including training load monitoring, fatigue and recovery, and growth and maturation.

The intermittent and stochastic nature of soccer requires players to sustain high-volume and high-intensity actions, involving powerful technical skills (e.g., dribbling, tackling, shooting) and dynamic movement patterns (e.g., sprints, jumps and changes of direction), that stress the bodily physiological and neuromuscular systems (Bangsbo et al., 2006; Vanrenterghem et al., 2017). Specifically, youth soccer players cover a total distance of 7500-11500 m and perform ~300 changes of direction per match (Morgan et al., 2022; Palucci Vieira et al., 2019). Additionally, youth players sustain HR intensities ranging from 82 to 90% of maximal HR (HR_{max}) (Castagna et al., 2009; Francini et al., 2019; Kim et al., 2023) and cover high-speed running (HSR) and sprinting running (SPR) distances at high speeds of movement, with execution of rapid accelerations and decelerations performed to meet the positional and tactical match demands (Parr et al., 2022). Therefore, measuring the external and internal load and its associated responses is a fundamental component of the training process. It enables practitioners to control training and competition stimuli and determine if responses to training are progressing as intended, or adjustments to the program are required (Coutts et al., 2018; Impellizzeri et al., 2019; Jeffries et al., 2022). Despite the widespread use of training monitoring systems across soccer academies (Salter et al., 2021), there is a paucity of information describing the training process using both external and internal load within youth soccer.

The demands of training and match-play can induce acute and residual fatigue, with various systems and processes impaired for minutes, hours or days (Gabbett and Oetter, 2024; Skorski et al., 2019). Fatigue and recovery are complex and multifaceted phenomena in team sports (Twist et al., 2012), serving as a vital part of the training process. Fatigue can originate from a variety of possible mechanisms related to the demands of the sport (Nedelec et al., 2012), manifesting as a decline in physical or mental performance and as an altered perception of effort (Enoka and Duchateau, 2016). Recovery of performance capacity following training and competition involves various restorative measures over time and allows the compensation of fatigue by reestablishing the bodily homeostatic balance (Kellmann et al., 2018). With an increasing number of technologies potentially useful for monitoring responses to match and training load, it is important to establish their validity, reliability, sensitivity to change and practicality of specific measures (e.g., performance, physiological and subjective tools) before implementation in a specific setting (Impellizzeri and Marcora, 2009; Thorpe et al., 2017). Given that youth soccer players possess different physical and physiological characteristics required for soccer performance (Radnor et al., 2018) and that they may engage in shorter matches (Palucci Vieira et al., 2019), it is relevant to investigate their responses to training and match demands. However, there is limited information on the magnitude of fatigue and the time course of recovery in youth soccer players. Ultimately, profiling fatigue and recovery with valid, reliable and practical measures which are sensitive to change can better inform players' recovery and training strategies.

Soccer imposes metabolic and neuromuscular demands, leading to separate physiological and biomechanical load-adaptation pathways (Vanrenterghem et al., 2017). For example, metabolic alterations induced by soccer match-play include elevated blood and muscle lactate levels, lowered phosphocreatine concentrations, decreased glycogen stores and increased plasma glycerol and free fatty acids (Silva et al., 2018). Physiological markers have the potential to provide objective information regarding the homeostatic disturbances occurring in response to soccer activities; however, their implementation for ongoing monitoring is often limited by the invasiveness of these techniques, the associated costs and the technical expertise required (Pérez-Castillo et al., 2023). Recent technological advancements have enabled the application of metabolomics, partly overcoming the limitations of traditional single-metabolite assessments typically performed in exercise physiology research (Schranner et al., 2020). Metabolomics allow the large-scale identification, quantification, and characterisation of metabolites within a biological system, being a potential approach for investigating mechanisms and responses to training and match demands (Owens and Bennett, 2024). Alongside the metabolic perturbations, the high neuro-mechanical demands induce temporary reductions in the force-generating capacity of the muscles (Brownstein et al., 2017; Rampinini et al., 2011). For instance, substantial decrements in neuromuscular contractile function were observed up to 72 h post-training in high-level youth soccer players, indicating prolonged recovery of peripheral mechanisms (Deely et al., 2022). In applied sport science research, physical performance measures such as vertical jumps and isometric tasks are typically used as proxy measures to assess acute responses following training and competition (Malone et al., 2015; Springham et al., 2024). The evaluation of the force-time curve using force platforms has been suggested to provide greater insights into the recovery of physical performance compared to the outcome measures (Bishop et al., 2023; Gathercole et al., 2015). Given the complexities of fatigue-induced mechanisms, comprehensive approaches and multiple measures are warranted to capture alterations in the various physiological and biomechanical processes that occur in response to load.

To restore performance capacity and ensure positive adaptation, integrating adequate recovery into the training process is essential (Reilly and Ekblom, 2005). With the growing competitive demands of modern soccer (Allen et al., 2024), a portion of the competitive microcycle is dedicated to rest and structured recovery, making regeneration a central component of the players' performance optimisation strategy (Field et al., 2021; Wiewelhove et al., 2024). The application of recovery modalities aims to mitigate the magnitude of fatigue and accelerate the recovery process following training and competition (Cross et al., 2019). Sleep and nutrition serve as fundamental strategies to hasten the recovery process, whilst a set of complementary interventions such as water immersion, active recovery, stretching and massage may also support the regenerative process (Fullagar et al., 2015; Querido et al., 2022). Due to the large variability in individual responses and the complex interaction between training load, fatigue, recovery and performance, manipulation of training load has been proposed as a primary strategy to optimise recovery and the overall training process (Driller and Leabeater, 2023; Mujika et al., 2018). This involves adjusting the volume and intensity of training sessions to achieve desired training effects. In the context of youth academies, manipulation of training load at post-match could offer an advantage compared to complementary recovery strategies as it would potentially optimise available training time for technical-tactical development, while supporting players' recovery after competition. Despite the frequent use of recovery modalities in elite soccer, research examining the effects of training load strategies on the recovery process of adolescent soccer players is warranted to optimise training programs.

1.2 Aims and Objectives

The overarching aim of this thesis is to investigate the training load, acute fatigue and post-match recovery responses in Italian Serie A youth soccer players. It is hoped that this research will expand the knowledge of how youth soccer players train, respond acutely to load, and recover after training and match-play, providing evidence and practical implications for coaches and sports scientists working with high-level adolescent players.

This will be achieved through the following objectives:

1. To quantify external and internal training and match loads in multiple academy age groups throughout a competitive season in Italian Serie A youth soccer players. This objective will be achieved through the completion of Study 1 (Chapter 3).

2. To quantify reliability and examine sensitivity to change in physical performance measures used to assess fatigue and recovery following match-play in Italian Serie A youth soccer players. This objective will be achieved through the completion of Study 2 (Chapter 4).

3. To describe the time course of recovery post-match and examine the effects of manipulating training volume 48 h following match-play in Italian Serie A youth soccer players. This objective will be achieved through the completion of Study 3 (Chapter 5).

4. To characterise the acute fatigue responses to training in physical performance, metabolic and perceptual measures in Italian Serie A youth soccer players. This objective will be achieved through the completion of Study 4 (Chapter 6).

2.1 Introduction

This chapter reviews the scientific literature on training load, fatigue and post-match recovery in soccer, specifically focusing on adolescent players. The review is organised into four main sections. The first section introduces the principles of training, fatigue and recovery in sports, presenting the theoretical basis, the conceptual frameworks and the integration of monitoring systems in soccer. The second section examines the construct of training load, its methods of measurement, and the physical and physiological demands of soccer match-play and training. The third section discusses post-match fatigue and recovery responses, exploring the physiological mechanisms underpinning match-induced fatigue, the type of tools and measurements used to describe responses to load, the time course of recovery, and the effectiveness of various recovery interventions employed in soccer. Finally, the chapter concludes with a summary of the existing literature on the topic.

2.2 Fundamentals of training, fatigue and recovery

2.2.1 Theoretical basis

The application of an appropriate exercise stimulus to enhance sports performance centres on the interaction between the training dose and recovery (Matveyev, 1981). In its simplest form, a single exercise bout induces acute adaptive psychophysiological responses across various levels of the organism (e.g., cellular, organ and systemic levels) (Skorski et al., 2019). When the current performance capacity of the organism is challenged to an appropriate level, the exercise stimulus disrupts homeostasis, resulting in acute reductions in performance (i.e., fatigue response) (Selye, 1956). With adequate recovery time between exercise bouts, homeostasis returns to baseline and a supercompensation effect is observed, with an enhancement of performance capacity compared to its initial level (Selye, 1956). However, this effect dissipates if subsequent exercise stimuli are not applied within a suitable timing and performance capacity will regress to pre-exercise levels (Selye, 1956). When exercise stimuli are systematically imposed over time, the resultant chronic adaptations may be either positive or negative, depending on the interplay between training dose and recovery response (Cunanan et al., 2018; Meeusen et al., 2013). Training and competition will result in both fitness (i.e., positive) and fatigue (i.e., negative) responses, with the interaction of these effects resulting in a change in performance (Bannister, 1991).

Fatigue is an integral component of exercise and is required to elicit both acute responses and chronic adaptations (Pyne and Martin, 2011). The application of successive exercise stimuli occurring during intensified periods of training (e.g., preparation phase) or competition (e.g., condensed competitive schedule) causes increased levels of accumulated fatigue, which may lead to a state of overreaching (Aubry et al., 2014). If followed by appropriate recovery, this state will result in functional overreaching, a positive adaptation to training characterised by superior performance capacity and improved resistance to disruption of homeostasis beyond pre-training levels (Meeusen et al., 2013). Conversely, prolonged and high training doses with inadequate recovery time will result in a state of non-functional overreaching, defined as a negative adaptation characterised by reduced performance capacity (Coutts et al., 2007; Kellmann et al., 2018). In severe cases, persistent performance decrements accompanied by psychological disturbances may develop into overtraining syndrome, a chronic and unexplained underperformance condition that persists even after significant reductions in training intensity and volume alongside prolonged recovery time (Budgett et al., 2000; Meeusen et al., 2013). Based on its severity, fatigue responses to exercise can be described as a continuum from acute fatigue induced by a single session to functional or non-functional overreaching occurring following intensified training periods, and finally in rare cases to overtraining syndrome (Halson and Jeukendrup, 2004; Meeusen et al., 2013) (Figure 1).

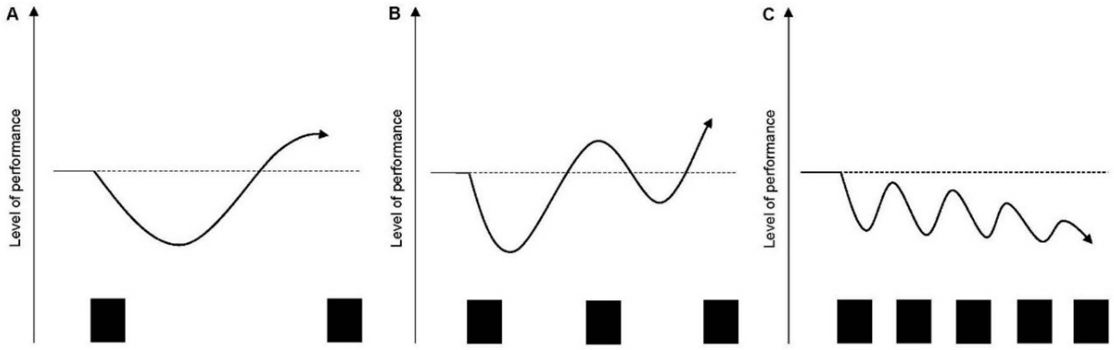

Figure 1. Training responses: (A) acute response to a single session (e.g., post-match fatigue); (B) response to multiple intensified sessions over time with optimal loading (e.g., functional overreaching); (C) response to multiple intensified sessions over time with too high and too frequent loading (e.g., non-functional overreaching). Black boxes represent the training load imposed over time. Adapted from Cunanan et al. (2018); Halson and Jeukendrup (2004); Meeusen et al. (2013).

The fitness-fatigue model can be used to understand the training-recovery cycle in response to single and multiple bouts of exercise (Bannister et al., 1975). This model provides a simplified approach to quantify the dose-response relationship between training, fitness, fatigue and performance. Following the application of a training program, the resultant performance is a function of the positive fitness effects (i.e., positive adaptation response) and the negative acute effects (i.e., acute and accumulated fatigue response) (Bannister, 1991; Bannister et al., 1975). Both fitness and fatigue responses arise from the application of a training stimulus, but they decay exponentially at different rates over time (Bannister et al., 1975; Busso, 2003). Fatigue typically dissipates at approximately twice the rate of fitness. Fatigue responses to exercise tend to be large in magnitude and short in duration, resulting in temporary reductions in performance in the hours or days following exercise (Nedelec et al., 2012; Silva et al., 2018). In contrast, fitness responses are smaller in magnitude but longer in duration, contributing to chronic adaptations that positively influence performance over time

(Gabbett et al., 2014). While the fitness-fatigue cycle appears simple, the complexity of the physiological mechanisms underlying training responses presents challenges in accurately predicting fitness and fatigue (Coutts et al., 2018).

The relationship between training dose and response suggests that disruption of homeostasis following exercise occurs in a dose-response manner (Bannister et al., 1975; Busso, 2003). For example, high-intensity training induces a larger acute fatigue response and necessitates a longer recovery time to return to homeostasis compared to low and moderate-intensity training (Skorski et al., 2019). The recovery time course following training and competition varies widely across physiological systems, ranging from minutes or hours to several days (Gabbett and Oetter, 2024; Silva et al., 2018). For instance, the depletion of phosphocreatine stores during high-intensity exercise directly impacts performance execution but typically recovers within minutes (Hargreaves and Spriet, 2020), whilst neuromuscular function may remain impaired for 24 to 96 h after team sports competitions (Aben et al., 2022). Furthermore, the response to a certain training stimulus can also be mediated by multiple factors such as the type of exercise, individual characteristics and environmental conditions (Skorski et al., 2019). For example, individuals with higher levels of aerobic fitness and strength can exhibit attenuated negative responses following soccer and rugby match-play (Abbott and Clifford, 2022; Johnston et al., 2013). The relationship between training load and performance has also been evaluated in adult and youth team sports players (Fox et al., 2018; Jaspers et al., 2017; Rice et al., 2022). Consequently, understanding the expected responses to a given training load is critical for the development of optimal training programs.

2.2.2 Conceptual frameworks of the training process

Training is defined as the process of systematically performing exercises to increase physical qualities and to acquire sports-specific skills to ultimately improve sports performance (Viru and Viru, 2000). Physical training refers to the systematic and periodised application of physical activities to pursue superior training and performance outcomes and is best accomplished by applying general sport training principles (Impellizzeri et al., 2019; Kasper, 2019). Therefore, in the context of the training process, the training stimulus should be applied to an appropriate level greater than the accustomed training stress, should be targeted to specific physiological and biomechanical characteristics that determine performance, should be applied for sufficient periods to avoid revert in adaptations, should also be organised into distinct periods with an appropriate and varied magnitude of stimuli and, ultimately, should be also tailored to the specific characteristics of an individual (Impellizzeri et al., 2005, 2019; Kasper, 2019; Morgans et al., 2014; Mujika et al., 2018).

Physical training can be described as processes and outcomes (Impellizzeri et al., 2005; Jeffries et al., 2022). The training process is the systematic repetition of physical exercises (Viru and Viru, 2000), whilst training outcomes include physiological, biochemical, anatomical and functional changes (Impellizzeri et al., 2019). The training process has been conceptualised using models and frameworks, which have attempted to illustrate the complex relationship between the training stimulus, its corresponding responses and the resultant performance (Bompa and Haff, 2009; Busso, 2003; Calvert et al., 1976; Selye, 1956). A training framework acts as a reference guide in both research and practice, aiming to assist in understanding the phenomena under investigation with the specific goal of synthesising the evidence and guiding the validation of measurement (Impellizzeri and Marcora, 2009; Jeffries et al., 2022). For example, the fitness-fatigue model proposed by Banister, considered athletic performance (output) to be measurable as the function of two training responses (fitness and fatigue) from the application of a training impulse (input) (Calvert et al., 1976; Morton et al., 1990).

Over the last two decades in the field of applied sports science research and practice, new models and updated frameworks of the training process have been proposed (Impellizzeri et al., 2005, 2019; Jeffries et al., 2022). The taxonomy of the training stimulus was first described in the context of physiological assessment in soccer (Impellizzeri et al., 2004, 2005) and was developed to define the measurable components of the training process and its outcome. Impellizzeri and colleagues proposed that the training outcome is the consequence of the internal training load determined by the individual characteristics (e.g., genetic, training experience) and the quality, quantity and organisation of the external load (Impellizzeri et al., 2005). A fundamental notion of this framework was that when delivered appropriately, and according to the training goal and plan, exercise will induce psychophysiological responses leading to adaptations. After 15 years, the same authors extended the theoretical framework of the training process by clarifying the definition of internal and external load, explaining the importance of integrating both external and internal load for a better understanding of the training process (Impellizzeri et al., 2019).

More recently, Jeffries and colleagues proposed a revised conceptual framework for physical training illustrating the complex relationship between training stimulus, training effects and sports performance (Jeffries et al., 2022). Along with explaining the fundamental concepts and their relationships, the framework provides constitutive and operational definitions for training prescription, training load, training effects, sports performance outcomes and influencing factors (individual and contextual factors). Training prescription refers to short (e.g., single session) to long (e.g., multiyear program) training plans defining the nature and organisation of the training supposed to target factors causally related to sports performance; it is influenced and adapted based on performance models, influencing factors and coach experience. Training load represents the amount of physical training that is completed and experienced by the individual. It can be quantified using indicators of external and internal load. The concept of training effects, previously referred to as training outcome or adaptation, describes the effects caused and occurring after a single or successive training session. Training effects can occur at different levels and can be quantified using functional or performance, physiological and subjective measures. These effects can be either acute and chronic, positive and negative. Finally, sports performance outcomes refer to the results of the balance between the positive and negative training effects and are influenced by contextual and individual factors. Measures of sport performance outcomes can include both absolute (e.g., time, distance, load lifted) or relative and aggregate measures (e.g., ranking, competitive level) (Jeffries et al., 2022). A representation of the conceptual framework is depicted in Figure 2.

Whilst this conceptual framework offers valuable definitions and effectively synthesises the training process, it also presents opportunities for further refinement to deepen understanding and improve the physical training process. One central element concerns the concept of training effects, which represent the effects caused and occurring in response to training. The current classification, which categorises training effects by temporal scale (i.e., acute and chronic) and directional outcome (i.e., positive and negative), is particularly useful when applied to performance measures such as an increase or decrease in peak power output in a vertical jump (Jeffries et al., 2022). However, this approach may oversimplify the multifaceted and complex nature of physiological responses, which can manifest across various biological levels (e.g., cellular, tissue and systemic levels) (Balagué et al., 2020). In particular, given the demands of team sports, changes occurring at one system and level may not be representative of the changes observed at other systems and levels (Gabbett and Oetter, 2025). Therefore, it appears to be important to adopt integrative approaches and contextualise observed physiological changes by evaluating whether they align with the intended adaptive stimulus.

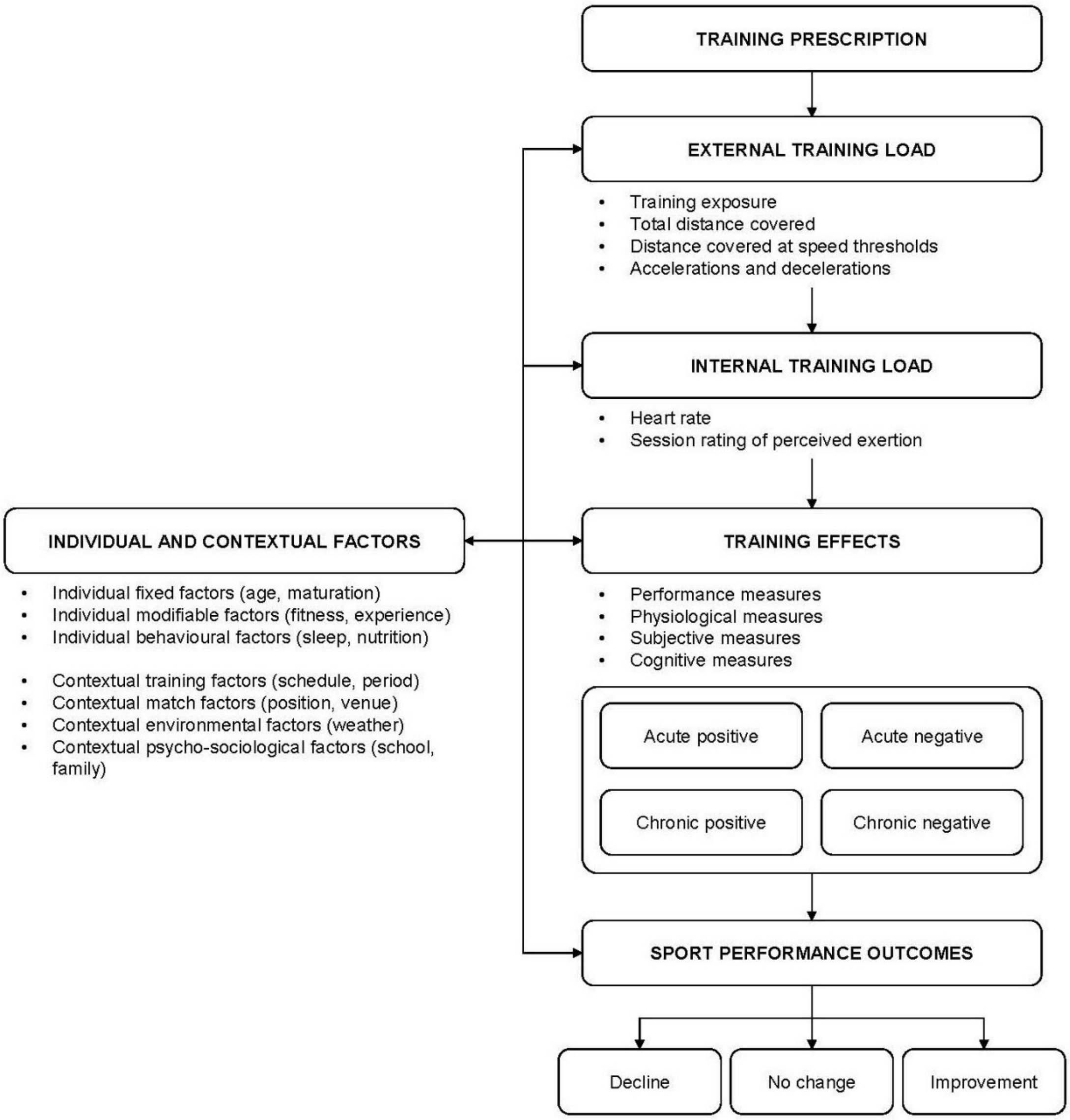

Figure 2. Conceptual framework of physical training in soccer, with examples of external and internal training load measures, training effects measures, and individual and contextual factors. Adapted from Jeffries et al. (2022).

2.2.3 Athlete monitoring systems

Based on the complexities of training responses to a given load, a critical challenge for sports scientists and coaches is to balance the application of training stress with appropriate recovery to allow positive adaptation (Halson and Jeukendrup, 2004). When the fundamental components of the training process are appropriately managed, performance capacity is enhanced (i.e., adaptation), whilst inappropriate combinations of these aspects can result in negative responses (i.e., maladaptation). To achieve the desired training outcomes, precise measurement and management of the training load are required (Impellizzeri et al., 2019). To support continuous physical development and performance in high-performance sports, training monitoring systems have been widely developed in the last two decades and are mainly constituted by methods and measures intended to quantify training and match load, assess fitness and performance levels, and monitor fatigue and recovery (Coutts et al., 2018; Sands et al., 2019). The former component includes methods and measures of training prescription, external and internal load, whereas the latter can be evaluated using objective and subjective tools such as fitness tests, physiological assessments and questionnaires (Bourdon et al., 2017). Training and recovery monitoring is regarded as an essential component of the training process, allowing practitioners to control training and competition load and determine if responses to training are progressing as intended, or if modifications to the training program need to be implemented (Halson, 2014; Impellizzeri et al., 2019; Kellmann et al., 2018; Wiewelhove et al., 2024). Contemporary athlete monitoring systems are in place to provide information to refine the training process, increase performance and reduce the risk of injury and illness as part of effective training systems. The application of athlete monitoring systems that concurrently assess both training load and responses to load is of particular relevance for practitioners working with adolescent athletes, given the unique individual and contextual factors that influence training load prescription and responses within this population. Further research is warranted to better understand the complex relationship between training load and responses, particularly in youth soccer.

2.3 Training loads in soccer

2.3.1 Training load construct

From a historical perspective, the first scientific study investigating the physical demands in soccer was completed in 1976 with the analysis of work rate in different positional roles in professional soccer players (Reilly and Thomas, 1976). However, the concept of training load was first introduced in 2003 at the 8th edition of the European Congress of Sport Science with a study on the training load sustained in youth soccer players (Impellizzeri, 2003), with subsequent publications in the following years (Impellizzeri et al., 2004, 2005). Training load is defined as a higher-order construct reflecting the amount of physical training that the athletes do and experience (Impellizzeri et al., 2022). As a multidimensional construct, it can be quantified using indicators of external and internal load, and it encompasses various measures including spatio-temporal, mechanical, psychological and physiological measures depending on if we are referring to measurable aspects occurring internally or externally (Jeffries et al., 2022).

External load refers to the physical work undertaken by athletes during training and competition. It represents the input variable manipulated to elicit the desired training responses (Impellizzeri et al., 2019). For instance, total distance is a typical measure of external load used in endurance and team sports, whilst the kilograms lifted are commonly reported in strength and power training (Bourdon et al., 2017). Internal load refers to the psychophysiological responses experienced internally by athletes during training and competition. Examples of internal load measures include the rating of perceived exertion (RPE) and heart rate (HR) measures (McLaren et al., 2018). Importantly, internal load represents the response that provides the initial stimulus for subsequent adaptation (Impellizzeri et al., 2019; McLaren et al., 2018). These constructs do not have a single or gold standard measure, but rather may be quantified by a myriad of variables, which describe the external load or the internal response during exercise (Impellizzeri et al., 2019).

External and internal load measures should be used in combination to provide a comprehensive picture of the training process and understand how athletes are coping with the training process (Bourdon et al., 2017; Halson, 2014). For instance, the uncoupling between internal and external load may be used to identify how an athlete is coping with their training program (e.g., athletes who exhibit a lower internal load to standardised external load completed in similar conditions, would be assumed to reflect increased fitness). By contrast, when the internal load is increased in this scenario, athletes may be losing fitness or suffering from fatigue (Impellizzeri et al., 2005). Therefore, the associations between internal and external measures of training load and intensity are also important in understanding the training process and the validity of specific internal measures (McLaren et al., 2018). Finally, the type of training load stresses various physiological and musculoskeletal systems leading to separate physiological and biomechanical load-adaptation pathways with dedicated external and internal training load measures (Vanrenterghem et al., 2017).

2.3.2 Methods for monitoring external and internal load

2.3.2.1 Measures of external load

External load can be measured in multiple ways depending on the monitoring goal, the mode of the sport and the available resources (Bourdon et al., 2017). In its simplest form, external load can be quantified using the duration and the frequency of training (Brownlee, O'Boyle, et al., 2018), whilst resistance training load can be quantified by multiplying the number of sets, reps and load during strength training sessions (McBride et al., 2009). In team sports, external load is commonly quantified using tracking systems such as global navigation satellite systems (GNSS), optical tracking systems, local positioning systems and inertial measurement units (IMU) (Crang et al., 2021; Torres-Ronda et al., 2022; Waldron et al., 2011). These systems quantify multiple measures including total distance, velocity-based threshold distances, accelerations and decelerations. External load measures can be distinct into three levels based on their similarities: 1) total distance covered, distances covered and occurrences in different velocity zones (e.g., HSR and SPR distance); 2) measures related to change in velocity, such as accelerations, decelerations and changes of direction expressed as number of events, distance covered or time spent; 3) measures derived from IMU such as accelerometry-derived load, impacts, collisions and strides variables (Buchheit and Simpson, 2017; Torres-Ronda et al., 2022).

In soccer, external load is typically quantified using GNSS coupled with IMU (e.g., accelerometer, gyroscope and magnetometer) for quantifying various activity measures (Torres-Ronda et al., 2022). These tracking systems have been shown to provide valid and reliable estimates of distance and velocity during a range of team sports activities (Beato et al., 2018; Thornton et al., 2019). In addition, they have also been shown to provide valid and reliable estimates of immediate and continuous movements during both linear and multidirectional movements (Coutts and Duffield, 2010; Varley et al., 2012). The validity and reliability of these systems are dependent upon a variety of factors including technology brand and model, sampling rate, intensity of exercise (e.g., walking vs sprinting), and type of movement performed (e.g., straight line, change of direction) (Crang et al., 2021). For instance, systems with a higher sampling rate (e.g., 10-15 Hz) has demonstrated higher accuracy in quantifying total distance, high-intensity running and peak speed compared to less powerful devices (e.g., 1 Hz and 5 Hz) (Scott et al., 2016). The inter-unit reliability of commonly used external load measures was high with intraclass correlation coefficients (ICCs) ranging from 0.90 to 0.99 for total distance, HSR, accelerations, decelerations, peak speed and metabolic distance during intermittent running activity (Beato et al., 2023).

Total distance, HSR and SPR distances, accelerations and decelerations are frequently monitored in elite soccer across European leagues, including the English Premier League, Spanish La Liga, Italian Serie A and French Ligue 1 (Akenhead et al., 2016; Buchheit, Simpson, et al., 2021; Gualtieri et al., 2020; Martín-García et al., 2018). Total distance is one of the most commonly reported measures of external load and can be expressed in the form of absolute or relative data (e.g., distance covered per minute) (Martín-García et al., 2018; Novak et al., 2021). HSR and SPR distances are therefore frequently adopted in soccer, reflecting the increased match-play intensity recorded over the last years (Allen et al., 2024; Barnes et al., 2014). Although there is no consensus on the definition of absolute and relative thresholds for these measures, a review of the literature by Gualtieri et al. (2023) found that the entry velocities for absolute HSR and SPR distances were set between 14.4 and 21.1 $km \cdot h^{-1}$, and between 19.8 and 30 $km \cdot h^{-1}$, respectively. However, HSR distance is mostly reported as a distance between 19.8 to 25.2 $km \cdot h^{-1}$, whilst SPR distance is a distance above 25.2 $km \cdot h^{-1}$ (Anderson et al., 2016; Malone et al., 2015). Due to the intermittent and stochastic nature of soccer, accelerations and decelerations are also considered important indicators of external load, with a greater frequency of high (e.g., above 2.5 $m \cdot s^{-2}$) and very high-intensity (e.g., above 3.5 $m \cdot s^{-2}$) decelerations compared to accelerations (Harper et al., 2019). Similarly to HSR, acceleration and deceleration thresholds vary between studies in soccer science literature (Silva et al., 2023).

2.3.2.2 Measures of internal load

Internal load is quantified to capture physiological (HR) and perceptual (RPE) responses through objective and subjective methods (Dudley et al., 2023; Impellizzeri et al., 2005). HR sensors are used to monitor exercise intensity and to quantify the cardiovascular responses during training and competition (Dellal et al., 2012; Drust et al., 2007). The use of HR monitoring in soccer is based on the linear relationship between HR and maximal oxygen consumption (VO_{2max}) during steady-state submaximal running exercise on a treadmill (Achten and Jeukendrup, 2003; Astrand and Rodahl, 1986). However, this linear relationship does not necessarily apply to soccer demands due to its high-intensity and intermittent nature (Akubat et al., 2012; Impellizzeri et al., 2004). Additionally, multiple individuals and contextual factors (e.g., fatigue, hydration and environmental conditions) can affect individual HR responses during endurance exercise (Lambert et al., 1998). In soccer, HR monitors are often utilised in combination with external load (Impellizzeri et al., 2019). HR-based internal load can be expressed as absolute (i.e., beats per minute) or relative data (i.e., based on the % of the maximum HR). When expressed relatively, HR data can be reported with the average percentage of HR_{max} or as the time spent in different heart rate thresholds, with specific reference to the HR intensities elicited during competitive match-play (Malone et al., 2015; Wrigley et al., 2012). In addition, the use of HR measurements in soccer is also incorporated into other methods such as the HR-derived training impulse (TRIMP), which combines the volume and intensity of exercise (Buchheit, 2014; McLaren et al., 2018).

Another method frequently adopted for quantifying internal load is RPE, which refers to the magnitude of effort perceived during exercise and is expressed with verbal anchors and numeric values ranging from minimum to maximum (Borg, 1970). RPE can be quantified using the session rating of perceived exertion (sRPE), which refers to the effort perceived throughout a training session or competition (Foster et al., 2001). Different RPE scales have been employed to quantify training intensity and internal load, including Borg’s 6-20 scale, Borg’s Category Ratio (CR) 10 scale and Borg’s CR 100 scale (Borg and Borg, 2002; Borg, 1982; Borg et al., 1985; Foster et al., 2001). The calculation of sRPE multiplied by the volume of exercise (duration) has been proposed as a global measure of internal load and is described as sRPE-training load (sRPE-TL) (Foster et al., 2001; McLaren et al., 2018). The CR 10 scale is considered the gold standard method for providing RPE due to its properties of CR scaling, and good levels of agreement have been reported between the sRPE-training load and HR measures for quantifying internal responses in soccer players (Alexiou and Coutts, 2008; Impellizzeri et al., 2004). RPE represents a valid, simple and practical internal load measure. However, it remains essential to use validated scales and educate players on the correct procedures when collecting RPE data.

2.3.3 Match demands in soccer

The physical and physiological demands of soccer match-play have been investigated for almost five decades to ensure that training preparation methods are specific in preparing players to perform optimally (Bangsbo, 1994; Bangsbo et al., 2006; Jerome et al., 2024; Oliva-Lozano et al., 2020; Reilly et al., 2009; Reilly and Thomas, 1976). The activity profile of players derived from match-play can be used as a reference for informing players' training strategies, including position-specific drills and physical conditioning programs (Ade et al., 2020; Torres-Ronda et al., 2022). Match physical demands have traditionally been measured over the whole match using aggregated measures, which provide basic information about the overall physical demands (Bradley et al., 2011; Di Salvo et al., 2009; Rampinini et al., 2007). However, this approach can underestimate the true match demands, considering the intermittent nature of physical running output (Mernagh et al., 2021; Schimpchen et al., 2021). Over the last two decades, the analysis of soccer match-play has evolved by evaluating peak intensity periods in which players face the highest running demands throughout the match. Different terminologies have been adopted to describe peak demands, including the most intense periods (Mohr et al., 2003), maximal intensity periods (MIPs) (Kim et al., 2023; Weaving et al., 2022), most demanding passages of play (Castellano et al., 2020) and worst-case scenarios (Novak et al., 2021). More recently, contextualised approaches have finally reported physical match demands integrated with key tactical actions and phases of play, providing additional context for better understanding match demands and consequently improving training strategies (Bradley and Ade, 2018; Jerome et al., 2024; Ju et al., 2022).

The intermittent and stochastic nature of soccer match-play requires players to sustain high-volume and high-intensity actions, involving powerful technical skills and dynamic movement patterns (Bangsbo et al., 2006). To meet these demands, energy is supplied through the hydrolysis of adenosine triphosphate (ATP) whose resynthesis is regulated by substrate-level phosphorylation (i.e., anaerobic metabolism) and oxidative phosphorylation (i.e., aerobic metabolism) pathways (Hargreaves and Spriet, 2020). Throughout the match, players consistently switch between short high-intensity activities and longer periods of low-intensity exercise (Hostrup and Bangsbo, 2022; Jerome et al., 2024; Stølen et al., 2005). Therefore, the aerobic energy system is highly stressed and provides ~90% of the player's energy source due to the large amount of low to moderate intensity activities performed during match-play (Stølen et al., 2005). HR responses during match-play (average HR (HR_{avg}) and peak HR (HR_{peak}): 85% and 98% of HR_{max}, respectively) correspond to an average oxygen uptake of 70-75% of the player's VO_{2max} (Bangsbo et al., 2006), confirming the prominent role of the aerobic energy system in soccer match-play. Although aerobic metabolism dominates energy production throughout a soccer match-play, high-intensity actions depend on the anaerobic energy system (Stølen et al., 2005). Analysis of muscle and blood metabolites during match-play indicated that players' blood lactate concentrations peak up to 10-12 $mmol \cdot L^{-1}$ and creatine phosphate concentration declines up to 30% of resting values following the most intense period (Krustrup et al., 2006), indicating a significant contribution of the anaerobic energy system.

The analysis of match demands has shown that elite soccer players cover a total distance from 9 to 14 km per match (Sarmento et al., 2014). More recent findings on match running performance of the UEFA Champions League and FIFA World Cup tournaments indicated an average total distance of 10 to 12 km for 90-minute official matches (Ju et al., 2024; Modric et al., 2023). Differences in total distance were identified across positional roles and playing formation, with central midfielders and central defenders covering the highest and the lowest total distance, respectively (Bradley et al., 2013; Modric et al., 2023). These differences seem to be associated with the tactical demands required for each position (e.g., midfielders are often involved in both offensive and defensive actions). The evolution of soccer match-play demands requires contemporary players to perform more high-intensity actions to fulfil tactical roles in all the phases of the match (e.g., possession, non-possession and ball transitions), including HSR and SPR demands (Allen et al., 2024; Barnes et al., 2014). The capability to perform high-intensity efforts is a key physical prerequisite for successful participation at the professional level. Exposure to low- and medium-intensity running is primarily supported by aerobic energy systems, whilst high-intensity running, including HSR and SPR distances, relies heavily on anaerobic systems. These high-intensity efforts that HSR and SPR distances inherently involve are considered paramount for physical development, soccer-specific performance and injury prevention (Beato et al., 2021). The associated training effects include both metabolic (e.g., improved aerobic and anaerobic performance) and mechanical adaptations (e.g., increased force and power production). Based on the current literature, the definitions of the thresholds of SPR and SPR are still arbitrary, with no clear consensus. Recently, the adoption of FIFA's preferred thresholds: 19 $km \cdot h^{-1}$ and 20 $km \cdot h^{-1}$ for HSR distance (female and male entry velocities, respectively), and 23 $km \cdot h^{-1}$ and 25 $km \cdot h^{-1}$ for SPR distance, was suggested (Gualtieri et al., 2023). During official matches, HSR and SPR distances ranged from 618 to 1001 m, and from 153 to 295 m, respectively, in male professional soccer players (Gualtieri et al., 2023). Wide midfielders have shown consistently greater HSR distance compared to other playing positions, whilst wide defenders and wide midfielders recorded the highest SPR demands (Bradley et al., 2009; Di Salvo et al., 2009). Importantly, the use of arbitrary speed thresholds (e.g., > 20 $km \cdot h^{-1}$) may lead to misinterpretation of HSR and SPR demands, as it assumes uniform physiological responses among players with differing physical capabilities. Conversely, individualised or relative speed thresholds, defined as a percentage of each player's maximal sprinting speed (e.g., > 80% of maximal sprinting velocity achieved during testing or match play), allow for a more accurate assessment (Beato et al., 2021). This approach could enhance the precision of load quantification and support more individualised training prescriptions. However, current evidence remains inconclusive regarding the superiority of absolute or relative thresholds in soccer, warranting further investigation.

In addition to high-intensity running demands, the intermittent nature of soccer implies frequent and sudden changes in the rate of speed, which need to be considered. In this light, quantifying accelerations and decelerations represents an important aspect when profiling soccer match-play demands as players frequently increase or decrease running speed (Silva et al., 2023). Soccer players execute a greater frequency of high and very high-intensity decelerations compared to accelerations during match-play (Harper et al., 2019). These intense events of change in velocity are part of soccer match-play and impose distinctive physiological and mechanical stress on the players with higher metabolic demands when performing accelerations (Hader et al., 2016), whilst decelerations have a higher mechanical load (Dalen et al., 2016).

2.3.3.1 Physical and physiological match demands in youth soccer players

Youth soccer match-play is an essential component of a player's physical development across all stages of growth (McBurnie et al., 2021). Adolescent players participate in competitive matches of varying durations and formats throughout childhood and adolescence. Match durations in youth soccer are generally shorter than those in adult competitions, typically ranging from 50 to 80 minutes (e.g., 2 x 25, 2 x 30, 2 x 35, 2 x 40 minutes) (Palucci Vieira et al., 2019). Additionally, game formats and pitch dimensions differ from the adult game, with youth players competing on smaller pitches and with a reduced number of players, especially during childhood (e.g., 5-a-side, 7-a-side, 9-a-side) (Palucci Vieira et al., 2019). However, from around 16 years of age, the structure of competitive soccer match-play aligns with the adult format, with late-stage youth players participating in full 11-a-side matches lasting 90 minutes. For instance, the match duration and format of official elite youth soccer competitions such as the FIFA Under-17 World Cup and the UEFA Youth League mirror those of adult soccer (UEFA, 2013). A recent study has investigated the differences in match physical demands across the last editions of the FIFA World Cup (i.e., Under-17 World Cup 2023, Under-20 World Cup 2023 and Men's World Cup 2022), observing higher variability in total distance and distances at different speed zones in the younger age groups compared to adult counterpart (Ju et al., 2025). Given the distinct characteristics of youth players and match formats compared to their adult counterparts, it is important to identify and characterise the specific demands of youth soccer match-play. This understanding is useful to inform training programmes and ensure adolescent players are adequately prepared for the movement, physical, and physiological demands of competitions.

Over the last two decades, numerous studies have investigated the movement, physical, and physiological characteristics of match-play in youth soccer, describing average and peak demands. Multiple individual factors (e.g., age, maturation) and contextual factors (e.g., player position, duration, pitch dimensions, players a-side, type of competition, country, technology) influence the demands of youth soccer competitions. The variability of match demands in youth soccer has been demonstrated in a systematic review reporting the demands of 2615 adolescent players (Palucci Vieira et al., 2019). Movement and physical demands of match-play have been assessed using data derived from microtechnologies or camera systems, including total distance and distances at different speed thresholds (Atan et al., 2016; Barreira et al., 2023; Buchheit et al., 2010; Buchheit and Mendez-Villanueva, 2014; de Hoyo et al., 2016; Duthie et al., 2018; Goto et al., 2015; Harley et al., 2010; Kim et al., 2023; Lovell et al., 2019; Mendez-Villanueva et al., 2013; Parr et al., 2022; Reynolds et al., 2021; Romagnoli et al., 2016), maximal speed (Al Haddad et al., 2015; Atan et al., 2016; Buchheit et al., 2010; Kyprianou et al., 2019; Parr et al., 2022), and the frequency of accelerations, decelerations and changes of directions (Barreira et al., 2023; Kim et al., 2023; Morgan et al., 2022; Parr et al., 2022; Springham et al., 2024). Physiological match demands have primarily been studied using HR measures, including HR_{avg}, HR_{peak} and the time spent at high HR intensities (Aslan et al., 2012; Atan et al., 2016; Capranica et al., 2001; Castagna et al., 2009; Coelho et al., 2011; Francini et al., 2019; Kim et al., 2023; Mendez-Villanueva et al., 2013; Strøyer et al., 2004; Wrigley et al., 2012), and blood lactate concentrations (Aslan et al., 2012; Capranica et al., 2001).

The average total distance covered by youth soccer players during official 11-a-side match-play ranges from approximately 4500 to 6000 m for matches lasting 60, 70 and 75 minutes (Atan et al., 2016; Buchheit et al., 2010; Castagna et al., 2009; Goto et al., 2015; Harley et al., 2010), while it ranges from approximately 7500 to 11500 m for 80-minute and 90-minute match durations (Atan et al., 2016; Barreira et al., 2024; Buchheit et al., 2010; de Hoyo et al., 2016; Goto et al., 2015; Harley et al., 2010; Parr et al., 2022; Romagnoli et al., 2016; Springham et al., 2024).

Distances covered at different speed thresholds are typically reported using either arbitrary fixed thresholds (e.g., > 19.1 $km \cdot h^{-1}$, > 19.8 $km \cdot h^{-1}$, > 25.2 $km \cdot h^{-1}$) or individualised thresholds derived from fitness testing protocols such as maximal linear sprint speed, lactate concentrations or speed attained at VO_{2max} (Palucci Vieira et al., 2019). For instance, Buchheit et al. (2010) quantified absolute HSR demands of youth soccer players using a threshold of 19.1 $km \cdot h^{-1}$, reporting average distances of 186-318 m in 70-minute matches, 384-449 m in 80-minute matches and up to 666 m in 90-minute matches. Similarly, Parr et al. (2022) examined HSR (> 19.8 $km \cdot h^{-1}$) and SPR (> 25.2 $km \cdot h^{-1}$) running demands in an English Premier League academy, with youth players covering on average 355-540 m and 45-94 m, respectively, in 80-minute matches. This lack of standardisation in speed thresholds across studies limits the ability to directly compare results, making it difficult to summarise youth soccer's HSR and SPR activities. To date, there is no consensus regarding the use of absolute or relative speed thresholds in youth soccer. Absolute thresholds facilitate longitudinal monitoring and between-player comparisons (e.g., multi-season analyses, comparison with adult players), but fail to account for differences in physical capabilities and maturation status. Conversely, relative thresholds provide a more accurate representation of players' HSR and SPR demands, yet they may compromise within-player comparisons over time as maximal sprinting speed naturally increases with growth and development.

The mechanical demands of youth soccer match-play are described by quantifying accelerations, decelerations and changes of direction. In agreement with the characteristics of adult soccer match-play, youth soccer competitions also require players to sustain a greater frequency of high-intensity decelerations compared to accelerations (Barreira et al., 2024; Parr et al., 2022; Springham et al., 2024). The classification of player acceleration and deceleration data into specific categories has been based on both absolute and relative thresholds, with absolute thresholds allowing comparison across studies and relative thresholds accounting for the individual capacity to accelerate (Kovacevic et al., 2022). Throughout 90-minute youth soccer match-play, accelerations > 3 $m \cdot s^{-2}$ were 64 ± 13 in English Premier League and 53 ± 13 in Portuguese youth soccer players, whilst decelerations > 3 $m \cdot s^{-2}$ were 72 ± 16 and 66 ± 14, respectively (Barreira et al., 2024; Springham et al., 2024). With 80-minute matches, the number of accelerations sustained by English Premier League youth soccer players ranged from 43 to 57 events > 3 $m \cdot s^{-2}$ (Parr et al., 2022). Repeated high acceleration bouts with short recovery, defined as a minimum of 3 accelerations with less than 45 s, occur frequently in youth soccer, with elite youth players performing on average 8 ± 5 bouts of high-intensity accelerations above 70% of the 5-m acceleration obtained during a sprint test (Serpiello et al., 2018). In addition to these movements associated with the ability to change velocity rapidly during match-play, late-stage youth soccer players perform on average 305 ± 50 changes of directions (CODs) per match, with approximately 19 seconds of recovery between events and the majority of CODs angles identified as less than 90° (77%) (Morgan et al., 2022). However, during 5-minute and 15-minute periods the average CODs performed are 16 and 25, respectively. A summary of the studies reporting physical demands of youth soccer match-play, including accelerations, decelerations and changes of direction, is reported in Table 1.

Table 1. Synthesis of the physical demands of 11-a-side youth soccer match-play.

Study (year)	**Players characteristics (*n*, country, level, age groups)**	**Match-play characteristics (duration, pitch sizes)**	**Total distance covered (m)**	**Distance covered at high-speed thresholds (m)**	**Maximal speed (km·h^{-1})**	**Accelerations, decelerations and changes of direction (counts)**
Al Haddad et al. (2015)	*n* = 180 Qatar Tier 3 U13 (*n* = 35) U14 (*n* = 44) U15 (*n* = 40) U16 (*n* = 37) U17 (*n* = 24)	80-90 min (2 x 35, 2 x 45), 100 x 70 m	-	-	U13: 23.4 ± 1.8 U14: 25.1 ± 2.3 U15: 25.6 ± 2.4 U16: 26.2 ± 2.5 U17: 26.8 ± 1.9	-
Aslan et al. (2012)	*n* = 47 Turkey Tier 3 U18	90 min (2 x 45), 105 x 68m	9900	*SPR > 24 km·h^{-1}*: 325	-	-
Atan et al. (2016)	*n* = 85 New Zealand Tier 2 U13 (*n* = 28) U14 (*n* = 27) U15 (*n* = 30)	U13: 60 min (2 x 30), 100 x 60 m U14: 70 min (2 x 35), 100 x 60 m U15: 80 min (2 x 40), 100 x 60 m	U13: 4516 ± 703 U14: 5385 ± 1296 U15: 6600 ± 1480	-	U13: 23.5 ± 1.7 U14: 25.4 ± 1.9 U15: 26.5 ± 1.7	-

Study (year)	Players characteristics (*n*, country, level, age groups)	Match-play characteristics (duration, pitch sizes)	Total distance covered (m)	Distance covered at high-speed thresholds (m)	Maximal speed (km·h^{-1})	Accelerations, decelerations and changes of direction (counts)
Barreira et al. (2016)	*n* = 21 Portugal Tier 3 U19	90 min (2 x 45), regular size	10777 ± 979	*HSR > 19.8 km·h^{-1}*: 773 ± 276 *SPR > 25.2 km·h^{-1}*: 202 ± 150	-	*ACC > 3 m·s^{-2}*: 53 ± 13 *DEC > -3 m·s^{-2}*: 66 ± 14
Buchheit et al. (2010)	*n* = 77 Qatar Tier 3 U13 (*n* = 7) U14 (*n* = 17) U15 (*n* = 10) U16 (*n* = 12) U17 (*n* = 17) U18 (*n* = 14)	U13, U14: 70 min (2 x 35), 100 x 70 m U15, U16, U17: 80 min (2 x 40), 100 x 70 m	U13: 6549 ± 597 U14: 7383 ± 640 U15: 8129 ± 879 U16: 8312 ± 1054 U17: 8707 ± 1101 U18: 8867 ± 859	*HSR > 19.1 km·h^{-1}*: U13: 186 ± 92 U14: 318 ± 183 U15: 410 ± 204 U16: 384 ± 163 U17: 449 ± 147 U18: 666 ± 256	U13: 22.3 ± 1.4 U14: 24.4 ± 1.8 U15: 26.0 ± 2.4 U16: 26.3 ± 2.3 U17: 26.6 ± 2.2 U18: 28.3 ± 2.2	-
Castagna et al. (2009)	*n* = 81 San Marino Tier 2 U15	60 min (2 x 30); regular size	6204 ± 731	*HSR > 18 km·h^{-1}*: 234 ± 137	-	-
De Hoyo et al. (2016)	*n* = 15 Spain Tier 3	90 min (2 x 45), regular size	9165 ± 1134	*HSR > 21km·h^{-1}*: 152 ± 128	-	-

Study (year)	Players characteristics (*n*, country, level, age groups)	Match-play characteristics (duration, pitch sizes)	Total distance covered (m)	Distance covered at high-speed thresholds (m)	Maximal speed (km·h^{-1})	Accelerations, decelerations and changes of direction (counts)
	U19					
Goto et al. (2015)	*n* = 81 England Tier 3 U11 (*n* = 18) U12 (*n* = 12) U13 (*n* = 12) U14 (*n* = 10) U15 (*n* = 13) U16 (*n* = 16)	U11, U12: 75 min (3 x 25), 79 x 54 m U13: 75 min (3 x 25), 88 x 64 m U14, U15, U16: 80 min (2 x 40), 101 x 68 m	U11: 5889 U12: 6068 U13: 6242 U14: 6378 U15: 6598 U16: 6587	*HSR > 21.6 km·h^{-1}:* U11: 29 U12: 52 U13: 72 U14: 118 U15: 148 U16: 64	-	-
Harley et al. (2010)	*n* = 112 England Tier 3 U12 (*n* = 22) U13 (*n* = 20) U14 (*n* = 25) U15 (*n* = 21) U16 (*n* = 24)	U12, U13: 75 min (3 x 25), 77 x 60 m U14, U15: 75 min (3 x 25), 99 x 65 m U16: 80 min (2 x 40), 99 x 65 m	U12: 5967 U13: 5813 U14: 5715 U15: 6016 U16: 7672	-	-	-
Morgan et al. (2022)	*n* = 24 England	90 min (2 x 45), regular size	-	-	-	*CODs*: 305 ± 50

Study (year)	Players characteristics (*n*, country, level, age groups)	Match-play characteristics (duration, pitch sizes)	Total distance covered (m)	Distance covered at high-speed thresholds (m)	Maximal speed (km·h^{-1})	Accelerations, decelerations and changes of direction (counts)
	Tier 4 U20					
Parr et al. (2022)	*n* = 37 England Tier 3 U14 (*n* = 21) U16 (*n* = 16)	U14: 80 min (2 x 40), 85 x 64 m U16: 80 min (2 x 40), 100 x 64 m	U14: 8521 ± 965 U16: 9005 ± 733	*HSR > 19.8 km·h^{-1}*: U14: 355 ± 225 U16: 540 ± 197 *SPR > 25.2 km·h^{-1}*: U14: 45 ± 73 U16: 94 ± 69	U14: 27.9 ± 2.2 U16: 29.8 ± 2.9	*ACC > 3 m·s^{-2}*: U14: 43 ± 14 U16: 57 ± 12
Reynolds et al. (2021)	*n* = 19 England Tier 3 U18	90 min (2 x 45), regular size	10259 ± 883	*HSR > 19.8 km·h^{-1}:* 626 ± 228 *SPR > 25.2 km·h^{-1}:* 110 ± 82	-	-
Romagnoli et al. (2016)	*n* = 18 Italy Tier 3 U20	90 min (2 x 45), regular size	11734 ± 1067	*HSR > 20 km·h^{-1}*: 905 ± 361	-	-
Springham et al. (2024)	*n* = 18 England Tier 4 U18	90 min (2 x 45), regular size	10229 ± 944	-	-	*ACC > 3 m·s^{-2}:* 64 ± 13 *DEC > -3 m·s^{-2}*: 72 ± 16

Abbreviations and notes: - indicates data not available in the original research; ACC: acceleration; COD: change of direction; DEC: deceleration; HSR: high-speed running; *n*: number of players (sample size); min: minute; m: meter; SPR: sprinting running; U: under. Data are presented as mean or mean ± SD. Players' level is defined according to the classification of McKay et al. (2022): Tier 0: Sedentary; Tier 1: Recreationally Active; Tier 2: Trained/Developmental; Tier 3: Highly Trained/National Level; Tier 4: Elite/International Level; or Tier 5: World Class.

The physiological demands of youth soccer match-play are characterised by the high involvement of the aerobic energy system with elevated HR intensities throughout the match-play. Strøyer et al. (2004) demonstrated that elite youth soccer players exhibit similar oxygen uptake values during match-play to those observed in adult players, with an average oxygen uptake corresponding to 70-80% of VO_{2max}. In the same study, the authors observed that elite youth players exhibited higher relative oxygen uptake and HR compared to non-elite counterparts of the same age. Adolescent players spend most of their playing time at high HR intensities during competitive matches (e.g., > 170 $b \cdot min^{-1}$, > 180 $b \cdot min^{-1}$, > 81% HR_{max}, > 85 % HR_{max}), with the amount of high HR intensity time decreasing from the first to the second half (Aslan et al., 2012; Capranica et al., 2001; Coelho et al., 2011; Francini et al., 2019; Mendez-Villanueva et al., 2013; Wrigley et al., 2012). The HR_{avg}, expressed as a percentage of HR_{max}, ranged from 82 to 90%, whilst observed HR_{peak} intensities attained up to 100% of HR_{max} (Aslan et al., 2012; Castagna et al., 2009; Coelho et al., 2011; Francini et al., 2019; Kim et al., 2023). For example, HR_{peak} recorded in Brazilian youth soccer matches were 201 ± 9 $b \cdot min^{-1}$ and 199 ± 7 $b \cdot min^{-1}$ in under-17 and under-20 players, respectively (Coelho et al., 2011). In another investigation, Atan et al. (2016) identified HR_{peak} corresponding to 202 ± 7 $b \cdot min^{-1}$ in under-13 players, 200 ± 12 $b \cdot min^{-1}$ in under-14 players, and 208 ± 12 $b \cdot min^{-1}$ in under-15 players. In addition, a study by Kim et al., (2023) characterised the HR MIPs with intensities ranging from 185 to 200 $b \cdot min^{-1}$ (92 to 95% HR_{max}) for the 1-min MIP, and from 171 to 184 $b \cdot min^{-1}$ (85 to 90% HR_{max}) for the 10-min MIP, highlighting near-to-maximal HR intensities throughout the most intense periods of the match in under-18 youth soccer players. Blood lactate concentration ranged from 3.1 to 8.1 $mmol \cdot L^{-1}$ in under-12 youth soccer players, whilst Aslan et al. (2012) observed a decrease from 4.5 to 3.4 $mmol \cdot L^{-1}$ from the first to the second half, respectively, with individual blood lactate values up to 12 $mmol \cdot L^{-1}$ in under-18 Turkish soccer players. Overall, these blood lactate concentrations recorded with youth players are on average lower than those observed in elite adult players (Bangsbo, 1994; Bangsbo et al., 2006; Stølen et al., 2005). A synthesis of the studies reporting physiological demands of youth soccer match-play is reported in Table 2.

Table 2. Synthesis of the physiological demands of 11-a-side youth soccer match-play.

Study (year)	**Players characteristics (*n*, country, level, age groups)**	**Match-play characteristics (duration, pitch sizes)**	**Heart rate measures**	**Blood lactate ($mmol \cdot L^{-1}$)**
Aslan et al. (2012)	*n* = 47 Turkey Tier 3 U18	90 min (2 x 45), 105 x 68 m	HR_{avg} *($b \cdot min^{-1}$)*: First half: 167 ± 9 Second half: 162 ± 8 HR_{avg} *(%)*: First half: 87 Second half: 84	First half: 4.5 ± 1.9 Second half: 3.4 ± 1.2
Atan et al. (2016)	*n* = 85 New Zealand Tier 2 U13 (*n* = 28) U14 (*n* = 27) U15 (*n* = 30)	U13: 60 min (2 x 30), 100 x 60 m U14: 70 min (2 x 35), 100 x 60 m U15: 80 min (2 x 40), 100 x 60 m	HR_{peak} *($b \cdot min^{-1}$)*: U13: 202 ± 7 U14: 200 ± 12 U15: 208 ± 12	-
Capranica et al. (2010)	*n* = 6 Italy Tier 2 U12	100 x 65 m, regular size	-	From 3.1 to 8.1
Castagna et al. (2009)	*n* = 81 San Marino Tier 2 U15	60 min (2 x 30); regular size	HR_{avg} *(%)*: First half: 86.0 ± 5 Second half: 85 ± 6 HR_{peak} *(%)*:	-

Study (year)	Players characteristics (*n*, country, level, age groups)	Match-play characteristics (duration, pitch sizes)	Heart rate measures	Blood lactate (mmol·L^{-1})
			First half: 100 ± 4 Second half: 99 ± 5	
Coelho et al. (2011)	*n* = 44 Brazil Tier 3 U17 (*n* = 26) U20 (*n* = 18)	90 min (2 x 45), regular size	*HR_{peak} (b·min^{-1})*: U17: 201 ± 9 U20: 199 ± 7 *HR_{avg} (%)*: U17: 84 ± 5 U20: 84 ± 4 *Time spent > 90% HR_{max} (%)*: U17-U20 First half: 37 U17-U20 Second half: 23	-
Francini et al. (2009)	*n* = 68 Italy Tier 3 U14 (*n* = 17) U15 (*n* = 17) U16 (*n* = 16) U18 (*n* = 18)	U14-U15: 70 min (2 x 35); 100 x 60 m U16-U17: 80 min (2 x 40); 100 x 60 m	*HR_{avg} (%)*: U14: 83.8 ± 4.4 U15: 81.6 ± 6.5 U16: 85.1 ± 3.7 U17: 85.5 ± 4.2 *Time spent > 85% HR_{max} (min; %)*: U14: 32 ± 14; 46 ± 20 U15: 29 ± 16; 41 ± 23 U16: 43 ± 16; 54 ± 20 U17: 41 ± 19; 51 ± 23 *Time spent > 90% HR_{max} (min; %)*:	-

Study (year)	Players characteristics (*n*, country, level, age groups)	Match-play characteristics (duration, pitch sizes)	Heart rate measures	Blood lactate (mmol·L^{-1})
			U14: 21 ± 14; 30 ± 20 U15: 16 ± 13; 22 ± 18 U16: 23 ± 14; 29 ± 17 U17: 23 ± 16; 29 ± 20	
Mendez-Villanueva et al. (2013)	*n* = 87 Qatar Tier 3 U14 (*n* = 20) U15 (*n* = 17) U16 (*n* = 18) U17 (*n* = 15) U18 (*n* = 17)	U14: 70 min (2 x 35); 100 x 70 m U15, U16, U17: 80 min (2 x 40); 100 x 70 m U18: 90 min (2 x 45), 100 x 70 m	*Time spent > 91% HR_{max} (%)*: U14 First half: 35 ± 12 U14 Second half: 32 ± 24 U15 First half: 45 ± 21 U15 Second half: 26 ± 17 U16 First half: 36 ± 21 U16 Second half: 35 ± 22 U17 First half: 36 ± 24 U17 Second half: 19 ± 19 U18 First half: 36 ± 23 U18 Second half: 23 ± 14	-
Romagnoli et al. (2016)	*n* = 18 Italy Tier 3 U20	90 min (2 x 45), regular size	*HR_{avg} (b·min^{-1}; %)*: First half: 176 ± 9; 88 ± 4 Second half: 164 ± 9; 82 ± 4 *HR_{peak} (b·min^{-1}; %)*: First half: 192 ± 7; 96 ± 3 Second half: 189 ± 7; 95 ± 3 *Time spent > 90% HR_{max} (min)*:	-

Study (year)	Players characteristics (*n*, country, level, age groups)	Match-play characteristics (duration, pitch sizes)	Heart rate measures	Blood lactate ($mmol \cdot L^{-1}$)
			First half: 18.8 ± 10.5 Second half: 6.3 ± 5.3	
Strøyer et al. (2004)	*n* = 16 Denmark Tier 3 U13 (*n* = 9) U15 (*n* = 7)	U13: 60 min (2 x 30) U15: 70 min (2 x 35)	HR_{avg} ($b \cdot min^{-1}$): U13 First half: 177 U13 Second half: 173 U15 First half: 176 U15 Second half: 172	-
Wrigley et al. (2012)	*n* = 24 England Tier 3 U14 (*n* = 8) U16 (*n* = 8) U18 (*n* = 8)	U14, U16: 80 min (2 x 40); regular size U18: 90 min (2 x 45); regular size	HR_{avg} ($b \cdot min^{-1}$): U14: 174 ± 5 U16: 176 ± 4 U18: 177 ± 4	-

Abbreviations and notes: - indicates data not available in the original research; HR_{avg}: average heart rate; HR_{max}: maximal heart rate; HR_{peak}: peak heart rate; *n*: number of players (sample size); min: minute; U: under. Players' level is defined according to the classification of McKay et al. (2022): Tier 0: Sedentary; Tier 1: Recreationally Active; Tier 2: Trained/Developmental; Tier 3: Highly Trained/National Level; Tier 4: Elite/International Level; or Tier 5: World Class.

Match demands in youth soccer vary across age groups, with older players demonstrating higher match demands compared to younger counterparts. For example, under-16 players consistently displayed greater physical match demands compared to under-14 counterparts during 80-minute matches in an English Premier League academy (Parr et al., 2022). Older presented higher total distance (+ 484 m), HSR distance (+ 185 m), SPR distance (+ 49 m), maximal speed (+ 1.9 $km \cdot h^{-1}$) and number of accelerations (+ 14 events) compared to under-14 players (Parr et al., 2022). In general, absolute total distance, distance covered at fixed high-speed thresholds and maximal speed increase with age in multiple cross-sectional studies (Al Haddad et al., 2015; Atan et al., 2016; Buchheit et al., 2010; Goto et al., 2015; Harley et al., 2010). For instance, Harley et al. (2010) demonstrated that under-16 players displayed higher absolute total distance, high-intensity distance and SPR distance compared to their younger counterparts (under-12 and under-13), whereas (Buchheit et al., 2010) observed that under-13 players covered significantly less total distance compared to older players (under-16, under-17 and under-18 players), and under-18 players covered significantly higher distances at very high-intensity (> 16 $km \cdot h^{-1}$) compared to younger age groups. In addition, maximal sprinting speed increased as a function of age in Qatari youth soccer players belonging to under-13 (23.4 ± 1.8 $km \cdot h^{-1}$), under-14 (25.1 ± 2.3 $km \cdot h^{-1}$), under-15 (25.6 ± 2.4 $km \cdot h^{-1}$), under-16 (26.2 ± 2.5 $km \cdot h^{-1}$) and under-17 (26.8 ± 1.9 $km \cdot h^{-1}$) (Al Haddad et al., 2015). However, when adjusted for playing time or when using individualised speed thresholds, differences in match running demands were less evident or not observed for total distance and HSR (Atan et al., 2016; Buchheit et al., 2010; Harley et al., 2010). These differences in match demands may stem from a combination of influencing factors, including game format (e.g., match duration, pitch dimension) and individual characteristics, such as enhanced physical attributes and greater maturity levels typically observed in older adolescent players.

Apart from the chronological age differences, biological maturation also appears to impact physical match demands in adolescent soccer players. Multiple investigations have reported significantly higher match demands in more mature players compared to earlier maturing players of the same chronological age, especially in under-14 and under-15 age groups (Buchheit et al., 2010; Buchheit and Mendez-Villanueva, 2014; Francini et al., 2019; Parr et al., 2022). For example, Buchheit and Mendez-Villanueva (2014) demonstrated the impact of maturation in under-15 soccer players for distance covered at high-intensity running (> 16 $km \cdot h^{-1}$), whilst Parr et al. (2022) observed that under-14 players more advanced in maturity typically covered greater distances at high speed, attained higher maximal sprinting speed and sustained more accelerations compared to less mature counterpart. However, the impact of maturation on match running demands appeared less evident with older players (e.g., under-16) of the same English Premier League soccer academy (Parr et al., 2022). Small associations between biological maturation and HSR (> 18 $km \cdot h^{-1}$) and SPR demands (> 23 $km \cdot h^{-1}$) were also observed in Italian semi-professional youth soccer players (Francini et al., 2019). In contrast, Lovell et al. (2019) observed that late maturing under-15 Australian national team soccer players covered substantially higher intensity running than their early maturing counterparts. These contrasting results may be due to the different methodologies used in the studies, including indicators of biological maturity (e.g., age at peak height velocity or percentage of predicted adult height) and contextual factors (e.g., match duration, scheduling, environmental conditions). In terms of technical skills, early maturing players also performed more tackles, blocks and interceptions compared to on-time maturing players (Saward et al., 2019). Therefore, players with advanced maturity status can have an advantage in anthropometric and physical performance characteristics compared to less mature players (Malina et al., 2004; Murtagh et al., 2018; Parr et al., 2020), likely resulting in greater physical output during competitive match-play.

The physical demands of youth soccer match-play are also position-dependent, with accentuated differences observed between positional roles. Central defenders emerge as the position with the lowest demands for both total distance and distance covered at HSR (Buchheit et al., 2010; Mendez-Villanueva et al., 2013). On the contrary, midfielders typically displayed the highest total distance covered and recorded higher HR responses during match-play (Buchheit et al., 2010; Kim et al., 2023; Parr et al., 2022). Wide defenders, wide midfielders and attackers have shown instead the greatest SPR demands (distance and peak speed) compared to other positional roles (Al Haddad et al., 2015; Buchheit et al., 2010; Parr et al., 2022). In another research, Duthie et al., (2018) demonstrated that during the MIPs of youth soccer matches, the peak running intensities differ between positional roles, with midfielders and wide defenders displaying higher intensities compared to central defenders and attackers. Similarly, Kim et al., (2023) identified the central defenders and central midfielders as the positions with the lowest and highest external (speed) and internal (HR) MIPs, respectively. In addition, wide defenders emerged as the players with the highest HSR, sprinting and acceleration intensities during MIPs. Overall, these results highlight the variability and position-specific nature of match demands across positional roles in youth soccer competitions.

2.3.4 Training demands in soccer

The overall aim of the training process in soccer is to administer an appropriate frequency, volume, intensity and mode of training to deliver a psychophysiological stimulus that achieves adaptations and consequently improves performance (Akenhead and Nassis, 2016). The complexity of soccer match-play requires the completion of a multi-dimensional training program with the inclusion of specific training plans for the development of energy systems and strength-power qualities to ensure that the movement, physical and physiological demands of soccer match-play are met (Bangsbo et al., 2006; Morgans et al., 2014; Walker and Hawkins, 2018). Specifically, physical training for soccer should incorporate methods and means that improve players' capacity to perform prolonged exercise, perform repeated bouts of high-intensity exercise, the ability to sprint and develop a high level of force and power output during match-play (Bangsbo et al., 2006).

To effectively prepare players for optimal performance, periodisation of training is often used as a tool to organise the training process. Different definitions and models of periodisation have been proposed (Afonso et al., 2020; Issurin, 2010; Kiely, 2018; Turner, 2011), however, Mujika et al. (2018) suggested that periodisation should be considered a systematic attempt to gain control of the training responses in preparation for competition by combining different training methods to yield better results than can be achieved through the exclusive use of a single method. In addition, Kiely (2018) critically evaluate the theory of training periodisation by proposing that it should be understood as hypothetical and tradition-driven assumptions rather than evidence-led constructs. In this context, coaches and athletes should shift from the preordained training structures toward a philosophy characterised by an adaptive readiness to respond to emerging information (Kiely, 2018). Within periodised training plans, the training process is typically structured using macrocycles, mesocycles, and microcycles (Mujika et al., 2018; Pass et al., 2022).

The periodisation of mesocycles and microcycles in soccer has received greater attention over the last decade, with research quantifying the training load imposed during the pre-season and in-season periods in adult professional players across different European leagues (Akenhead et al., 2016; Anderson et al., 2016; Fleming et al., 2023; Gualtieri et al., 2020; Kelly et al., 2020; Malone et al., 2015; Martín-García et al., 2018). In particular, the distribution of training load across the weekly microcycle represents a fundamental aspect in the management of training load in soccer, with the quantification of training load with respect to the distance from match day (MD) (Buchheit et al., 2021; Silva et al., 2023). For example, Malone et al. (2015) examined pre-season and in-season training loads in English Premier League players, revealing no differences in external load (total distance, HSR distance, average speed) and internal load (% HR_{max}, RPE) during pre-season weekly microcycles. More recently, Kelly et al. (2020) reported limited variation in training load during competitive mesocycles, whilst revealing marked fluctuation in load within the weekly microcycles in English Premier League players, with the central days of the microcycle characterised by the highest load of the week. A similar microcycle periodisation was evident in Spanish La Liga soccer players with substantial variations of daily load based on the training day (training load declined as competition approached) and player position (full backs performed more HSR and SPR distance than other positions) (Martín-García et al., 2018). Despite different training methodologies and periodisation strategies adopted across European leagues, most of the published research reported a substantial reduction in training load on MD-1 compared to the central days of the weekly microcycle (MD-4 and MD-3).

2.3.4.1 Training loads in youth soccer players

The importance of the training process is particularly relevant within youth soccer academies, where developmental and training programmes are in place to maximise the chance of success (McBurnie et al., 2021; Ryan et al., 2017). Throughout adolescence, youth soccer players face unique challenges due to the growing training and match demands (Hannon, Coleman, et al., 2021) and the inconsistency in the timing and tempo of their physical growth and maturity (Johnson et al., 2022). Therefore, a systematic approach to training load monitoring and management is recommended within youth sports to support the development of talented individuals and consequently reduce the likelihood of negative outcomes such as non-functional overreaching, injury and illness (Bowen et al., 2017; Murray, 2017; Towlson et al., 2021).

Designing periodised training programs for high-level youth soccer players presents unique challenges due to the numerous contextual and individual factors that influence the training process (Pass et al., 2022). Compared to adult soccer players, adolescent players possess markedly different physical and physiological characteristics which develop as a function of age and maturation (Radnor et al., 2018). These differences between senior and youth soccer players may also be reflected in the training load sustained during the training week. For instance, Houtmeyers et al. (2021) examined differences in weekly training load between first team and under-19 players in an Eredivisie club, revealing that first team players covered more SPR distance (> 25 km·h^{-1}) than the under-19 players, and that training intensity expressed, as distance per minute at low and high-velocity zones, were also lower in younger players during weekly microcycles. More recently, Taylor et al. (2023) compared the weekly external and internal loads of under-16, under-18 and under-23 English Premier League youth soccer players, showing that older players (under-18 and under-23) sustain higher training loads compared to younger counterparts (under-16) throughout a 5-week mesocycle. Despite the widespread use of external and internal load indicators among the elite youth soccer academies (Salter et al., 2021), longitudinal studies integrating both dimensions of external and internal load across different age groups are scarce within this population with few studies reporting typical training loads experienced by youth players.

Research on youth soccer players has predominantly quantified typical training loads using a single dimension of load (Brownlee, O'Boyle, et al., 2018) and often over a short time period (Coutinho et al., 2015; Wrigley et al., 2012). Only one study has documented training loads in high-level youth soccer players across multiple age groups across an entire season, exclusively reporting external loads (Hannon, Coleman, et al., 2021). Weekly training volume exhibited progressive increases throughout the academy pathway in English Premier League youth soccer players, with training duration and total distance showing higher loads in under-15 (duration: 421 ± 15 min; total distance: 26.2 ± 2.1 km), under-16 (duration: 427 ± 20 min; total distance: 25.9 ± 2.5 km), under-18 (duration: 398 ± 30 min; total distance: 26.1 ± 2.6 km) compared to under-12 (duration: 329 ± 29 min; total distance: 19.9 ± 2.2 km), under-13 (duration: 323 ± 29 min; total distance: 20.0 ± 2.0 km) and under-14 (duration: 339 ± 25 min; total distance: 21.7 ± 2.0 km) age groups. Similarly, weekly HSR distance (between 19.8 and 25.2 km·h^{-1}) and sprinting distance (> 25.2 km·h^{-1}) were higher in under-16 (HSR: 749 ± 152 m; SPR: 95 ± 55 m) and under-18 (HSR: 979 ± 254 m; SPR: 123 ± 56 m) compared to under-12 (HSR: 220 ± 95 m; SPR: 6 ± 9 m) and under-13 (HSR: 331 ± 212 m; SPR: 6 ± 13 m) age groups. In another study conducted with an English Premier League academy, Brownlee et al. (2018) observed similar results with increases in weekly training duration from under-9 (268 ± 25 min) to under-14 (477 ± 19 min) age groups. Differences between academy age groups were also investigated for internal training load measures, including measures of RPE and HR (Wrigley et al., 2012). In this study, the authors observed that the cumulative weekly sRPE-training load increased with age (under-14: 2524 ± 128 AU vs under-16: 2919 ± 136 AU vs under-18: 3948 ± 222 AU) over two weeks (Wrigley et al., 2012). Similarly, HR training load reported as time spent above 90% HR_{max} was lower in under-14 (3 ± 1 %) compared to under-16 (5 ± 1 %) and under-18 (6 ± 3 %) age groups (Wrigley et al., 2012). In addition, another study from an under-18 English Premier League squad reported descriptive data on the volume sustained across a typical week, with average total distance ranging from 19759 to 30714 m and average HSR distance > 20 $km \cdot h^{-1}$ ranging from 856 to 1448 m (Bowen et al., 2017).

Another relevant aspect of the training load sustained by youth soccer players is related to the distribution of daily load across the competitive microcycles. Periodisation of training load in high-level youth soccer players has shown that external and internal load can vary across the microcycles based on age groups and training days (Coutinho et al., 2015; Hannon, Coleman, et al., 2021; Maughan et al., 2021; Szigeti et al., 2022; Wrigley et al., 2012). For example, Coutinho et al. (2015) examined the periodisation of loading throughout a single week of training in Portuguese youth players from the under-15, under-17 and under-19 age groups. Differences in the distribution of load, expressed with average speed and number of sprints, emerged in under-19 players with the highest daily load occurring at the start of the week and in under-17 players with the mid-week training session eliciting the highest load. Conversely, no evidence of periodisation emerged with under-15 players (Coutinho et al., 2015). Marked fluctuations of daily load across the microcycle were also noted in older academy players (under-16 and under-18) compared to younger counterparts (under-12 and under-13) in an English Premier League academy (Hannon, Coleman, et al., 2021). Interestingly, under-16 and under-18 age groups daily training loads exhibited higher external load on the central days of the week (MD-4 and MD-2) compared to the sessions at the beginning (MD-5) and at the end (MD-1) of the weekly microcycle (Hannon, Coleman, et al., 2021). Differences in daily load were also observed in youth national team players with gradual decreases in training volume as the match approached (MD-3 > MD-2 > MD-1) (Szigeti et al., 2022). The proximity of training to match day was identified as the most influential factor explaining variation in training load in a seasonal-long analysis performed with Scottish youth soccer players, with the day before match-play characterised by the lowest load of the week and the mid-week training days remaining consistent (MD-4, MD-3 and MD-2) (Maughan et al., 2021).

The current evidence on weekly accumulated training loads and the periodisation of load within the microcycle presents limited information regarding a number of factors impacting the planning, monitoring and manipulation of training load. In particular, there is a paucity of data integrating external and internal load with youth soccer academies. Arbitrary speed thresholds are commonly adopted for quantifying HSR and SPR distances in youth soccer players as opposed to individualised speed zones. Overall, based on the current literature, it seems that absolute thresholds may be more suitable for long-term monitoring and comparison between groups, whilst relative speed zones may be preferable for more precise programming of the training load, which could help to design the appropriate dose of high-speed running and sprinting distance (Beato et al., 2021). Given the role of internal load on subsequent training responses and adaptation, it is fundamental to describe both dimensions of the training load within this population (Impellizzeri et al., 2019). As youth players grow and develop with different timing and tempo, detailed information on match and training demands sustained by adolescent players is needed to characterise the training process with age-specific information. Additionally, most of the published research has documented training load characteristics of youth soccer players from the United Kingdom. Considering the varied training approaches across European countries (Roca and Ford, 2020), describing the training load in high-level youth academies in other countries is of interest for practitioners working within this setting. Finally, given the long-term approach required to develop the physical performance components of the adolescent player, longitudinal data on the typical training loads endured across one or more seasons are required. Information on these aspects related to the monitoring and management of training load would benefit practitioners in informing the design and programming of contextualised training plans within youth soccer.

2.4 Post-match fatigue and recovery responses in soccer

2.4.1 Concept of fatigue and recovery

Fatigue is a complex phenomenon with definitions that vary across disciplines, including medicine, physiology and psychology (Behrens et al., 2022). In the field of exercise physiology, fatigue is defined as a self-reported disabling symptom that limits physical and cognitive function, arising from the interactions between performance fatigability and perceived fatigability (Enoka and Duchateau, 2016). Performance fatigability refers to a measurable decline in physical performance (e.g., reduced power output), whilst perceived fatigability refers to an altered perception of effort that maintains an individual's integrity (e.g., increased muscle soreness). In applied settings, the manifestation of fatigue is shaped by the interplay between performance and perceived fatigability, influenced by the demands of the sport as well as the athlete's capacity to tolerate and adapt to the cumulative stress (Grainger et al., 2024). From an applied sports science perspective, fatigue is commonly conceptualised as a state induced by physiological and psychological constraints, resulting in diminished physical or mental performance (Hauswirth and Mujika, 2013). Alternatively, it may be defined as the inability to complete a task previously achievable within a recent timeframe (Halson, 2014).

Fatigue can be compensated with recovery, a multifaceted and complex process that involves various restorative mechanisms over time, serving as an essential component of the overall training process (Kellmann et al., 2018; Mujika et al., 2018). Its complexity arises from the different time course of recovery required for various physiological and psychological processes to return to baseline following exercise (Skorski et al., 2019). Recovery is defined as the time during which biological responses to training load occur, restoring the body's allostatic balance through the replenishment of physiological and psychological resources expended during exercise (Kellmann et al., 2018).

2.4.2 Mechanisms of match-related fatigue in soccer

The demands of training and competition elicit various effects and responses, influenced by the characteristics of the stimulus (e.g., duration, intensity and nature), individual factors (e.g., age, genetics, fitness level) and contextual factors (e.g., environmental conditions, scheduling, opposition level) (Skorski et al., 2019). These demands cause fatigue, leading to alterations to multiple physiological systems, including metabolic and biomechanical perturbations (e.g., dehydration, glycogen depletion), impaired mechanical function and reduced performance capacity (e.g., increased muscle damage and reduced force), along with worsened perception of fatigue and muscle soreness (Silva et al., 2018). Match-related fatigue is evident during the most demanding phases of play (Schimpchen et al., 2021), towards the end of the match-play (Mohr et al., 2023) and in the subsequent days (Krustrup et al., 2011). An understanding of the mechanisms and processes related to match-related fatigue provides the rationale for the selection of appropriate recovery interventions (Nedelec et al., 2012; Thorpe, 2021). A set of potential causes and mechanisms responsible for match-induced fatigue is discussed in this section.

2.4.2.1 Neuromuscular fatigue

Match-related fatigue is a multifaceted phenomenon determined by a combination of central and peripheral factors, including mechanisms of the central nervous system, muscle cells and energy production (Brownstein et al., 2017; Krustrup et al., 2006; Mohr et al., 2023; Rampinini et al., 2011). Central fatigue arises from a diminished neural drive to the muscles originating in the brain and the spinal cord, whereas peripheral fatigue reflects impairments in muscle contractile properties or disruption at the neuromuscular junction level (Enoka and Duchateau, 2016). The impaired capacity of the central nervous system to activate muscles following soccer match-play is caused by multiple mechanisms (Brownstein et al., 2017; Carroll et al., 2017). One factor may be related to the inhibitory feedback provided by group III and IV muscle afferents to various sites within the central nervous system, which respond to inflammation markers produced during eccentric exercise (Amann et al., 2015; Goodall et al., 2017; Sidhu et al., 2017). Differently, peripheral perturbations are attributed to metabolic and mechanical factors that adversely affect the excitation-contraction coupling process and neuromuscular transmission at the sarcolemma (Allen et al., 2008). While metabolic disturbances, such as the accumulation of intramuscular metabolites and ATP depletion, recover relatively quickly, the prolonged recovery of contractile function is likely due to mechanical stress. This includes myofibrillar damage, sarcomere disorganisation, and disruptions in calcium (Ca^{2+}) handling within muscle fibres caused by the demands of physical exercise (Skurvydas et al., 2016).

In soccer, Brownstein et al. (2017) demonstrated that semi-professional players experienced reductions in voluntary activation (i.e., motor point stimulation of the quadriceps) and impairments in muscle contractile function (i.e., potentiated twitch force) up to 24 h post-match but resolved within 48 h. Similarly, Rampinini et al. (2011) documented significant alterations of central and peripheral mechanisms following a simulated protocol in Italian Serie A soccer players, with a return to baseline values observed 48 h post-exercise. In youth soccer players, a recent study from Massamba et al. (2024) revealed that the hamstring muscle displays greater acute peripheral fatigue compared to the quadriceps muscles following match-play, fully recovering 24 h post-match. Conversely, research by Deely et al. (2022) observed fatigue responses after high-intensity training sessions with acute reductions in voluntary activation recovered within 24 h, but prolonged impairment of contractile function for up to 72 h. These findings highlight the extended recovery period required for peripheral mechanisms compared to central processes following competitive match-play and high-intensity training sessions in both senior and youth players.

2.4.2.2 Metabolic alterations

During soccer match-play both aerobic and anaerobic energy systems are substantially taxed to sustain the required intermittent and high-intensity actions (Hostrup and Bangsbo, 2022; Stølen et al., 2005). Alterations in metabolic pathways, including carbohydrates, lipids and protein are already evident at match half and match end (Silva et al., 2018). Muscle glycogen is the main substrate for energy production during a soccer match-play and its depletion has been associated with fatigue development at the end of the match (Mohr et al., 2005, 2022). Evidence of decreased muscle glycogen concentration was first documented in a study by Saltin (1973) who reported almost fully depleted contents following a soccer match-play in both players with normal and reduced pre-match glycogen levels. More recent research reported substantial muscle glycogen content depletion (~40% compared to pre-match levels), with 50-70% of slow twitch and fast fibres glycogen content being almost empty following 90-minute matches in male and female soccer players (Krustrup et al., 2006, 2022). Interestingly, a more severe and accentuated reduction of muscle glycogen content was observed following a 120-minute competitive match-play, with a further decline of 30% at 120-min post-match compared with 90-min post-match, and ~75% of all muscle fibres low on glycogen (Mohr et al., 2023). These reductions in glycogen concentrations at post-match were also associated with deterioration of physical performance (e.g., total distance, accelerations and decelerations), impaired muscle function (e.g., isometric force), repeated sprint ability and vertical jump performance (Mohr et al., 2023). The time course of muscle glycogen to fully replenish the stores ranged between 48 to 72 h, suggesting the role of nutritional strategies for optimal post-match recovery (Gunnarsson et al., 2013; Jacobs et al., 1982; Krustrup et al., 2006, 2011; Mohr et al., 2005).

Alongside the depletion of muscle glycogen stores, during prolonged exercise an accelerated reliance on fat to fuel ATP resynthesis is also observed. An increased rate of lipolysis is evident at half-match and match end with elevated free fatty acids and glycerol levels (Krustrup et al., 2006; Mohr et al., 2022; Silva et al., 2018). These energetic and metabolic alterations in response to soccer match-play demonstrated that muscle glycogen metabolism is notably elevated. However, the exact mechanisms by which reduced glycogen impairs muscle function and consequently physical performance remain unclear (Mohr et al., 2022; Vigh-Larsen et al., 2021). Potential mechanisms include altered substrate metabolism, calcium (Ca^{2+}) regulation, muscle excitability, and myofibrillar contractile function. Glycogen particles are located in three distinct cell compartments, including myosin-ATPase, sarcoplasmic reticulum Ca^{2+} ATPase, and Na^{+}-K^{+} ATPase, in proximity to the main energy-consuming steps of the excitation-contraction coupling. As these subcellular glycogen fractions are utilised during high-intensity exercise, this may affect the excitation-contraction function and negatively affect steps such as action potential propagation, calcium handling and cross-bridge cycling through reductions in muscle ATP, thus providing a link between reduced muscle glycogen and down-regulation of muscle contractility (Vigh-Larsen et al., 2021).

2.4.2.3 Muscle damage

The eccentric, high-intensity, and repetitive nature of soccer activities (e.g., sprints, accelerations, and decelerations) imposes substantial mechanical and metabolic stress on the muscles and consequently may lead to exercise-induced muscle damage (EIMD) (Hader et al., 2019; Silva et al., 2018; Simmons et al., 2021). Muscle damage is defined as a two-phase process that includes a primary mechanical damage occurring acutely during exercise and secondary damage driven by inflammatory responses that amplify tissue disruption (Owens et al., 2019). EIMD is characterised by decreased muscle function and force capacity, reduced range of motion and increased delayed onset of muscle soreness (DOMS), along with increases in intramuscular proteins in circulation and increased swelling of the affected muscles (Byrne et al., 2004; Howatson and Van Someren, 2008). For example, Pooley et al. (2020) showed that soccer match-play of high-level youth soccer players induced muscle damage that remained elevated for up to 48 h post-match. Similarly, adult soccer players demonstrated elevated and prolonged levels of muscle damage following competitive and simulated match-play by displaying altered DOMS and elevated creatine kinase (CK) levels up to 48-72 h (Ribeiro et al., 2022; Silva et al., 2018). The sensation of muscle soreness which inhibits physical performance likely results from the complex interaction of damage to the muscle structure, disrupted calcium homeostasis and sensitisation of nociceptors from inflammatory cell infiltrates (Hyldahl and Hubal, 2014).

Mechanical loading during exercise is considered the primary mechanism of initial muscle damage, causing both structural and non-structural disruption, which is then followed by membrane damage and excitation-contraction coupling dysfunction (Proske and Morgan, 2001). Eccentric contractions are characterised by lower motor unit activation compared to concentric or isometric contractions and therefore place higher mechanical stress on fewer muscle fibres, particularly fast-twitch fibres that are preferentially recruited during eccentric exercise. In addition, sarcomeres lengthen in a non-uniform manner, exceeding myofilament overlap and increasing tension on passive structures, leading to the deformation of non-contractile proteins (Friden et al., 1983; Morgan et al., 1999; Proske and Morgan, 2001). Furthermore, excitation-contraction coupling failure contributes to the primary damage phase with a reduction in force production and diminished sarcoplasmic reticulum Ca^{2+} release (Ingalls et al., 1998). Secondary damage proliferates tissue damage through processes associated with the inflammatory responses. An uncontrolled influx of Ca^{2+} into the cytoplasm results in the degradation of structural proteins (Gissel, 2006), leading to mitochondrial calcium overload. It causes inner mitochondrial membrane permeabilisation and opening of the permeabilisation transition pore, resulting in elevated intracellular calcium concentrations that cause cell apoptosis and necrosis (Gissel, 2006). This process, coupled with the initial mechanical damage, results in a subsequent inflammatory cascade that represents a vital process in the removal of damaged cells initiating the repair and recovery process (Owens et al., 2019). The repairing process consists then of the immune cells (e.g., mast cells, neutrophils, macrophages and T-lymphocytes, along with satellite cells and stromal cells) infiltrating the damaged tissue following EIMD (Peake et al., 2017).

2.4.2.4 Dehydration

Dehydration, defined as the process of body water loss, is also commonly quantified by changes in body mass during acute exercise (Edwards and Noakes, 2009). In competitive soccer match-play conducted in thermoneutral environments, a negative fluid balance of ~2% of pre-match body mass is frequently observed (Andersson et al., 2008; Bangsbo, 1994; Edwards and Noakes, 2009; Mohr et al., 2010; Reilly, 1997). However, matches played in challenging conditions, such as higher temperatures and humidity, amplify cardiovascular, thermoregulatory, metabolic, and perceptual strain. These environmental factors result in elevated sweat rates and increased fluid loss during soccer matches and training sessions (Collins et al., 2020; Henderson et al., 2023; Sawka et al., 2007). Therefore, dehydration has been identified as a contributing factor to the development of match-related fatigue at the end stage of the match (Mohr et al., 2005). A recent multi-centre study has also demonstrated that warmer environmental conditions have effects on physical match demands with associations between warmer temperatures and lower total distance, HSR and SPR distances covered by professional soccer players (Schwarz et al., 2024). These responses may result from an increased thermoregulatory load or indirectly from an adapted individual or team-tactical pacing strategy in warmer conditions. For example, Sabou et al. (2020) demonstrated that training in warmer environments as opposed to cooler environments resulted in higher sweat rate, total sweat and sodium loss in English Championship League soccer players. Collectively, the implicated physiological changes (e.g., a decrease in stroke volume and an increased HR) impair high-intensity endurance performance by reducing repeated sprint ability and compromising the capacity to regulate core temperature, which is linked to the perception of fatigue (Nedelec et al., 2012; Skorski et al., 2019). Dehydration is associated with a reduction of glycogen and protein synthesis. Therefore, rehydration appears to be a determinant factor as high-cell volume contributes to stimulating metabolic processes after match-play (Keller et al., 2003).

2.4.2.5 Mental fatigue

Alongside the physiological disturbance of match-play, soccer competition may also induce psychological stress due to the need for sustained concentration, perceptual skills and decision-making combined with opponent pressure during the match (Nedelec et al., 2012). Mental fatigue is a psychobiological state, characterised by feelings of tiredness and lack of energy, which emerges as a result of prolonged periods of demanding cognitive activity that requires sustained mental efficiency (Marcora et al., 2009). Smith et al. (2016) demonstrated diminished physical performance capacity and altered perception of effort in soccer players following a mentally fatiguing protocol (i.e. the Stroop task) compared to a control situation. In addition, less accurate passes and shots on goal in the Loughborough Soccer Passing and Shooting Tests were observed, resulting in diminished technical accuracy. However, when evaluated in less controlled environments (e.g., applied setting), the influence of mental fatigue on physical performance remains unclear likely due to the open nature of soccer-specific training drills such as small-sided games (Badin et al., 2016; Coutinho et al., 2017, 2018). In general, mental fatigue may contribute to performance decrements associated with match-related fatigue in soccer, inducing detrimental effects on soccer-specific physical, technical, tactical performance and decision-making (Smith et al., 2018).

2.4.3 Measuring response to load in soccer

Measuring response to load, also referred to as training effects or adaptations, is a fundamental component of the training process, serving to understand how players are coping with the cumulative stress of training and competition (Coutts et al., 2018). As previously introduced, training effects can be either beneficial (i.e., positive) or detrimental (i.e., negative), and can lead to acute or chronic responses that influence sports performance outcomes (Jeffries et al., 2022). Acute responses refer to the training effects that occur within a short time frame (i.e., from a single session up to a training week), while chronic responses are cumulative training effects observed over a more extended period (i.e., weeks, months or years) (Jeffries et al., 2022). Considering the applied nature of the thesis, this section discusses objective and subjective tools applied to evaluate the influence of match-play and training in the applied setting.

Measures of response to load can be classified into three main groups based on the nature of measurement: performance, physiological and subjective. This classification is based on a recent conceptual framework (Jeffries et al., 2022) and in agreement with the classifications used in published reviews on fatigue and recovery in team sports (Aben et al., 2022; Bestwick-Stevenson et al., 2022; Grainger et al., 2023; Kellmann et al., 2018; Naughton et al., 2023; Nedelec et al., 2012, 2013; Pernigoni et al., 2024; Silva et al., 2018; Skorski et al., 2019; Tavares et al., 2017; Thorpe et al., 2017; Wiewelhove et al., 2024). Moreover, these measures may also be classified based on the level of measurements, including cellular, tissue and organ, organ system and organism levels (Sullivan, 2022), with different responses to load attributed to specific tissues and systems (Gabbett and Oetter, 2024). For example, the recovery of individual tissues to training stress varies markedly from as little as 30 minutes (e.g., cartilage reformation in response to walking) to 72 or 96 h post-exercise (e.g., eccentric exercise-induced muscle damage). A synthesis of the measures used to quantify fatigue and recovery in applied soccer research is reported in Table 3.

Table 3. Real-world fatigue and recovery measures commonly used in soccer.

Group	Sub-group	Example of fatigue and recovery measures
Performance measures	Strength and power	Vertical jumps (CMJ, repeated jumps) and isometric tasks (hamstring and adductor).
	Speed and agility	Linear sprint (20m sprint) and change of direction tests (T-test).
	Endurance	Intermittent-running endurance (Yo-yo Intermittent Recovery Test) and repeated sprint ability tests.
	Flexibility	Joint range of motion and flexibility assessments (ankle, knee and hip).
Physiological measures	Metabolic alterations	Metabolites (lactate, urea) and substrates (glycogen, triglycerides).
	Muscle damage	CK, myoglobin, lactate dehydrogenase.
	Endocrinal response	Cortisol and testosterone.
	Inflammatory and immunological	Inflammatory (C-reactive protein, interleukin 6) and immunological (immunoglobulins and white blood cells) markers.
	Oxidative stress	Lipid and protein peroxidation.
	Autonomic nervous system	HR-derived indices including resting heart rate, heart rate exercise, heart rate variability, heart rate recovery.
Subjective measures	Multiple items	Athlete-reported outcome measures from questionnaires (Short Recovery Stress Scale, Recovery-Stress Questionnaire Athletes).
	Single-item	Athlete-reported outcome measures from scales (muscle soreness, recovery, fatigue, sleep).

Abbreviations and notes: CMJ: countermovement jump; CK: creatine kinase; HR: heart rate.

2.4.3.1 Performance measures

Performance or functional measures refer to measures of performance evaluated during a task that is related to sports performance or is thought to measure a specific physical performance component (Jeffries et al., 2022). These measures include strength and power measures (e.g., derived from dynamic movements or isometric tasks), speed and agility measures (e.g., linear sprint and change of direction tests), endurance measures (e.g., derived from repeated sprint ability and endurance tests) or flexibility measures (e.g., joint range of motion and flexibility assessments) (Silva et al., 2018). Despite their availability, the application of certain physical performance assessments (e.g., maximal sprint and endurance tests), which are exhaustive and time-consuming, is impractical for use in team sports environments. Over the last years, the quantification of fatigue and recovery following training and competition has been focused on strength and power assessments that constitute proxy measures of neuromuscular fatigue (Brownstein et al., 2017; Deely et al., 2022; Norris et al., 2021). Vertical jumps (e.g., countermovement jump (CMJ), drop jump, repeated jumps) and isometric tests (e.g., squat, mid-thigh pull, posterior chain, adductors and abductors) are often used in combination to evaluate neuromuscular function given their relevance to performance and feasibility within the environment (Bishop et al., 2020, 2022; Bromley et al., 2021; Constantine et al., 2019; Wollin et al., 2017). For example, Norris et al. (2021) examined the impact of match load following competitive matches in Australian football players using both CMJ and isometric mid-thigh pull tests, whilst Springham et al. (2024) investigated the time course of recovery following match-play in English Premier League youth soccer players using the CMJ and isometric tests.

Nowadays, force platforms allow in-depth analyses of the time-force curve during both isometric and dynamic muscle actions in the applied setting. CMJ has been traditionally reported using outcome measures such as jump height (Claudino et al., 2017). For example, CMJ height was tracked in youth soccer players across a competitive microcycle, showing limited changes in response to daily load (Malone et al., 2015). Differently, other CMJ measures derived from the force-time curve have been shown to better detect changes in physical performance and neuromuscular fatigue following exercise (Gathercole et al., 2015). In addition, isometric tests measuring the strength of posterior chain muscles (i.e., hamstring) and groin muscles (i.e., adductors and abductors) have received greater attention due to their high involvement in soccer (McCall et al., 2015; Paul et al., 2014; Wollin et al., 2020). These assessments can be either multi-joint or single-joint muscle actions. In soccer, the isometric posterior chain muscle test is an assessment of isometric knee flexion and hip extension, typically performed supine with heels on a raised surface to create either a 90° or 30° at the knee. The isometric posterior chain (IPC) lower-limb muscle test is commonly used to evaluate the fatigue status of hamstring muscles in male (Alcaraz et al., 2017; McCall et al., 2015), female (Cuthbert et al., 2021) and youth academy (Constantine et al., 2019) soccer players. Recently, adductor and abductor isometric tests have also become frequently used to profile performance and recovery in soccer players (O'Connor et al., 2024; Springham et al., 2024).

2.4.3.2 Physiological measures

Physiological measures refer to the numerous biomarkers derived from different physiological systems used to monitor acute or chronic training effects. These include measures derived from the autonomic nervous system such as heart rate variability (Mirto et al., 2024) and biological indicators, including measurable molecules in blood, urine, saliva, or any other human body source, that reflect underlying changes of a physiological process over time (Pedlar et al., 2019; Pérez-Castillo et al., 2023; Silva et al., 2018; Springham et al., 2022). Physiological measures can include metabolic pathways (e.g. metabolites and substrates such as lactate and glycogen), muscle damage (e.g., CK), endocrine response (e.g., cortisol and testosterone), inflammation and immunological (e.g., immunoglobins concentrations and cytokines response) and oxidative stress markers (e.g., lipid and protein peroxidation) (Silva et al., 2018). For example, CK is of interest in football as it provides information on the mechanical and metabolic effects of intensive periods of training and competitions in elite soccer players (Hecksteden and Meyer, 2020; Ribeiro et al., 2022). In addition, other immunological markers such as salivary immunoglobulin-A, testosterone, and cortisol measured following soccer activities have shown promising results as part of a multivariate player's monitoring system (Springham et al., 2022).

Given the complexities of fatigue-induced changes, physiological measures have the potential to provide objective information regarding the homeostatic disturbances occurring in response to training and match load. However, limited longitudinal data exist in team sports due to the high associated costs, the level of expertise required and the high degree of variability observed in the majority of these markers (Twist and Highton, 2013). To date, no single gold-standard biomarker of match-induced fatigue exists (Pérez-Castillo et al., 2023). To comprehensively analyse metabolites following periods of training, competition and recovery, new non-invasive methods are becoming increasingly available to fully characterise the physiological changes in response to training and competition (Owens and Bennett, 2024). Metabolomics techniques allow exercise physiologists to comprehensively analyse multiple metabolites within a biological system, revealing the metabolic pathways and processes occurring within an organism and broadening the analytical lens beyond single-metabolite assays (Khoramipour et al., 2022; Schranner et al., 2020). For example, metabolomics studies performed in soccer identified specific metabolic pathways following single training sessions (Alzharani et al., 2020; Pitti et al., 2019; Zhao et al., 2020), periods of training (Quintas et al., 2020) and competition (Pitti et al., 2019; Prado et al., 2017).

2.4.3.3 Subjective measures

Subjective measures or athlete-reported outcomes measures (AROMs) refer to questionnaires and scales used to monitor training responses in athletic populations (Jeffries et al., 2020). Subjective measures can provide better sensitivity to change in acute and chronic training loads than objective measures (Saw et al., 2016). The importance of subjective measures is particularly relevant given the role of individuals' perceptions within the fatigue and recovery mechanisms (Kellmann et al., 2018). A systematic review of subjective measures has revealed the most used AROMs in the field of sports science with muscle soreness, fatigue, recovery and wellness being the most used single-item instruments, and Profile of Mood State, Recovery-Stress Questionnaire Athletes and Daily Analysis of Life Demands being among the most used multiple-item questionnaires (Jeffries et al., 2020). Nevertheless, multiple-item instruments are often time-consuming, limiting their applicability to monitoring training responses (Thorpe, et al., 2017). Conversely, shorter questionnaires such as the Short Recovery and Stress Scale have been developed to be less time-consuming and consequently allow high-frequency measurements in the real world (Kölling et al., 2020; Nässi et al., 2017). Alongside shorter questionnaires, single-item tools are widely administered on a daily basis due to their suitability within high-performance sports, including Likert scales and visual analogue scales (VAS) that assess mainly domains such as muscle soreness, fatigue and recovery. These tools are widely adopted also in applied sport science research with specific reference to studies examining recovery responses and interventions (Abbott et al., 2023; Cross et al., 2023; Ishida et al., 2021; Russell et al., 2021; Wiewelhove et al., 2022). Despite the wide and frequent use in the applied setting, most AROMs have not been validated and further work in this area is required to establish the measurement properties of these subjective measures (Jeffries et al., 2020).

2.4.3.4 Measurement characteristics

When aiming to assess response to load, a critical aspect centres on the measurement characteristics of the tools and measures adopted within a sporting environment (Currell and Jeukendrup, 2008; Impellizzeri and Marcora, 2009). In order to identify meaningful changes occurring in response to competition and training stressors, it is important to distinguish between meaningful changes (i.e., signal) from the biological and methodological variability (i.e., noise) of a test (Hopkins et al., 2001; Howarth et al., 2022). Therefore, to effectively monitor changes in response to training load, valid and reliable measures which are sensitive to change are required. Additionally, considering the challenges of team-sport settings, tests used for load-response monitoring should be selected according to their relevance to performance and feasibility within the environment (Bishop et al., 2022).

Validity refers to the degree to which a test measures what it is designed to measure (George et al., 2003). Several types of validity exist, including content validity, criterion validity, construct validity, ecological validity and face validity (McGuigan, 2017). In the context of applied sports science, construct validity and ecological validity are considered the most relevant. Construct validity refers to the extent to which the test or measure actually measures what it purports to measure, whilst ecological validity refers to how closely the research data and the experiment can be applied in a real-performance setting (McGuigan, 2017). Reliability or reproducibility refers to the degree of consistency of a measure between repeated tests within a practically relevant timeframe (Atkinson and Nevill, 1998; Batterham and George, 2003). Absolute reliability refers to a measure of variability that indicates the degree to which individuals' scores did not change in magnitude or value, whilst relative reliability indicates the degree to which individuals maintain their position within a group, for example, from trial to trial within a day, day to day, or rater to rater (Atkinson and Nevill, 1998). Parameters of absolute reliability include the change in mean, the standard or typical error (TE) of measurement, and the coefficient of variation (CV). Relative reliability is typically reported with the ICC (Impellizzeri and Marcora, 2009). Previous studies have quantified test-retest reproducibility in soccer-related performance tests (Enright et al., 2018; Fitzpatrick et al., 2019; Paul and Nassis, 2015). Sensitivity to change refers to the ability of a measure to change over a particular timeframe in response to a training or competition load (Rowell et al., 2017). For example, Rowell et al. (2017) identified that CMJ flight time to contraction time ratio provided a more sensitive measure of recovery post-match compared to the commonly reported jump height.

Despite the wide range of measurement tools available for monitoring training and competition responses in soccer, it is crucial to evaluate their measurement properties and applicability within the youth soccer context. Advances in technology have enabled more detailed analyses of physical performance (e.g., force-time curve assessment using force platforms) and physiological status (e.g., comprehensive metabolite profiling). However, applied research on youth soccer players has not explored the typical responses to training and match demands using these advanced tools in combination. Given the complex and multifaceted nature of fatigue in soccer, adopting comprehensive approaches to assess post-exercise responses is essential and could improve the understanding of fatigue and recovery processes in adolescent soccer players.

2.4.4 Time course of recovery following match-play in youth soccer players

The evaluation of recovery following competitive soccer match-play is fundamental to informing players' readiness to train and consequently training prescription and periodisation strategies. The physical demands of 90-minute soccer matches induce both acute (i.e., immediate post-match) and residual fatigue (i.e., in the days following the match), with various restorative measures impaired up to 72 h in professional male and female soccer players (Goulart et al., 2022; Silva et al., 2018). In youth soccer players match duration varies with age, with adolescent players typically competing in shorter matches (e.g., 70-80 minutes) until the age of 15 before transitioning to full 90-minute games from the age of 16 (Palucci Vieira et al., 2019). Over the past decade, a growing body of studies has described acute fatigue and recovery responses following official and friendly matches in youth soccer players. Therefore, in this section, a comprehensive analysis of the time course of recovery following match-play in youth soccer players is provided, detailing players' characteristics (country, level, age, height and body mass), match-play characteristics (type, duration, external and internal load) and post-match recovery measures (type and time-points). Table 4 reports the details of the referenced observational studies profiling post-match fatigue and recovery responses with the youth soccer population.

Table 4. Characteristics of the referenced observational studies profiling fatigue and recovery following match-play in youth soccer players.

Study (year)	**Players' characteristics**				**Match-play characteristics**				**Type of recovery measures**			**Time-points of recovery**				
	n	**Country**	**Level**	**Age (years)**	**Type of match**	**Duration**	**External load**	**Internal load**	**Perf.**	**Phys.**	**Subj.**	**Pre**	**Post**	**24h Post**	**48h Post**	**72h Post**
Barreira et al (2024)	21	Portugal	Tier 3	18.4 ± 0.7	Official	90 min	×		×			×	×	×	×	
Bromley et al. (2021)	14	England	Tier 2	17.6 ± 0.5	Official	90 min			×			×	×	×	×	×
Constantine et al. (2019)	14	England	Tier 2	16.9 ± 0.7	Official	90 min			×			×	×	×	×	×
De Hoyo et al. (2016)	15	Spain	Tier 3	18 ± 1	Official	90 min	×		×	×		×	×	×	×	
De Ste Croix et al. (2019)	9	Czech Republic	Tier 3	15.8 ± 0.1	Official	80 min		×	×	×	×	×	×			
	15	Czech Republic	Tier 3	13.6 ± 0.3	Official	70 min		×	×	×	×	×	×			
Fornaziero et al. (2023)	10	Brasil	Tier 3	18.3 ± 0.4	Friendly	90 min		×		×		×	×			
Izquierdo et al. (2020)	198	Spain	Tier 3	17.6 ± 0.8	Official	90 min			×			×	×			
Martin-Garetxana et al. (2024)	10	Spain	Tier 3	15.2 ± 0.3	Official	80 min		×	×	×	×	×	×			
	22	Spain	Tier 3	13.2 ± 0.7	Official	70 min		×	×	×	×	×	×			
Paul et al. (2019)	11	Qatar	Tier 2	16.2 ± 1.2	Official	90 min		×			×	×	×	×		
Romagnoli et al. (2016)	16	Italy	Tier 3	19.5	Official	90 min	×	×	×	×	×	×	×	×	×	

Study (year)	Players' characteristics				Match-play characteristics				Type of recovery measures			Time-points of recovery				
	n	Country	Level	Age (years)	Type of match	Duration	External load	Internal load	Perf.	Phys.	Subj.	Pre	Post	24h Post	48h Post	72h Post
Springham et al. (2024)	18	England	Tier 4	17.0 ± 0.7	Official	90 min	×		×		×	×	×	×	×	×
Wollin et al. (2017)	14	Australia	Tier 4	16.7 ± 0.4	Official	90 min		×	×			×	×	×	×	×

Abbreviations and notes: min: minute; *n*: number of players (sample size); Perf.: Performance measures; Phys.: Physiological measures; Pre: pre-match measurement (baseline); Post: post-match measurement (within 1 hour); Subj.: Subjective measures; Players' level is defined according to the classification of McKay et al. (2022): Tier 0: Sedentary; Tier 1: Recreationally Active; Tier 2: Trained/Developmental; Tier 3: Highly Trained/National Level; Tier 4: Elite/International Level; or Tier 5: World Class.

The time course of recovery following match-play has been mainly reported in late-stage adolescent players ranging from 16 to 19 years of age, whilst less evidence exists on the recovery kinetics of younger players (e.g., 13 to 15 years old). For example, the recovery response profile of youth players belonging to under-18 and under-19 age-groups has been described in multiple studies involving high-level soccer players from Australia, Brazil, England, Italy, Portugal, Qatar and Spain. Conversely, only two studies reported acute fatigue responses following match-play in under-14, under-15 and under-16 soccer players, without analysing the time course of recovery in the following days (De Ste Croix et al., 2019; Martin-Garetxana et al., 2024). Consequently, except for these previously mentioned studies, which used 70- or 80-minute match durations, most of the available research utilised a 90-minute match duration. Most studies analysed the recovery time course using a competitive match-play as the intervention, whilst one study employed a friendly match (Fornaziero et al., 2023). Reporting of physical (i.e., external load) and physiological (i.e., internal load) match demands was inconsistent across studies. External load was reported using GNSS (Barreira et al., 2024; de Hoyo et al., 2016; Springham et al., 2024) or video-based tracking systems (Romagnoli et al., 2016), including various measures. Internal load was quantified using RPE (De Ste Croix et al., 2019; Martin-Garetxana et al., 2024; Paul et al., 2019; Wollin et al., 2017) and HR sensors (Fornaziero et al., 2023; Romagnoli et al., 2016), reporting measures such as sRPE, session rating of perceived exertion training load (sRPE-TL), HR_{avg}, HR_{max} and the time spent at different HR zones. Notably, only one study reported both external and internal load sustained during match-play (Romagnoli et al., 2016).

The time course of recovery following match-play in youth soccer players has been assessed using performance, physiological and subjective measures, with some studies reporting single or multiple measures. Romagnoli et al. (2016) investigated the time course of recovery up to 48 h in high-level youth soccer players using blood markers, a CMJ test and a VAS for the assessment of muscle soreness. More recently, two studies evaluated acute match-related fatigue in younger players participating in 70- and 80-minute matches using a combination of physical performance tests (CMJ, repeated jump test, sprint test), muscle damage markers (CK) and perceived muscle soreness (De Ste Croix et al., 2019; Martin-Garetxana et al., 2024). Post-match recovery responses in the youth soccer population have been profiled with differences between baseline (pre-match) and post-match time points, including immediate post-match, at 24 h, at 48 h and at 72 h post-match. For example, Constantine et al. (2019) and Wollin et al. (2017)

investigated the time course of recovery of hamstring muscle strength up to 3 days after match-play in youth soccer players. A detailed summary of the published data on the time course of recovery in youth soccer players is reported in Table 5 for performance recovery, Table 6 for physiological recovery, and Table 7 for subjective recovery.

2.4.4.1 Performance recovery response following match-play

The time course of performance recovery in youth soccer players has been assessed using physical performance tests, including vertical and horizontal jump protocols, isometric muscle-specific tests, sprint tests and range of motion assessments. A youth soccer match-play induced significant reductions in jump height measured during a CMJ immediately post-match (mean changes (Δ) ranged from -3 to -7% compared to baseline) (Barreira et al., 2024; de Hoyo et al., 2016; Izquierdo et al., 2020; Martin-Garetxana et al., 2024; Romagnoli et al., 2016; Springham et al., 2024). At +24 h following match-play, jump height remained altered (Δ ranged from -3 to -13% compared to baseline) (Barreira et al., 2024; de Hoyo et al., 2016; Romagnoli et al., 2016), whilst at +48 h post-match conflicting results were observed with players returning to baseline values (Barreira et al., 2024) or remaining significantly reduced (Δ ranged from -3% to -6%) (de Hoyo et al., 2016; Romagnoli et al., 2016). Interestingly, in a recent study conducted with under-18 English Premier League soccer players, jump height (calculated using flight time method) was still impaired at 48 h post-match, whilst the same outcome measure calculated using the impulse moment method showed complete recovery (Springham et al., 2024).

CMJ peak power showed limited sensitivity to change following youth soccer match-play with unchanged performance at post-match and in the days after (Romagnoli et al., 2016), whilst CMJ peak force was unaltered immediately post-match but showed conflicting results across studies in the days following the game (de Hoyo et al., 2016; Romagnoli et al., 2016; Springham et al., 2024). For example, De Hoyo et al. (2016) recorded significant reductions in CMJ concentric peak force 24 h (-3%) and 48 h (-4%) after match-play in under-19 Spanish soccer players, whilst Springham et al. (2024) and Romagnoli et al. (2016) found no changes at the same time points in English and Italian youth soccer players. Conversely, CMJ eccentric peak force was significantly diminished immediately post-match (Δ ranged from -3 to -4%) and then fully recovered 48 h post-match (Romagnoli et al., 2016; Springham et al., 2024). Finally, no changes were observed acutely and in the days after match-play for CMJ time-based measures such as the flight time:contraction time ratio and eccentric duration (Springham et al., 2024). In summary, CMJ height can be reduced immediately after and at +24 h post-match, with a tendency towards recovery at 48 h post-match and observations of complete recovery 72 h post-match in youth soccer players. Significant acute changes were also observed in CMJ eccentric peak force at post-match, whilst concentric peak force, peak power and time-based measures remain unaltered.

In addition, other jump, sprint, strength and range of motion protocols have been used to profile post-match performance recovery in youth soccer (Barreira et al., 2024; Bromley et al., 2021; De Ste Croix et al., 2019; Izquierdo et al., 2020; Martin-Garetxana et al., 2024; Wollin et al., 2017). Acute significant impairments of reactive strength index (RSI), measured during repeated jump protocols (e.g., hop test), were observed in under-16 players (Δ ranged from -8 to -12%) and under-14 players (Δ ranged from -5% to -15%) immediately post-match (De Ste Croix et al., 2019; Martin-Garetxana et al., 2024). Post-match reductions in single-leg CMJ were also observed immediately post-match and in the days following the match for eccentric impulse, concentric impulse, and peak force measures of both lower limbs, whilst no changes in jump height were reported (Bromley et al., 2021). No changes in horizontal jump distance following match-play and at +24 h, with improved horizontal jump performance at +48 h compared to baseline in under-19 Portuguese youth players (Barreira et al., 2024). Sprint performance assessed in response to match demands showed increases of ~2% on 20m sprint time, of ~3% on 30m sprint time and ~4% on 40m sprint time immediately post-match (Izquierdo et al., 2020; Martin-Garetxana et al., 2024).

Range of motion showed trends of reduction following match-play in Australian national team under-17 players across knee and ankle measurements, including non-significant reductions in ankle dorsiflexion (i.e., knee-to-wall method) and knee flexion (both passive and active), whilst hip extension range of motion remained essentially unchanged following post-match (Wollin et al., 2017). More recently, the time course of performance recovery has been investigated using barbell velocity during strength exercises such as the half squat and the hip thrust (Barreira et al., 2024). Whilst half squat barbell velocity remained unchanged in response to match-play, hip thrust barbell velocity exhibited significant reductions acutely (-13% at post-match) and in the days after the match (-11% at +24 h and -6% at + 48 h) suggesting the importance of profiling lower limb posterior chain muscle function (Barreira et al., 2024). Overall, physical performance capacity can be impaired acutely post-match in youth soccer players with reductions in some measures of muscle-tendon unit function (i.e., stretch-shortening cycle (SSC)) including RSI, impulse and sprint time. Range of motion at the ankle, knee and hip locations are likely to remain relatively unchanged in response to match-play.

Muscle-specific isometric protocols are often utilised in conjunction with dynamic measures of physical performance to assess post-match recovery (Norris et al., 2021). In youth players, hamstring, adductor and abductor muscle strength have shown significant alterations following match-play both acutely and in the days after (Constantine et al., 2019; Springham et al., 2024; Wollin et al., 2017). Hamstring peak force and torque demonstrated significant reductions at immediate post-match (mean changes ranged from -6 to -21%) and at +24 h post-match (Δ ranged from -3 to -12%) using various isometric hamstring protocols (Constantine et al., 2019; Springham et al., 2024; Wollin et al., 2017). Two days after match-play these measures showed complete recovery in peak force and peak torque in youth players following 90-minute match-play (Constantine et al., 2019; Springham et al., 2024; Wollin et al., 2017). A recent study by Springham et al. (2024) also assessed the time course of recovery of adductor and abductor muscles at post-match, +48 h and 72 h in under-18 English Premier League players. Peak adductor and abductor forces were diminished immediately after match-play by observing a greater reduction (-15%) in adductor muscles compared to abductor muscles (-7%) (Springham et al., 2024). The time course of recovery showed complete restoration of abductor force at +72 h post-match and incomplete recovery of adductor force at the same time point. These results indicate that match-related acute fatigue may also manifest with reductions in isometric muscle force of the main muscle groups involved during competition, which can be altered up to 48 or 72 h.

The analysis of post-match responses in physical performance indicated that youth soccer players experience acute reductions immediately after match-play and may exhibit altered recovery patterns in the subsequent days across assessments of vertical jump, strength, and sprint performance. The magnitude of post-match changes varied across studies and tests; however, measures of hamstring muscle function demonstrated larger decrements from baseline and a more prolonged recovery time course compared with other muscle groups, likely reflecting their substantial involvement during high-intensity actions in match-play (Silva et al., 2018). To determine whether these changes are meaningful, information on test reliability and sensitivity to change is essential to support the selection of appropriate monitoring measures, given the limited evidence available in youth soccer populations (Enright et al., 2018; Fitzpatrick et al., 2019; Paul and Nassis, 2015).

Table 5. Results of referenced studies investigating the time course of performance recovery following match-play in youth soccer players.

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
Barreira et al. (2024)	CMJ	Jump height (cm)	39.6 ± 6.3	36.9 ± 5.6	36.7 ± 6.4	38.3 ± 5.9		Post: ↓ (-7%) 24h Post: ↓ (-7%) 48h Post: ↔ (-3%)
	Horizontal jump	Jump distance (m)	2.25 ± 0.16	2.24 ± 0.15	2.27 ± 0.15	2.29 ± 0.15		Post: ↔ (0%) 24h Post: ↔ (1%) 48h Post: ↑ (2%)
	Half squat	Bar velocity ($m \cdot s^{-1}$)	0.67 ± 0.09	0.64 ± 0.09	0.65 ± 0.09	0.69 ± 0.10		Post: ↓ (-4%) 24h Post: ↔ (-3%) 48h Post: ↔ (3%)
	Hip thrust	Bar velocity ($m \cdot s^{-1}$)	0.62 ± 0.10	0.54 ± 0.09	0.55 ± 0.10	0.58 ± 0.11		Post: ↓ (-13%) 24h Post: ↓ (-11%) 48h Post: ↓ (-6%)
Bromley et al. (2021)	SL CMJ	Eccentric impulse right leg (Ns)	174 ± 12	135 ± 12	135 ± 16	153 ± 18	141 ± 12	Post: ↓ (-22%) 24h Post: ↓ (-22%) 48h Post: ↓ (-12%) 72h Post: ↓ (-19%)
	SL CMJ	Eccentric impulse left leg (Ns)	135 ± 13	92 ± 10	96 ± 12	131 ± 15	110 ± 13	Post: ↓ (-32%) 24h Post: ↓ (-29%) 48h Post: ↔ (-3%) 72h Post: ↓ (-18%)
	SL CMJ	Concentric impulse right leg (Ns)	158 ± 29	125 ± 22	135 ± 28	141 ± 30	132 ± 28	Post: ↓ (-21%) 24h Post: ↔ (-14%) 48h Post: ↔ (-10%) 72h Post: ↓ (-16%)
	SL CMJ	Concentric impulse left leg (Ns)	147 ± 30	112 ± 23	110 ± 25	130 ± 31	112 ± 23	Post: ↓ (-24%) 24h Post: ↓ (-25%) 48h Post: ↔ (-12%) 72h Post: ↓ (-24%)
	SL CMJ	Peak force right leg (N)	1679 ± 93	1278 ± 104	1281 ± 124	1428 ± 119	1325 ± 105	Post: ↓ (-24%) 24h Post: ↓ (-24%) 48h Post: ↓ (-15%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
								72h Post: ↓ (-21%)
	SL CMJ	Peak force left leg (N)	1432 ± 101	871 ± 93	903 ± 129	1206 ± 148	1053 ± 122	Post: ↓ (-39%) 24h Post: ↓ (-37%) 48h Post: ↓ (-16%) 72h Post: ↓ (-26%)
	SL CMJ	Jump height right leg (cm)	19 ± 4	19 ± 6	16 ± 3	16 ± 4	17 ± 4	Post: ↔ (0%) 24h Post: ↔ (-16%) 48h Post: ↔ (-16%) 72h Post ↔ (-11%)
	SL CMJ	Jump height left leg (cm)	19 ± 7	20 ± 6	16 ± 4	17 ± 4	20 ± 6	Post: ↔ (5%) 24h Post: ↔ (-16%) 48h Post: ↔ (0%)
Constantine et al. (2019)	Hamstring	IPC peak force at 90° ($N{\cdot}kg^{-1}$)	6.5 ± 1.4	5.8 ± 1.7	6.3 ± 1.2	6.8 ± 1.2	7.1 ± 1.3	Post: ↓ (-11%) 24h Post: ↓ (-3%) 48h Post: ↑ (5%) 72h Post: ↑ (9%)
	Hamstring	IPC peak force at 30° ($N{\cdot}kg^{-1}$)	5.8 ± 1.5	4.6 ± 1.2	5.1 ± 1.6	5.6 ± 1.5	6.8 ± 1.3	Post: ↓ (-21%) 24h Post: ↓ (-12%) 48h Post: ↓ (-3%) 72h Post: ↑ (17%)
De Hoyo et al. (2016)	CMJ	Jump height (cm)	36.3 ± 3.8	34.8 ± 3.7	31.6 ± 9.8	34.1 ± 4.0		Post: ↓ (-4%) 24h Post: ↓ (-13%) 48h Post: ↓ (-6%)
	CMJ	Average eccentric force (N)	671 ± 52	651 ± 58	657 ± 66	674 ± 41		Post: ↓ (-3%) 24h Post: ↓ (-2%) 48h Post: ↔ (0%)
	CMJ	Average concentric force (N)	1465 ± 151	1425 ± 173	1423 ± 186	1400 ± 143		Post: ↔ (-3%) 24h Post: ↓ (-3%) 48h Post: ↓ (-4%)
De Ste Croix et al. (2019) -	5-maximum hop test	Reactive strength index	2.54 ± 0.31	2.41 ± 0.32				Post: ↓ (-5%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
circa PHV group	5-maximum hop test	Contact time (s)	0.19 ± 0.02	0.19 ± 0.02				Post: ↔ (0%)
	5-maximum hop test	Flight time (s)	0.47 ± 0.02	0.45 ± 0.01				Post: ↓ (-4%)
	Sub-maximal hopping protocol	Absolute leg stiffness (kN)	23.2 ± 5.2	23.1 ± 4.5				Post: ↔ (0%)
	Sub-maximal hopping protocol	Relative leg stiffness ($kN \cdot m^{-1}$)	35.6 ± 6.4	35.3 ± 5.4				Post: ↔ (-1%)
De Ste Croix et al. (2019) - post PHV group	5-maximum hop test	Reactive strength index	2.94 ± 0.25	2.60 ± 0.26				Post: ↓ (-12%)
	5-maximum hop test	Contact time (s)	0.18 ± 0.02	0.19 ± 0.02				Post: ↑ (6%)
	5-maximum hop test	Flight time (s)	0.51 ± 0.01	0.48 ± 0.03				Post: ↓ (-6%)
	Sub-maximal hopping protocol	Absolute leg stiffness (kN)	28.8 ± 4.1	29.6 ± 4.5				Post: ↔ (3%)
	Sub-maximal hopping protocol	Relative leg stiffness ($kN \cdot m^{-1}$)	39.2 ± 4.8	40.0 ± 3.4				Post: ↔ (2%)
	Sprint	30m sprint time (s)	4.68 ± 0.24	4.82 ± 0.25				Post: ↑ (3%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
Izquierdo et al. (2020)	Sprint	40m sprint time (s)	5.95 ± 0.31	6.16 ± 0.31				Post: ↑ (4%)
	CMJ	Jump height (cm)	35.7 ± 4.7	34.1 ± 4.8				Post: ↓ (-4%)
Martin-Garetxana et al. (2024) - U14 group	5-maximum hop test	Reactive strength index	1.21 ± 0.33	1.03 ± 0.31				Post: ↓ (-15%)
	Sub-maximal hopping protocol	Relative leg stiffness (kN·m^{-1})	28.9 ± 3.5	27.2 ± 3.3				Post: ↓ (-6%)
	Sprint test	20m sprint time (s)	3.27 ± 0.12	3.35 ± 0.13				Post: ↑ (2%)
	CMJ	Jump height (cm)	36.6 ± 3.4	34.7 ± 4				Post: ↓ (-5%)
Martin-Garetxana et al. (2024) - U16 group	5-maximum hop test	Reactive strength index	1.08 ± 0.26	0.99 ± 0.27				Post: ↓ (-8%)
	Sub-maximal hopping protocol	Relative leg stiffness (kN·m^{-1})	27.4 ± 4.6	25.8 ± 4.3				Post: ↓ (-6%)
	Sprint test	20m sprint time (s)	3.12 ± 0.09	3.19 ± 0.16				Post: ↔ (2%)
	CMJ	Jump height (cm)	42.8 ± 3.2	41.7 ± 3.2				Post: ↔ (-3%)
Romagnoli et al. (2016)	CMJ	Jump height (cm)	49.6 ± 5.1	48.0 ± 6.0	48.3 ± 5.6	48.1 ± 5.0		Post: ↓ (-3%) 24h Post: ↓ (-3%) 48h Post: ↓ (-3%)
	CMJ	Peak power (W)	3919 ± 538	3977 ± 586	3933 ± 576	3928 ± 577		Post: ↔ (1%) 24h Post: ↔ (0%) 48h Post: ↔ (0%)
	CMJ	Relative peak power (W·kg^{-1})	54.9 ± 5.9	55.6 ± 234	55.0 ± 6.2	54.9 ± 6.2		Post: ↔ (1%) 24h Post: ↔ (0%) 48h Post: ↔ (0%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
	CMJ	Peak force (N)	1833 ± 181	1809 ± 234	1830 ± 209	1824 ± 175		Post: ↔ (-1%) 24h Post: ↔ (0%) 48h Post: ↔ (0%)
	CMJ	Relative peak force ($N \cdot kg^{-1}$)	25.7 ± 2.4	25.3 ± 2.8	25.7 ± 2.8	25.6 ± 2.4		Post: ↔ (-2%) 24h Post: ↔ (0%) 48h Post: ↔ (0%)
Springham et al. (2024)	CMJ	Relative concentric peak force ($N \cdot kg^{-1}$)	26.8 ± 2.8	26.7 ± 3		26.5 ± 2.8	26.4 ± 3.1	Post: ↔ (0%) 24h Post: NA 48h Post: ↔ (-1%) 72h Post: ↔ (-1%)
	CMJ	Relative eccentric peak force ($N \cdot kg^{-1}$)	25.6 ± 3.4	24.5 ± 4.1		25.4 ± 2.9	25.3 ± 3.2	Post: ↓ (-4%) 24h Post: NA 48h Post: ↔ (-1%) 72h Post: ↔ (-1%)
	CMJ	Flight time:contraction time ratio	0.82 ± 0.12	0.81 ± 0.14		0.81 ± 0.12	0.81 ± 0.13	Post: ↔ (-1%) 24h Post: NA 48h Post: ↔ (-1%) 72h Post: ↔ (-1%)
	CMJ	Jump height (FT) (cm)	41.0 ± 3.9	39.9 ± 4.3		39.8 ± 3.1	40.8 ± 3.9	Post: ↓ (-3%) 24h Post: NA 48h Post: ↓ (-3%) 72h Post: ↔ (0%)
	CMJ	Jump height (IM) (cm)	37.9 ± 4.6	36.8 ± 5.8		37.5 ± 4.1	38.3 ± 4.1	Post: ↔ (-3%) 24h Post: NA 48h Post: ↔ (-1%) 72h Post: ↔ (1%)
	CMJ	Eccentric duration (ms)	453.2 ± 52.1	459 ± 70.7		451.3 ± 52.4	459.7 ± 49.7	Post: ↔ (1%) 24h Post: NA 48h Post: ↔ (0%) 72h Post: ↔ (1%)
	CMJ	Eccentric deceleration RFD ($N \cdot s^{-1}$)	7823.5 ± 3609	6887.2 ± 3662.7		7736.1 ± 3136.8	7398.6 ± 3132.0	Post: ↓ (-12%) 24h Post: NA 48h Post: ↔ (-1%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
								72h Post: ↔ (-5%)
	Hamstring	IPC peak force (N)	352.8 ± 68.1	312.3 ± 71.9		348.3 ± 63.5	354.1 ± 57.9	Post: ↓ (-11%) 24h Post: NA 48h Post: ↔ (-1%) 72h Post: ↔ (0%)
	Adductor	Peak adductor force (N)	414.2 ± 87.2	351.4 ± 104.3		403.8 ± 89.9	393.3 ± 81.7	Post: ↓ (-15%) 24h Post: NA 48h Post: ↔ (-3%) 72h Post: ↓ (-5%)
	Adductor	Peak adductor impulse (Ns)	1786.3 ± 541.2	1284.0 ± 385.2		1891.3 ± 538.3	1810.9 ± 495.6	Post: ↓ (-28%) 24h Post: NA 48h Post: ↔ (6%) 72h Post: ↔ (1%)
	Abductor	Peak abductor force (N)	398.7 ± 66.9	369.3 ± 86.3		393.8 ± 70.2	390.7 ± 65.0	Post: ↓ (-7%) 24h Post: NA 48h Post: ↔ (-1%) 72h Post: ↔ (-2%)
	Abductor	Peak abductor impulse (Ns)	1659.2 ± 460.0	1356.3 ± 540.5		1765.9 ± 514.7	1722.0 ± 465.5	Post: ↓ (-18%) 24h Post: NA 48h Post: ↔ (6%) 72h Post: ↔ (4%)
Wollin et al. (2017)	Hamstring	Peak torque ($Nm \cdot kg^{-1}$)	2.4 ± 0.3	2.0 ± 0.4	2.3 ± 0.3	2.4 ± 0.4	2.4 ± 0.3	Post: ↓ (-18%) 24h Post: ↓ (-5%) 48h Post: ↔ (-2%) 72h Post: ↔ (-2%)
	Range of motion	Ankle dorsiflexion (cm)	11.8 ± 1.9	11.1 ± 1.9	11.4 ± 1.5	10.9 ± 1.9	11.2 ± 1.8	Post: ↔ (-6%) 24h Post: ↔ (-4%) 48h Post: ↔ (-8%) 72h Post: ↔ (-5%)
	Range of motion	Hip extension (°)	17.4 ± 9.5	17.6 ± 6.8	18.0 ± 8.7	17.7 ± 7.8	16.8 ± 8.7	Post: ↔ (1%) 24h Post: ↔ (4%) 48h Post: ↔ (2%) 72h Post: ↔ (-3%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
	Range of motion	Active knee extension (°)	169.1 ± 7.8	164.3 ± 7.6	167.1 ± 8.8	169.3 ± 7.6	168.7 ± 6.8	Post: ↔ (-3%) 24h Post: ↔ (-1%) 48h Post: ↔ (0%) 72h Post: ↔ (0%)
	Range of motion	Prone knee bend (°)	133.7 ± 6.8	130.6 ± 5.9	131.8 ± 5.9	132.3 ± 6.4	133.4 ± 5.9	Post: ↔ (-2%) 24h Post: ↔ (-1%) 48h Post: ↔ (-1%) 72h Post: ↔ (0%)

Abbreviations and notes: ↑ significantly increase from baseline (pre); ↓ significantly decrease from baseline (pre); ↔ no significant change from baseline (pre); cm: centimetres; FT: flight time method; IM: impulse momentum method; kg: kilogram; N: Newtons; NA: not applicable; PHV = peak height velocity; Pre: pre-match measurement (baseline); Post: post-match measurement (within 1 hour); s: second; U: under; W: watt.

2.4.4.2 Physiological recovery response following match-play

Metabolic and biochemical markers found in blood, saliva and urine have been used to profile fatigue and recovery in response to soccer match-play. The analysis of various blood markers following competition in youth soccer players, including metabolites and substrates alterations, muscle damage, endocrine response, inflammatory and immunological markers, has been performed using venous blood techniques (Fornaziero et al., 2023; Romagnoli et al., 2016) and capillary blood techniques (de Hoyo et al., 2016; De Ste Croix et al., 2019; Martin-Garetxana et al., 2024). Markers of metabolic pathways were also analysed in youth soccer players following match-play. Urea concentrations, end product of the degradation of proteins, were found to increase in response to 70-, 80- and 90-minute match-play, evidencing the strenuous nature of the match load sustained in youth competitions (Fornaziero et al., 2023; Martin-Garetxana et al., 2024). In addition, Fornaziero et al. (2023) investigated the acute fatigue following a youth friendly match in under-18 players with observations of altered lactate and glucose concentrations compared to pre-match, with both markers increasing at post-match as a result of involvement of anaerobic metabolism.

CK is a protein which have been seen to leak into plasma following skeletal muscle tissue damage, and it has been used as an indirect biomarker of muscle damage evaluated in response to match demands. Following youth soccer match-play, CK was significantly elevated immediately after the game, with relative changes compared to pre-match condition ranging from 30 to 129% (de Hoyo et al., 2016; De Ste Croix et al., 2019; Fornaziero et al., 2023; Martin-Garetxana et al., 2024; Romagnoli et al., 2016). At 24 h post-match, CK values continue to increase with Δ ranging from 52 to 145% compared to baseline; at this time point, CK concentrations peaked and remained substantially altered at 48 h post-match (Δ ranging from 23 to 78%) (de Hoyo et al., 2016; Romagnoli et al., 2016). For example, Romagnoli et al. (2016) observed that CK increased from 247 ± 113 $U \cdot L^{-1}$ to 565 ± 185 $U \cdot L^{-1}$ in response to a 90-minute soccer match, then peaked at 24 h (604 ± 253 $U \cdot L^{-1}$) and remained significantly elevated two days after match (461 ± 205 $U \cdot L^{-1}$) in Italian under-19 youth players. A similar time course of CK recovery was also observed in Spanish under-19-players (de Hoyo et al., 2016). In addition to CK, other muscle damage markers such as the lactate dehydrogenase concentration showed significant increase from pre-match (349 ± 37 $U \cdot L^{-1}$) to post-match (415 ± 27 $U \cdot L^{-1}$) in Brazilian youth soccer players (Fornaziero et al., 2023).

Endocrinal (cortisol and testosterone), inflammatory (acute phase C-Reactive protein and interleukin 6) and immunological (number of circulating leukocytes, neutrophils and monocytes) markers were found to be altered at post-match in response to youth soccer competition (Fornaziero et al., 2023; Romagnoli et al., 2016). In response to an under-19 match-play among Italian players, Romagnoli et al. (2016) observed that cortisol and testosterone concentrations were diminished at post-match and in the two days after the match (24 and 48 h post), with Δ ranging from -4 to -36%. In the same research, alongside the previously mentioned increases in CK, also the neutrophil count was found to be elevated during the entire period up to 48 h (Romagnoli et al., 2016). Inflammatory responses were also evident with an increase in serum interleukin 6 at post-match and a gradual return to baseline by 48 h after the match (Romagnoli et al., 2016). Despite the limited data available within the youth soccer population, these alterations evidenced at post-match and in the days following competition suggest that youth soccer players experience metabolic perturbations, muscle damage and inflammation, with high variability between markers and various time courses of physiological recovery in the days post-match. In summary, elevated concentrations of CK are commonly observed at 48 h in adolescent soccer players in response to match load.

Table 6. Results of referenced studies investigating the time course of physiological recovery following match-play in youth soccer players.

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
De Hoyo et al. (2016)	Capillary blood	Creatine kinase (U·L^{-1})	290.2 ± 145.8	377.5 ± 214.8	441.1 ± 308.8	357.8 ± 176.2		Post: ↑ (30%) 24h Post: ↑ (52%) 48h Post: ↑ (23%)
De Ste Croix et al. (2019) - post PHV group	Capillary blood	Creatine kinase (U·L^{-1})	172.6 ± 98.7	384.6 ± 171.8				Post: ↑ (123%)
De Ste Croix et al. (2019) - circa PHV group	Capillary blood	Creatine kinase (U·L^{-1})	208.9 ± 68	360.3 ± 130.2				Post: ↑ (72%)
Fornaziero et al. (2023)	Venous blood	Leukocytes (/mm^3)	6920 ± 1949	13890 ± 3292				Post: ↑ (101%)
	Venous blood	Platelets (/mm^3)	240700 ± 38807	302400 ± 52073				Post: ↑ (26%)
	Venous blood	Cortisol (µg·dL^{-1})	10.8 ± 3.6	19.2 ± 7.4				Post: ↑ (78%)
	Venous blood	Creatine kinase (U·L^{-1})	516.5 ± 248.5	713.7 ± 308.2				Post: ↑ (38%)
	Venous blood	Lactate dehydrogenase (U·L^{-1})	348.8 ± 36.5	414.8 ± 26.6				Post: ↑ (19%)
	Venous blood	Lactate (mmol·L^{-1})	1.1 ± 0.3	3.2 ± 1.6				Post: ↑ (191%)
	Venous blood	Glucose (mg·dL^{-1})	72.5 ± 9.8	101.4 ± 19.9				Post: ↑ (40%)
	Venous blood	Erythrocytes (millions/mm^3)	5.03 ± 0.19	5.06 ± 0.25				Post: ↔ (1%)
	Venous blood	Hemoglobin (g·dL^{-1})	14.2 ± 0.9	14.4 ± 0.9				Post: ↔ (1%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
	Venous blood	Hematocrit (%)	42.8 ± 2.1	42.9 ± 1.9				Post: ↔ (0%)
	Venous blood	Urea (mg·dL^{-1})	40.9 ± 6.6	42.6 ± 5.3				Post: ↔ (4%)
	Venous blood	Calcium (mg·dL^{-1})	10.3 ± 0.3	9.4 ± 0.3				Post: ↓ (-9%)
	Venous blood	Sodium (mEq·L^{-1})	136.4 ± 1.07	136.8 ± 1.5				Post: ↔ (0%)
	Venous blood	Potassium (mEq·L^{-1})	7.3 ± 1	6.9 ± 1				Post: ↔ (-5%)
Martin-Garetxana et al. (2024) - U16 group	Capillary blood	Creatine kinase (U·L^{-1})	291.8 ± 257.0	570.1 ± 368.7				Post: ↑ (95%)
	Capillary blood	Urea (mmol·L^{-1})	5.1 ± 1.4	5.6 ± 1.7				Post: ↑ (10%)
Martin-Garetxana et al. (2024) - U14 group	Capillary blood	Creatine kinase (U·L^{-1})	191.1 ± 125.9	323.5 ± 324.7				Post: ↑ (69%)
	Capillary blood	Urea (mmol·L^{-1})	4.9 ± 1.2	6.2 ± 1.8				Post: ↑ (27%)
Romagnoli et al. (2016)	Venous blood	White blood cell (10^3/µL)	6.1 ± 1.9	13.1 ± 5.5	6.8 ± 2.0	6.8 ± 2.0		Post: ↑ (115%) 24h Post: ↔ (11%) 48h Post: ↔ (12%)
	Venous blood	Lymphocytes (10^3/µL)	2.3 ± 0.6	2.1 ± 0.6	2.2 ± 0.7	2.2 ± 0.4		Post: ↔ (-8%) 24h Post: ↔ (-2%) 48h Post: ↔ (-4%)
	Venous blood	Neutrophils (10^3/µL)	3.1 ± 1.4	10.1 ± 5.1	4.0 ± 1.5	4.0 ± 1.6		Post: ↑ (221%) 24h Post: ↑ (27%) 48h Post: ↑ (27%)
	Venous blood	Monocytes (10^3/µL)	0.5 ± 0.2	1.0 ± 0.4	0.6 ± 0.2	0.6 ± 0.2		Post: ↑ (96%) 24h Post: ↔ (12%) 48h Post: ↔ (17%)
	Venous blood	C-Reactive protein (mg·L^{-1})	0.08 (0.05-0.14)	0.07 (0.05-0.13)	0.24 (0.10-0.35)	0.14 (0.08-0.25)		Post: ↔ (-13%) 24h Post: ↑ (200%) 48h Post: ↔ (75%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
	Venous blood	Interleukin 6 ($pg·mL^{-1}$)	1.9 (1.8-3.1)	3.1 (2.6-6.1)	2.1 (2.0-2.2)	2.0 (1.9-2.2)		Post: ↔ (62%) 24h Post: ↑ (9%) 48h Post: ↔ (7%)
	Venous blood	Cortisol ($\mu g·L^{-1}$)	219.2 ± 51.7	210.1 ± 81.6	139.2 ± 44.8	145.8 ± 44.9		Post: ↔ (-4%) 24h Post: ↓ (-36%) 48h Post: ↓ (-34%)
	Venous blood	Testosterone ($ng·mL^{-1}$)	6.5 ± 1.5	4.8 ± 2.4	5.0 ± 1.9	4.5 ± 1.7		Post: ↓ (-26%) 24h Post: ↓ (-22%) 48h Post: ↓ (-31%)
	Venous blood	Free testosterone to cortisol ratio	0.8 ± 0.2	0.7 ± 0.7	1.0 ± 0.4	0.9 ± 0.4		Post: ↔ (-3%) 24h Post: ↔ (25%) 48h Post: ↔ (12%)
	Venous blood	Creatine kinase ($U·L^{-1}$)	246.7 ± 112.6	565.3 ± 185.1	604.5 ± 253.1	460.8 ± 204.7		Post: ↑ (129%) 24h Post: ↑ (145%) 48h Post: ↑ (87%)

Abbreviations and notes: ↑ significantly increase from baseline (pre); ↓ significantly decrease from baseline (pre); ↔ no significant change from baseline (pre); PHV = peak height velocity; Pre: pre-match measurement (baseline); Post: post-match measurement (within 1 hour); U: under.

2.4.4.3 Subjective recovery response following match-play

The time course of subjective recovery following match-play in youth soccer players has been assessed using VAS or Likert scales, reporting perceptual responses of muscle soreness, fatigue, recovery and mood. Perceived muscle soreness is typically assessed at post-match and in the days after match-play. Increased levels of self-reported muscle soreness were observed in multiple investigations conducted with adolescent soccer players in response to 70-, 80- and 90-minute matches, with increases ranging from 22 to 302% compared to baseline (De Ste Croix et al., 2019; Martin-Garetxana et al., 2024; Romagnoli et al., 2016; Springham et al., 2024). In the days after match-play, perceived muscle soreness returned to pre-match level, showing complete recovery in youth players (Romagnoli et al., 2016; Springham et al., 2024). Other subjective measures, such as the perceived recovery scale, have been used to profile recovery responses following youth soccer match-play, observing significant reduction in perceived recovery status from pre-match (7.1 ± 1.3 AU) to post-match (4.0 ± 1.5 AU) and a return to baseline 24 h post-match (6.1 ± 1.3 AU) (Paul et al., 2019). As perception is an integral component of the construct of fatigue, profiling post-match recovery utilising perceived scales (e.g., fatigue, recovery, and muscle soreness) alongside the assessment of objective measures completes the comprehensive analysis of the time course of recovery in youth soccer players.

The current evidence on post-match fatigue and recovery in youth soccer players has mainly examined acute post-match responses (i.e., pre to post-match changes) using performance, physiological and subjective measures. Conversely, the description of the time course of recovery needs further investigation. The recovery of physical performance exhibited acute reductions of CMJ performance and hamstring and adductor muscle force at post-match, showing conflicting results on their recovery at 48-72 h post-match across published studies. CK demonstrated that youth soccer match-play induced a high level of muscle damage immediately post-match and in the days after (+24 h and +48 h), with altered physiological concentrations persisting two days after match-play. Finally, the perception of post-match recovery was markedly altered at post-match, showing complete recovery in the days following match-play. From the analysis of the literature, post-match fatigue and recovery responses have been mainly described in late-stage adolescent players (16 to 19 years old) in response to 90-minute matches, whilst there is a paucity of data on the recovery kinetics of younger players (e.g., 13 to 15 years old) following 80- or 70-minute competitions.

In summary, the available evidence on the time course of recovery in youth soccer players suggests that adolescent athletes also experience acute physiological and performance alterations in response to match-play. However, due to the limited research on post-match recovery following shorter match durations (i.e., 70 or 80 minutes) and the scarcity of studies assessing physical performance, physiological, and subjective measures concurrently, a comprehensive understanding of their recovery processes remains limited. Moreover, the available research has rarely reported the associated physical (i.e., external load) and physiological (i.e., internal load) match demands. Most studies have focused on acute changes (e.g., immediately post-match) rather than extended recovery time points (e.g., 48 h or 72 h post-match). Therefore, further research is needed to establish the measurement characteristics (e.g., reliability, sensitivity) of response to load measures and to characterise recovery responses in youth soccer players, with the ultimate aim of informing readiness to train and recovery interventions in this population.

Table 7. Results of referenced studies investigating the time course of subjective recovery following match-play in youth soccer players.

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
De Ste Croix et al. (2019) - post PHV group	VAS	Muscle soreness (cm)	1.7 ± 2.1	6.8 ± 1.5				Post: ↑ (300%)
De Ste Croix et al. (2019) - circa PHV group	VAS	Muscle soreness (cm)	1.1 ± 1.3	2.8 ± 2.3				Post: ↑ (155%)
Martin-Garetxana et al. (2024) - U16 group	VAS	Muscle soreness (cm)	1.5 ± 1.1	2.8 ± 1.4				Post: ↑ (87%)
Martin-Garetxana et al. (2024) - U14 group	VAS	Muscle soreness (cm)	0.4 ± 0.6	1.2 ± 1.3				Post: ↑ (208%)
Paul et al. (2019)	Perceived recovery scale	Perceived recovery scale (au)	7.1 ± 1.3	4.0 ± 1.5	6.1 ± 1.3			Post: ↓ (-44%) 24h Post: ↔ (-14%)
Romagnoli et al. (2016)	VAS	Lower-limb muscle pain (cm)	1.0 ± 1.0	3.9 ± 1.7	1.7 ± 1.3	1.6 ± 1.1		Post: ↑ (302%) 24h Post: ↔ (74%) 48h Post: ↔ (66%)
Springham et al. (2024)	ASRM (Likert 1-5 scale)	Fatigue (au)	4.2 ± 0.6	2.9 ± 0.5		3.9 ± 0.5	4.1 ± 0.5	Post: ↓ (-31%) 24h Post: NA 48h Post: ↔ (-7%) 72h Post: ↔ (-2%)
	ASRM (Likert 1-5 scale)	Muscle soreness (au)	4.5 ± 0.4	3.5 ± 0.6		4.3 ± 0.6	4.3 ± 0.5	Post: ↓ (-22%) 24h Post: NA 48h Post: ↔ (-4%) 72h Post: ↔ (-4%)

Study (year)	Test	Outcome measure	Pre	Post	24h Post	48h Post	72h Post	Results compared to baseline (Pre)
	ASRM (Likert 1-5 scale)	Mood (au)	4.0 ± 0.6	3.6 ± 0.7		3.9 ± 0.6	3.8 ± 0.5	Post: ↓ (-10%) 24h Post: NA 48h Post: ↔ (-3%) 72h Post: ↔ (-5%)

Abbreviations and notes: ↑ significantly increase from baseline (pre); ↓ significantly decrease from baseline (pre); ↔ no significant change from baseline (pre); ASRM = athlete self-reported measure; au = arbitrary unit; cm: centimetre; NA = not applicable; PHV = peak height velocity; Pre: pre-match measurement (baseline); Post: post-match measurement (within 1 hour); U: under; VAS = visual analogue scale.

2.4.5 Recovery interventions in youth soccer players

Following the characterisation of the recovery responses, in this section, the effectiveness of recovery modalities in youth soccer players is discussed throughout the analysis of experimental studies. The application of recovery interventions, including nutritional, regeneration, and training strategies, aims to support recovery processes and provides the opportunity to increase training quality and tolerance, support competition performance, and accelerate the restoration of performance after competition or exhaustive training (Wiewelhove et al., 2024). These interventions are therefore targeted against the major causes and mechanisms of fatigue, such as metabolic fatigue and mechanical stress (Thorpe, 2021). Structuring recovery within the training process to appropriately distribute both training stress and accumulated fatigue is fundamental to maximise performance. Similarly to training prescription, recovery should also be periodised through the phases of the season (e.g., pre-season vs in-season) and the days of the competitive microcycle (e.g., on the days in proximity or following match-play) to positively influence chronic and acute training adaptations (Mujika et al., 2018). For instance, the application of recovery strategies following match-play in elite soccer players is emphasised during periods of congested fixtures for alleviating muscle damage, minimising injury risk, and optimising performance capacity (Cross et al., 2019; Field et al., 2021). Conversely, during training periods planned (e.g., pre-season), the use of recovery strategies may be withheld as post-exercise fatigue and inflammation are also necessary to promote long-term adaptations and improvements in performance (Mujika et al., 2018).

Adult soccer players are exposed to a combination of recovery and training methods to reduce the magnitude of fatigue and accelerate the time taken to return to a recovery state (Altarriba-Bartes et al., 2020; Calleja-González et al., 2021; Querido et al., 2022). Sleep, nutrition and hydration represent the fundamental interventions that impact recovery (Fullagar et al., 2015; Querido et al., 2024). In addition to these modalities, a wide range of complementary interventions, including water immersion modalities, active recovery, stretching, massage and compression garments, are commonly used in elite soccer and may contribute to accelerating the return of the body to a homeostatic state. However, the efficacy of these modalities in improving the recovery process has been uncertain or minimal, with significant variability in individual responses (Wiewelhove et al., 2024). Thus, alongside the fundamentals of sleep and nutrition, the manipulation of training load following match-play has been suggested to optimise recovery and performance capacity

(Driller and Leabeater, 2023; Slattery et al., 2012; Thorpe et al., 2017). From the end of the match up to 48 h post-match, performance practitioners and scientists tend to promote recovery by adjusting and managing the training load imposed on soccer players with structured recovery and active recovery, or an extra rest day being most frequent among high-performance practitioners in soccer (Cross et al., 2019; Field et al., 2021).

In youth soccer, information on how various training and recovery interventions administered following match-play impact the recovery process is limited. Given that academy soccer players may practice sub-optimal fuelling and recovery strategies due to school, training and travel demands (Stables et al., 2024), it is important to determine the effects of nutritional, regeneration and training strategies in promoting post-match recovery. To date, research conducted with adolescent soccer players has evaluated the effects of single or combined modalities with specific emphasis on nutritional strategies (Abbott et al., 2020, 2023; Altarriba-Bartes et al., 2023), on water immersion modalities (Altarriba-Bartes et al., 2023; Ascensão et al., 2011; Kinugasa and Kilding, 2009; Rowsell et al., 2009), on stretching and active recovery protocols (Altarriba-Bartes et al., 2023; Kinugasa and Kilding, 2009; Pooley et al., 2017, 2020; Trecroci et al., 2020, 2021) and, more recently, on training interventions including periodisation and manipulation of training load (Trecroci et al., 2020, 2021). In these studies, adolescent soccer players completed an official or a friendly match and were subsequently exposed to one or more recovery interventions based on the specific study design. The effectiveness of recovery and training intervention has been evaluated using multiple outcomes including performance measures (e.g., vertical jump, sprint test, maximal voluntary force, isometric strength), physiological measures (e.g., muscle damage, inflammatory and immunological markers) and subjective measures (e.g., total quality recovery scale, perceived muscle soreness, perceived fatigue, perceived well-being). A schematic representation of the recovery strategies commonly employed in soccer is reported in Figure 3. A synthesis of the experimental studies investigating the effect of recovery and training modalities on post-match recovery in youth soccer players is reported in Table 8.

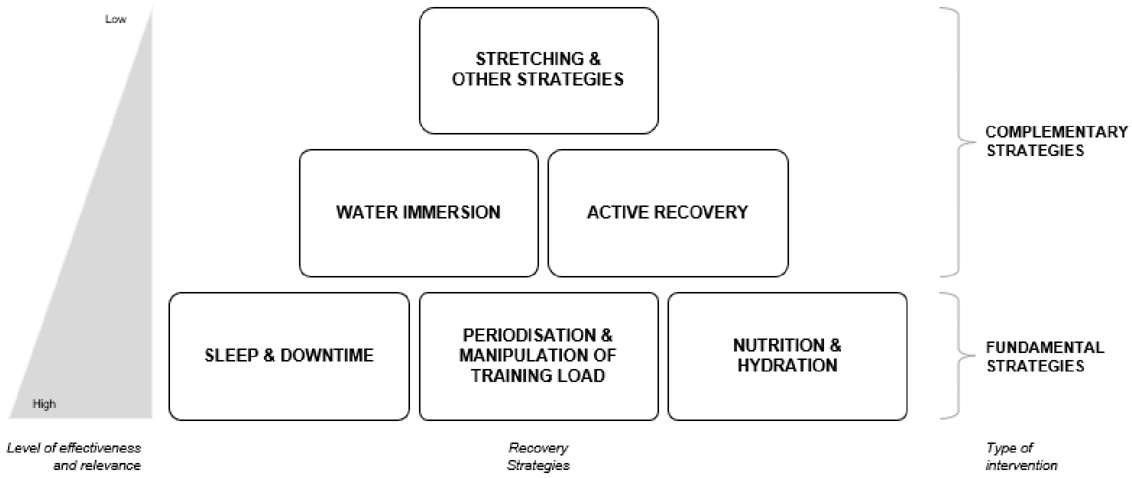

Figure 3. Recovery interventions in youth soccer players: fundamental and complementary strategies following match-play. Adapted from Driller and Leabeater (2023); Stephens and Halson (2021).

2.4.5.1 Nutritional strategies

The effects of nutritional strategies on post-match recovery of youth soccer players have been evaluated using tart cherry juice supplement, curcumin supplement, carbohydrate and protein shake compared to a control supplement (Abbott et al., 2020, 2023; Altarriba-Bartes et al., 2023). For example, Abbott et al. (2023) investigated the effects of 500 $mg \cdot d^{-1}$ of curcumin supplement in English Premier League youth soccer players in a randomised, placebo-controlled and cross-over design, observing that curcumin attenuated deficits in CMJ and RSI, perceived muscle soreness in the 60 h following competitive match-play and therefore expedited the recovery process compared to a placebo control condition. In another investigation, Abbott et al. (2020) also found that tart cherry juice did not hasten post-match recovery in English Premier League youth soccer players compared to a control supplement. Similar outcomes were also observed in an experimental study conducted with youth national team players from Mexico, with no differences between two combined recovery modalities (i.e., nutritional, active recovery and water immersion protocols) on the performance, physiological and perceived recovery (Altarriba-Bartes et al., 2023). In detail, the nutritional strategies adopted in the two groups consisted of 1) a 250 mL of carbohydrate and protein shake and 30 mL of cherry juice tart compared to 2) a 250 mL of carbohydrate and protein shake only. Apart from the positive benefits observed of curcumin supplements on the post-match recovery process, limited data are available on the effects of nutritional strategies on recovery following match-play in adolescent players.

2.4.5.2 Water immersion modalities

Water immersion constitutes one of the most utilised recovery strategies in soccer, with different modalities (e.g., cold water immersion (CWI), thermoneutral water immersion (TWI) and contrast water immersion (CWT)) and protocols (e.g., continuous or intermittent) being applied at post-match and in the days following the match-play (Allan et al., 2022; Altarriba-Bartes et al., 2020; Field et al., 2021; Querido et al., 2022). Research conducted with youth soccer players evaluated the effects of CWI (temperature ranging from 10°C to 14°C), TWI (temperature ranging from 34°C to 35°C) and CWT (CWI at 12°C and hot shower at 38°C) on the recovery process as a single modality (Ascensão et al., 2011; Kinugasa and Kilding, 2009; Pooley et al., 2020; Rowsell et al., 2009) or integrated into a structured recovery protocol (Altarriba-Bartes et al., 2023; Kinugasa and Kilding, 2009). CWI performed at post-match as both continuous or intermittent protocols have shown superior effects on the recovery process of perceived fatigue and muscle soreness compared to TWI in under-17 and under-19 youth soccer players (Ascensão et al., 2011; Rowsell et al., 2011). However, in the same studies, no differences between protocols were observed in the recovery of physical performance measures, including submaximal shuttle run test, vertical jumps, sprint and repeated sprint ability. More recently, Pooley et al. (2020) investigated the effects of CWI compared to active recovery and stretching protocols using a cross-over design with English Premier League youth soccer players competing in 80-minute match-play. CWI significantly attenuated markers of muscle damage (CK) and physical performance (CMJ) in the 48 h following match-play compared to static stretching; moreover, CWI had also a superior effect on muscle damage recovery response compared to active recovery. Finally, when comparing the effects of continuous CWI (10 min at 13-14°C) and intermittent CWI (5 x 2 min at 13-14°C) in a structured recovery protocol, no differences were observed in national team youth soccer players (Altarriba-Bartes et al., 2023). In summary, the CWI modality had superior benefits in promoting post-match recovery in youth soccer players compared to TWI or other strategies such as active recovery and stretching.

2.4.5.3 Active recovery and stretching

Active recovery and stretching are other commonly used recovery modalities in soccer, from youth to senior populations. In youth soccer players, active recovery and stretching protocols are implemented both at post-match and in the two days after the game (Altarriba-Bartes et al., 2023; Kinugasa and Kilding, 2009; Pooley et al., 2017, 2020; Trecroci et al., 2020, 2021). Static stretching protocols emerged as a less effective recovery strategy compared to passive recovery, active recovery and combined modalities (CWI and active recovery) in youth soccer players (Kinugasa and Kilding, 2009; Pooley et al., 2017, 2020). For example, Pooley et al. (2017) observed that static stretching, consisting of 2 x 15 s stretches to the main lower-limb muscles, does not enhance performance and physiological recovery compared to 10 min passive seating in English Premier League youth players. In a subsequent study, the authors reported that the application of active recovery immediately post-match, consisting of 10 min low-intensity cycling at 80-100 rpm, had superior effects on recovery compared to static stretching in the 48 h after the game (Pooley et al., 2020). Interestingly, when active recovery is adopted as a recovery strategy in conjunction with CWI, improved perception of recovery was observed compared to stretching and CWI protocols in under-15 youth soccer players (Kinugasa and Kilding, 2009). Stretching modalities, including static stretching or foam roller activities, had similar effects on the recovery responses of national team youth soccer players (Altarriba-Bartes et al., 2023). Active recovery protocols have also been administered two days after the competition in Italian youth soccer players, showing a positive effect in a range of recovery measures (e.g., knee flexor maximal voluntary force, CK and perceived muscle soreness) compared to regular soccer-specific training (Trecroci et al., 2020, 2021). Therefore, active recovery protocols can aid the recovery process to a greater extent compared to stretching and high-intensity soccer-specific training administered immediately at post-match or two days after the competition, respectively.

2.4.5.4 Periodisation and manipulation of training load

Along with the application of fundamental and complementary recovery strategies following match-play, accurate prescription and periodisation of training load have been suggested as a key area of recovery and training optimisation (Driller and Leabeater, 2023; Mujika et al., 2018). Manipulation of training load during the microcycle involves adjustments of the frequency, duration and intensity of training sessions to achieve desired training effects (Douchet et al., 2024; Slattery et al., 2012). Previous research conducted with youth soccer players showed that an active recovery session conducted 48 h post-match more effectively restores knee flexor muscle strength, decreases CK levels, and reduces muscle soreness compared to typical training sessions in high-level youth soccer players (Trecroci et al., 2020, 2021). The training session lasted 55 minutes, consisting of warm-up, small-sided games, tactical situations, whilst the active recovery protocol consisted of dynamic mobility and low-intensity running without the inclusion of soccer-specific drills. Therefore, information on the impact of various soccer-specific training interventions given when adolescent players return to training two days after a match is lacking. However, given that the time course of recovery may extend up to 48-72 h for certain restorative measures, understanding how different soccer training interventions impact recovery in the days following match-play is a fundamental aspect for informing training prescription and recovery strategies.

The current evidence on the efficacy of recovery modalities in improving post-match regeneration and performance capacity of youth soccer players has grown in recent years. Based on the available research on youth soccer players, active recovery and CWI protocols have shown superior benefits in promoting post-match recovery compared to other modalities, such as static stretching and TWI. However, given the high variability between responses and the small effects of recovery modalities in high-performance sports (Wiewelhove et al., 2024), examining the impact of different training interventions in the days following match-play may provide superior insights compared to the other complementary recovery interventions. Considering the relevance of training load management in soccer and the wider accessibility of GNSS and HR technologies, gaining insight into how training programs of different intensity and volume (e.g., high intensity vs moderate intensity) affect the recovery process when youth soccer players may be still recovering from match-play (e.g., 24, 48 or 72 h) is essential to inform microcycle periodisation and recovery modalities. Finally, the periodisation and manipulation of training load in the days post-match represents a practical aspect of contemporary sport science research and practice.

Table 8. Protocols and results of referenced studies investigating the effect of recovery interventions on post-match recovery responses in youth soccer players.

Study (year)	**Players characteristics (*n*, country, level, age)**	**Interventions (protocol and details)**	**Time-points of recovery**					**Outcome recovery measures**	**Synthesis of results**
			Pre	**Post**	**24h Post**	**48h Post**	**72h Post**		
Abbott et al. (2020)	*n* = 10 England Tier 4 19 ± 1 years	**Tart cherry juice supplement [TCJ]** (2 x 30 mL gel concentration of tart cherry juice poured into a bottle and filled with water to make a 250 mL serving) **Control supplement [CON]** (2 x 250 mL of isocaloric cherry-flavoured control drink)	×	×	×	×	×	*Performance measures*: CMJ, RSI *Subjective measures*: perceived muscle soreness, perceived well-being	No significant difference between recovery interventions.
Abbott et al. (2023)	*n* = 11 England Tier 4 19 ± 1 years	**Curcumin supplement [CURC]** (500 mg·d^{-1} of curcumin supplement) **Control supplement [CON]** (1000 mg·d^{-1} of medium chain triglyceride oil serving as control)	×	×	×	×	×	*Performance measures*: CMJ, RSI *Subjective measures*: perceived muscle soreness, perceived well-being	CURC > CON
Altarriba-Bartes et al. (2023)	*n* = 18 Mexico Tier 4 19.5 ± 0.6 years	**Combined modalities 1 [COMB 1]** (structured recovery strategy including 250 mL of carbohydrate and protein shake, 30 mL of tart cherry juice concentrate, foam roller activity for 45s with 15s rest for quadriceps, adductors, hamstrings, abductors and gastrocnemius, and 10 min of CWI at 13-14°C)	×	×	×	×	×	*Performance measures*: CMJ, hamstring strength *Physiological measures*: creatine kinase (CK) *Subjective measures*: TQR, perceived muscle soreness	No difference between recovery interventions.

Study (year)	Players characteristics (*n*, country, level, age)	Interventions (protocol and details)	Time-points of recovery					Outcome recovery measures	Synthesis of results
			Pre	Post	24h Post	48h Post	72h Post		
		Combined modalities 2 [COMB 2] (structured recovery strategy including 250 mL of carbohydrate and protein shake, 10 min of static stretching involving 2 x 30s stretches to the quadriceps, adductors, hamstrings, abductors, and gastrocnemius muscles, and intermittent cold-water immersion consisting of 5 x 2 min of CWI at 13-14°C followed by 2 min of rest in ambient air)							
Ascensao et al. (2011)	*n* = 20 Portugal Tier 3 18.2 ± 1.2 years	**Cold water immersion [CWI]** (10 min of CWI to the iliac crest at 10°C) **Thermoneutral water immersion [TWI]** (10 min of TWI to the iliac crest at 35°C)	×	×	×	×		*Performance measures*: CMJ, SJ, 20m sprint, peak quadriceps torque *Physiological measures*: CK, myoglobin, C-reactive protein *Subjective measures*: perceived muscle soreness of quadriceps, hamstrings, calves and adductors	CWI > TWI for peak quadriceps torque, physiological and perceptual measures. No significant difference between interventions for performance measures.

Study (year)	Players characteristics (*n*, country, level, age)	Interventions (protocol and details)	Time-points of recovery					Outcome recovery measures	Synthesis of results
			Pre	Post	24h Post	48h Post	72h Post		
Kinugasa et al. (2009)	*n* = 28 New Zealand Tier 2 14.3 ± 0.7 years	**Contrast water immersion [CWT]** (3 x 1 min of CWI at 12°C followed by 2 min hot shower at 38°C) **Combined modalities [COMB]** (3 x 1 min of CWI at 12°C followed by active recovery on a cycle ergometer for 2 min at 60-80 rpm, 90-110 W) **Stretching [STR]** (7 min of static stretching and 2 min with legs raised above heart level)	×	×	×			*Performance measures*: CMJ *Physiological measures*: resting HR tympanic temperature *Subjective measures*: TQR, perceived thermal sensations, perceived leg heaviness	No significant difference between recovery interventions, apart from perceived recovery (COMB > CWT, STR).
Pooley et al. (2017)	*n* = 10 England Tier 4 16.0 ± 1.0 years	**Stretching [STR]** (2 x 15s stretches to the gastrocnemius, hamstrings, quadriceps, glutes, hip flexors, adductors, and abductors) **Passive recovery [PASS]** (10 min of passing seating)	×	×		×		*Performance measures*: CMJ *Physiological measures*: muscle oedema, CK *Subjective measures*: perceived muscle soreness	No significant difference between recovery interventions.
Pooley et al. (2020)	*n* = 15 England Tier 4 16.0 ± 1.0 years	**Stretching [STR]** (2 x 15s stretches to the gastrocnemius, hamstrings, quadriceps, glutes, hip flexors, adductors, and abductors) **Cold water immersion [CWI]** (10min of CWI to the point of the iliac crest at 14°C) **Active recovery [AR]** (10 min of low-intensity exercise on a cycle ergometer at 80-100 rpm, ~80 W)	×	×		×		*Performance measures*: CMJ *Physiological measures*: muscle oedema, CK *Subjective measures*: perceived muscle soreness	CWI and AR > SS. No significant difference between CWI and AR, apart from CK (CWI > AR).

Study (year)	Players characteristics (*n*, country, level, age)	Interventions (protocol and details)	Time-points of recovery					Outcome recovery measures	Synthesis of results
			Pre	Post	24h Post	48h Post	72h Post		
Rowsell et al. (2009)	*n* = 20 Australia Tier 3 15.9 ± 0.6 years	**Cold water immersion [CWI]** (5 x 1 min of CWI at 10°C followed by 1 min seated rest on a chair with 24°C room temperature) **Thermoneutral water immersion [TWI]** (5 x 1 min of TWI at 34°C followed by 1 min seated rest on a chair with 24°C room temperature)	×	×	×	×	×	*Performance measures*: CMJ, RSA, submaximal shuttle run test *Physiological measures*: interleukin-1b, interleukin -6, interleukin-10, CK, lactate dehydrogenase, fatty acid binding protein, myoglobin *Subjective measures*: perceived leg soreness, perceived general fatigue	No significant difference between recovery interventions, apart from perceived fatigue and leg soreness (CWI > TWI).
Trecroci et al. (2020)	*n* = 9 Italy Tier 3 17-18 years	**Active recovery [AR]** (30 min active recovery session consisting of 15 min low-intensity technical drills, 5 min of dynamic stretching and 10 min of straight-line jogging activities) **Regular training [TR]** (60 min of soccer-specific training including 10 min of warm-up activities, 20 min of small-sided games, 15 min of tactical situations and 10 min of set plays)	×	×			×	*Performance measures*: knee flexors MVF, knee extensors MVF, 30m sprint, RSA	No significant difference between training interventions on recovery, apart from knee flexor MVF (AR > TR).

Study (year)	Players characteristics (*n*, country, level, age)	Interventions (protocol and details)	Time-points of recovery					Outcome recovery measures	Synthesis of results
			Pre	Post	24h Post	48h Post	72h Post		
Trecroci et al. (2021)	*n* = 9 Italy Tier 3 17-18 years	**Active recovery [AR]** (30 min active recovery session consisting of 15 min low-intensity technical drills, 5min of dynamic stretching and 10 min of straight-line jogging activities) **Regular training [TR]** (60 min of soccer-specific training including 10 min of warm-up activities, 20 min of small-sided games, 15 min of tactical situations and 10 min of set plays)	×	×			×	*Physiological measures*: CK, C-reactive protein, interleukin-6, lymphocytes, neutrophils, monocytes, cortisol *Subjective measures*: TQR, perceived muscle soreness	AR > TR for CK and perceived muscle soreness, no significant difference in the other measures.

Abbreviations and notes: > indicates a significant beneficial effect on recovery compared to the other intervention(s); AR: active recovery; CMJ: countermovement jump; CON: control; COMB: combined modalities; CURC: curcumin; CWI: cold water immersion; CWT: contrast water immersion; HR: heart rate; MVF: maximal voluntary force; min: minute; *n*: number of players (sample size); rpm: repetitions per minute; PASS: passive recovery; RSA: repeated sprint ability; s: second; STR: stretching; TCJ: tart cherry juice; TQR: total quality recovery; TR: training; TWI: thermoneutral water immersion; W: watt. Players' level is defined according to the classification of McKay et al. (2022): Tier 0: Sedentary; Tier 1: Recreationally Active; Tier 2: Trained/Developmental; Tier 3: Highly Trained/National Level; Tier 4: Elite/International Level; or Tier 5: World Class.

2.5 Summary and future directions

This chapter comprehensively explored and critically examined the current body of literature concerning training load, fatigue, and post-match recovery in youth soccer. Although these topics have been previously investigated in adult populations, this review has identified important gaps in existing knowledge specific to adolescent soccer players which require targeted scientific investigations.

It is well established that adolescent athletes grow and develop across the academy pathway with different timing and tempo, with concurrent increases in physical performance and changes in body composition. However, no longitudinal research has examined training and match loads in multiple age groups using both external and internal load measures. Given the role of internal load on subsequent training response and adaptation, it is important to quantify both dimensions of the load construct to fully characterise the training stimulus.

When assessing players' responses to training and match load, it is fundamental that monitoring tools and measures are valid, reliable and sensitive to change to determine meaningful changes. Despite the widespread use of physical performance tests in the applied setting, evidence regarding their measurement characteristics in the youth population is limited. Moreover, the emergence of novel technologies for monitoring fatigue and recovery highlights the need for rigorous validation of these tools within adolescent cohorts.

Training and match demands can induce both acute and residual fatigue in youth soccer players. However, no studies to date have comprehensively examined the acute effects of training by integrating performance, physiological and subjective measures. Furthermore, the current body of literature on post-match recovery responses has mainly focused on examining acute changes (e.g., immediately post-match) rather than extended recovery time points (e.g., 48 h or 72 h post-match). Since youth soccer players may compete in shorter match durations, examining post-match recovery of various restorative measures is important in addressing their specific recovery needs.

It is also of practical importance to evaluate the impact of various recovery interventions in promoting the regeneration process in the days following match-play. However, limited information exists on the effects of different training interventions post-match in youth soccer. Given the importance of periodisation and manipulation of training load, further investigation into its effects on recovery is warranted to inform readiness to train.

CHAPTER THREE · TRAINING LOADS AND MICROCYCLE PERIODISATION IN ITALIAN SERIE A YOUTH SOCCER PLAYERS

Peer-reviewed publications from this chapter:

Franceschi, A., Robinson, M. A., Owens, D. J., Brownlee, T., Bampouras, T. M., Ferrari Bravo, D., & Enright, K. (2024). Training loads and microcycle periodisation in Italian Serie A youth soccer players. *Journal of Sports Sciences*, 42(15), 1410-1420. https://doi.org/10.1080/02640414.2024.2391648.

Conference presentations from this chapter:

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Franceschi, A., Robinson, M. A., Owens, D. J., Brownlee, T., Bampouras, T. M., Ferrari Bravo, D., & Enright, K. (2024). Training loads in congested and non-congested microcycles in elite youth soccer players. *Isokinetic Medical Conference, Madrid, Spain.* Oral Presentation.

TRAINING LOADS AND MICROCYCLE PERIODISATION IN ITALIAN SERIE A YOUTH SOCCER PLAYERS

3.1 Abstract

Purpose: Training microcycles are fundamental structures for training prescription and load management, helping to optimise training effects and performance. This study aimed to quantify external and internal training and match loads of Italian Serie A youth soccer players across competitive weeks and their periodisation within microcycles.

Methods: Data were collected from 90 high-level youth players belonging to four academy age groups (under-19, under-17, under-16, under-15) across a full competitive season. Methods of monitoring external (duration and GNSS) and internal loads (HR and RPE) were employed. Linear mixed models were used to assess the variability of training load across age groups, training days, microcycles and player positions. Estimated marginal means, 95% confidence intervals (CIs) and effect sizes (Cohen's *d*) were calculated. Bonferroni correction was applied to adjust for pairwise multiple-test comparisons.

Results: Under-19 and under-17 players trained five times per week, while younger players trained four times. Late-stage academy players (under-19 and -17) underwent training regimes characterised by higher weekly accumulated external and sRPE training load compared to their younger counterparts ($p < 0.05$), whilst weekly accumulated HR internal loads were higher in under-15 players ($p < 0.05$). Marked fluctuations of daily load were observed across microcycles in under-19 and under-17 groups compared to younger groups ($p < 0.05$). MD demonstrated the highest load across the microcycle, while reductions in load were observed in the last training session before competition ($p < 0.05$). MD-5 and MD-3 sessions emerged instead as the most physically demanding training days ($p < 0.05$). During congested microcycles, under-19 players' training loads decreased on MD-2 compared to non-congested microcycles ($p < 0.05$).

Conclusion: Weekly accumulated external and sRPE training loads increase throughout the development pathway, while HR internal load provide different information. Late-stage academy players train with marked periodisation of daily load compared to younger players.

3.2 Introduction

Training load monitoring is a core aspect of contemporary sports science research and practice (Coutts et al., 2018). Following two decades of research and application across various sports settings, the concept of training load has been refined as a higher-order construct reflecting the amount of physical training that the athletes do and experience (Impellizzeri et al., 2022). As a multidimensional construct, it encompasses various measures and can be quantified using indicators of external and internal load (Jeffries et al., 2022). In the context of sports training, external load refers to the physical work undertaken by athletes during training and competition. It represents the input variable that is manipulated to elicit the desired training responses or effects (Impellizzeri et al., 2019). The athlete's psychophysiological responses to a given external load occurring during the execution of exercise correspond to internal load. In team sports, external load can be quantified using camera systems and microtechnologies such as GNSS, which enable the tracking of player activities including distances in different velocity zones and events associated with changes in velocity (e.g., accelerations and decelerations) (Torres-Ronda et al., 2022). Internal load can be quantified using HR sensors and RPE to capture physiological and perceptual responses during exercise, respectively (Impellizzeri et al., 2005). In light of the multidimensional construct and the demands of team sports, a single measure cannot encapsulate all dimensions of the training load construct (Jeffries et al., 2022). Therefore, to effectively quantify the training stimulus and identify how players are coping with the training programme, a combination of external and internal load measures is essential (Impellizzeri et al., 2019).

The importance of the training process is particularly relevant within professional youth soccer academies, where pathway development programs are in place to maximise the chance of career success (McBurnie et al., 2021; Ryan et al., 2017). Throughout adolescence, youth players face unique challenges due to the growing training and match demands (Hannon, Coleman, et al., 2021) alongside the inconsistency in the timing and tempo of their physical growth and maturity (Johnson et al., 2022). Training to improve physical qualities in youth soccer players is a longitudinal process that requires comprehensive planning and manipulation of the training stimulus, incorporating the different aspects of the demands of match-play and understanding of growth and maturation processes (McBurnie et al., 2021). To ensure sustained physical development, a systematic approach to training load monitoring is recommended; this guarantees that youth athletes undergo positive adaptations and progress during years of rapid growth, thereby mitigating the risks of negative outcomes such as injuries and illnesses (Towlson et al., 2021). Despite the widespread use of training monitoring systems among youth soccer academies (Salter et al., 2021), longitudinal studies integrating both external and internal load across different age groups are scarce within the youth population. To date, published research on youth soccer players has predominantly quantified training load using a single dimension of load (Brownlee, O'Boyle, et al., 2018) and often over a short period (Coutinho et al., 2015). Only a single study has documented seasonal training loads in youth soccer players across multiple age groups; notably, this study exclusively reported external load measures (Hannon, Coleman, et al., 2021). Therefore, there is a need for high-quality and longitudinal information on the training load endured and experienced by high-level youth soccer players to support the physical development pathway over the different stages of adolescence.

In soccer, a myriad of modifiable and non-modifiable factors can influence the training process and consequently sports performance. Designing periodised training programmes for high-level academy players presents unique challenges due to the numerous contextual and individual factors that influence the training process (Pass et al., 2022). To address these challenges, coaches and sports scientists utilise periodisation as a training principle and planning tool, aiming to organise training programmes for effectively preparing athletes for optimal performance (Mujika et al., 2018). Although different definitions and models of periodisation exist, they commonly adopt similar structures, organising training periods into macro-, meso- and micro-cycles (Mujika et al., 2018). In recent years, there has been growing interest in the training load distribution of professional soccer players during weekly microcycles (Buchheit, Sandua, et al., 2021), which represent fundamental blocks of the training plan. Published literature has mainly examined training load microcycle periodisation in professional adult soccer players (Anderson et al., 2016; Malone, Di Michele, et al., 2015; Martín-García et al., 2018), with limited information available on the youth soccer population. As adolescent players possess markedly different physical and physiological characteristics required for soccer performance (Radnor et al., 2018), detailed investigations of training loads and periodisation practices of the youth soccer population are warranted. The description of the distribution of training load from different academy environments is of interest to practitioners and can facilitate the design of contextualised training plans for youth soccer players.

High-level adolescent players participate in multiple domestic (e.g., national championships) and international tournaments (e.g., UEFA Youth League) throughout the competitive season. The demanding nature of these competitions, coupled with congested fixture schedules, often requires talented youth players to play successive matches with limited recovery time, typically of 2 or 3 days (Castellano et al., 2020). Effective management of the training load and recovery during these condensed match periods thus becomes paramount for soccer practitioners (Buchheit et al., 2023; Cross et al., 2019; Field et al., 2021; Noor et al., 2021). The frequency of matches within weekly microcycles and the microcycles' length can affect the accumulated training load and the loading periodisation in professional adult soccer players (Anderson et al., 2016; Oliva-Lozano et al., 2022). However, in the context of youth soccer, research has primarily focused on quantifying training load periodisation during typical microcycles, characterised by one match per week (Coutinho et al., 2015; Hannon, Coleman, et al., 2021; Maughan et al., 2021). Investigating the periodisation practices of training load within congested microcycles in high-level youth soccer players holds significant relevance, especially for practitioners supporting late-stage academy soccer players transitioning from the academy to the first team environment or from club to national team setting.

Therefore, this study aimed to quantify external and internal training and match load in Italian Serie A youth soccer players across competitive weeks and their periodisation within microcycles. The specific objectives of the study were to: 1) quantify accumulated weekly training loads in multiple academy age groups during typical competitive microcycles; 2) analyse the periodisation of daily training loads within competitive microcycle in multiple academy age groups; 3) compare external and internal load during congested and non-congested microcycles in under-19 players, participating in multiple national and international tournaments.

3.3 Methods

3.3.1 Participants

A group of 93 outfield youth soccer players from the under-19 (n = 25), under-17 (n = 22), under-16 (n = 22) and under-15 (n = 24) squads of a professional soccer academy in the Italian Serie A were initially recruited to participate in this study. Participants' characteristics are presented in Table 9. Subjects were classified as highly trained (Tier 3) or elite (Tier 4) (McKay et al., 2022). Data collection was part of the club's monitoring system, and written informed consent was provided by parents or legal guardians and players. The study received ethics approval from the University Research Ethics Committee (22/SPS/025) and was conducted in accordance with the Declaration of Helsinki.

Table 9. Participant characteristics for each academy age group.

Age group	*n*	Age (years)	Body mass (kg)	Height (cm)	Predicted adult height (%)	Maturity offset (years)
Under-19	25	18.2 ± 0.5	75.8 ± 6.5	181.9 ± 7.7	100.0 ± 0.5	-
Under-17	22	16.5 ± 0.3	70.4 ± 6.6	180.2 ± 5.9	99.4 ± 0.6	2.6 ± 0.5
Under-16	22	15.6 ± 0.2	67.5 ± 6.8	177.1 ± 5.8	98.0 ± 1.0	1.8 ± 0.6
Under-15	24	14.5 ± 0.3	63.2 ± 8.5	175.3 ± 6.1	96.1 ± 1.3	1.0 ± 0.5

Abbreviations and notes: kg: kilogram; cm: centimetre; SD: standard deviation. Data are mean ± SD.

3.3.2 Experimental design

Training and match load data were collected across a full competitive season from August to June as part of the club's monitoring strategy. External and internal loads were quantified using GNSS, HR sensors and RPE. From these competitive microcycles, only the main team training sessions and matches were included in the analysis, while individual sessions (i.e., individualised or rehabilitation) were excluded. Other training weeks (e.g., pre-season and international window) were not considered for analysis. Weekly training loads (i.e., cumulative training and match load for a specific week) were computed for each player and each competitive week, with players required to have completed all the team's training sessions that specific week and at least 70% of the competitive match. Periodisation of daily training loads was analysed with respect to the distance from MD: MD-5, MD-4, MD-3, MD-2, MD-1, MD+1 (Malone et al., 2015). With this approach, 90 players, 970 weekly microcycles and 7530 individual training sessions were included in the final analysis.

3.3.3 Experimental procedures

3.3.3.1 Training microcycles

Competitive weekly microcycles for under-19 players consisted either of one official match or two official matches due to the participation in multiple national (Primavera 1 League, Primavera 1 Cup) and international competitions (UEFA Youth League). Typical (or non-congested) microcycles (i.e., 1 match per week) consisted of five training days, a match and a rest day, while congested microcycles (i.e., 2 matches per week) consisted of four training sessions, two matches and a recovery day. Competitive weekly microcycles for under-17 players consisted of one official match, five training days, and one rest day. Competitive weekly microcycles for under-16s and under-15s consisted of one official match, four training days, and two rest days. An overview of the training microcycles is depicted in Figure 4. Training sessions on the competitive microcycle were comprised mainly of technical and tactical drills including technical circuits, possession games, phase of play drills (e.g., offensive and defensive situations) and training matches (e.g., small-, medium- and large- sided games). As part of the club's physical development programme, players were exposed to athletic development sessions, including conditioning runs on MD-5, sprinting and agility training on MD-3 and MD-2. In addition to pitch-based training, gym-based sessions were performed on MD-4 and MD-2 to develop players' physical capabilities (strength and power). On MD, players took part in official competitive matches of different durations based on their age group as regulated by the Italian Football Federation: under-19 and under-17: 90 minutes, under-16: 80 minutes, and under-15: 70 minutes. In the case of congested microcycles of under-19 players, the training session performed the day after the match (MD+1) was organized to expose starting players (e.g., those who played > 60 minutes of competition) to a structured recovery session (e.g., low impact activities, active recovery, and cold-water immersion), and non-starting players to a compensatory training session to partly replicate competition load. All the age groups trained for the whole season on official full-size pitches of the same dimensions. The training session content was planned weekly by the coaching staff.

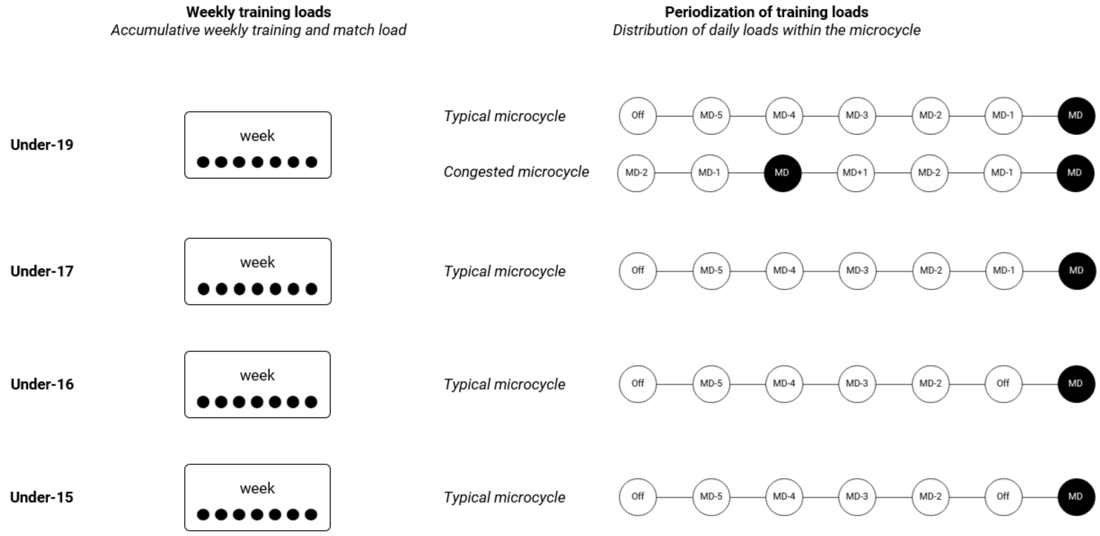

Figure 4. Overview of the training microcycles analysed throughout the youth academy squads. Abbreviations: Off: day off, rest; MD: match day; MD-x: training session with respect to the distance prior to the next competitive match; MD+1: training session with respect to the distance following the last competitive match.

3.3.3.2 Quantification of external training and match load

External load was quantified using GNSS (Apex Pro Series, 10Hz GNSS, STATSports, Newry, Northern Ireland). GNSS units (30 × 80 mm, 48 g) sample at 10 Hz, providing information on positioning and time, and thus velocity and distance are monitored. The GNSS unit was placed inside a custom-made manufacturer-provided vest that held the unit on the upper back between the shoulder blades, allowing exposure of the GNSS antennae to acquire a clear satellite connection. Each player wore the same GNSS unit for the whole experimental period and the units were turned on around 15 minutes before their use to obtain a sufficient satellite signal and to synchronise the GNSS clock with the atomic clock in the satellites (Beato et al., 2023). The number of satellites connected during sessions was 17 ± 4, and the horizontal dilution of precision was 0.5 ± 0.1. At the end of each session, data were downloaded and then cropped from the start of the first activity to the end of the last drill or end of match-play on Sonra software (version 4.1.31, STATSports, Newry, Northern Ireland). This tracking system provides valid and reliable estimates of distance and velocity during team sports activities, including linear and multidirectional movements (Beato et al., 2023; Coutts and Duffield, 2010). Sessions with "estimated data" either due to malfunctioning hardware or players forgetting to wear the GNSS were removed from the analysis (5% of the initial dataset). The external load measures selected for the analyses were duration (min), total distance (m), distance > 20 $km \cdot h^{-1}$ (m), distance > 25 $km \cdot h^{-1}$ (m), accelerations > 3 $m \cdot s^{-2}$ (count) and decelerations < -3 $m \cdot s^{-2}$ (count). The selected speed thresholds (> 20 $km \cdot h^{-1}$ for HSR and > 25 $km \cdot h^{-1}$ for SPR) align with FIFA's preferred entry velocities for male players, reflecting current practical standards despite the lack of consensus in the literature (Gualtieri et al., 2023). These external load measures are linked with the intermittent and high-intensity nature of soccer and are deemed important for optimising the training process (Buchheit and Simpson, 2017).

3.3.3.3 Quantification of internal training and match load

Internal load was quantified using HR sensors (Polar H10, Polar, Kempele, Finland). HR sensors use an electrocardiogram to measure HR and monitor the cardiovascular response during exercise (Drust et al., 2007). Each player wore the same HR sensor around the chest immediately below the chest muscles and with the connector placed in a central and upright position. Players were advised to adjust the strap length to fit tightly and comfortably around the chest. At the end of each training and match session, HR data were transferred and downloaded on Sonra software using Bluetooth technology. HR traces of each player were visually examined on Sonra software to verify recording quality. In case of signal loss or multiple drops within a session, HR data were removed (19% of the initial dataset). HR sensors were not worn during the MD sessions, thus no data was presented for this specific day of the microcycle. The HR_{max} of each player was assessed using the Yo-Yo intermittent recovery test (Bangsbo et al., 2008). The HR internal load measures selected for the analyses were time spent > 85% HR_{max} (min) and time spent > 90% HR_{max} (min). These thresholds reflect the intensities recorded during soccer matches and are employed for aerobic fitness development (Dellal et al., 2012). Internal load was also quantified using the session RPE (sRPE) method, measured using Borg's CR-10 scale (Foster et al., 2001; Impellizzeri et al., 2004). sRPE was collected ~30 min following each training session and match. sRPE-TL for each session was subsequently calculated by multiplying the player's sRPE by the duration of the session (Foster et al., 2001). sRPE (arbitrary units, AU) and sRPE training load (AU) were used for the analyses.

3.3.4 Statistical analysis

Data were analysed using mixed modelling as a flexible approach to account primarily for the unbalanced repeated measures nature of the data (e.g., differing frequency of observations of players) (Newans et al., 2022). Linear mixed models were used to detect the variability of external and internal load measures across the different age groups (under-19, under-17, under-16, under-15), training days (MD-5, MD-4, MD-3, MD-2, MD-1, MD), microcycles (congested, non-congested) and player positions (central defender, wide defender, central midfielder, wide midfielder, attacker). Age group, training day, microcycle and player position were included in the model as fixed effects, while individual players were random effects. A first mixed model was employed to analyse the variability of weekly training load measures across age groups and player positions. A second mixed model was employed to analyse the variability of daily training load measures across training days and age groups. A third mixed model was employed to analyse the variability of daily training loads across microcycles and training days, for under-19 players only. Estimated marginal means and 95% CIs were calculated for each mixed model. A Bonferroni correction was applied to adjust for pairwise multiple-test comparisons. The magnitude of differences was computed using Cohen's *d* effect size as an additional statistic to better interpret differences. Threshold criteria for effect size statistics were interpreted as follows: *trivial* (< 0.20), *small* (0.20-0.59), *moderate* (0.60-1.19), *large* (1.20-1.99) and *very large* (> 2.0) (Hopkins et al., 2009). Statistical significance was set at $p < 0.05$. Data presented are calculated as mean and standard deviation (SD), or 95% CIs where shown. Analyses were conducted using JAMOVI statistical software (the jamovi project, version 2.3, Sydney, Australia).

3.4 Results

3.4.1 Weekly accumulated training loads

No significant interactions were observed between age groups and player positions ($p > 0.05$), except for weekly distance covered > 25 km·h^{-1} ($p = 0.017$). Weekly distance covered > 25 km·h^{-1} was higher in under-19 wide defenders (494.6 ± 182.5 m) than in under-16 wide defenders (250.5 ± 121.6 m; $p = 0.024$; d: 1.65) and under-15 wide defenders (221.4 ± 115.9 m; $p < 0.001$; d: 1.85). Additionally, weekly distance covered > 25 km·h^{-1} was higher in under-19 wide defenders (494.6 ± 182.5 m) than in under-19 wide midfielders (264.9 ± 131.4 m; $p = 0.034$; d: 1.42), under-19 central midfielders (139.0 ± 73.5 m; $p < 0.001$; d: 2.57) and under-19 central defenders (180.0 ± 98.7 m; $p < 0.001$; d: 2.15). A significant main effect of player position was observed for weekly distance covered > 20 km/h and weekly distance covered > 25 km·h^{-1} ($p < 0.001$). Weekly distance covered > 20 km·h^{-1} was higher in wide defenders (1585.5 ± 609.4 m) than in all the other positions ($p < 0.001$ for all comparisons; d: from 0.48 to 0.95). Weekly distance covered > 25 km·h^{-1} was higher in wide defenders (304.9 ± 173.0 m) than in central defenders (176.9 ± 100.0 m; $p < 0.001$; d: 0.89), central midfielders (170.1 ± 115.8 m; $p < 0.001$; $d = 0.92$) and wide midfielders (210.4 ± 142.5 m; $p < 0.05$; d: 0.59). Additionally, it was higher in attackers (255.0 ± 129.7 m) compared to central defenders ($p < 0.05$; d: 0.66). No significant differences were observed between other player positions ($p > 0.05$). A significant main effect of age group was observed for all weekly external and internal training load measures ($p < 0.001$). Weekly external and internal loads performed during competitive microcycles for each age group are displayed in Figure 5 and Table 10, respectively.

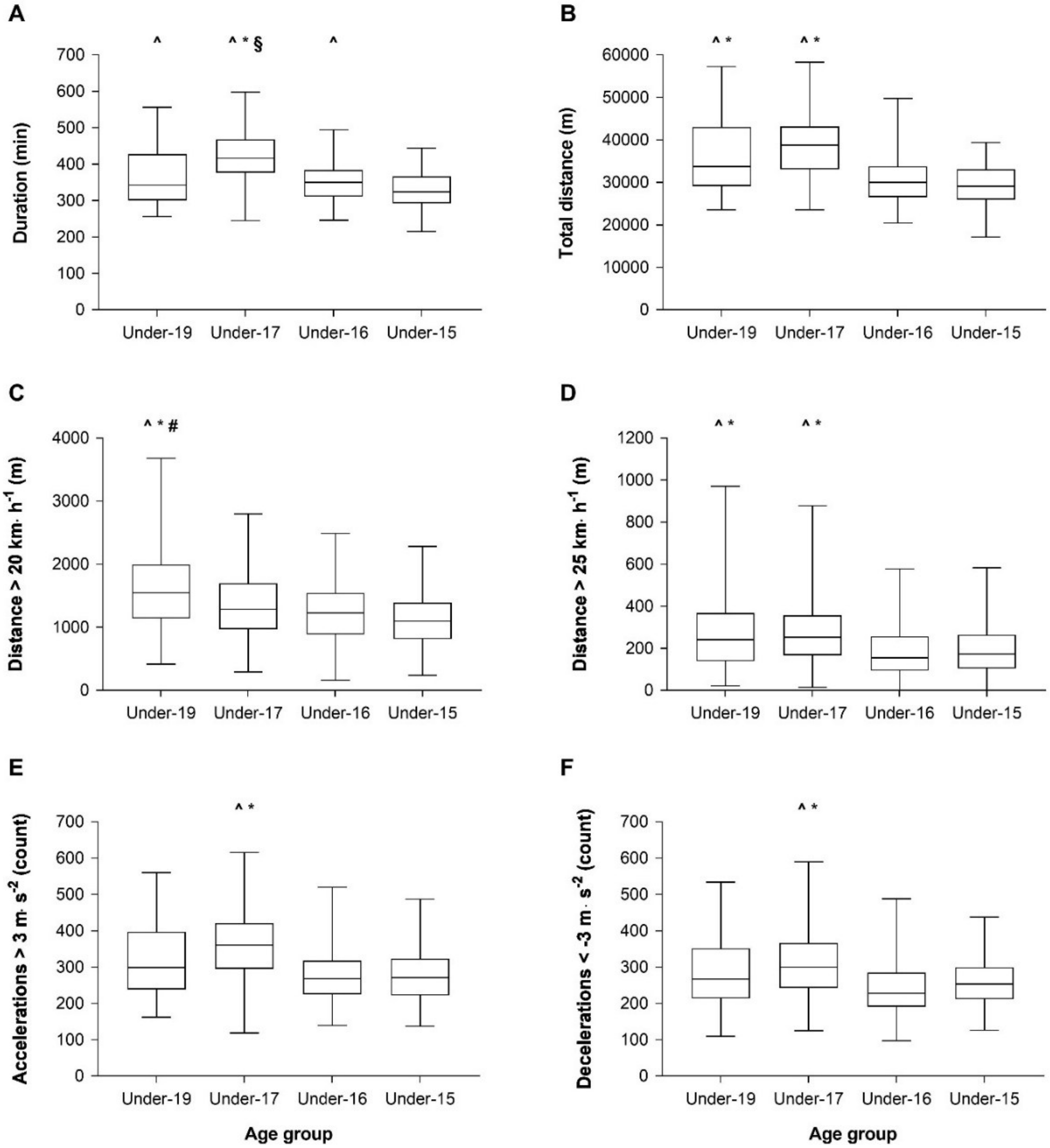

Figure 5. Weekly accumulated external loads in Italian Serie A youth soccer players during competitive microcycles (*n* = 90). (A) duration, (B) total distance, (C) distance > 20 km·h^{-1}, (D) distance > 25 km·h^{-1}, (E) accelerations > 3 m·s^{-2}, (F) decelerations < -3 m·s^{-2}. Box and whiskers graphs display median, lower and upper quartiles, and min and max values. Statistically significant differences ($p < 0.05$) across age groups are reported as follows: ^ significantly higher than under-15; * significantly higher than under-16; # significantly higher than under-17; § significantly higher than under-19.

Table 10. Weekly accumulated internal loads in Italian Serie A youth soccer players during competitive microcycles (*n* = 90).

	Under-19	**Under-17**	**Under-16**	**Under-15**
Time spent > 85% HR_{max} (min)	35.6 ± 28.5	48.8 ± 33.4	40.8 ± 28.2	64.4 ± 28.9 * # §
Time spent > 90% HR_{max} (min)	10.3 ± 12.6	15.4 ± 17.0	12.2 ± 14.6	26.3 ± 17.0 * # §
sRPE (AU)	4.3 ± 0.5 ^ #	3.9 ± 0.5	4.4 ± 0.5 ^ #	4.0 ± 0.6
sRPE-TL (AU)	1690.9 ± 444.2 ^	1722.5 ± 409.0 ^	1575.3 ± 316.8 ^	1353.1 ± 264.4

Abbreviations and notes: HR: heart rate; MD: match day; sRPE: session rating of perceived exertion; SD: standard deviation; TL: training load; AU: arbitrary units.
Data are mean ± SD. HR measures represent the weekly sum of the training sessions, with the exclusion of MD (i.e., no HR data recorded during match).
Significant between-group differences ($p < 0.05$) are reported as follows: ^ significantly higher than under-15; * significantly higher than under-16; # significantly higher than under-17; § significantly higher than under-19.

3.4.2 Periodisation of training loads

A significant interaction was observed between training days and age groups for all external and internal training load measures ($p < 0.001$). Periodisation of external load during competitive microcycles for each age group and training day is displayed in Figure 6, Figure 7, and Figure 8. Periodisation of internal load during competitive microcycles for each age group and training day is reported in Table 11.

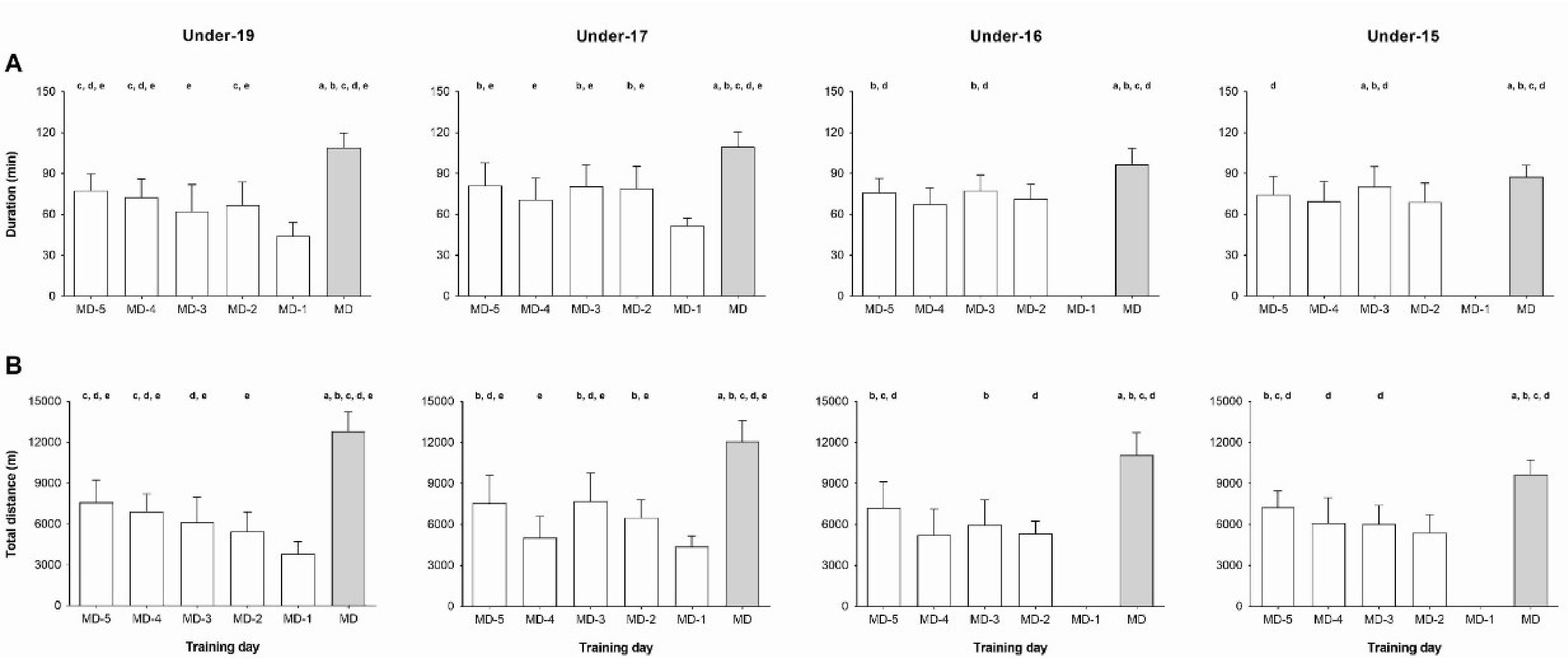

Figure 6. Microcycle periodisation of external training and match loads in Italian Serie A youth soccer players (*n* = 90) during a competitive season. (A) duration, (B) total distance. Vertical bars display mean ± standard deviation (SD) for each age group. White bars represent training days (MD-5, MD-4, MD-3, MD-2, MD-1) and grey bars represent match day (MD). Statistically significant differences ($p < 0.05$) across training days are reported as follows: a significantly higher than MD-5; b significantly higher than MD-4; c significantly higher than MD-3; d significantly higher than MD-2; e significantly higher than MD-1; f significantly higher than MD.

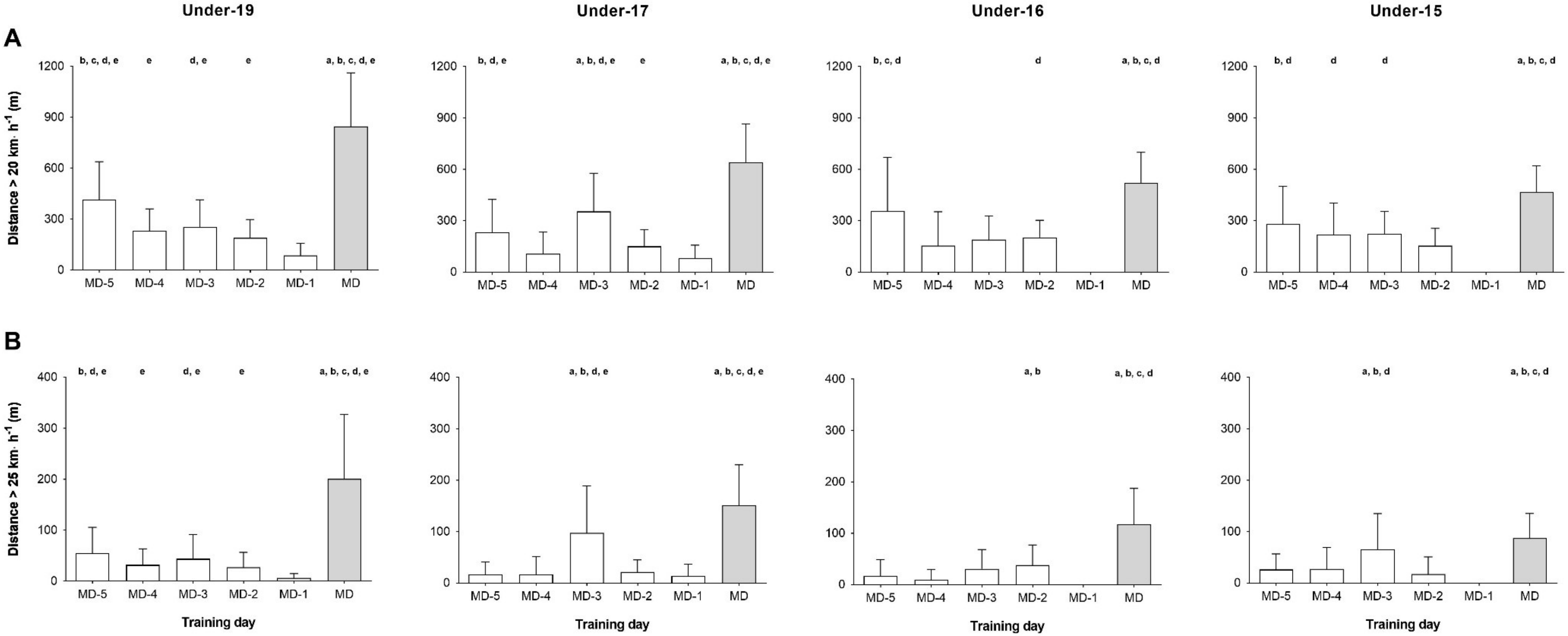

Figure 7. Microcycle periodisation of external training and match loads in Italian Serie A youth soccer players (*n* = 90) during a competitive season. (A) distance > 20 km·h^{-1}, (B) distance > 25 km·h^{-1}. White bars represent training days (MD-5, MD-4, MD-3, MD-2, MD-1) and grey bars represent match day (MD). Statistically significant differences ($p < 0.05$) across training days are reported as follows: a significantly higher than MD-5; b significantly higher than MD-4; c significantly higher than MD-3; d significantly higher than MD-2; e significantly higher than MD-1; f significantly higher than MD.

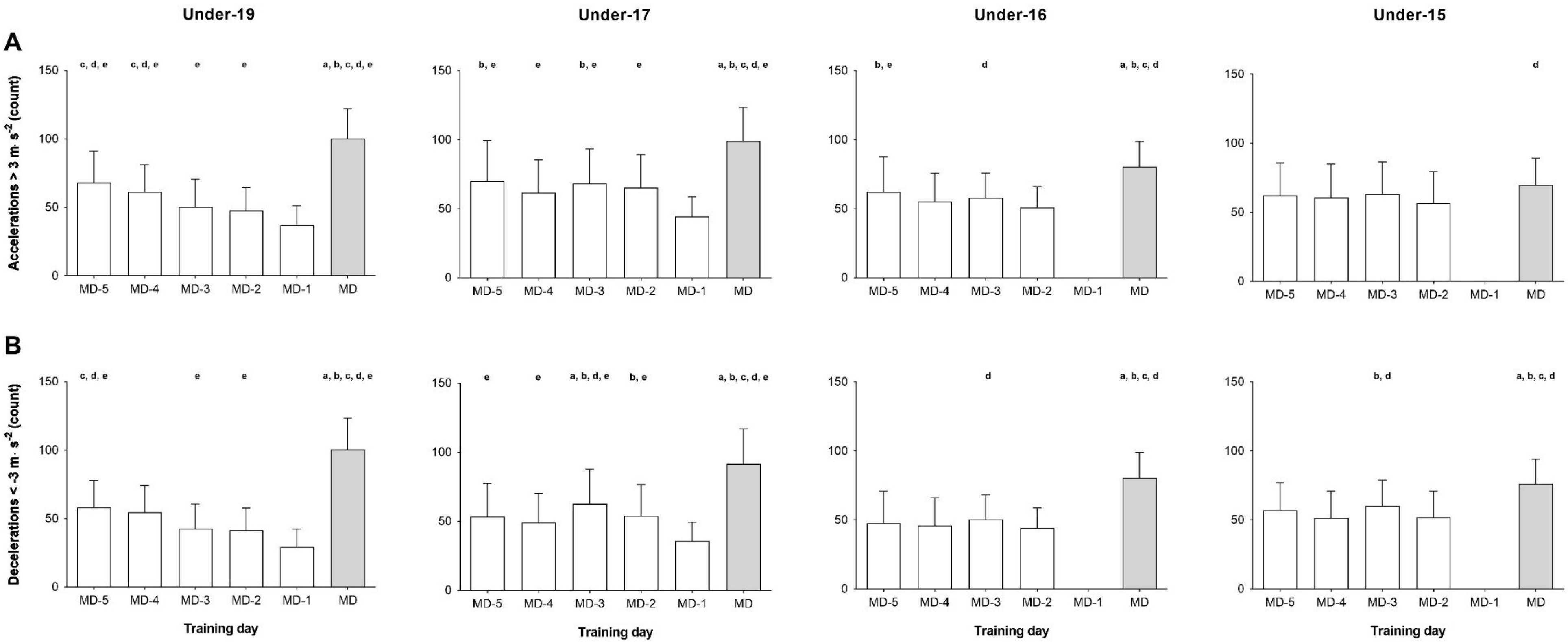

Figure 8. Microcycle periodisation of external training and match loads in Italian Serie A youth soccer players (n = 90) during a competitive season. (A) accelerations > 3 m·s^{-2}, (B) decelerations < -3 m·s^{-2}. White bars represent training days (MD-5, MD-4, MD-3, MD-2, MD-1) and grey bars represent match day (MD). Statistically significant differences ($p < 0.05$) across training days are reported as follows: a significantly higher than MD-5; b significantly higher than MD-4; c significantly higher than MD-3; d significantly higher than MD-2; e significantly higher than MD-1; f significantly higher than MD.

Table 11. Microcycle periodisation of internal training and match loads in Italian Serie A youth soccer players (*n* = 90) during a competitive season.

	Age-group	**MD-5**	**MD-4**	**MD-3**	**MD-2**	**MD-1**	**MD**
Time spent > 85% HR_{max} (min)	Under-19	15.2 ± 11.6 [b c d e]	10.6 ± 10.3 [c d e]	7.2 ± 8.1 [d e]	4.3 ± 5.0	2.5 ± 3.8	-
	Under-17	16.1 ± 14.1 [b d e]	8.6 ± 8.8 [e]	14.8 ± 11.7 [§ b d e]	8.1 ± 8.3 [e]	5.2 ± 5.0	-
	Under-16	16.7 ± 13.8 [b c d]	9.6 ± 9.6 [d]	11.1 ± 10.5 [d]	5.9 ± 6.1	-	-
	Under-15	24.8 ± 12.9 [* # § b c d]	18.5 ± 12.7 [* # § d]	16.6 ± 9.7 [§ d]	10.3 ± 8.9 [§]	-	-
Time spent > 90% HR_{max} (min)	Under-19	5.7 ± 7.0 [b c d e]	2.9 ± 4.6 [d e]	2.0 ± 3.7 [e]	0.8 ± 1.6	0.4 ± 1.1	-
	Under-17	5.6 ± 7.9 [b d e]	3.0 ± 4.9 [d]	4.4 ± 5.8 [b d e]	2.2 ± 3.9	1.4 ± 2.6	-
	Under-16	6.2 ± 8.4 [b c d]	2.9 ± 5.1 [d]	3.2 ± 5.3 [d]	1.3 ± 2.4	-	-
	Under-15	11.9 ± 8.7 [* # § b c d]	8.3 ± 8.3 [* # § c d]	5.9 ± 5.5 [§ d]	3.3 ± 4.7	-	-
sRPE (AU)	Under-19	5.0 ± 1.0 [^ * # b c d e]	4.4 ± 1.0 [^ # d e]	4.2 ± 0.9 [d e]	3.5 ± 0.7 [e]	2.5 ± 0.6	7.1 ± 0.9 [^ * a b c d e]
	Under-17	3.9 ± 0.9 [b d e]	3.7 ± 0.8 [d e]	4.2 ± 0.8 [a b d e]	3.3 ± 0.5 [e]	2.5 ± 0.5	6.9 ± 1.1 [^ * a b c d e]
	Under-16	4.6 ± 1.0 [# b d]	4.2 ± 0.8 [d]	4.4 ± 0.9 [d]	3.8 ± 0.7 [^ # §]	-	5.9 ± 0.9 [^ a b c d]
	Under-15	4.3 ± 1.1 [# b d]	3.9 ± 0.9 [d]	4.3 ± 1.0 [b d]	3.5 ± 0.8	-	5.2 ± 0.9 [a b c d]
sRPE-TL (AU)	Under-19	389.5 ± 86.7 [^ # b c d e]	326.3 ± 92.8 [^ c d e]	267.9 ± 110.9 [d e]	236.5 ± 80.1 [e]	112.4 ± 38.3	776.9 ± 141.8 [^ * a b c d e]
	Under-17	323.5 ± 113.6 [b d e]	261.1 ± 85.3	344.5 ± 98.4 [b d e]	261.2 ± 75.6 [§ e]	129.7 ± 33.3	764.4 ± 167.2 [^ * a b c d e]
	Under-16	352.4 ± 103.8 [b d]	284.7 ± 77.7	342.7 ± 95.8 [b d]	275.6 ± 68.2 [§]	-	576.4 ± 130.4 [^ a b c d]
	Under-15	323.9 ± 101.9 [b d]	284.0 ± 93.1 [d]	349.8 ± 110.7 [§ b d]	242.7 ± 82.4	-	454.0 ± 94.7 [a b c d]

Abbreviations and notes: - indicates data not available; sRPE: session rating of perceived exertion; TL: training load; AU: arbitrary units. Data are mean ± SD. No HR data was recorded during MD. Between-group differences are reported as follows: ^ significantly greater than under-15 ($p < 0.05$); * significantly greater than under-16 ($p < 0.05$); # significantly greater than under-17 ($p < 0.05$); § significantly greater than under-19 ($p < 0.05$). Significant between-day differences ($p < 0.05$) are reported as follows: a significantly higher than MD-5; b significantly higher than MD-4; c significantly higher than MD-3; d significantly higher than MD-2; e significantly higher than MD-1; f significantly higher than MD.

3.4.3 Differences in training loads between congested and non-congested microcycles

A significant interaction was observed between microcycles and training days for duration, total distance, sRPE and sRPE-TL measures ($p < 0.001$). No significant interactions were observed for the other training load measures ($p > 0.05$). On MD-2 duration was higher in non-congested microcycles (67.1 ± 16.6 min) compared to congested microcycles (52.3 ± 12.8 min; $p < 0.001$; *d*: 1.01). On MD-2 total distance was higher in non-congested microcycles (5461.6 ± 1434.4 m) compared to congested microcycles (4876.8 ± 1140.7 m; $p < 0.001$; *d*: 0.46). On MD-2 sRPE was higher non-congested microcycles (3.5 ± 0.7 AU) compared to congested microcycles (3.3 ± 0.9 AU; $p = 0.002$; *d*: 0.27). On MD-2 sRPE-TL was higher in non-congested microcycles (236.5 ± 80.1 AU) compared to congested microcycles (175.7 ± 68.9 AU; $p < 0.001$; *d*: 0.82). On MD-1 total distance was higher in non-congested microcycles (3795.4 ± 926.3 m) compared to congested microcycles (3470.0 ± 887.3 m; $p < 0.001$; *d*: 0.36). No differences between microcycle types were observed on MD ($p > 0.05$; *d*: -0.21 to 0.20). Figure 9 displays the magnitude of differences of external and internal loads between microcycles and training days in under-19.

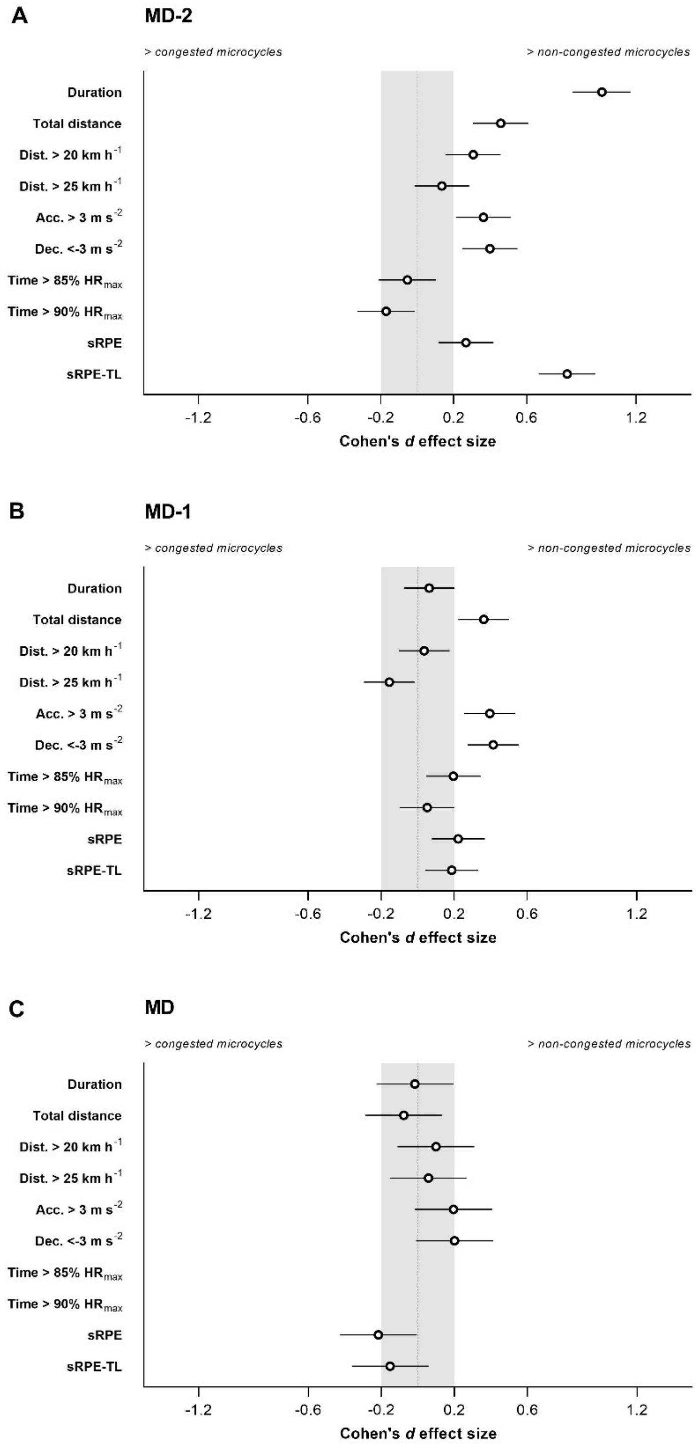

Figure 9. Magnitude of differences (Cohen's d ± 95% CI) of daily training and match loads between congested and non-congested microcycles in under-19 Italian Serie A soccer players (*n* = 25). (A) MD-2, (B) MD-1, (C) MD. A negative effect size indicates a higher training load on congested microcycles, while a positive effect size indicates a higher training load on non-congested microcycles. The grey areas represent the trivial effect size thresholds. Statistically significant differences ($p < 0.05$) are indicated with a *. Abbreviations: CI: confidence intervals; MD: match day; HR: heart rate; sRPE: session rating of perceived exertion; TL: training load.

3.5 Discussion

The purpose of the current study was to quantify external and internal load accrued and experienced by Italian Serie A youth soccer players across a competitive season. This may be the first study that characterises both external and internal loads in a cohort of high-level youth soccer players throughout a full competitive season across multiple academy age groups. We reported weekly training loads and the distribution of daily loads within a microcycle using the most commonly utilised methods of monitoring external (duration and GNSS) and internal (HR and RPE) loads in adolescent athletes (Dudley et al., 2023). Analyses of the results highlighted that weekly accumulated training loads increase progressively, with late-stage academy players training with higher external loads and sRPE-TL compared to their younger counterparts. Periodisation of loading within the competitive microcycle varied across age groups and training days, with marked fluctuations of daily load across the microcycle in the under-19 and under-17 groups as opposed to a less evident loading distribution in the younger groups. Despite variability in loading distribution, common periodisation practices were highlighted with MD-5 and MD-3 sessions emerging as the most physically demanding training days. On MD high-level youth soccer players experienced the highest load of the microcycle, while on the last training session prior to competition (MD-1 or MD-2) the lowest load of the week. Additionally, during congested microcycles under-19 players' training loads decreased on MD-2 for volume and sRPE measures in comparison to typical microcycles, whilst MD load was not affected by the type of the preceding microcycle.

Late-stage academy players, those in the under-19 and under-17 age groups, recorded higher duration, external loads and sRPE-TL compared to their younger counterparts (under-16 and under-15), suggesting a progressive increase in accumulated training loads throughout the academy pathway. Our findings appear to be influenced by both the number of training sessions completed throughout the microcycle (under-19 and under-17: 5 training days vs. under-16 and under-15: 4 training days) and the different match-play durations on MD (under-19 and under-17: 90 min vs. under-16 and under-15: 80 and 70 min, respectively). These weekly external training loads are higher than those sustained by English Premier League and Eredivisie youth academy players for total distance and sprinting distance (i.e., > 25 km·h^{-1}) (Bowen et al., 2017; Hannon, Coleman, et al., 2021; Houtmeyers et al., 2021). Whereas sRPE training loads are lower in our cohort than those reported in Italian national-level and English Premier League youth academy players (Impellizzeri et al., 2006; Wrigley et al., 2012). The progression in weekly loads agrees with previous observations of English Premier League academy soccer players with age group-related increases in external load (Hannon, Coleman, et al., 2021) and sRPE training load (Wrigley et al., 2012). It seems also congruent with training principles and development strategies advised for the long-term athletic development of adolescent athletes (Lloyd and Oliver, 2012). Progressive increases in weekly external loads also align with growth-related changes in body composition (Hannon, Carney, et al., 2020) and physical performance (Murtagh et al., 2018; Parr et al., 2020). Taken together, increases in weekly accumulated training loads across age groups appear to be the result of weekly scheduling (e.g., number of training days), training strategies, and changes in body composition and physical performance associated with growth and maturation.

HR-based measures revealed greater weekly accumulated time spent at high intensities (> 85% and > 90% HR_{max}) in under-15 players compared to the older age groups, highlighting the importance of integrating internal load measures with external load to fully quantify training demands and responses in high-level youth soccer. In contrast with our result, time spent > 90% HR_{max} during training sessions was higher in under-18 players compared to younger counterparts in English Premier League youth soccer players (Wrigley et al., 2012). The reason for the discrepancy between the results of the present study and those of Wrigley might be related to the length of the training observation, as we reported HR-based internal loads during a full competitive season as opposed to two weeks in Wrigley's study (Wrigley et al., 2012). Additionally, these differences may also reflect a shift in the training methodology as players progress through the academy pathway, with a focus on technical development (e.g., technical skills from game situations in small group) in the younger age groups and an approach directed towards match preparation (e.g., phase of play with larger group) in older age groups. As a smaller number of players during soccer-specific training demonstrated greater HR intensity (Hill-Haas et al., 2011), differences in time spent at high HR zones could be partially explained by the design of the drills prescribed throughout the microcycle. Notably, multiple individual (e.g., genetics, age) or contextual (e.g., coaching, competitive level) factors can alter or influence the internal load, having an integrated relationship with the training load construct (Jeffries et al., 2022).

Limited variations in weekly training loads were observed between playing positions, with exceptions for HSR (> 20 $km \cdot h^{-1}$) and SPR (> 25 $km \cdot h^{-1}$) distances. Wide defenders emerged as a distinct position, with unique HSR and sprinting demands compared with all other positions during the competitive week. Similar to our findings, accentuated HSR demands of this tactical role were observed in Spanish La Liga soccer players during the central days of the competitive week (Martín-García et al., 2018), while English Premier League wide midfielders denoted higher HSR distances compared with all the other positions across the microcycle (Malone, et al., 2015). Apart from high-speed running and sprinting distances, weekly external and internal loads were similar across tactical roles. This finding agrees with previous research conducted with youth academy players (Maughan et al., 2021). These limited positional differences may be due to the player's stage of development and the training activities adopted at the club, with position-specific drills limited compared to more role-independent drills. Additionally, these results were also affected by the adoption of absolute speed thresholds (i.e., > 20 km·h^{-1} and > 25 km·h^{-1}) as opposed to the use of relative speed zones, which account for players' individual capabilities (e.g., maximal sprinting speed). In accordance with talent development models, intensified and specialised training (e.g., number of training sessions per week, position-specific training) is generally employed towards the end of the academy development pathway (Ford et al., 2020). However, these results emphasised the unique weekly HSR loads experienced by wide defenders, suggesting position-specific needs in terms of players' preparation and development.

Periodisation of daily training loads varied across age groups and training days, suggesting variations in the distribution of the load within the competitive microcycle. Between-age group differences in loading distribution were also observed in English Premier League and Portuguese national-level academy players during a typical microcycle (Coutinho et al., 2015; Wrigley et al., 2012), emphasising the diversified training approaches employed by coaches guiding different academy squads. Of significance, a tendency towards a more structured and periodised microcycle emerged in the older age groups (under-19 and under-17) as opposed to a comparatively less evident structure in the younger counterparts (under-16 and under-15). For instance, accelerations and deceleration counts remained relatively stable throughout the microcycle in the younger age groups, while marked fluctuations in loads were observed in older age groups across a range of external and internal load measures. These different distributions of load observed throughout the microcycle were likely influenced by the number of training days available per week. These findings agree with previous research conducted with English Premier League academies, which observed a clear periodisation of loading in under-16 and under-18 age groups only (Hannon, Coleman, et al., 2021).

Progression in training methodology may have influenced the training organisation and consequently the periodisation of the load during the microcycle.

Italian Serie A youth soccer players encountered their highest load on match day across the competitive microcycle, spanning from under-15 to under-19, as observed for all external and internal load measures. The comparison of daily loads sustained on MD with all the other training days emphasized that certain volumes (e.g., total distance) and intensities (e.g., sprinting distances and sRPE) are experienced only during match-play. This consistent finding across all age groups in our study aligns with previous research (Hannon, Coleman, et al., 2021; Maughan et al., 2021), reaffirming the pivotal role of soccer match-play as a key component of youth players' development pathway (Morgans et al., 2018). This information regarding the physical demands of the match experienced by youth soccer players can serve as a reference point to effectively plan the microcycle. In contrast, a noticeable reduction in training load was observed in the last training session preceding a competition denoted as MD-1 for the older groups and MD-2 for the younger groups. This unloading practice is consistent with findings in both youth (Coutinho et al., 2015; Hannon et al., 2021; Malone et al., 2015; Maughan et al., 2021) and senior soccer players (Anderson et al., 2016; Kelly et al., 2020; Malone et al., 2015; Martín-García et al., 2018) and represents a common strategy employed by technical staff across different competitive levels and age groups (Owen et al., 2017).

MD-5 and MD-3 training sessions emerged as the most physically demanding days, characterised by higher levels of both external and internal loads when compared to the other days within the microcycle. For instance, in under-17 players training load measures peaked on MD-3, indicating a pattern of alternating high and low load days within the competitive microcycle. This observation agrees with previous studies where the central days of the microcycle such as MD-4 and MD-3 exhibited the highest training loads across a range of measures in both youth (Hannon, Coleman, et al., 2021; Maughan et al., 2021; Szigeti et al., 2022) and senior professional soccer players (Fleming et al., 2023; Kelly et al., 2020; Martín-García et al., 2018; Oliva-Lozano et al., 2022). These central days of the microcycle constitute a pivotal component of the week as they generally provide an opportunity to impose higher training loads due to the distance from the previous and subsequent match. Interestingly, a different distribution of the load emerged with under-19 players, with most of the training load measures peaking on MD-5. This suggests an unloading strategy characterised by higher loads during the earlier phase of the training week and reduced loads in proximity to the match. A similar pattern was also observed in under-18 English Premier League soccer players who adopted a decreasing load strategy for sRPE training load (Wrigley et al., 2012). Remarkably, this finding is in contrast with the weekly load distribution observed in adult professional players, where an MD-5 training session is typically characterised by lower demands compared to the subsequent training sessions of the week (Silva, Bio, et al., 2023). This disparity in load distribution might also be attributed to differences in competition standards and stage of development between the two populations, with coaches of senior players emphasising recovery optimisation and match preparedness compared to a developmental training approach in youth players.

Alongside typical microcycles, under-19 players experienced fixture congestion with the occurrence of congested microcycles. When comparing the common daily loads (MD-2, MD-1 and MD) of the two microcycle structures, higher training loads on MD-2 were observed across various measures in favour of non-congested microcycles. These differences tended to diminish on both MD-1 and MD. Our results demonstrated that congested fixtures could influence training load distribution in under-19 high-level youth soccer players participating in both national and international competitions. The match-play demands of international youth competitions, such as the UEFA Youth League were demonstrated to be higher for total distance and HSR compared to those of national competitions in under-19 Spanish soccer players (Castellano et al., 2020). Strategies for programming training and recovery strategies within the microcycle are widely adopted with senior soccer players, including a structured recovery session on MD+1 (Field et al., 2021) and the programming of a day off on MD+2 (Buchheit et al., 2023). In our analysis of the influence of microcycle type, MD-2 training sessions of congested microcycles occurred 48 h after the match. Therefore, the observed reduction in training volume may be seen as a training load-based strategy to improve recovery while guaranteeing training time for under-19 players. As available training time for preparing for subsequent matches decreases, advanced player management strategies can be adopted to guarantee both training time and facilitate recovery to optimise player readiness in late-stage youth soccer players.

Despite efforts to quantify two key constructs of training load, the current research has several limitations. First, the use of absolute external load data and the lack of individualised speed thresholds have affected the quantification of training load, particularly given the longer session durations and advanced maturation status of players in the older age groups (i.e., greater opportunity to increase training volume and advantages in physical performance capacities). Incorporating individualised speed thresholds and relative measures (e.g., meters per minute) would likely have provided a better characterisation of training demands across developmental stages. Second, as the study involved players from four age groups within a single academy, the generalisability of our findings is limited to other academies due to contextual factors such as training methodologies and socio-cultural aspects. Finally, the study did not include HR data during competitive matches, limiting the understanding of internal load in match contexts. Additionally, the absence of detailed information regarding the training drills across the microcycle constrains the interpretation of how training design influenced the observed load patterns.

3.6 Conclusion

The findings of this research provide new insights into the training loads and periodisation practices experienced by high-level youth soccer players from an Italian Serie A academy. Weekly accumulated training loads exhibited a progressive increase along the player development pathway: late-stage academy players underwent training with higher session frequency and, elevated external and sRPE training load in comparison to their younger counterparts, with minimal variations observed across different playing positions. Weekly accumulated internal loads revealed distinct patterns, with under-15 players displaying higher HR training loads. Late-stage academy players highlighted a more periodised approach by showing marked fluctuations of daily load throughout the microcycle, contrasting with the less pronounced loading distribution evident in the younger counterparts. On MD youth soccer players experienced the highest load of the microcycle, while on the last training session before competition (MD-1 or MD-2), the lowest load of the microcycle. Finally, during congested microcycles, under-19 players' training loads decreased on MD-2 compared to non-congested weekly microcycles, whilst MD load was not affected by the type of the preceding microcycle. As the two constructs of the training load provide distinct insights into the loading strategies adopted across a competitive microcycle, it is essential to monitor both external and internal load in high-level youth soccer players. Finally, practitioners working with academy soccer players should understand the influence of individual factors (e.g., age) and contextual factors (e.g., playing position) and adjust the training plans and their periodisation practices to align with specific goals.

CHAPTER FOUR · RELIABILITY AND SENSITIVITY TO CHANGE OF POST-MATCH PHYSICAL PERFORMANCE MEASURES IN ITALIAN SERIE A YOUTH SOCCER PLAYERS

Peer-reviewed publications from this chapter:

Franceschi, A., Robinson, M. A., Owens, D.J., Brownlee, T., Ferrari Bravo, D., & Enright, K. (2023). Reliability and sensitivity to change of post-match physical performance measures in elite youth soccer players. *Frontiers in Sports and Active Living*, 5, 1173621. https://doi.org/10.3389/fspor.2023.1173621.

Conference presentations from this chapter:

Franceschi, A., Robinson, M. A., Owens, D.J., Brownlee, T., Connolly, D.R., Ferrari Bravo, D., & Enright, K. (2022). The reliability and sensitivity of post-match physical performance measures in elite youth soccer players. *World Congress on Science and Soccer (WCSS), Coimbra, Portugal.* Oral Presentation.

RELIABILITY AND SENSITIVITY TO CHANGE OF POST-MATCH PHYSICAL PERFORMANCE MEASURES IN ITALIAN SERIE A YOUTH SOCCER PLAYERS

4.1 Abstract

Purpose: To effectively monitor post-match changes in physical performance, valid, reliable and practical measures sensitive to change are required. This study aimed to quantify the reliability and sensitivity to change of a range of physical performance measures recorded during an IPC lower-limb muscle test and a CMJ test in Italian Serie A youth soccer players

Methods: Eighteen youth soccer players performed three IPC repetitions per limb and five CMJ trials in four testing sessions. Test-retest reliability was evaluated between two testing sessions seven days apart, using TE of measurement, CV and ICC. Sensitivity to change was assessed on two additional testing sessions performed before and immediately after a soccer match through Hedges' *g* effect size (*g*) and comparisons to TE.

Results: Absolute reliability (CVs) ranged from 1.5 to 8.8%. IPC and CMJ measures demonstrated *moderate* to *excellent* relative reliability (ICCs ranged from 0.70 to 0.98). A wide range of physical performance measures showed significant alterations post-match ($p < 0.05$; *g*: *small* to *moderate*). IPC peak force and torque, CMJ RSI modified, CMJ eccentric forces (mean breaking force, mean deceleration force, peak force, force at zero velocity) and CMJ mean power measures had mean post-match changes greater than their typical variation, demonstrating acceptable sensitivity in detecting performance changes at post-match.

Conclusion: IPC peak force and torque, CMJ reactive strength index modified, CMJ eccentric phase forces and CMJ mean power were found to be both reliable and sensitive to change, and may be appropriate for monitoring post-match physical performance in high-level youth soccer players.

4.2 Introduction

Findings from Study 1 (Chapter 3) have shown that MD represents the greatest stimulus of the weekly microcycle in Italian Serie A youth soccer players. The demands of soccer competition cause metabolic and mechanical fatigue in the days following the match in elite senior and youth soccer players (de Hoyo et al., 2016; Deely et al., 2022; Rampinini et al., 2011). Nowadays, high-level youth soccer players can be exposed to demanding periods of training and competition with limited between-match recovery time (Castellano et al., 2020). The collective stresses accumulated during the competitive season may lead players to a fatigued status, which may impact their preparedness for subsequent competition and increase the risk of non-functional overreaching, injury, and illness (Dupont et al., 2010). This scenario has prompted a greater interest in monitoring players' readiness to train to inform training and recovery periodisation within the weekly microcycle (Thorpe et al., 2017). A myriad of field-based neuromuscular tests is used to indirectly assess individual responses following training or competition (Alba-Jiménez et al., 2022), including isometric tests (e.g., squat, mid-thigh pull, posterior chain) and dynamic measures such as vertical jumps (Norris et al., 2021). Despite the widespread use of these player monitoring tools, evidence regarding the suitability of a comprehensive range of physical performance measures for monitoring post-match responses in a youth soccer population is limited.

A suitable measure used for effectively monitoring post-match response should possess high reproducibility between repeated tests performed under similar conditions (i.e., reliability) (Atkinson and Nevill, 1998; Hopkins, 2000) and should be capable of detecting changes induced by training or a match (i.e., sensitivity to change or responsiveness) (Thorpe et al., 2017). Quantifying both the reliability ("noise") and sensitivity ("signal") of post-match neuromuscular fatigue measures has been recommended to better interpret individual responses in competitive sports (Howarth et al., 2022; Mercer et al., 2022). Additionally, considering the challenges of team-sport settings, tests used for post-match response monitoring tools should be selected according to their relevance to performance and feasibility within the environment (Bishop et al., 2022) . Although numerous studies have reported the reliability of physical performance measures in youth soccer players (Brown et al., 2021; Enright et al., 2018; Fitzpatrick, Hicks, et al., 2019), limited information exists on the examination of reliability in conjunction with the sensitivity following match-play (Rowell et al., 2017).

CMJ test is widely used in high-performance sports to monitor changes in neuromuscular fatigue and subsequent recovery in both team (Beattie et al., 2020) and individual sports (Franceschi et al., 2020). Previous research conducted with youth soccer has mainly investigated the reliability of CMJ outcome measures such as jump height (CVs: 4.3-4.8%; ICCs: 0.83-0.88) (Enright et al., 2018; Fitzpatrick, Hicks, et al., 2019). Despite possessing acceptable levels of reliability, jump height has been demonstrated to have limited sensitivity in response to training loads in youth and senior soccer players (Malone, Murtagh, et al., 2015; Thorpe et al., 2015). Considering the complexity of changes associated with neuromuscular fatigue, measuring ground reaction forces during the CMJ task may offer superior insights for neuromuscular fatigue detection. Previous research has examined the reliability and sensitivity of multiple CMJ measures in other sports, demonstrating their suitability for ongoing monitoring (Gathercole et al., 2015; Heishman et al., 2020; Howarth et al., 2022; Rowell et al., 2017). To inform post-match readiness to training in the context of youth soccer, additional research is required to identify reliable CMJ measures capable of detecting changes in physical performance and neuromuscular function.

In team sports, physical performance monitoring also includes isometric tests, used in combination with vertical jumps (Norris et al., 2021) or as an alternative evaluation (Brownlee, Murtagh, et al., 2018). Predominantly due to the growing HSR demands (T. Allen et al., 2024; Barnes et al., 2014) and the role of fatigue on hamstring strain injuries in soccer (Huygaerts et al., 2020), hamstring strength protocols were introduced as a tool to quantify muscle-specific neuromuscular fatigue during the competitive season. IPC test has been proposed to measure the peak forces generated by the posterior chain musculature at 30° and 90° knee flexion in professional soccer players (McCall et al., 2015). IPC peak forces have been demonstrated to be reliable (Cuthbert et al., 2021; McCall et al., 2015) and sensitive to changes following a competitive match-play (Constantine et al., 2019; McCall et al., 2015). Despite its applicability, peak force does not account for individual differences in limb length and research examining the peak torque generated from the maximal voluntary contraction during the IPC is lacking. Hence, it is important to demonstrate the reliability and sensitivity of IPC peak torque in the specific population to inform practitioners of the potential applications of this test.

Therefore, this study aimed to quantify reliability and examine the sensitivity to change of a range of physical performance measures (isometric, eccentric and concentric) from the IPC lower-limb muscle test and the CMJ test in high-level youth soccer players.

4.3 Methods

4.3.1 Participants

Eighteen high-level youth soccer players (mean ± SD, age: 16.7 ± 0.3 years, body mass: 70.4 ± 4.4 kg, height: 177.5 ± 5.9 cm, predicted adult height: 99.5 ± 0.5 %, maturity offset: 2.6 ± 0.5 years) from a youth academy squad of an in the Italian Serie A team participated in this study. Subjects were classified as highly trained (Tier 3) or elite (Tier 4) (McKay et al., 2022). All players were free from injury and illness and completed on ~10 h of training per week, plus a competitive match. Data collection was part of the club's monitoring system and written informed consent was provided by parents or legal guardians and players. The study received ethics approval from the University Research Ethics Committee (22/SPS/006) and was conducted in accordance with the Declaration of Helsinki.

4.3.2 Experimental design

A schematic representation of the experimental design is displayed in Figure 10. The study was completed during the competitive season and consisted of reliability and sensitivity to change assessments of physical performance measures commonly used for post-match monitoring. The IPC and the CMJ test were used for all test sessions. All players received a minimum of two familiarisation sessions in the weeks before the experimental trials. Reliability assessment consisted of two testing sessions spaced 7 days apart using a test-retest design. Test-retest reliability sessions were conducted following a 72-hour rest period during which players refrained from participating in training and vigorous activity. Sensitivity to change was evaluated using a friendly match-play (2 x 40 minutes, 105 x 68 m, artificial turf) as the intervention. External and internal match load were quantified using GNSS, HR and RPE. Each testing session was conducted at the same time of the day (i.e., early afternoon) to limit the influence of circadian variation and took place following a standardized 5-minute warm-up, except for the session performed immediately after the match. Testing sessions for sensitivity were performed pre- (i.e., 1 hour before the commencement of the match) and immediately post-match (i.e., within 30 minutes of completing the match), including only the players who completed the whole 80-minute duration. Players were instructed to maintain their normal dietary intake throughout the experimental period. Eighteen players completed the tests for reliability, while thirteen players completed the entire match and performed the tests for the assessment of sensitivity.

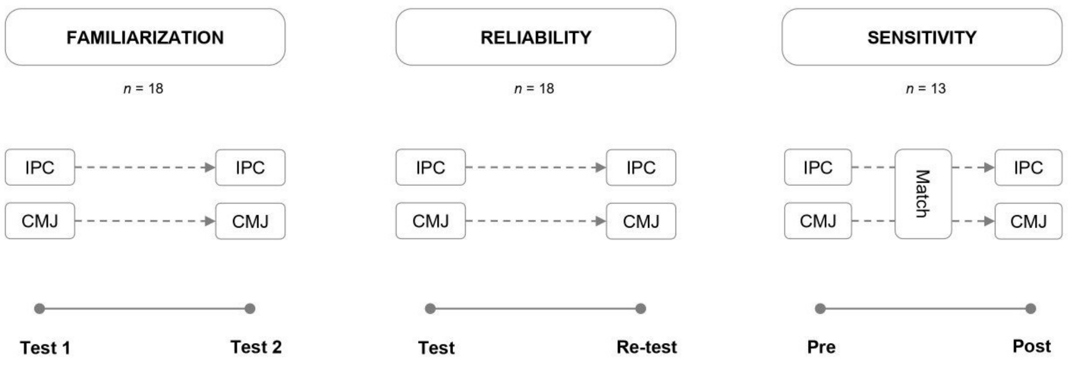

Figure 10. A schematic representation of the experimental design. Following the familiarisation sessions, reliability was evaluated using a test-retest design seven days apart. Sensitivity to change was evaluated following a match with testing sessions performed before and immediately after. Abbreviations: IPC: isometric posterior-chain; CMJ: countermovement jump.

4.3.3 Experimental procedures

4.3.3.1 Quantification of external and internal match load

External match load was quantified using GNSS technology (Apex Pro Series, 10Hz GNSS, STATSports, Newry, Northern Ireland), in accordance with the procedures outlined in Study 1 (Chapter 3). Internal match load was quantified using HR sensors (Polar H10, Polar, Kempele, Finland) and sRPE, in accordance with the procedures outlined in Study 1 (Chapter 3). In addition to the external and internal load measures outlined in the previous chapter, in the current study, maximal speed (km·h^{-1}), HR_{avg} (b·min^{-1}) and HR_{peak} (b·min^{-1}) were also reported to describe match demands.

4.3.3.2 Isometric posterior chain (IPC) lower-limb muscle test

Players performed a 3 s maximal contraction with ~30 s of rest between trials into a force platform (ForceDecks Dual Force Plate System FD lite, VALD Performance, Newstead, Australia), similar to methods previously reported (McCall et al., 2015). ForceDecks software (VALD Performance, Newstead, Australia) was used to analyse and calculate the selected measures with a sampling rate of 1000 Hz. The force plates were zeroed before testing each player. Before each testing trial, players laid in a supine position with their knee at 90° and 30° of flexion, with their calcaneus on the centre of the force platform and the non-test leg extended alongside a box at an appropriate height for each participant (i.e., lower shank to be parallel to the floor) as reported in Figure 11. The height of the box was adjusted for each player by using boxes of different heights to ensure positioning at 90° and 30° of flexion during testing. All testing sessions were supervised by the same tester, who ensured the correct positioning of both legs and applied pressure to the contralateral hip to maintain participant posture (i.e., keeping the buttocks, hips and head on the floor). The selected knee flexion angles were confirmed using a goniometer (FysioSupplies, Groningen, The Netherlands) for both legs. Players were instructed to push their heel maximally, down into the force platform, and were required to repeat trials if a measurement error in posture was observed. Three trials on each limb and each position (90° and 30° of flexion) were executed with ~30 s rest between trials. Peak force was quantified for each trial. Moment arm length was measured from the joint axis of rotation to the point of application of the force and peak torque was calculated by multiplying the peak force by the length of the moment arm. Peak force dominant leg (N), peak force non-dominant leg (N), peak torque dominant leg (Nm), peak torque non-dominant leg (Nm) were analysed.

Figure 11. Representation of participant positioning for the isometric posterior chain (IPC) lower-limb muscle test at 90° knee flexion used to quantify posterior chain muscle strength in response to match-play.

4.3.3.3 Countermovement jump (CMJ) test

Players performed five CMJ trials with ~20 s rest between trials on a force platform (ForceDecks Dual Force Plate System FD lite, VALD Performance, Newstead, Australia), using methods previously described (Barillas et al., 2021; McMahon et al., 2018). ForceDecks software (VALD Performance, Newstead, Australia) was used to analyse and calculate the selected measures with a sampling rate of 1000 Hz. The force plates were zeroed before testing each player. Before the commencement of each jump, players were advised to stand upright, with their hands on their hips and their feet hip-shoulder width apart. Once the starting position was adopted, players remained as still as possible for at least 3 s before the start of the trial for the collection of the player's body weight. During the countermovement players were instructed to rapidly squat to their preferred depth and immediately jump as high as possible and as quick as possible, with no knee or hip flexion during the flight phase, maintaining their hands on the hips. Finally, players were encouraged to "absorb" the landing by flexing at the hips, knees, and ankles after impacting the force platform. The CMJ measures described in Table 12 were analysed from the force-time curve and used for subsequent statistical analysis. These measures were selected to describe both outcome and movement strategy measures (Gathercole et al., 2015) and agree with previous works completed in other high-performance environments (Howarth et al., 2022; Mercer et al., 2022).

Table 12. Definition of countermovement jump (CMJ) measures analysed from the force-time curve.

CMJ measure	**Definition**
Jump height (cm)	Maximal jump height computed using impulse-momentum method.
Contraction time (ms)	Duration from jump initiation to take-off.
RSI-modified ($m \cdot s^{-1}$)	Jump height divided by contraction time.
Concentric duration (ms)	Duration of the concentric phase (time from zero velocity to take-off).
Concentric peak force (N)	Greatest force achieved during the concentric phase.
Concentric peak velocity ($m \cdot s^{-1}$)	Greatest velocity achieved during the concentric phase.
Concentric mean power (W)	Mean power during the concentric phase.

CMJ measure	Definition
Peak power (W)	Maximum power achieved during the concentric phase.
Eccentric duration (ms)	Duration of the eccentric phase.
Eccentric braking phase duration (s)	Period from the minimum force to the start of the concentric phase.
Eccentric deceleration phase duration (s)	Time period from maximum negative velocity to zero velocity at the end of the eccentric phase.
Eccentric mean braking force (N)	Mean force during the eccentric breaking phase from minimum force to zero velocity at the end of the eccentric phase.
Eccentric mean deceleration force (N)	Mean force during the eccentric breaking phase from minimum force to zero velocity.
Eccentric peak force (N)	Greatest force achieved during the eccentric phase.
Force at zero velocity (N)	Force exerted at concentric onset.
Eccentric mean power (W)	Mean power during the eccentric phase from start of movement to zero velocity.

Abbreviations and notes: cm: centimeter; ms: millisecond; N: Newton; W: Watt. Measures definitions according to ForceDecks software (VALD Performance, Newstead, Australia).

4.3.4 Statistical analysis

Descriptive data are reported as mean ± SD or as mean (95% CI). The assumption of normality was assessed using a Shapiro-Wilk test. Differences between the two reliability test sessions and between pre- and post-match for sensitivity were tested for each measure using a paired t-test with alpha ≤ 0.05. For the reliability analysis, the TE of measurement and the CV were reported as measures of absolute reliability, while the $ICC_{3,1}$ (2-way mixed-effects) with 95% CIs was reported as a measure of relative reliability (Hopkins, 2000; Weir, 2005). ICCs were interpreted in line with the lower 95% CI boundary based on previous recommendations: *excellent* (> 0.90), *good* (0.75-0.90), *moderate* (0.50-0.75) and *poor* (< 0.50) (Koo and Li, 2016). For the sensitivity to change analysis, changes were evaluated against TE values to assess each measure's ability to detect meaningful post-match variations. If post-match changes were greater than 1.5 times the TE in the test, changes were deemed as sensitive to change (i.e., responsive) (Hopkins, 2000). In addition, Hedges' *g* effect sizes (*g*) were calculated to assess the magnitude of differences and were interpreted as follows: *trivial* (< 0.20), *small* (0.20-0.59), *moderate* (0.60-1.19), *large* (1.20-1.99) and *very large* (> 2.0) (Hopkins et al., 2009). The statistical analysis was performed using SPSS statistical software (IBM SPSS version 26, Chicago, IL, USA).

4.4 Results

4.4.1 Match load characteristics

Match external load (mean ± SD) was characterised by 10091.4 ± 834.1 m of total distance covered, with 720.3 ± 203.2 m of distance covered > 20 $km \cdot h^{-1}$ and 159.0 ± 90.8 m of distance covered > 25 $km \cdot h^{-1}$. The number of accelerations (> 3 $m \cdot s^{-2}$) and decelerations (< -3 $m \cdot s^{-2}$) performed during match-play were 60.1 ± 13.9 and 69.4 ± 15.3, respectively. Match internal load (mean ± SD) was characterised by 165.8 ± 10.9 $b \cdot min^{-1}$ of HR_{avg}, with HR_{peak} of 197.1 ± 5.7 $b \cdot min^{-1}$. On average, players spent 29.9 ± 16.4 minutes > 85% HR_{max} and 9.2 ± 6.3 minutes > 90% HR_{max}. sRPE was 5.8 ± 1.0 AU.

4.4.2 Reliability of physical performance measures

Absolute reliability (CVs) ranged from 1.5 to 8.8%. Relative reliability (ICCs) ranged from *good* to *excellent* for IPC measures (ICC ≥ 0.93; 95% CI: 0.79 to 0.99), whilst it ranged from *moderate* to *excellent* for the CMJ measures (ICC ≥ 0.85; 95% CI: 0.61 to 0.99), except for eccentric braking phase duration and eccentric deceleration phase duration (ICC: 0.70 and 0.77; 95% CI: 0.37 to 0.88, and 0.51 to 0.91, respectively). Full reliability results are shown in Table 13.

4.4.3 Acute post-match changes and sensitivity to change of physical performance measures

A wide range of IPC and CMJ measures showed significant acute alterations at post-match ($p < 0.05$). The magnitude of change at post-match was *moderate* (Δ: from -10.0 to – 10.6%; *g*: from -0.58 to -0.53) for IPC measures, while it ranged from *trivial* to *moderate* (Δ: from -0.8 to -10.7%; *g*: from -0.78 to 0.65) for CMJ measures. Eleven measures (IPC peak force and torque dominant leg, IPC peak force and torque non-dominant leg, CMJ RSI-modified, CMJ eccentric and concentric mean power, and CMJ eccentric forces, including mean braking force, mean deceleration force, peak force and force at zero velocity) displayed mean changes greater than typical variation (i.e., 1.5 times the TE). Conversely, the other remaining CMJ measures (jump height, contraction time, concentric peak force, eccentric duration, eccentric braking phase duration, eccentric deceleration phase duration, concentric duration, concentric peak velocity and peak power) displayed mean changes lower than their corresponding typical variation. Full results on the sensitivity to change analysis reporting acute changes following match-play are reported in Table 14, Figure 12 and Figure 13.

Table 13. Reliability of physical performance measures derived from the isometric posterior chain (IPC) and the countermovement jump (CMJ) test in Italian Serie A youth soccer players (n = 18).

	Test	Re-test	Test vs Re-test				
			p-value	Δ (95% CI)	TE	CV	ICC (95% CI)
Isometric posterior-chain test							
Peak force dominant leg at 90° knee flexion (N)	317.2 ± 54.5	319.9 ± 57.1	0.406	-2.7 (-9.6; 4.1)	9.7	3.0	0.97 (0.92; 0.99)
Peak force non-dominant leg at 90° knee flexion (N)	289.9 ± 49.2	296.5 ± 47.2	0.123	-6.6 (-15.3; 2.0)	12.3	4.2	0.93 (0.84; 0.97)
Peak torque dominant leg at 90° knee flexion (Nm)	128.3 ± 23.3	129.6 ± 24.1	0.307	-1.3 (-3.9; 1.3)	3.7	2.9	0.98 (0.93; 0.99)
Peak torque non-dominant leg at 90° knee flexion (Nm)	117.4 ± 21.7	120.4 ± 20.6	0.081	-3.0 (-6.3; 0.4)	4.8	4.0	0.95 (0.89; 0.98)
Peak force dominant leg at 30° knee flexion (N)	299.2 ± 49.1	299.4 ± 45.8	0.966	-0.2 (-9.8; 9.4)	13.6	4.6	0.92 (0.79; 0.97)
Peak force non-dominant leg at 30° knee flexion (N)	268.9 ± 47.2	275.1 ± 45.6	0.174	-6.2 (-15.3; 3.0)	13.0	4.8	0.92 (0.80; 0.97)
Peak torque dominant leg at 30° knee flexion (Nm)	121.0 ± 21.1	121.1 ± 19.6	0.965	-0.1 (-4.0; 3.8)	5.6	4.6	0.93 (0.81; 0.97)
Peak torque non-dominant leg at 30° knee flexion (Nm)	108.8 ± 19.7	111.2 ± 20.1	0.155	-2.7 (-6.4; 1.1)	5.4	4.9	0.93 (0.82; 0.97)
Countermovement jump test							
Jump height (cm)	37.0 ± 3.9	36.8 ± 3.7	0.437	0.2 (-0.4; 0.9)	1.0	2.6	0.93 (0.83; 0.97)
Contraction time (ms)	713.6 ± 73.1	719.6 ± 84.6	0.570	-6.0 (-27.7; 15.8)	30.9	4.3	0.85 (0.64; 0.94)
RSI-modified ($m \cdot s^{-1}$)	0.53 ± 0.08	0.52 ± 0.09	0.296	0.01 (-0.01; 0.03)	0.02	4.0	0.93 (0.83; 0.97)
Concentric duration (ms)	260.9 ± 28.7	262.4 ± 34.7	0.702	-1.5 (-9.9; 6.8)	11.9	4.5	0.86 (0.66; 0.95)
Concentric peak force (N)	1757.4 ± 204.1	1749.7 ± 238.5	0.693	7.7 (-32.8; 48.2)	57.6	3.3	0.93 (0.83; 0.97)
Concentric peak velocity ($m \cdot s^{-1}$)	2.77 ± 0.13	2.77 ± 0.14	0.578	0.01 (-0.02; 0.04)	0.04	1.5	0.91 (0.77; 0.96)
Concentric mean power (W)	2087.5 ± 350.0	2083.6 ± 398.0	0.847	3.8 (-37.4; 45.1)	58.6	2.8	0.97 (0.94; 0.99)
Peak power (W)	3702.6 ± 651.1	3723.0 ± 682.8	0.524	-20.4 (-86.5; 45.7)	94.0	2.5	0.98 (0.95; 0.99)
Eccentric duration (ms)	455.2 ± 48.6	457.1 ± 54.8	0.764	-2.0 (-15.6; 11.6)	19.3	4.2	0.86 (0.67; 0.95)
Eccentric braking phase duration (s)	0.28 ± 0.44	0.28 ± 0.43	0.875	0.00 (-0.01; 0.02)	0.02	7.6	0.77 (0.51; 0.91)
Eccentric deceleration phase duration (s)	0.16 ± 0.27	0.16 ± 0.28	0.584	0.00 (-0.01; 0.01)	0.01	8.8	0.70 (0.37; 0.88)
Eccentric mean braking force (N)	896.8 ± 91.5	900.5 ± 95.2	0.614	-3.7 (-19.0; 11.6)	21.8	2.4	0.95 (0.86; 0.98)
Eccentric mean deceleration force (N)	1348.5 ± 142.8	1335.5 ± 167.1	0.440	13.0 (-21.7; 47.7)	49.4	3.7	0.90 (0.75; 0.96)
Eccentric peak force (N)	1739.9 ± 192.6	1737.2 ± 230.5	0.926	-2.7 (-42.9; 48.2)	64.8	3.7	0.91 (0.77; 0.96)

	Test	Re-test	Test vs Re-test				
			p-value	**Δ (95% CI)**	**TE**	**CV**	**ICC (95% CI)**
Force at zero velocity (N)	1729.5 ± 194.6	1725.5 ± 236.4	0.903	4.0 (-42.6; 50.6)	66.3	3.8	0.91 (0.77; 0.97)
Eccentric mean power (W)	498.1 ± 76.6	498.8 ± 61.6	0.860	-0.7 (-16.8; 15.4)	22.8	4.6	0.89 (0.73; 0.96)

Abbreviations and notes: IPC: isometric posterior-chain; CMJ: countermovement jump; SD: standard deviation; Δ: mean change; CI: confidence interval; TE: typical error of measurement; CV: coefficient of variation; ICC: intraclass correlation coefficient, RSI: reactive strength index. Data are reported as mean ± SD or as mean (95% CIs).

Table 14. Acute post-match changes and sensitivity to change of physical performance measures from the isometric posterior chain (IPC) and the countermovement jump (CMJ) test in Italian Serie A youth soccer players ($n = 13$).

	Pre-match	Post-match	Pre-match vs Post-match			
			p-value	Δ (95% CI)	TE x 1.5	Hedges' *g*
Isometric posterior-chain test						
Peak force dominant leg at 90° knee flexion (N)	302.2 ± 46.9	272.6 ± 52.0 ^{*M}	0.002	-29.6 (-46.2; -12.9)	14.5	-0.58
Peak force non-dominant leg at 90° knee flexion (N)	289.1 ± 42.6	259.5 ± 54.0 ^{*M}	0.005	-29.6 (-47.9; -11.2)	18.4	-0.59
Peak torque dominant leg at 90° knee flexion (Nm)	120.7 ± 19.9	109.1 ± 22.6 ^{*M}	0.003	-11.6 (-5.0; -18.2)	5.5	-0.53
Peak torque non-dominant leg at 90° knee flexion (Nm)	115.5 ± 18.8	103.8 ± 23.5 ^{*M}	0.005	-11.7 (-4.3; -19.1)	7.2	-0.53
Countermovement jump test						
Jump height (cm)	39.5 ± 4.6	38.4 ± 5.0 ^{*S}	0.005	-1.1 (-1.9; -0.4)	1.4	-0.22
Contraction time (ms)	692.1 ± 76.7	720.9 ± 89.1 ^{S}	0.236	28.8 (-21.5; 79.2)	46.4	0.34
RSI-modified ($m \cdot s^{-1}$)	0.58 ± 0.11	0.55 ± 0.11 ^{*S}	0.013	-0.03 (-0.06; 0.01)	0.03	-0.26
Concentric duration (ms)	244.2 ± 31.6	245.9 ± 30.6	0.756	1.7 (-9.8; 13.1)	17.8	0.05
Concentric peak force (N)	1843.2 ± 185.1	1765.7 ± 181.5 ^{*S}	0.008	-77.5 (-130.5; -24.5)	86.3	-0.41
Concentric peak velocity ($m \cdot s^{-1}$)	2.86 ± 0.15	2.82 ± 0.17 ^{S}	0.051	-0.04 (-0.07; 0.00)	0.06	-0.24
Concentric mean power (W)	2239.3 ± 315.4	2141.2 ± 290.1 ^{*S}	0.000	-98.1 (-142.2; -54.0)	87.9	-0.31
Peak power (W)	3981.9 ± 523.7	3943.9 ± 483	0.282	-38.0 (-111.6; 35.6)	141.0	-0.07
Eccentric duration (ms)	447.8 ± 56.0	475.1 ± 66.2 ^{S}	0.173	27.2 (-13.7; 68.2)	29.0	0.43
Eccentric braking phase duration (s)	0.27 ± 0.05	0.29 ± 0.05 ^{S}	0.212	0.02 (-0.01; 0.05)	0.03	0.35
Eccentric deceleration phase duration (s)	0.15 ± 0.03	0.17 ± 0.03 ^{M}	0.089	0.02 (-0.00; 0.04)	0.02	0.65
Eccentric mean braking force (N)	888.6 ± 77.5	850.3 ± 75.1 ^{*S}	0.025	-38.3 (71.0; -5.6)	32.7	-0.49
Eccentric mean deceleration force (N)	1344.7 ± 151.1	1229.9 ± 133.2 ^{*M}	0.002	-114.8 (-178.7; -50.9)	74.0	-0.78
Eccentric peak force (N)	1769.8 ± 213.1	1621.2 ± 194.7 ^{*M}	0.000	-148.6 (-205.4; - 91.8)	97.2	-0.71
Force at zero velocity (N)	1761 ± 215.2	1613.6 ± 194.4 ^{*M}	0.000	-147.4 (-204.9; -89.8)	99.4	-0.70
Eccentric mean power (W)	487.5 ± 76.7	442.1 ± 65.9 ^{*M}	0.005	-45.5 (-74.0; -16.9)	34.3	-0.61

Abbreviations and notes: SD: standard deviation; Δ: mean change; CI: confidence interval; TE: typical error of measurement; CV: coefficient of variation; RSI: reactive strength index. Data are reported as mean ± SD or as mean (95% CIs).* significant change from Pre-match ($p < 0.05$). S: small; M: moderate; L: large effect sizes compared with Pre. Trivial effect sizes are not reported. Sensitivity to change: absolute change at post-match > TE x 1.5 (Hopkins, 2000).

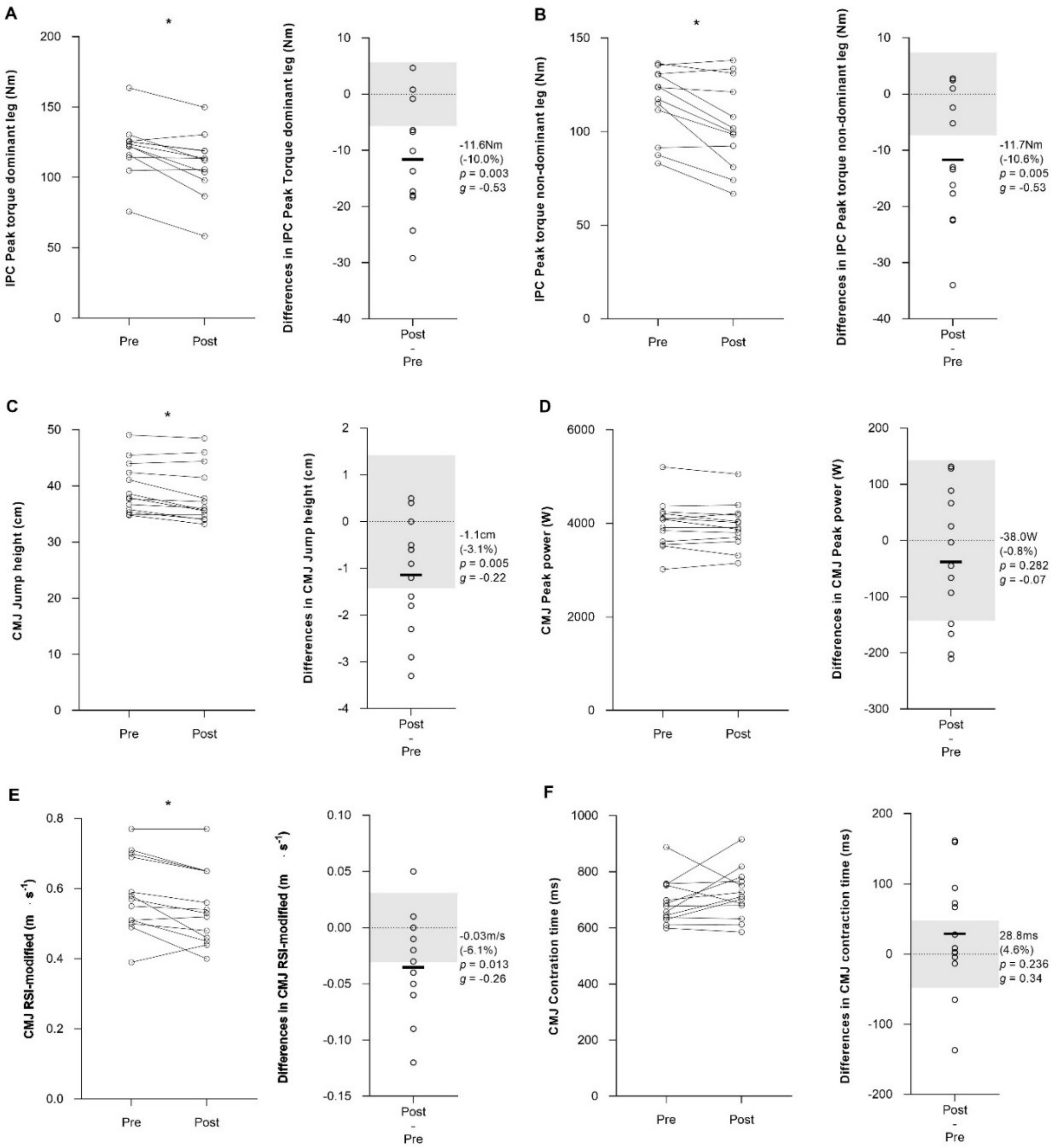

Figure 12. Post-match individual changes, mean difference (absolute and relative), p-value and Hedges' g effect size of physical performance measures in Italian Serie A youth soccer players (*n* = 13). (A) IPC peak torque dominant leg at 90° knee flexion, (B) IPC peak torque non-dominant leg at 90° knee flexion, (C) CMJ jump height, (D) CMJ peak power, (E) CMJ RSI-modified, (F) CMJ contraction time. Light grey boxes represent the 1.5 times the TE of each measure to identify the players who exhibited changes greater than the typical variance in the IPC and CMJ tests. * indicates a significant mean difference at post-match ($p \leq 0.05$). Abbreviations: Pre: Pre-match; Post: Post-match; IPC: isometric posterior chain; CMJ: countermovement jump; RSI: reactive strength index.

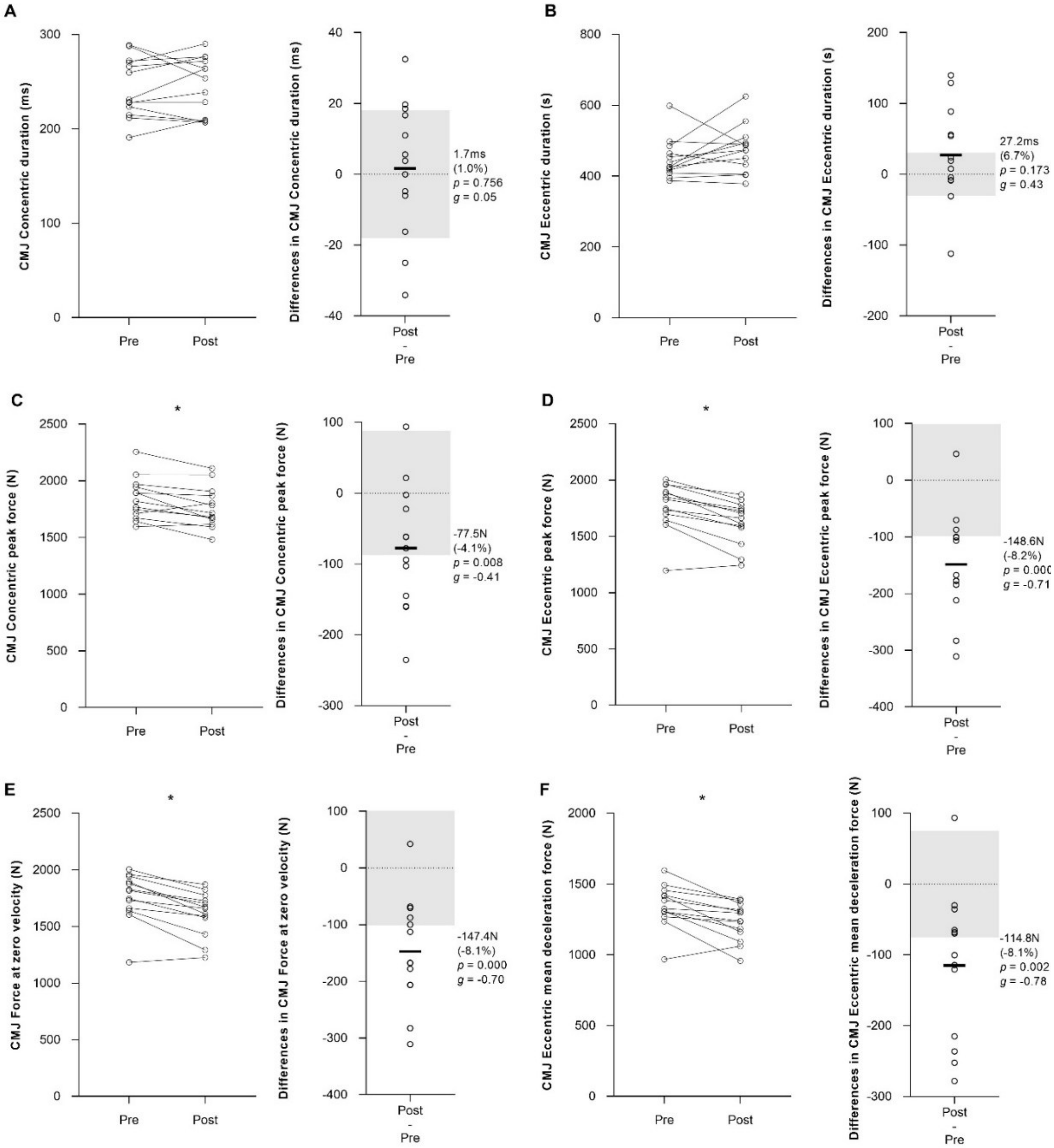

Figure 13. Post-match individual changes, mean difference (absolute and relative), p-value and Hedges' g effect size of physical performance measures in Italian Serie A youth soccer players (*n* = 13). (A) CMJ concentric duration, (B) CMJ eccentric duration, (C) concentric peak force, (D) eccentric peak force, (E) force at zero velocity, (F) eccentric mean deceleration force. Light grey boxes represent the 1.5 times the TE of each measure to identify the players who exhibited changes greater than the typical variance in the IPC and CMJ tests. * indicates a significant mean difference at post-match ($p \leq 0.05$). Pre: Pre-match; Post: Post-match; CMJ: countermovement jump; RSI: reactive strength index.

4.5 Discussion

This study aimed to quantify the reliability and examine the sensitivity to change of a range of physical performance measures in a group of Italian Serie A youth soccer players. The main results from this study were: 1) IPC and CMJ neuromuscular measures demonstrated a high level of absolute reliability (CVs from 1.5 to 8.8%) and *moderate* to *excellent* level of relative reliability (ICCs from 0.70 to 0.98); 2) IPC peak force and torque, CMJ RSI-modified, CMJ eccentric forces (mean breaking force, mean deceleration force, peak force, force at zero velocity) and CMJ mean power measures showed significant reductions of *small* to *moderate* effect and greater sensitivity by displaying mean post-match changes greater than their typical variation; and 3) CMJ concentric phase measures and jump height showed *trivial* to *small* alterations by displaying mean post-match changes similar to their typical variation in youth soccer players. These findings suggest that IPC peak force and torque, CMJ RSI-modified, CMJ eccentric phase forces and CMJ mean power may be considered more suitable measures for monitoring players' post-match physical performance in high-level youth soccer players.

IPC lower-limb muscle peak force and torque were demonstrated to be reliable for both dominant and non-dominant leg at 90° and 30° knee flexion. There is no direct comparative reliability data reporting peak torque recorded during the IPC test in youth soccer players. However, our findings are consistent with previous literature on professional soccer players which have reported better repeatability at 90° knee flexion compared to 30° knee flexion position (CV: 4.3 and 6.3%, respectively) (McCall et al., 2015). When comparing our reliability data with that of peak force from previous studies (Cuthbert et al., 2021; McCall et al., 2015), it appears that peak torque has greater absolute and relative reliability (CV < 5%; ICC > 0.90) compared to peak force. One important consideration in reporting peak torque rather than peak force data is that it accounts for individual differences in limb length (Baltzopoulos et al., 2012). Practitioners may therefore consider the IPC as a reliable neuromuscular performance test for monitoring post-match response in youth soccer players.

Most of the CMJ measures from the eccentric and concentric phases demonstrated a high level of absolute and relative reliability in our sample. Previous literature in youth soccer quantified the reliability of jump height only (Enright et al., 2018; Fitzpatrick, Hicks, et al., 2019). Our results showed greater absolute (CV: 2.6%) and relative (ICC: 0.93) reliability for jump height. These differences may be a result of the different technologies used between studies (force platform vs. contact mat). Additionally, we quantified the reliability of a wide range of eccentric and concentric phase measures which may provide deeper insights related to both jump outcome and movement strategy (Gathercole et al., 2015). Our CVs are lower than in previous literature that used a similar methodology (Gathercole et al., 2015; Heishman et al., 2020), which may be due to the differences in testing protocols, environment and population. However, CVs (1.7-11.0%) and ICCs (0.70-0.99) were similar to those of a recent study conducted with professional rugby union players, which quantified the reliability of 86 CMJ measures (Howarth et al., 2022). Interestingly, CMJ concentric phase and jump outcome measures (e.g., jump height and peak power) displayed better reliability statistics when compared with time-based CMJ measures, suggesting greater variability of jump strategy measures. Despite this trend, several jump strategy measures (e.g., eccentric duration, force at zero velocity, RSI-modified) demonstrated an acceptable level of reliability and therefore may be valuable for monitoring post-match physical performance. In this light, this study uniquely provides reliability reference data of a comprehensive range of CMJ measures within a professional youth soccer academy environment.

Determining the inclusion or exclusion of neuromuscular performance measures based on reliability alone may lead to erroneous conclusions. A novel aspect of the present study was to establish the level of reliability in conjunction with the sensitivity to change for effectively monitoring post-match neuromuscular performance in youth soccer players. The significant reductions in IPC measures at 90° dominant and non-dominant leg (-10% at post-match) suggest that soccer match-play results in acute alterations of hamstring neuromuscular function in youth soccer players, in agreement with previous literature (Constantine et al., 2019). However, the magnitude of post-match decline recorded in our research is smaller compared to previous studies (-15% at post-match) that assess hamstring neuromuscular function following a 90-minute competitive match (McCall et al., 2015; Wollin et al., 2017). Despite the difference in the magnitude of change, IPC peak force and torque were demonstrated to be sensitive to change by detecting mean post-match changes greater than the typical variation. In the dominant and non-dominant leg, 10 and 8 of 13 players, respectively, exhibited changes exceeding the lower bound of the typical variation, suggesting a high probability of detecting a meaningful post-match reduction. Conversely, no players demonstrated post-match changes exceeding the upper bound of the typical variation in the IPC measures. These moderate declines in force and torque (-10% at post-match) likely reflect the high eccentric involvement of the hamstring muscles during repeated sprinting, which could alter muscle function and lead to exercise-induced muscle damage in the days following the competition (Owens et al., 2019). Considering that neuromuscular fatigue is one potential hamstring strain injury risk factor, our findings support the use of IPC test to indirectly monitor post-match neuromuscular function in the youth soccer population.

A key finding of the present study was that CMJ eccentric phase measures had greater post-match changes compared with CMJ jump height and concentric phase measures. In line with previous studies on elite youth soccer players (de Hoyo et al., 2016; Romagnoli et al., 2016), jump height showed a significant reduction but demonstrated limited sensitivity by displaying post-match changes similar to the typical variation, with only 5 of 13 players exhibiting changes greater than the typical variation (i.e., all showing reduced jump height). It has been reported that jump height may not be sensitive to training and match loads in elite soccer players (Malone, Murtagh, et al., 2015; Thorpe, Strudwick, et al., 2017). Therefore, CMJ time-based measures may hold superior sensitivity to change following official matches and fatiguing intermittent protocol (Gathercole et al., 2015; Rowell et al., 2017). Our analysis of CMJ measures revealed that RSI-modified, eccentric forces and mean power demonstrated an acceptable level of sensitivity, with mean changes greater than the typical variation (i.e., 1.5 x TE). Across these measures, 7 to 9 of 13 players showed post-match changes beyond the bounds of the typical variation, predominantly exceeding the lower bound, indicating a reduction in neuromuscular performance. Gathercole and colleagues demonstrated a similar level of sensitivity to alternative CMJ measures in a group of collegiate team sports athletes, showing acute changes greater than their typical variation and confidence intervals (Gathercole et al., 2015). The observed responses suggest that high-level youth soccer players may experience acute reductions in neuromuscular function, which have been attributed to a reduced central drive and metabolic disturbances that impair excitation-contraction coupling and reduce stretch-reflex sensitivity, muscle stiffness, and force production (Komi, 2000). The greater magnitude of change of CMJ eccentric forces may be associated with the frequent, intense acceleration and deceleration actions performed during the match (Hader et al., 2019). Overall, the acute changes in time-based measures may reflect the altered SSC function and movement strategy employed over the downward phase of the CMJ (Komi, 2000). The current findings demonstrate CMJ eccentric force measures may reveal alterations in jump strategy which underline the presence of altered SSC and neuromuscular fatigue following match-play. As time, force and velocity used to perform soccer-specific actions are considered fundamental for success in professional soccer, these alterations in CMJ eccentric force measures may have relevant implications in monitoring players' physical performance.

This study provides practitioners with a range of physical performance measures suitable for indirectly monitoring players' post-match performance capacity in youth soccer players. It is important to highlight the main limitations inherent in this work. Despite the ecological validity of the study, sensitivity to change was evaluated using a single match of a shorter duration compared to the official match (i.e., 80 vs 90 minutes), with match demands inherently variable between players. Thus, match demands might have influenced the magnitude of alterations post-match. Another limitation of our study is the lack of investigation into the association between changes in physical performance and match demands. Examining this association may provide valuable insights for predicting post-match acute and residual fatigue (Hader et al., 2019). In addition, a comprehensive analysis of the force-time curve of the IPC test was not performed. Although peak force and torque measures demonstrated acceptable measurement properties, examining how force was expressed over time (e.g., force at early time points) may provide insights for performance monitoring.

4.6 Conclusion

The present study demonstrated that IPC and CMJ tests are reliable and sensitive tools for monitoring post-match changes in physical performance of elite youth soccer players. Our findings indicated that IPC peak force and torque, CMJ RSI-modified, CMJ eccentric measures (mean braking force, mean deceleration force, peak force and force at zero velocity) and CMJ mean power may be more appropriate to detect physical performance changes following match-play. Conversely, typically reported CMJ measures such as jump height and peak power showed limited sensitivity in detecting post-match changes. Performance practitioners could therefore consider including such measures for monitoring post-match physical performance. This might allow coaches and scientists to optimise the scheduling of training across the microcycle, facilitating recovery whilst also optimising the physical conditioning of players.

CHAPTER FIVE · POST-MATCH FATIGUE AND RECOVERY RESPONSES IN ITALIAN SERIE A YOUTH SOCCER PLAYERS: EFFECTS OF MANIPULATING TRAINING VOLUME 48 HOURS AFTER A MATCH

Peer-reviewed publications from this chapter:

Franceschi, A., Robinson, M. A., Owens, D. J., Brownlee, T., Connolly, D. R., Coutts, A. J., Ferrari Bravo, D., & Enright, K. (2025). Post-Match Recovery Responses in Italian Serie A Youth Soccer Players: Effects of Manipulating Training Load 48 h After Match Play. *European Journal of Sport Science*, 25(5), e12297. https://doi.org/10.1002/ejsc.12297.

Conference presentations from this chapter:

Franceschi, A., Robinson, M. A., Owens, D.J., Brownlee, T., Connolly, D.R., Ferrari Bravo, D., & Enright, K. (2023). Manipulating training load 48 hours after a match: effects on recovery responses in elite youth soccer players. *European Congress of Sport Science (ECSS), Paris, France.* Poster Presentation.

Franceschi, A., Robinson, M. A., Owens, D. J., Brownlee, T., Connolly, D. R., Coutts, A.J., Ferrari Bravo, D., & Enright, K. (2025). Training load manipulation 48 hours after match play influences post-match recovery responses in Italian Serie A youth soccer players. *World Congress on Science and Soccer (WCSS), Glasgow, United Kingdom.* Oral Presentation.

POST-MATCH FATIGUE AND RECOVERY RESPONSES IN ITALIAN SERIE A YOUTH SOCCER PLAYERS: EFFECTS OF MANIPULATING TRAINING VOLUME 48 HOURS AFTER A MATCH

5.1 Abstract

Purpose: Recovery is a multifaceted process that involves various restorative mechanisms over time. Understanding fatigue and recovery responses following match-play and training sessions is thus important to inform training. This study described the time course of recovery following match-play and examined the effects of manipulating training volume 48 h post-match in Italian Serie A youth soccer players.

Methods: Forty-eight high-level youth soccer players were assessed using CMJ test, IPC lower-limb muscle test, muscle soreness and fatigue (via VAS) before (pre) and after (0.5 h post, 48 h post, 72 h post) an 80-minute match. At 48 h post-match, players were randomly assigned to a complete training (CT; $n = 26$) or a reduced training (RT; $n = 22$) group. Differences in recovery responses were assessed using analysis of variance (ANOVA) between time points and training groups. Training load differences were evaluated between groups on MD and two days after the match (MD+2) using independent t-tests.

Results: Recovery measures were impaired immediately post-match ($p < 0.05$). IPC and muscle soreness demonstrated incomplete recovery 48 h post-match ($p < 0.05$), while CMJ and fatigue returned to baseline ($p > 0.05$). Training load on MD did not differ between groups ($p > 0.05$), while the CT group had higher loads on MD+2 compared to RT ($p < 0.05$). A significant time x group interaction was observed for CMJ height and IPC measures ($p < 0.05$), with reductions in physical performance observed in the CT group from 48 h to 72 h post-match ($p < 0.05$).

Conclusion: A youth soccer match acutely impaired physical performance and recovery status, with prolonged and incomplete recovery of hamstring strength and elevated muscle soreness 48 h post-match. A high-volume training session administered 48 h post-match may negatively influence physical performance compared to a moderate volume session, suggesting the importance of carefully managing players' training load in the days following a match.

5.2 Introduction

Effective management of fatigue and recovery is a primary responsibility of sports scientists and coaches (Skorski et al., 2019; Thorpe et al., 2017). Following the quantification of typical training loads (Study 1, Chapter 3) and the characterisation of acute fatigue responses to soccer match play (Study 2, Chapter 4), the present chapter aims to extend this line of research by examining post-match recovery responses. Recovery is a complex process that involves various restorative measures over time, serving as a vital part of the overall training program (Kellmann et al., 2018; Mujika et al., 2018). The training regimen consists of the systematic execution of physical activities, encompassing both external and internal training loads, along with their respective training effects, which can be either beneficial or detrimental, and can lead to acute or chronic responses that influence sports performance outcomes (Jeffries et al., 2022). To maximise positive training impacts while minimising negative interactions with training adaptations, it is advised to adopt a structured, periodised, specific and individualised strategy for training and recovery monitoring (Coutts et al., 2018; Impellizzeri et al., 2019; Wiewelhove et al., 2024).

The physical demands of soccer matches cause fatigue, leading to changes in physiological and biochemical balance, reduced neuro-mechanical function, and alterations in psychological perceptions (Brownstein et al., 2017; Krustrup et al., 2006; Mohr et al., 2023; Rampinini et al., 2011). Fatigue is characterised by a decrease in performance and an altered perception of effort that maintains an individual's integrity (Enoka and Duchateau, 2016). In soccer, diminished hamstring muscle function and CMJ performance, along with increased muscle soreness and CK levels, indicate a prolonged recovery period. Players' physiological states and performance capacities remain significantly impaired 48 h post-match, with some alterations evident up to 72 h after the match in professional players (Silva et al., 2018) . Although numerous studies have characterised recovery responses in adult players, limited information exists on the recovery time course of youth players following match-play.

Significant changes in physical performance (e.g., vertical jumps, hamstring strength), physiological markers (e.g., metabolic, inflammatory, and muscle damage), and subjective measures (e.g., muscle soreness, fatigue) have been documented after youth soccer matches (Barreira et al., 2024; Bromley et al., 2021; Constantine et al., 2019; de Hoyo et al., 2016; De Ste Croix et al., 2019; Fornaziero et al., 2023; Izquierdo et al., 2020; Martin-Garetxana et al., 2024; Romagnoli et al., 2016; Wollin et al., 2017). Studies showed inconsistent results regarding the recovery of physical performance two days post-match in under-19 players who compete in 90-minute games (Barreira et al., 2024; de Hoyo et al., 2016; Romagnoli et al., 2016). More recently, Springham and colleagues (2024) examined the time course of recovery to under-18 English Premier League soccer match-play, reporting match-induced reductions in isometric strength measures (posterior chain, adductor and abductor muscles) which normalised between two and three days post-match. Considering that youth players frequently engage in shorter matches of 80 or 70 minutes (Palucci Vieira et al., 2019), it is conceivable that their recovery responses might vary in magnitude and duration compared to adult players.

Following competitive matches, soccer players often employ several recovery and training methods to reduce fatigue and speed up recuperation (Field et al., 2021). Nonetheless, the success of these methods in improving recovery has been uncertain or minimal, with significant variability in individual responses (Wiewelhove et al., 2024). Thus, it is crucial to focus on key aspects of recovery and training management, such as adequate sleep, proper nutrition, and precise training load and periodisation planning, to optimise recovery and performance (Driller and Leabeater, 2023). Despite extensive research on recovery methods in soccer (Altarriba-Bartes et al., 2020; Calleja-González et al., 2021; Querido et al., 2022), there is a lack of information regarding the effect of training within 48-72 h post-match on the recovery process. Gaining insights into how different training loads impact recovery when players resume training 48 h post-match would assist practitioners in creating training programs that balance recovery needs with sport-specific preparation for youth soccer players.

Manipulation of training load during the competitive microcycle involves adjusting the frequency, duration and intensity of training sessions to achieve desired training effects (Douchet et al., 2024; Slattery et al., 2012; Thorpe et al., 2017). Prior studies indicate that an active recovery session conducted 48 h post-match more effectively restores knee flexor muscle strength, decreases CK levels, and reduces muscle soreness compared to standard training sessions in highly trained youth soccer players (Trecroci et al., 2020, 2021). Nevertheless, there is limited information on the impact of various soccer-specific training interventions given when adolescent players return to training two days after a match. As soccer players exhibit altered recovery states and higher perceived fatigue 48 h after matches (Di Salvo et al., 2023), it is important to prescribe an appropriate training stimulus early in the microcycle to facilitate recovery and ensure proper preparation for forthcoming matches.

Therefore, this study aimed: 1) to describe the time course of recovery response up to 48 h after a match, and 2) to examine the effects of two training load interventions given 48 h post-match on these recovery responses in high-level youth soccer players.

5.3 Methods

5.3.1 Participants

Sixty youth soccer players belonging to the academy squads of a professional soccer team in the Italian Serie A were initially recruited to participate in this study. Players were free from injury and illness and participated in an average of 8 to 10 h of training and a competitive match per week. Subjects were classified as highly trained (Tier 3) or elite (Tier 4) (McKay et al., 2022). From the initial sample, 10 players were excluded for not completing the full match, and an additional 2 players were excluded due to incomplete testing procedures (i.e., absence from the MD+3 testing session). This resulted in a final sample of 48 youth soccer players (age: 15.4 ± 0.9 years; height: 178.0 ± 6.2 cm; body mass: 66.5 ± 7.3 kg; percentage adult height: 98.0 ± 1.6 %; maturity offset: 1.8 ± 0.8 years). A schematic overview of the participants' flow chart is depicted in Figure 14. Parents or legal guardians provided written informed consent prior to the commencement of the study. The study received ethics approval from the University Research Ethics Committee (23/SPS/006) and was conducted in accordance with the Declaration of Helsinki.

5.3.2 Experimental design

A schematic overview of the study design is depicted in Figure 14. Players were assessed at four time points during a microcycle: -24 h before the match (pre), immediately after the match (0.5h post), and two and three days after the match (48h post and 72h post). At each time point, physical performance (CMJ and IPC lower-limb muscle test) and perceptual recovery measures (VAS for muscle soreness and perceived fatigue) were collected to evaluate recovery responses. Players were familiarised with all testing and monitoring procedures. Baseline testing sessions were preceded by 48 h of rest. Three friendly matches were organised and each participant played an 80-minute friendly match-play (MD) (2 x 40 min, 105 x 68 m, artificial turf). The matches were preceded by a 20-minute standardised warm-up. Players had to complete the entire match to be included in the analyses. On MD+1, players had a rest day, without exposure to any physical activity. On MD+2, players were assigned to either a CT group (100-minute session; n = 26) or a RT (70-minute session; n = 22) using a randomised parallel group design. Training and match loads were quantified using GNSS, HR sensors, and sRPE. Players were asked to refrain from any additional training or strenuous physical activity throughout the experimental period, specifically from the end of match-play until the

MD+2 testing session. In addition, players were instructed not to perform any additional recovery strategies (e.g., CWI, massage, stretching), ensuring that post-match responses reflected their normal physiological time course without external recovery interventions. Players were also instructed to maintain their normal dietary intake and hydration practices during the experimental period.

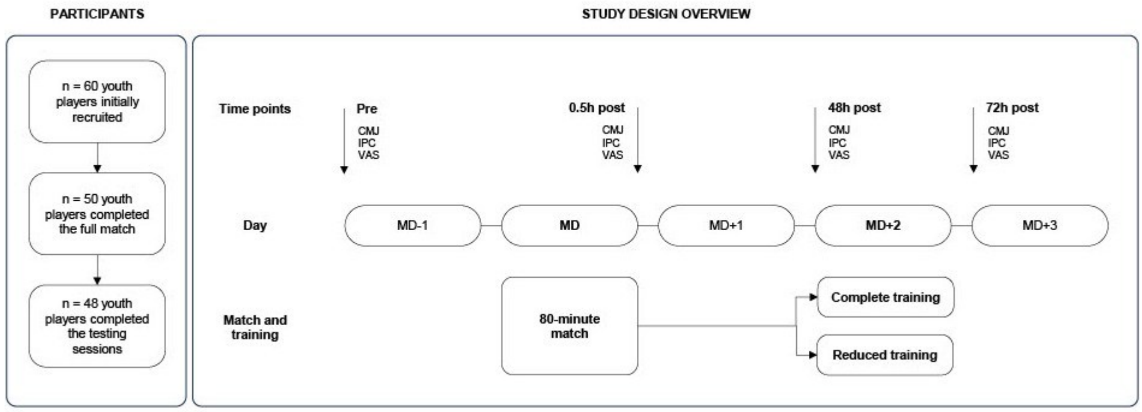

Figure 14. Participants and study design overview. Physical performance (CMJ, IPC) and perceptual recovery measures (VAS for muscle soreness and fatigue) were collected during the microcycle at four time points before (pre) and after (0.5h post, 48h post and 72h post) a match. Two days after match (MD+2), players were assigned to either a complete training group (CT: 100-minute session; *n* = 26) or a reduced training group (RT: 70-minute session; *n* = 22). Abbreviations: CMJ: countermovement jump; IPC: isometric posterior chain; VAS: visual analogue scale; MD: match day; + and -: plus and minus symbols represent the training days with respect to the distance to the match; h: hours.

5.3.3 Experimental procedures

5.3.3.1 Quantification of training and match load

External match load was quantified using GNSS technology (Apex Pro Series, 10Hz GNSS, STATSports, Newry, Northern Ireland), in accordance with the procedures outlined in Study 1 (Chapter 3). During the experimental match and training sessions, the average number of satellite signals was 18 ± 4 and the horizontal dilution of precision was 0.5 ± 0.1. Internal match load was quantified using HR sensors (Polar H10, Polar, Kempele, Finland) and sRPE, in accordance with the procedures outlined in Study 1

(Chapter 3). In addition to the external and internal load measures outlined in Study 1 (Chapter 3), in the current study maximal speed ($km \cdot h^{-1}$), HR_{avg} ($b \cdot min^{-1}$) and HR_{peak} ($b \cdot min^{-1}$) were also reported to describe match and training demands.

5.3.3.2 Training load interventions

Players were randomly assigned to either a CT (100 minutes; $n = 26$) or a RT (70 minutes; $n = 22$) session, using a stratified block randomisation based on age and player position. The exclusion of two players from the final sample, both allocated to the RT group, due to incomplete testing procedures on MD+3 (i.e., absence from the training session) resulted in an unbalanced group allocation. Session duration was calculated from the start of the first activity to the end of the last drill. The definition of CT reflects the typical training load sustained by Italian youth soccer players two days after match-play, analysed and quantified in Study 1 (Chapter 3). The 30-minute between-group difference was selected to align with practical aspects of training load management adopted in soccer. The CT session consisted of warm-up (15 min), technical passing drills (15 min), ball possession games (15 min; 6 vs 6 with floaters; 45 x 40 m), small-sided games (25 min; 5 vs 5 with goalkeepers and regular target; 35 x 40 m), position-specific technical drills (15 min) and high-intensity intermittent runs (5 min; 15 s work, 15 s rest). The RT session consisted of warm-up (15 min), technical passing drills (15 min), ball possession games (15 min; 6 vs 6 with floaters; 45 x 40 m) and position-specific technical drills (15 min). The RT session was planned with a shorter duration, volume and intensity by including technical-tactical drills with limited impact and physical demands. Experimental training sessions were also monitored with live tracking technology using Sonra Live App (version 2.8, STATSports, Newry, Northern Ireland). This tracking system has been shown to provide valid data both in real-time and post-activity in team sports (Johnston et al., 2020).

5.3.3.3 Isometric posterior chain (IPC) lower-limb muscle test

Players performed three trials for each lower-limb, consisting each of 3 s maximal contraction with ~30 s of rest between trials into a force platform (ForceDecks Dual Force Plate System FD lite, VALD Performance, Newstead, Australia), similar to methods previously reported (McCall et al., 2015). ForceDecks software (VALD Performance, Newstead, Australia) was used to analyse and calculate the selected measures with a sampling rate of 1000 Hz. The IPC was executed in accordance with the procedures outlined in Study 2 (Chapter 4). For the current study players performed the IPC with their knee at 90° of flexion, with peak force dominant leg (N), peak force non-dominant leg (N), peak torque dominant leg (Nm), peak torque non-dominant leg (Nm) quantified for subsequent analyses.

5.3.3.4 Countermovement jump (CMJ) test

Players performed three CMJ trials with ~20 s rest between trials on a force platform (ForceDecks Dual Force Plate System FD lite, VALD Performance, Newstead, Australia), using methods previously described (Barillas et al., 2021; McMahon et al., 2018). ForceDecks software (VALD Performance, Newstead, Australia) was used to analyse and calculate the selected measures with a sampling rate of 1000 Hz. The CMJ was executed in accordance with the procedures outlined in Study 2 (Chapter 4). For the current study, jump height (cm), peak power (W), force at zero velocity (N) and reactive strength index (RSI) modified ($m \cdot s^{-1}$) were quantified and used for subsequent analyses. These measures were chosen due to their suitability in the context of physical performance profiling (jump height and peak power) (Bishop et al., 2023) and post-match fatigue monitoring (force at zero velocity and RSI-modified) in alignment with the findings from Study 2 (Chapter 4).

5.3.3.5 Visual analogue scales (VAS)

At each measurement time point, players rated their perceived level of muscle soreness and fatigue using VAS (0 = no soreness/fatigue; 10 = extreme muscle soreness/fatigue) (Abbott and Clifford, 2022; Cross et al., 2023). Both measurements were reported in centimetres.

5.3.4 Statistical analysis

Data are presented as mean ± SD or as mean (95% CI). Analysis of training load and recovery response measures commenced following the assessment of normality using Shapiro-Wilk test and of equality of variance using Levene's test. To analyse the time course of recovery, one-way ANOVAs were performed for each recovery measure to examine differences between time points (pre, 0.5h post, 48h post). Sphericity was assessed using the Mauchly test and if violated, the Greenhouse-Geisser correction was used to adjust the degrees of freedom. Where a significant main effect was present, a Bonferroni post-hoc analysis was conducted to locate specific differences. A separate parallel analysis of variance, 2 x 2 mixed ANOVA were performed to investigate the effects of the two training load interventions on recovery responses between time points (48h post and 72h post) and training groups (CT and RT). Within this analysis, these time points reflect pre (48h post) and post (72h post) training load intervention measurements. An independent t-test was performed to analyse the differences in external and internal load measures between the training groups on MD (match) and MD+2 (training load interventions). The magnitude of differences in training load and recovery measures was also assessed using Cohen's *d* effect size (*d*) and was interpreted as follows: *trivial* (< 0.20), *small* (0.20-0.59), *moderate* (0.60-1.19), *large* (1.20-1.99) and *very large* (> 2.0) (Hopkins et al., 2009). Statistical significance was set with alpha < 0.05. Statistical analyses were performed using JASP statistical software (JASP 0.18.3 version, University of Amsterdam, Amsterdam, The Netherlands).

5.4 Results

5.4.1 Time-course of recovery following match-play

CMJ measures were significantly reduced from pre to 0.5h post-match (Δ: from -2.7 % to -6.5 %; *d*: from 0.15 to 0.43; $p < 0.001$) and returned to baseline levels at 48h post-match (*d*: from -0.09 to 0.05; $p > 0.05$). IPC measures were significantly reduced from pre to 0.5h post-match (Δ: from -15.0 % to -17.1 %; *d*: from 0.83 to 1.19; $p < 0.001$), but remained reduced at 48h post-match (Δ: from -7.2 % to -7.8 %; *d*: from 0.43 to 0.50; $p < 0.001$). Perceived muscle soreness (*d*: 1.97; $p < 0.001$) and fatigue (*d*: 1.72; $p < 0.001$) were significantly increased from pre to 0.5h post-match. At 48h post-match, muscle soreness remained above baseline (*d*: 0.58; $p < 0.001$), while fatigue returned to baseline levels (*d*: 0.11; $p = 1.000$). Descriptive, inferential and effect size statistics of the time course of recovery following match-play are reported in Table 15. Individual responses of CMJ and IPC tests assessed at pre, 0.5h post and 48h post are reported in Figure 15.

5.4.2 Match and training load characteristics

No between-groups differences were observed on MD, with groups exposed to similar external and internal load ($p > 0.05$; d: ranged from *trivial* to *small*; Table 16). On MD+2 the CT group had significantly higher training loads than the RT group for all external and internal load measures ($p < 0.05$, d: ranged from *moderate* to *very large*; Table 17).

5.4.3 Effects of different training load interventions on recovery response

At 48h post-match, no significant differences were observed between groups for all recovery measures ($p > 0.05$). A significant time x group interaction was observed for CMJ height ($p = 0.005$), IPC peak force dominant leg ($p < 0.001$), IPC peak force non-dominant leg ($p = 0.033$), IPC peak torque dominant leg ($p < 0.001$), and IPC peak torque non-dominant leg ($p = 0.037$). From 48h post to 72h post, these physical performance measures were significantly reduced in the CT group ($p < 0.05$), while they remained unchanged in the RT group ($p > 0.05$). Conversely, following training load interventions no significant time x group interaction was observed for CMJ peak power ($p = 0.453$), CMJ force at zero velocity ($p = 0.331$), CMJ RSI-modified ($p = 0.845$), muscle soreness ($p = 0.433$) and fatigue ($p = 0.088$). The effects of CT and RT interventions performed on MD+2 on recovery responses are reported in Table 18. Individual responses to training load interventions are reported in Figure 16.

Table 15. Time course of recovery responses following match-play in Italian Serie A youth soccer players (*n* = 48).

	Pre	0.5h Post	48h Post	Pre vs 0.5h Post			Pre vs 48h Post		
				Δ (95% CI)	p-value	Cohen's *d*	Δ (95% CI)	p-value	Cohen's *d*
Countermovement jump test									
Jump height (cm)	35.0 ± 5.3	33.4 ± 5.3 *S	35.4 ± 5.5	-1.6 (-2.2; -0.9)	< 0.001	0.30	0.4 (-0.3; 1.0)	0.484	-0.07
Peak power (W)	3469.2 ± 591.9	3375.6 ± 599.3 *S	3526.7 ± 623.9	-93 (-147; -40)	< 0.001	0.15	58 (-2; 111)	0.059	-0.09
Force at zero velocity (N)	1743.4 ± 245.7	1629.3 ± 255.1 *S	1729.6 ± 289.0	-114 (-152; -77)	< 0.001	0.43	-13 (-51; 24)	1.000	0.05
RSI-modified ($m \cdot s^{-1}$)	0.53 ± 0.09	0.50 ± 0.09 *S	0.53 ± 0.11	-0.03 (-0.04; -0.01)	< 0.001	0.29	0.00 (-0.02; 0.02)	1.000	-0.01
Isometric posterior chain lower-limb muscle test									
Peak force dominant leg (N)	299.5 ± 55.6	254.4 ± 50.8 *M	276.3 ± 48.5 *S	-46 (-55; -35)	< 0.001	0.87	-24 (-34; -13)	< 0.001	0.45
Peak force non-dominant leg (N)	286.0 ± 42.6	237.1 ± 40.2 *M	265.5 ± 40.4 S	-49 (-59; -39)	< 0.001	1.19	-20 (-31; -11)	< 0.001	0.50
Peak torque dominant leg (Nm)	116.1 ± 22.9	98.7 ± 20.8 *M	107.0 ± 19.5 *S	-17 (-22; -13)	< 0.001	0.83	-9 (-13; -5)	< 0.001	0.43
Peak torque non-dominant leg (Nm)	110.8 ± 18.4	91.8 ± 17.1 *M	102.8 ± 16.7 S	-19 (-23; -15)	< 0.001	1.09	-8 (-12; -4)	< 0.001	0.46
Perceptual measures									
Muscle soreness (cm)	1.9 ± 1.3	5.3 ± 1.9 *L	2.9 ± 1.9 *S	3.4 (2.7; 4.0)	< 0.001	1.97	1.0 (0.3; 1.7)	0.001	0.58
Fatigue (cm)	2.6 ± 1.3	5.0 ± 1.3 *L	2.8 ± 1.5	2.3 (1.7; 3.0)	< 0.001	1.72	0.2 (-0.5; 0.8)	1.000	0.11

Abbreviations: SD: standard deviation; Δ: mean change; RSI: reactive strength index; AU: arbitrary units. * significant change from baseline (Pre) ($p < 0.05$). S: small; M: moderate; L: large effect sizes compared with Pre. Trivial effect sizes are not reported. Data are mean ± SD or as mean (95% CIs).

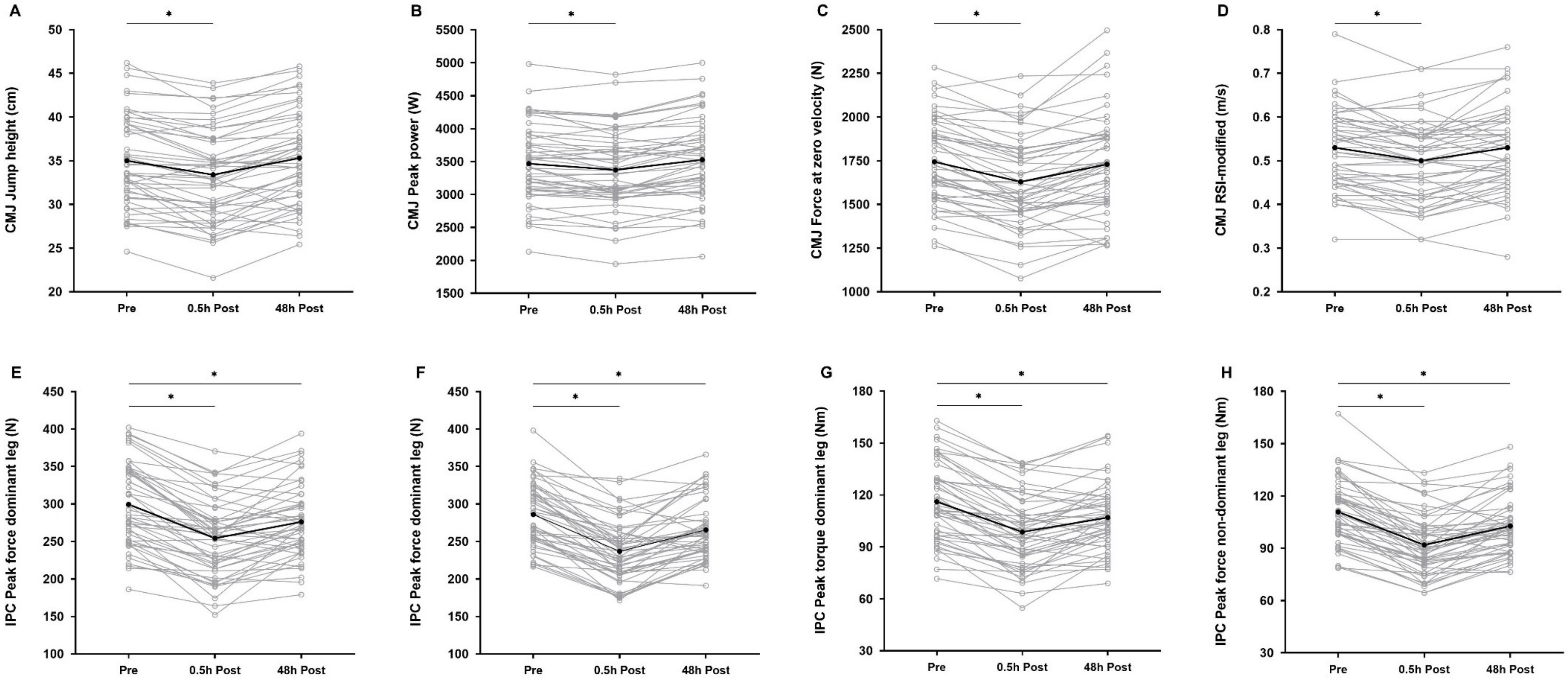

Figure 15. Individual responses of countermovement jump (A: jump height; B: peak power; C: force at zero velocity; D: RSI-modified) and isometric posterior chain (E: peak force dominant leg; F: peak force non-dominant leg; G: peak torque dominant leg; H: peak torque non-dominant leg) measured at pre, 0.5h post and 48h post in high-level youth soccer players (*n* = 48). Individual responses are plotted with grey circles and lines, while mean responses are plotted with black dots and lines. Significant changes in comparison with baseline (pre) are indicated with * ($p < 0.05$). Abbreviations: CMJ: countermovement jump; IPC: isometric posterior chain; h: hours; RSI: reactive strength index.

Table 16. Match load characteristics: descriptive, inferential and effect size statistics of external and internal load measures between complete and reduced training groups.

	Complete training (n = 26)	Reduced training (n = 22)	Mean difference (95% CI)	p-value	Cohen's *d* (95% CI)	Interpretation
External load						
Total distance (m)	11248 ± 719	11041 ± 787	207 (-230; 645)	0.345	0.28 (-0.3; 0.85)	*S*
Distance > 20 km/h (m)	560 ± 200	525 ± 211	35 (-84; 155)	0.554	0.17 (-0.4; 0.74)	*T*
Distance > 25 km/h (m)	114 ± 74	104 ± 94	10 (-39; 59)	0.692	0.12 (-0.45; 0.68)	*T*
Maximal speed ($km\cdot h^{-1}$)	29.8 ± 1.9	29.6 ± 2.5	0.2 (-1.1; 1.5)	0.757	0.09 (-0.48; 0.66)	*T*
Accelerations > 3 m/s^2 (count)	71 ± 19	68 ± 14	3 (-8; 12)	0.661	0.13 (-0.44; 0.70)	*T*
Decelerations < -3 m/s^2 (count)	80 ± 19	73 ± 20	7 (-4; 19)	0.216	0.36 (-0.21; 0.93)	*S*
Internal load						
HR_{avg} ($b\cdot pm^{-1}$)	158 ± 12	148 ± 20	10 (-0.0; 20)	0.056	0.65 (-0.01; 1.30)	*M*
HR_{peak} ($b\cdot pm^{-1}$)	196 ± 8	190 ± 12	6 (-1; 12)	0.079	0.57 (-0.07; 1.19)	*S*
Time > 85% HR_{max} (min)	42 ± 18	32 ± 22	10 (-3; 22)	0.117	0.50 (-0.12; 1.11)	*S*
Time > 90% HR_{max} (min)	18 ± 14	15 ± 16	3 (-6; 12)	0.502	0.21 (-0.40; 0.82)	*S*
sRPE (AU)	5.6 ± 1.0	5.5 ± 1.0	0.1 (-0.4; 0.7)	0.624	0.14 (-0.43; 0.71)	*T*
sRPE-TL (AU)	587 ± 101	571 ± 91	16 (-40; 72)	0.572	0.17 (-0.41; 0.73)	*T*

Abbreviations and notes: CI: confidence interval; m: meters; n: number; HR: heart rate; $b\cdot pm^{-1}$: beat per minute; TL: training load; AU: arbitrary units. Data are mean ± SD or as mean (95% CIs). Effect size: T: trivial; S: small; M: moderate

Table 17. Training load interventions characteristics on MD+2: descriptive, inferential and effect size statistics of external and internal load measures between complete and reduced training groups.

	Complete training (*n* = 26)	Reduced training (*n* = 22)	Mean difference (95% CI)	p-value	Cohen's d (95% CI)	Interpretation
External load						
Total distance (m)	7842 ± 839	4371 ± 816	3471 (2988; 3955)	< 0.001	4.19 (3.16; 5.21)	*VL*
Distance > 20 km/h (m)	180 ± 131	58 ± 44	122 (63; 180)	< 0.001	1.21 (0.58; 1.82)	*L*
Distance > 25 km/h (m)	12 ± 10	3 ± 5	9 (4; 13)	< 0.001	1.06 (0.45; 1.66)	*M*
Maximal speed ($km \cdot h^{-1}$)	26.9 ± 2	24.8 ± 2.1	2.1 (0.9; 3.3)	< 0.001	1.02 (0.41; 1.62)	*M*
Accelerations > 3 m/s^2 (count)	70 ± 17	39 ± 11	31 (23; 40)	< 0.001	2.16 (1.44; 2.87)	*VL*
Decelerations < -3 m/s^2 (count)	68 ± 16	33 ± 14	35 (27; 44)	< 0.001	2.37 (1.62; 3.11)	*VL*
Internal load						
HR_{avg} ($b \cdot pm^{-1}$)	151 ± 12	140 ± 19	10 (-0; 20)	0.054	0.65 (-0.01; 1.30)	*M*
HR_{peak} ($b \cdot pm^{-1}$)	196 ± 7	188 ± 15	8 (1; 16)	0.024	0.77 (0.10; 1.43)	*M*
Time > 85% HR_{max} (min)	29 ± 12	12 ± 11	16 (9; 24)	< 0.001	1.36 (0.67; 2.03)	*L*
Time > 90% HR_{max} (min)	12 ± 9	6 ± 7	6 (1; 12)	0.014	0.80 (0.16; 1.42)	*M*
sRPE (AU)	4.1 ± 0.8	3.3 ± 0.8	0.8 (0.3; 1.219)	0.002	0.96 (0.36; 1.56)	*M*
sRPE-TL (AU)	348 ± 86	195 ± 103	153 (99; 209)	< 0.001	1.63 (0.97; 2.28)	*L*

Abbreviations: CI: confidence interval; m: meters; n: number; HR: heart rate; bpm: beats per minute; TL: training load; AU: arbitrary units. Data are mean ± SD or as mean (95% CIs). Effect size: M: moderate; L: large; VL: very large.

Table 18. Effects of complete and reduced training load interventions performed 48 h after a match on the recovery responses of Italian Serie A youth soccer players (n = 48).

	Complete training (n = 26)		**Reduced training (n = 22)**		**Main effect (p-value)**		
	Pre-intervention (48h Post)	**Post-intervention (72h Post)**	**Pre-intervention (48h Post)**	**Post-intervention (72h Post)**	**Time x group**	**Time**	**Group**
Countermovement jump test							
Jump height (cm)	35.5 ± 5.7	34.1 ± 5.3 *	35.1 ± 5.2	35.3 ± 4.8	0.005 #	0.016	0.806
Peak power (W)	3517.7 ± 591.0	3446.2 ± 562.9	3537.2 ± 674.7	3497.5 ± 645.5	0.453	0.011	0.843
Force at zero velocity (N)	1737.6 ± 271.9	1694.3 ± 258.1	1720.0 ± 314.1	1679.3 ± 317.0	0.918	0.002	0.845
RSI-modified (m/s)	0.53 ± 0.10	0.51 ± 0.10	0.53 ± 0.10	0.52 ± 0.08	0.331	0.006	0.802
Isometric posterior chain lower-limb muscle test							
Peak force dominant leg (N)	282.5 ± 47.5	266.3 ± 50.4 *	269.0 ± 49.8	279.7 ± 54.3	< 0.001 #	0.450	0.994
Peak force non-dominant leg (N)	271.0 ± 41.9	258.4 ± 43.4 *	258.9 ± 38.5	259.8 ± 38.0	0.033 #	0.064	0.641
Peak torque dominant leg (Nm)	108.8 ± 18.5	102.5 ± 19.8 *	104.9 ± 20.8	109.2 ± 23.4	< 0.001 #	0.479	0.820
Peak torque non-dominant leg (Nm)	104.4 ± 17.1	99.7 ± 18.0 *	100.8 ± 16.3	101.2 ± 15.8	0.037 #	0.067	0.829
Perceptual measures							
Muscle soreness (cm)	2.8 ± 2.2	3.0 ± 2.3	2.9 ± 1.6	2.7 ± 2.1	0.433	0.984	0.790
Fatigue (cm)	2.5 ± 1.5	2.8 ± 1.4	3.0 ± 1.4	2.9 ± 1.6	0.088	0.571	0.464

Abbreviations and notes: MD: match day; SD: standard deviation; CI: confidence intervals; RSI: reactive strength index; AU: arbitrary units. Data are mean ± SD.

* significant within-group change from Pre-intervention (48h Post) ($p < 0.05$).

significant time x group interaction ($p < 0.05$)

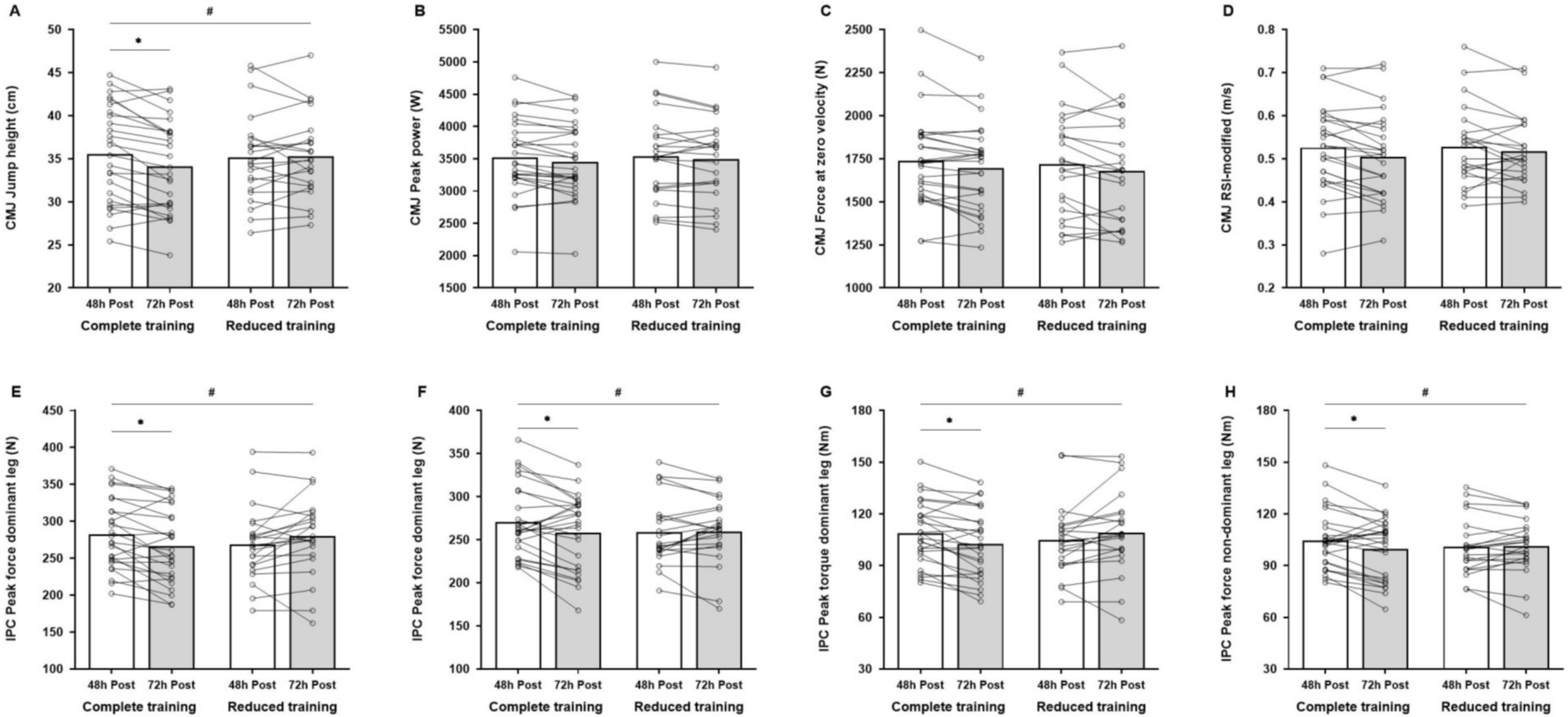

Figure 16. Individual (lines) and group (bars) responses to complete and reduce training load interventions in Italian Serie A youth soccer players on countermovement jump (A: jump height; B: peak power; C: force at zero velocity; D: RSI-modified) and isometric posterior chain (E: peak force dominant leg; F: peak force non-dominant leg; G: peak torque dominant leg; H: peak torque non-dominant leg) measured at 48h post (white bars) and 72h post (grey bars). Significant changes in comparison with 48h post are indicated with * ($p < 0.05$), while significant time x group interactions are indicated with # ($p < 0.05$). Abbreviations: CMJ: countermovement jump; IPC: isometric posterior chain; h: hours; RSI: reactive strength index.

5.5 Discussion

This study aimed to describe the time course of recovery responses following match-play and to examine the effects of two different training load interventions administered 48 h post-match on recovery in high-level youth soccer players. Based on current evidence, this may be the first study to concurrently examine the time course of recovery post-match and the impact of manipulating training volume two days after match-play in youth soccer players. The primary results demonstrated that an 80-minute youth soccer match significantly impaired physical performance and perceptual recovery both immediately and in the subsequent days. Recovery patterns showed variation, with CMJ performance and perceived fatigue returning to baseline levels 48 h post-match, whereas hamstring muscle force and perceived muscle soreness had not fully recovered by that time. Additionally, a high-volume training session conducted on MD+2 may further impair physical performance recovery, whilst a moderate-volume training session may support the recovery process without further impairment of performance. Nevertheless, the overall training did not alter the perceived recovery of these high-level youth players.

An 80-minute soccer match significantly reduced CMJ performance, hamstring strength, and increased muscle soreness and fatigue, showing acute fatigue in youth players. CMJ measures showed significant reductions ranging from -3% to -8% at post-match. The magnitude of change observed in CMJ height (-5%; *small* effect) is consistent with previous studies (Barreira et al., 2024; de Hoyo et al., 2016; Izquierdo et al., 2020; Martin-Garetxana et al., 2024; Romagnoli et al., 2016). However, the observed reduction in CMJ peak power (-3%; *trivial* effect) was larger than that reported in similar research on youth soccer players (Romagnoli et al., 2016). Although frequently documented, CMJ height and peak power may display post-match and post-training changes within their typical variation, as supported by the findings of Study 2 (Chapter 4) and in agreement with previous literature (Malone et al., 2015; Thorpe et al., 2017). Similarly, in this study, CMJ peak power showed mean post-match changes within the typical variation observed in the reliability analysis of Chapter 4 (Δ: - 93 W; TE x 1.5: 141 W), whilst CMJ jump height showed mean post-match changes greater than the typical variation (Δ: - 1.6 cm; TE x 1.5: 1.4 cm). In contrast, CMJ measures derived from the analysis of the force-time curve, such as force at zero velocity and RSI-modified in the current study (-7% and -6%, respectively; *small* effect), demonstrated a higher probability of change following soccer match-play. In addition, the documented acute post-match changes in force at zero velocity and RSI-modified were greater than the typical variation (i.e., TE x 1.5). Previous research has shown marked variations in the eccentric force components of the CMJ in responses to youth soccer match-play (de Hoyo et al., 2016; Springham et al., 2024). These observations suggest that CMJ eccentric force components may better reflect the neuromuscular reduction and the movement strategy adjustments following soccer competitions.

Hamstring muscle function was also significantly impaired at post-match, with reductions in IPC peak force and peak torque for both dominant and non-dominant legs ranging from -15% to -17% (*moderate* effect). These declines in IPC measures were also greater than the typical variation determined with the reliability analysis in Chapter 4 (i.e., acute changes > TE x 1.5). The magnitude of post-match changes aligns with previous studies assessing acute changes following 90-minute matches in youth soccer players (Constantine et al., 2019; Wollin et al., 2017), indicating the high involvement of hamstring muscles in youth soccer match-play. Perceived muscle soreness and fatigue exhibited similar acute responses compared to the pre-match condition. This also agrees with the impaired perceptions of recovery and fatigue observed in youth soccer players after competitive matches (De Ste Croix et al., 2019; Martin-Garetxana et al., 2024; Romagnoli et al., 2016). These combined acute changes in physical performance and perceptions of fatigue likely reflect perturbations in the central nervous system and muscle function, the depletion of muscle glycogen levels and the onset of match-induced muscle damage, commonly observed at the end of soccer matches and intense training sessions (Brownstein et al., 2017; Deely et al., 2022; Mohr et al., 2022). In particular, the reduction of the force-generating capacity of the hamstring muscles accompanied by increased perceived muscle soreness can be attributed to the muscle damage experienced by high-level youth soccer players following soccer match-play (Pooley et al., 2020).

Following acute impairments of physical performance and perceptual state after match-play, the time course of recovery exhibited distinct patterns. While CMJ and perceived fatigue recovered 48 h post-match, IPC and perceived muscle soreness were still not fully recovered. Our data indicated a complete recovery of CMJ performance 48 h post-match in all measures analysed. Previous studies on youth soccer have yielded mixed outcomes regarding CMJ performance; under-19 Spanish and Italian players exhibited a sustained decrease in jump height (-3% to -6% from baseline) 48 h post-match (de Hoyo et al., 2016; Romagnoli et al., 2016). In contrast, similar to our findings, under-19 Portuguese players showed complete CMJ recovery at this timeframe (Barreira et al., 2024; Springham et al., 2024). This recovery kinetics also aligns with measures of central and peripheral fatigue, which showed a return to baseline values 48 h after the match in adult soccer players (Brownstein et al., 2017). Collectively, these findings suggest that the time to restoration of CMJ appears to be shorter in youth soccer players than those observed in the adult population (Silva et al., 2018).

Conversely, hamstring muscle function remained impaired 48 h post-match. IPC peak force and torque did not return to baseline values in either the dominant and non-dominant legs (-8% and -7%, respectively), with significant changes of *small* effect compared to pre-match. The observed changes at 48 h post-match were also greater than the typical variation determined with the reliability analysis in Chapter 4 (i.e., acute changes > TE x 1.5). While some studies reported a return to baseline in high-level youth soccer players within this timeframe (Constantine et al., 2019; Springham et al., 2024; Wollin et al., 2017), more recent findings by Barreira et al. (2023) align with our results, documenting impaired posterior-chain muscle function two days after a match in under-19 Portuguese players. Our data suggest that youth players require a longer recovery period for hamstring muscle function, similar to professional adult players who show prolonged recovery times up to 72 h post-match (J. R. Silva et al., 2018). The current study found that moderate reductions in hamstring function persist 48 h post-match in youth players, likely due to the heavy involvement of hamstring muscles during high-intensity actions and eccentric activities, which induce muscle damage in the days post-match (Carmona et al., 2024). Forty-eight hours after the match, hamstring muscle force had not fully recovered, and perceived muscle soreness remained high, indicating incomplete recovery. Previous studies have recorded increased muscle damage markers 48 h post-match in adolescent players (de Hoyo et al., 2016; Romagnoli et al., 2016), indicating that the recovery time reflects both mechanical stress from eccentric contractions and metabolic fatigue caused by match-play (Thorpe, 2021). These findings indicate that youth soccer players' performance capacity may not be fully restored two days after an 80-minute match-play due to the elevated perception of muscle soreness and the reduced hamstring muscle function.

The CT session, characterised by higher training volume, affected physical performance responses compared to the RT session. Our findings reveal substantial differences between training load interventions (*moderate* to *very large* effect in the training load sustained on MD+2), leading to significant *small* reductions in CMJ height and all IPC measures from 48 to 72 h post-match in the CT group. These outcomes are consistent with previous research reporting better restoration of knee flexor muscle force production and lower CK levels following an active recovery session 48 h post-match compared to a typical training session (Trecroci et al., 2020, 2021). Similarly, an active recovery protocol performed immediately after the match showed improved recovery responses 48 h after the match in under-18 English soccer players compared to a static stretching protocol (Pooley et al., 2020). However, it is important to note that IPC peak force and torque values of the dominant leg increased from 48 to 72 h post-match in the RT group, and that the pre-intervention values (48 h post-match) were higher compared to the CT group. These factors likely contributed to the significant time x group interaction observed. Therefore, the interaction effects should be interpreted with caution, as they may partially reflect between-group variability rather than true experimental differences. Despite the impact on physical performance capacity, our training load interventions did not influence the perceived recovery state and the other CMJ measures. This result appears to reflect the lower physical and physiological demands experienced by players during training sessions compared to those during matches. Conversely, the RT group did not show declines in physical performance and perceived recovery from 48 to 72 h post-match, suggesting that a moderate training session (sRPE: 3.3 ± 0.8 AU) allows the maintenance of performance capacity early in the microcycle.

Despite practitioners' inclination towards prioritising recovery within the initial 48-hour post-match window in elite adult soccer (Buchheit, Sandua, et al., 2021; Cross et al., 2019), findings from Study 1 (Chapter 3) have shown that youth soccer players can be subjected to elevated training loads two days post-match. In this view, the current study provides new insights into the effects of soccer-specific training on recovery in high-level youth soccer players. Taken together, the results of this research suggest that two days after match-play adolescent players' performance capacity may not be fully restored, and that a high volume training session administered within this time point might further affect the recovery of performance 72 h post-match. However, given the *small* effect sizes and the parallel group design of this research, it is difficult to assert whether the additional training volume imposed on the CT group altered the recovery process to a critical degree. Furthermore, in light of the reliability analysis reported in Chapter 4, the between-group differences identified following the manipulation of training volume, although statistically significant, fell within the typical variation of the measurement tools (e.g., between-groups difference in CMJ jump height: 1.2 cm; TE x 1.5: 1.4 cm), suggesting limited practical significance.

Manipulation and periodisation of training load can serve as a practical tool to affect acute performance and recovery responses across the microcycle (Douchet et al., 2022, 2024; Slattery et al., 2012). In the present study, training volume was specifically manipulated to promote recovery of performance capacity in youth soccer players. Nonetheless, other training variables (e.g., mode, intensity and frequency) can also be modified in the days following match-play to expedite recovery and improve readiness to train (Driller & Leabeater, 2023; Field et al., 2021; Mujika et al., 2018). For instance, Trecroci et al. (2020) compared the effects of different training modalities (soccer-specific training vs active recovery) on post-match recovery, demonstrating that a regime of active recovery promoted better restoration of knee flexor muscle force compared to a typical training session within 72 h after a match in youth soccer players. Similarly, Slattery et al. (2012) examined the effects of two different training loads (sRPE) across a week in team sport players, reporting that higher training load between simulated matches altered the metabolic and inflammatory response to high-intensity intermittent exercise compared to the low training load condition. The manipulation of these variables has been demonstrated to be an important factor in influencing training responses, performance and injury rate in professional soccer (Buchheit et al., 2023).

While our study provides insights into post-match recovery responses of high-level youth soccer players, it has limitations that should be acknowledged. A major limitation concerns the statistical approach used to analyse the effects of manipulating training volume 48 hours after match-play, given the parallel group design. Specifically, the 2 x 2 mixed ANOVA employed did not include pre-intervention (48 h post-match) values of the dependent variables as covariates, which may lead to the regression to the mean phenomenon (Lolli et al., 2025). Therefore, 2 x 2 ANCOVA would have represented a more appropriate statistical approach. This methodological choice may have affected the outcomes of the time x group interaction, and further research should adopt an ANCOVA statistical test or cross-over designs to elucidate the effects of different training volumes on post-match recovery. Second, we did not assess the long-term effects of the training volume manipulation on subsequent match performance and training effects over the microcycle (Slattery et al., 2012). Alternatively, training with incomplete recovery of performance capacity might also enhance robustness and subsequently promote chronic adaptations in youth soccer players. Third, while the decision to use a friendly match-play enhanced ecological validity and increased sample size, it also resulted in less control over the match stimulus compared to a match-simulation protocol (Field et al., 2022).

Finally, incorporating physiological markers, such as muscle damage and inflammation, could provide a more comprehensive understanding of the recovery process of youth soccer players.

5.6 Conclusion

An 80-minute soccer match significantly impaired both physical performance and perceptual recovery in Italian Serie A youth players. Recovery responses exhibited varied timelines, with CMJ and perceptual fatigue returning to baseline levels within 48 h post-match, whereas hamstring muscle force and perceptions of muscle soreness were not fully recovered. Additionally, a high-volume training session conducted on MD+2 may further impair physical performance recovery, whilst a moderate-volume training session may support the recovery process without further impairment of performance. These results underscore the necessity of carefully managing training loads in the days following a match to ensure an appropriate recovery of performance capacity.

CHAPTER SIX · ACUTE FATIGUE RESPONSES TO TRAINING IN PHYSICAL PERFORMANCE, METABOLIC AND PERCEPTUAL MEASURES IN ITALIAN SERIE A YOUTH SOCCER PLAYERS

ACUTE FATIGUE RESPONSES TO TRAINING IN PHYSICAL PERFORMANCE, METABOLIC AND PERCEPTUAL MEASURES IN ITALIAN SERIE A YOUTH SOCCER PLAYERS

6.1 Abstract

Purpose: Optimising training and performance in soccer requires a comprehensive understanding of the acute responses to training load. This study aimed to characterise the acute responses to a typical training session in Italian Serie A youth soccer players by integrating performance, metabolic, and perceptual measures.

Methods: Thirteen high-level youth players were assessed before (pre) and after (post) a typical soccer training session using physical performance tests (CMJ and IPC test), metabolic markers (capillary blood sample) and perceptual measures (VAS for muscle soreness and fatigue). Training load and energy intake were controlled and quantified. From the capillary blood samples, serum fractions were assessed via untargeted proton nuclear magnetic resonance (^{1}H-NMR) metabolomics. Differences between pre- and post-training in physical performance and perceptual measures were analysed using paired *t*-tests and Hedge's *g (g)* effect size. Metabolites were analysed using multivariate and univariate analyses to identify differences in the serum metabolome between pre- and post-training.

Results: Physical performance and perceptual measures showed no changes post-training ($p > 0.05$; *g*: *trivial* to *small*), except for significant reductions in CMJ eccentric peak force, concentric peak force and force at zero velocity ($p < 0.05$; *g*: *small* to *moderate*). Of the 54 identified serum metabolites, 21 showed significant changes post-training ($p < 0.05$), with increased concentration of lactate, alanine, isoleucine, tyrosine and 3-hydroxisobutyrate, and decreased abundance in 16 other metabolites, including markers related to amino acid and lipid metabolism.

Conclusion: Although a moderate-intensity training session elicited minimal acute changes in physical performance and perceptual fatigue measures, it induced significant perturbations in the serum metabolome, particularly in energy metabolism pathways. This study suggests the importance of integrating both physiological and neuromuscular response measures for comprehensively understanding acute responses and informing periodisation of training and recovery strategies.

6.2 Introduction

The application of an appropriate exercise stimulus to enhance sports performance centres on the interaction between the training dose and recovery (Kellmann et al., 2018). Exercise imposes physiological stress, disrupting homeostasis across multiple systems of the organism to fulfil the increased ATP demands (Hargreaves and Spriet, 2020). In soccer, both the aerobic and anaerobic energy systems are engaged due to the frequent transitions from low-intensity activities and high-intensity efforts (e.g., sprinting and kicking) (Hostrup and Bangsbo, 2022). Following intense training, the body initiates adaptive responses to return to baseline levels with different magnitudes of fatigue and recovery time courses varying from minutes to several days, depending on the characteristics of the training stimulus and the physiological systems involved (Gabbett and Oetter, 2024; Skorski et al., 2019). The high-intensity and intermittent nature of soccer contributes to both metabolic fatigue and mechanical stress to the bodily tissues, resulting in biochemical perturbations, reduced mechanical function and physical performance capacity, and poorer subjective perception of recovery (Thorpe, 2021). In the previous experimental studies of this thesis (Chapter 4 and Chapter 5), match-induced changes in physical performance and perceptual recovery were documented, both immediately post-match and in the days after, with different recovery patterns observed in Italian Serie A youth soccer players. However, despite reporting internal load, these studies did not incorporate physiological markers to describe the metabolic and biochemical responses to soccer-specific activities. Given the substantial metabolic and neuromuscular demands imposed by soccer (Vanrenterghem et al., 2017), it is important to adopt a holistic approach to comprehensively characterise acute responses across multiple physiological systems.

The high-intensity demands of soccer can lead to temporary reductions in the muscle force-generating capacity, resulting in neuromuscular fatigue and decreased physical performance (Mohr et al., 2005, 2023). Previous research indicated that both central and peripheral mechanisms of neuromuscular fatigue are affected following competitive match-play in high-level soccer players (Brownstein et al., 2017; Rampinini et al., 2011). In youth players, marked impairments in neuromuscular contractile function have been observed up to 72 h post-training, suggesting prolonged recovery of peripheral mechanisms (Deely et al., 2022). Interestingly, the magnitude of match-induced fatigue following simulated match-play was greater in the hamstring muscles compared to the quadriceps in a group of youth soccer players (Massamba et al., 2024), emphasising the importance of assessing muscle-specific force production capacity. This delayed recovery in hamstring muscle function was also evident in Study 3 (Chapter 5), supporting the hypothesis that soccer training induces muscle damage through substantial mechanical loading in adolescent players (Pooley et al., 2020). In applied sport science research, physical performance tests such as vertical jumps and isometric strength assessments (e.g., hamstring tests) are commonly used as practical proxies for monitoring acute fatigue following training and competition (Deely et al., 2022; Malone, Murtagh, et al., 2015; Martin-Garetxana et al., 2024; Springham et al., 2024). Accordingly, experimental studies in this thesis utilise the IPC lower-limb muscle test and the CMJ test to describe the force-time characteristics using force platforms. Studies 2 and 3 revealed the importance of match-induced changes in the CMJ eccentric forces and the IPC peak forces and torques. Despite these findings expanding previous research on the acute effect of match-play on physical performance, acute responses to soccer training have mainly been investigated using jump height, with limited information on the variations of the force-time curve measures (Ellis et al., 2022; Malone, Murtagh, et al., 2015; Thorpe et al., 2015).

In addition to the impairments of neuromuscular function and physical performance, soccer training and match-play heavily tax both aerobic and anaerobic energy systems to meet the sport's demands (Hostrup and Bangsbo, 2022; Stølen et al., 2005). Traditionally, metabolic responses to exercise have been assessed using targeted single-metabolite analyses, documenting reduced blood and muscle pH, elevated blood and muscle lactate levels, lowered phosphocreatine concentrations, decreased glycogen stores and increased plasma glycerol and free fatty acids in adult soccer players (J. R. Silva et al., 2018). However, recent technological advancements have enabled the application of analytical chemical techniques, including mass spectrometry (MS) and NMR spectroscopy, which have facilitated the profiling of metabolite concentrations in response to exercise (Bongiovanni et al., 2022; Owens and Bennett, 2024). Metabolomics is a discipline focused on the large-scale identification, quantification, and characterisation of metabolites within a biological system, providing a detailed biochemical fingerprint of cellular activity (Khoramipour et al., 2021; Owens and Bennett, 2024). Metabolomics analyses have used various biological samples (e.g., plasma, urine and saliva) and analytical techniques (e.g., MS and NMR) to characterise the metabolic perturbations after a training session (Alzharani et al., 2020; Luti et al., 2022; Zhao et al., 2020), a match-play (França et al., 2023; Marinho et al., 2022; Pitti et al., 2019; Prado et al., 2017; Ra et al., 2014) and seasonal changes in response to training loads (Quintas et al., 2020;

Rodas et al., 2022) in soccer players. Collectively, these studies evidenced extensive perturbations provoked by soccer activities in youth soccer players. Therefore, metabolomics appears to be a promising approach to investigating fatigue and recovery responses, with the potential of uncovering key pathways underpinning adaptation and performance (Pedroso et al., 2025).

Given the complex mechanisms underlying fatigue response to soccer activities, more comprehensive approaches are necessary to fully capture the acute changes in the various physiological and biomechanical processes involved. Therefore, this study aimed to characterise the acute responses to a training session in high-level youth soccer players throughout the integration of physical performance, metabolic markers, and perceptual response measures.

6.3 Methods

6.3.1 Participants

Fourteen high-level youth soccer players (age: 18.2 ± 0.6 years; height: 183.0 ± 6.3 cm; body mass: 75.1 ± 6.9 kg, percentage adult height: 100.0 ± 0.4 %) from a professional soccer academy in the Italian Serie A were initially selected to participate in this research. Subjects were classified as highly trained (Tier 3) or elite (Tier 4) (McKay et al., 2022). Parents or legal guardians and players provided written informed consent before commencing the study. The study received ethics approval from the University Research Ethics Committee (23/SPS/006) and was conducted in accordance with the Declaration of Helsinki.

6.3.2 Experimental design

A schematic overview of the study design is depicted in Figure 17. On a single day, a group of high-level youth soccer players completed a training session and were tested before (pre-training) and immediately after (post-training). The training session was preceded by 48 h of rest. Players were assessed with physical performance tests (CMJ and IPC test), metabolomics (capillary blood sample) and perceptual measures (VAS for muscle soreness and fatigue) to characterise the acute responses to a typical training session. At pre-training, capillary blood samples were collected in the morning ~2 h before the commencement of the training session, with players in a fasted state; whilst physical performance tests and perceptual measures were collected ~30 minutes before the commencement of training. Post-training testing sessions were executed immediately after the conclusion of the training session, within ~10 minutes for capillary blood samples and ~30 minutes for physical performance and perceptual measures. Following centrifugation, serum fractions were then transported and immediately stored at -80°C until analysis in a university laboratory using untargeted ^{1}H-NMR metabolomics. External and internal training loads were quantified using GNSS, HR sensors, and sRPE. Energy and macronutrient intake of the breakfast preceding the training session were also recorded using the remote food photographic method (RFPM). Of the fourteen players initially enrolled in the study, thirteen completed the physical performance tests and perceptual measures, whereas eleven completed the capillary blood sampling and were included in the final analyses. One player was excluded from the final analyses as he did not participate in the full training session.

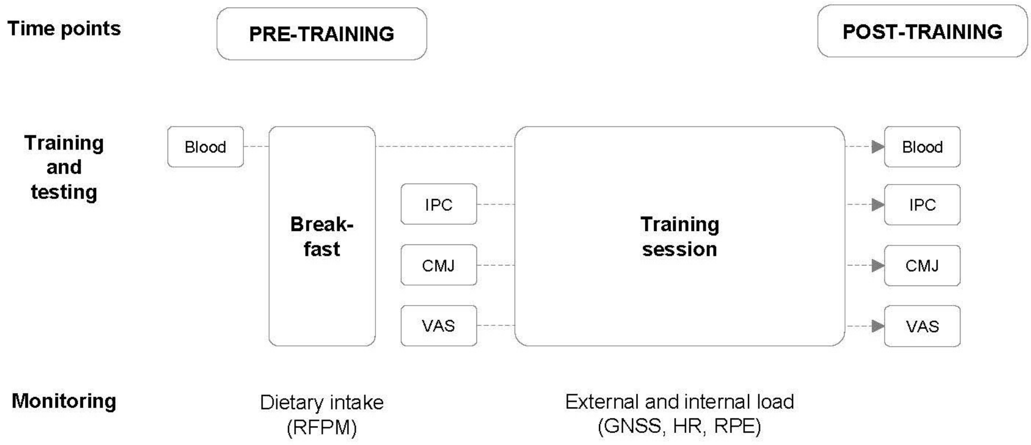

Figure 17. Study design overview. Capillary blood sampling (blood), physical performance tests (IPC and CMJ) and perceptual scales (VAS for muscle soreness and fatigue) were collected before (pre-training) and immediately after a training session (post-training). Capillary blood samples were obtained within ~10 minutes post-training, while physical performance tests and perceptual scales were completed within ~30 minutes following the session. Abbreviations: blood: capillary blood sampling; CMJ: countermovement jump; IPC: isometric posterior chain; VAS: visual analogue scale; RFPM: remote food photographic method; GNSS: global navigation satellite system; HR: heart rate; RPE: rating of perceived exertion.

6.3.3 Experimental procedures

6.3.3.1 Quantification of training load

External training load was quantified using GNSS technology (Apex Pro Series, 10Hz GNSS, STATSports, Newry, Northern Ireland), in accordance with the procedures outlined in Study 1 (Chapter 3). During the experimental match and training sessions, the average number of satellite signals was 18 ± 4 and the horizontal dilution of precision was 0.5 ± 0.1. Internal match load was quantified using HR sensors (Polar H10, Polar, Kempele, Finland) and sRPE, in accordance with the procedures outlined in Study 1 (Chapter 3). Based on the procedures of previous chapters (Study 1 and Study 3), the following external and internal load measures were selected: duration (min), total distance (m), distance covered > 20 km·h^{-1} (m), distance covered > 25 km·h^{-1} (m), accelerations > 3 m·s^{-2} (count), decelerations < -3 m·s^{-2} (count), maximal speed (km·h^{-1}), HR_{avg} (b·min^{-}

^{1}), HR_{peak} (b·min^{-1}), time spent > 85% HR_{max} (min), time spent > 90% HR_{max} (min), sRPE (AU) and sRPE-TL (AU).

6.3.3.2 Quantification of energy intake

Dietary intake of the breakfast preceding the training session was recorded to account for metabolites associated with the ingestion of foods (O'Gorman et al., 2013). Self-reported energy and macronutrient intakes were quantified using the RFPM (Martin et al., 2012). This method has been previously validated in adolescent team sport athletes (Costello et al., 2017) and was used in previous research conducted with youth soccer players (Hannon, Parker, et al., 2021; Stables et al., 2022). Before commencing data collection, players were instructed and familiarised via an educational workshop on the RFPM method and its associated procedures. Players had their breakfast at the club's training ground with two members of the research team present to assist players with the procedure. Players provided a photograph of their food and drink before and after consumption at breakfast preceding the experimental training and match sessions. Players were instructed to take two images (at 90 and 45 degrees) of any food or drink they consumed during the two meals pre-training and pre-match. If required, a third image was taken of any leftovers. Players were then instructed to send the images alongside a short description of the food and drink consumed to the principal researcher on a smartphone via WhatsApp messaging service (Costello et al., 2017). Dietary intakes were analysed using Nutritics (Nutritics Ltd., Dublin, Ireland) by a sports and exercise nutritionist to calculate energy and macronutrient intake for each player. Absolute and relative energy and macronutrient intakes were reported in kilocalories and grams.

6.3.3.3 Isometric posterior chain (IPC) lower-limb muscle test

Players performed three trials for each lower-limb, consisting each of 3 s maximal contraction with ~30 s of rest between trials into a force platform (ForceDecks Dual Force Plate System FD lite, VALD Performance, Newstead, Australia), similar to methods previously reported (McCall et al., 2015). ForceDecks software (VALD Performance, Newstead, Australia) was used to analyse and calculate the selected measures with a sampling rate of 1000 Hz. The IPC was executed in accordance with the procedures outlined in Study 2 and Study 3 (Chapter 4, 5). For this study players performed the IPC with their knee at 90° of flexion, with peak force dominant leg (N), peak force non-dominant leg (N), peak torque dominant leg (Nm), peak torque non-dominant leg (Nm) quantified for subsequent analyses, in accordance with the findings of Study 2 and Study 3 (Chapter 4, 5).

6.3.3.4 Countermovement jump (CMJ) test

Players performed three CMJ trials with ~20 s rest between trials on a force platform (ForceDecks Dual Force Plate System FD lite, VALD Performance, Newstead, Australia), using methods previously described (Barillas et al., 2021; McMahon et al., 2018). ForceDecks software (VALD Performance, Newstead, Australia) was used to analyse and calculate the selected measures with a sampling rate of 1000 Hz. The CMJ was executed in accordance with the procedures outlined in Study 2 and Study 3 (Chapter 4, 5). For the current study, jump height (cm), peak power (W), concentric and eccentric duration (ms), concentric and eccentric peak force (N), force at zero velocity (N) and RSI-modified ($m \cdot s^{-1}$) were quantified and used for subsequent analyses. These measures were chosen due to their suitability in the context of physical performance profiling (C. Bishop et al., 2023) and post-match fatigue monitoring in alignment with the findings from Study 2 (Chapter 4).

6.3.3.5 Visual analogue scales (VAS)

VAS for muscle soreness and fatigue was collected pre- and post-training in accordance with the procedures outlined in Study 3 (Chapter 5).

6.3.3.6 Capillary blood sampling

Fasted capillary blood samples were collected from players in the morning (8.00-8.30 am), ~2 h before the start of the training session. Post-training blood samples were obtained within ~10 minutes after the soccer activities concluded. The research team was assisted by a group of medical doctors experienced with capillary blood collection, with 4 players at a time having blood samples taken. Each capillary blood sample (300-400 µl) was drawn from the fingertip of the third finger, near the end of the capillary (middle point), with the blood collection process taking 2 to 4 minutes per player. At this site, a skin puncture was performed using a safety lancet (Sarstedt, Nümbrecht, Germany), and samples were collected using capillary micro containers (Microvette, 500 µl, Nümbrecht, Germany). These containers were inverted 10 times and allowed to clot at room temperature (20 ± 1 °C) for 30 minutes before centrifugation at 1300 x g for 10 minutes. The serum was aliquoted, and samples were then transported and immediately stored at -

80°C until analysis in a university laboratory. Upon completion of the capillary samples collection, the samples were then transported with dry ice to a second university laboratory where sample preparation took place before they were then analysed. All blood samples were processed uniformly, in line with the recommendations of a recent review on the topic (Owens and Bennett, 2024).

6.3.3.7 ^{1}H-NMR metabolomics

Sample preparation for ^{1}H-NMR metabolomics was performed according to standard protocols (Beckonert et al., 2007), with previously aliquoted serum samples thawed and diluted at 50% with 10% NMR buffer ($^{2}H_{2}0$ with 100 mM sodium phosphate buffer pH 7.4 and 0.1% azide) before centrifugation. Three hundred microlitres of the centrifuged sample was pipetted into 5 mm glass SampleJet NMR tubes (Bruker, Coventry, United Kingdom). Spectra were acquired on a Bruker 700 MHz Avance III HD spectrometer equipped with a TCI cryoprobe and chilled autosampler (Bruker, Ettlingen, Germany). Standard vendor pulse sequences were applied to collect 1D ^{1}H-NMR spectra (cpmg1dpr). A Carr-Purcell-Meiboom-Gill (CPMG) edited pulse sequence was employed to attenuate signals from macromolecules present (e.g., proteins). Serum spectra were collected at 37°C with 32 transients, tissue extract spectra were collected at 25°C with 128 transients for optimal sensitivity, with all other parameters kept constant. Throughout the spectra processing procedures, spectra were automatically pre-processed at the spectrometer by Fourier transformation, phase correction and baseline correction using standard vendor routines (apk0.noe) and referenced indirectly via the anomeric glucose signal (serum). Spectra were subjected to quality control procedures and reporting standards as recommended by Metabolomics Standards Initiative (Salek et al., 2013; Sumner et al., 2007), comprising an appraisal of baseline, linewidth, residual water signal width, phase, and signal-to-noise. Spectra were bucketed according to the peak boundaries defined with each bucket the sum of the integral for that region divided by the region width. Metabolites were annotated via metabolite recognition software, Chenomx (Chenomx v 8.2, Chenomx Ltd, Edmonton, Canada) and the respective buckets were annotated before statistical analysis. Metabolite identities were confirmed (where possible) via comparison to the in-house metabolite library

6.3.4 Statistical analysis

Descriptive data are reported as mean ± standard deviation or as mean ± 95% confidence intervals (CI). The assumption of normality was assessed using Shapiro-Wilk test.

Differences between pre- and post-training were analysed for each physical performance and perceptual measure using a paired t-test with alpha < 0.05. The magnitude of differences was computed using Hedges's *g* effect size as an additional statistic to better interpret differences. Threshold criteria for effect size statistics were interpreted as follows: *trivial* (< 0.20), *small* (0.20-0.59), *moderate* (0.60-1.19), *large* (1.20-1.99) and *very large* (> 2.0) (Hopkins et al., 2009). Statistical analyses for physical performance and perceptual measures were performed using JAMOVI statistical software (the jamovi project, version 2.3, Sydney, Australia). Metabolomics analyses were performed using the statistical software R and RStudio with scripts provided by the Computational Biology Facility at the University of Liverpool. All spectra were normalised and scaled by probabilistic quotient normalisation (PQN), and Pareto (with mean scaling) approaches, respectively, due to the robustness of PQN in the analysis of complex biofluids (Kohl et al., 2012) and the optimal ability to identify small biologically significant variations in metabolites (Smolinska et al., 2012). Multivariate and univariate analyses were employed to reveal the acute changes in metabolites from pre- to post-training, using principal component analysis (PCA) and paired Welch tests. P-values were adjusted for false discovery rate using the Benjamini-Hochberg method, with adjusted p-values < 0.05 considered significant. To gain further insight into metabolite differences following training, relative metabolite abundance was calculated.

6.4 Results

6.4.1 Training load characteristics

The experimental training session consisted of a warm-up (10 min of active mobility, running drills and preparatory movements), a 6 vs 6 ball possession game with 2 floaters and 2 goalkeepers included (20 min; pitch size: 20 x 30 m and 25 x 30 m), a linear running drill (5 min; 6 x 50 m, 10 s work, 20 s rest) and a 7 vs 7 small-sided game (25 min; pitch size: 52 x 40 m; 2 goalkeepers and regular target), for total 60-minute duration. The corresponding external and internal training loads are reported in Table 19.

6.4.2 Energy intake characteristics

Energy and macronutrient intake from the breakfast consumed after fasting blood collections are reported in Table 20.

6.4.3 Acute changes in physical performance

CMJ height (Δ: -0.7 cm; g: -0.16; $p = 0.313$) and peak power (Δ: 29.1 W; g: 0.05; $p = 0.555$) remained unchanged from pre to post-training, whilst concentric peak force was significantly reduced post-training (Δ: -102.3 N; g: -0.48; $p < 0.001$). Concentric duration, eccentric duration and RSI-modified remained also unchanged (g: ranged from -0.30 to 0.30; $p > 0.005$), whilst eccentric peak force (Δ: -155.3 N; g: -0.75; $p < 0.001$) and force at zero velocity (Δ: -147.2 N; g: -0.69; $p < 0.001$) showed significant reductions post-training. IPC peak force and torque remained unchanged in both dominant and non-dominant legs at post-training (g: ranged from -0.01 to 0.16; $p > 0.005$). The full results on the acute changes in CMJ and IPC measures are reported in Table 21 and Figure 18.

6.4.4 Acute changes in perceptual measures

Perceived muscle soreness (Δ: 0.0 cm; g: 0.00; $p = 0.947$) and perceived fatigue (Δ: 0.5 cm; g: 0.30; $p = 0.281$) remained unchanged from pre to post-training. The full results are reported in Table 21 and Figure 18.

Table 19. External and internal load characteristics of the experimental training session performed with Italian Serie A youth soccer players (n = 13).

Training load measures	Mean ± SD
External load	
Total distance (m)	5008.9 ± 439.7
Distance > 20 $km \cdot h^{-1}$ (m)	309.8 ± 49.4
Distance > 25 $km \cdot h^{-1}$ (m)	25.0 ± 18.9
Maximal speed ($km \cdot h^{-1}$)	28.1 ± 1.8
Accelerations > 3 $m \cdot s^{-2}$ (count)	53.2 ± 16.6
Decelerations < -3 $m \cdot s^{-2}$ (count)	47.6 ± 20.0
Internal load	
HR_{avg} ($b \cdot min^{-1}$)	137.5 ± 10.6
HR_{peak} ($b \cdot min^{-1}$)	183.0 ± 6.3
Time > 85% HR_{max} (min)	8.4 ± 7.0
Time > 90% HR_{max} (min)	1.1 ± 1.2
sRPE (AU)	3.3 ± 0.7
sRPE-TL (AU)	200.0 ± 43.1

Abbreviations: AU: arbitrary units; $b \cdot min^{-1}$: beats per minute; HR_{avg}: average heart rate; HR_{peak}: peak heart rate; HR_{max}: maximal heart rate; SD: standard deviation; TL: training load.

Table 20. Energy and macronutrient intake from the breakfast consumed after fasting blood sample collections in Italian Serie A youth soccer players (n = 13). Data are mean ± SD.

	Absolute intake	Relative intake
Energy intake (kcal or $klcal \cdot kg^{-1}$)	894.9 ± 176.3	12.0 ± 2.2
Carbohydrate (g or $g \cdot kg^{-1}$)	118.3 ± 27.2	1.6 ± 0.4
Protein (g or $g \cdot kg^{-1}$)	44.8 ± 16.4	0.6 ± 0.2
Fat (g or $g \cdot kg^{-1}$)	26.9 ± 12.0	0.4 ± 0.2

Abbreviations: kcal: kilocalories; kg; kilograms; g: grams.

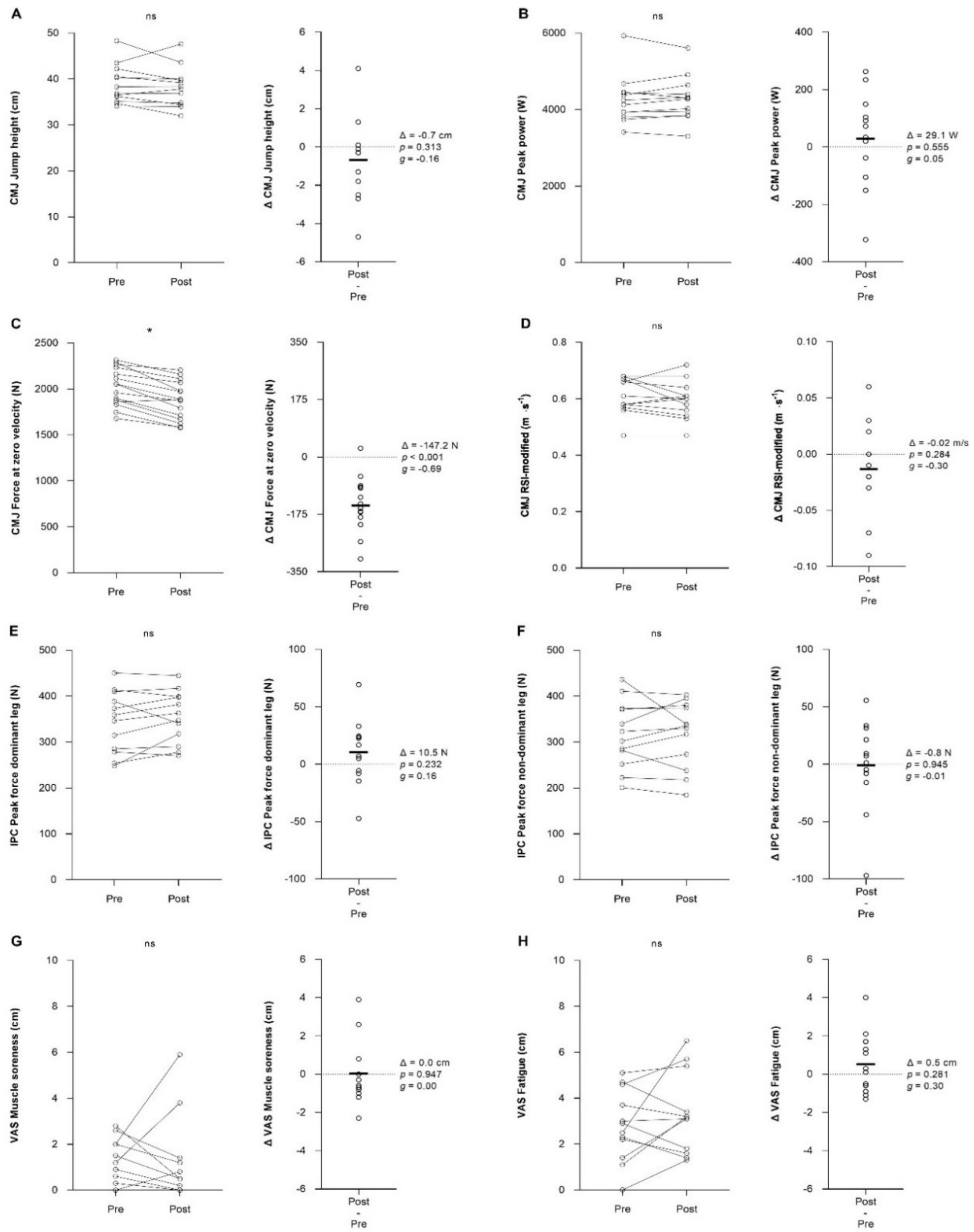

Figure 18. Individual changes, mean difference, p-value and Hedges' g effect size of physical performance (A: CMJ jump height; B: CMJ peak power; C: CMJ force at zero velocity; D: CMJ RSI-modified; E: IPC peak force dominant leg; F: IPC peak force non-dominant leg) and perceptual measures (G: VAS muscle soreness; H: VAS fatigue) to a training session in Italian Serie A youth soccer players. Significant pre to post-changes are reported with * ($p < 0.05$), whilst non-significant changes with ns ($p > 0.05$). Abbreviations: CMJ: countermovement jump; RSI: reactive strength index; IPC: isometric posterior-chain; VAS: visual analogue scale; Δ: mean change.

Table 21. Acute changes to training in physical performance and perceptual measures in Italian Serie A youth soccer players (n = 13). Data are mean ± SD or as mean (95% CIs).

	Pre	Post	Pre vs Post		
			Δ (95% CI)	**p-value**	**Hedge's *g* (95% CI)**
Countermovement jump test					
Jump height (cm)	38.9 ± 4.2	38.2 ± 4.4	-0.7 (-2.0; 0.7)	0.313	-0.16 (-1.01; 0.69)
Peak power (W)	4254.4 ± 638.7	4283.4 ± 589.5	29.1 (-76.1; 134.2)	0.555	0.05 (-0.80; 0.89)
Concentric duration (ms)	246.8 ± 30.8	249.4 ± 34.3	2.5 (-4.1; 9.1)	0.416	0.08 (-0.77; 0.92)
Eccentric duration (ms)	422.6 ± 36.8	434.5 ± 40.5 ^{S}	11.9 (-1.7; 25.6)	0.081	0.30 (-0.55; 1.15)
Concentric peak force (N)	2075.6 ± 200.7	1973.3 ± 209.7 ^{*S}	-102.3 (-153.0; -51.6)	< .001	-0.48 (-1.34; 0.38)
Eccentric peak force (N)	2085.4 ± 201.4	1930.1 ± 200.6 ^{*M}	-155.3 (-213.5; -97.1)	< .001	-0.75 (-1.62; 0.13)
Force at zero velocity (N)	2063.0 ± 206.4	1915.8 ± 201.4 ^{*M}	-147.2 (-204.2; -90.2)	< .001	-0.69 (-1.56; 0.18)
RSI-modified ($m \cdot s^{-1}$)	0.61 ± 0.06	0.59 ± 0.07 ^{S}	-0.02 (-0.04; 0.02)	0.284	-0.30 (-1.15; 0.56)
Isometric posterior chain lower-limb muscle test					
Peak force dominant leg (N)	343.5 ± 67.0	354.0 ± 56.7	10.5 (-7.8; 28.9)	0.232	0.16 (-0.68; 1.01)
Peak force non-dominant leg (N)	316.5 ± 73.0	315.7 ± 72.2	-0.8 (-26.2; 24.5)	0.945	-0.01 (-0.86; 0.84)
Peak torque dominant leg (Nm)	137.0 ± 29.2	141.1 ± 25.1	4.1 (-3.2; 11.4)	0.241	0.15 (-0.70; 0.99)
Peak torque non-dominant leg (Nm)	126.2 ± 30.8	125.9 ± 30.7	-0.3 (-10.6; 10.0)	0.951	-0.01 (-0.86; 0.84)
Perceptual measures					
Muscle soreness (cm)	1.2 ± 1.0	1.2 ± 1.8	0.0 (-1.0; 1.1)	0.947	0.00 (-0.81; 0.81)
Fatigue (cm)	2.8 ± 1.5	3.3 ± 1.7 ^{S}	0.5 (-0.5; 1.5)	0.281	0.30 (-0.55; 1.15)

Abbreviations: Δ: mean change; CI: confidence intervals; RSI: reactive strength index; SD: standard deviation.

* significant change from Pre ($p < 0.05$).

S: small; M: moderate; L: large effect sizes compared with Pre. Trivial effect sizes are not reported.

6.4.5 Acute changes in serum metabolome

A total of 54 unique metabolites were identified from 141 spectral bins across the ^{1}H-NMR spectra of the human serum. Where multiple bins represented one metabolite, a single representative bin for each metabolite was identified via in-house criteria determined by correlation reliability score. Unsupervised multivariate analysis of serum metabolomes between pre- and post-training was conducted to identify whether any underlying structures in the data were present, and a possible separation between pre- to post-training was noted as preliminary analysis (Figure 19). In addition, univariate analysis revealed differences in serum metabolome post-training, with 21 metabolites significantly changed at post-training. Five metabolites increased (lactate, alanine, isoleucine, tyrosine and 3-hydroxisobutyrate) and sixteen metabolites decreased (3-methylhistidine, asparagine, glutathione, glycine, kynurenine, N-acetyl lysine, N-acetyl tyrosine, tryptophan, acetate, CH3 mobile lipids, glycholate, HDL 2, HDL 3, phosphatidylcholine, glycoprotein A, glycoprotein B). Activation of muscle energy metabolism was evident via glycolysis, tricarboxylic acid cycle and gluconeogenesis. The complete list of 54 metabolites identified from the human serum and their acute changes to training are reported in Table 22, whereas the 21 significantly changed metabolites are depicted in Figure 20.

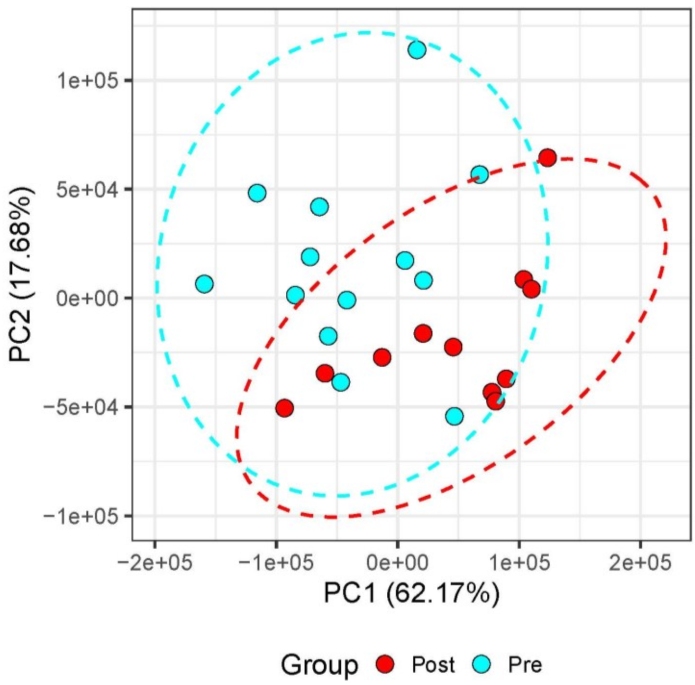

Figure 19. Multivariate principal component analysis (PCA) of the human serum pre- and post-training in Italian Serie A youth soccer players (pre: n = 13; post: n = 11). Ellipses represent the 95% confidence region.

Table 22. List of the 54 unique metabolites identified from the human serum and their acute changes to a training session in Italian Serie A youth soccer players.

Metabolite	**95% CI Mean**	**Unadjusted p-value**	**Benjamini-Hochberg p-value**	**Bonferroni p-value**		**Direction of change**
3-Hydroxybutyrate	(-0.08816; 49.57608)	0.051	0.103	1.000		
3-Hydroxyisoburate	(-84.17313; -23.6962)	0.002	0.012	0.118	*	↑
3-Hydroxykynurenine phenyalanine	(-1.56899; 27.40198)	0.078	0.150	1.000		
3-Methylhistidine	(11.46954; 102.81183)	0.017	0.047	0.935	*	↓
Acetate	(49.35108; 160.92545)	0.001	0.007	0.050	*	↓
Acetoacetate	(-50.43776; 43.45157)	0.877	0.894	1.000		
Acetone	(-214.91542; -0.74001)	0.049	0.103	1.000		
Alanine	(-196.30941; -56.64468)	0.001	0.008	0.068	*	↑
Arginine	(-33.84846; 39.69168)	0.870	0.894	1.000		
Asparagine	(16.13779; 52.8695)	0.001	0.007	0.042	*	↓
Caffeine	(-44.99425; 83.85797)	0.538	0.645	1.000		
CH Unsaturated mobile lipids	(-7.90985; 86.18052)	0.099	0.172	1.000		
CH3 Mobile lipids	(74.23368; 303.74403)	0.003	0.012	0.134	*	↓
Cholate	(-11.43729; 20.70539)	0.554	0.650	1.000		
Citrate	(-63.34165; 0.2533)	0.052	0.103	1.000		
Creatine	(-141.21225; 45.31178)	0.294	0.396	1.000		
Creatinine	(-33.37462; 45.43886)	0.753	0.797	1.000		
Formate	(-4.75402; 48.70145)	0.099	0.172	1.000		
Glucarate	(-6.27956; 44.98296)	0.131	0.209	1.000		
Glucose 114	(-79.19029; 76.19208)	0.968	0.968	1.000		
Glucose 75	(-112.70535; 67.01316)	0.602	0.677	1.000		
Glutamate	(-45.9834; 24.35677)	0.526	0.645	1.000		
Glutathione	(28.65457; 82.82086)	0.000	0.004	0.020	*	↓
Glycholate	(70.26291; 165.71687)	0.000	0.001	0.002	*	↓
Glycine	(38.38735; 213.25848)	0.007	0.023	0.369	*	↓
Glycoprotein A	(114.77575; 254.55197)	0.000	0.000	0.001	*	↓
Glycoprotein B	(56.96091; 193.32762)	0.001	0.008	0.062	*	↓
Glycylproline	(-9.88694; 95.07187)	0.107	0.174	1.000		
HDL	(-301.32917; 85.35942)	0.258	0.366	1.000		
HDL 2	(61.65073; 400.70284)	0.010	0.031	0.529	*	↓
HDL 3	(161.40782; 319.31478)	0.000	0.000	0.000	*	↓
Histidine	(-9.96146; 35.13334)	0.256	0.366	1.000		
Isoleucine	(-101.48078; -10.24367)	0.019	0.050	1.000	*	↑
Isopropanol	(-8.57958; 56.07161)	0.140	0.216	1.000		
Kynurenine	(7.42163; 34.56683)	0.004	0.017	0.219	*	↓

Metabolite	95% CI Mean	Unadjusted p-value	Benjamini-Hochberg p-value	Bonferroni p-value		Direction of change
Lactate	(-266.47646; -61.25055)	0.004	0.017	0.238	*	↑
LDL	(22.27642; 287.59538)	0.024	0.059	1.000		
Leucine	(-26.54785; 112.62886)	0.211	0.316	1.000		
Lysine	(9.08513; 123.76194)	0.025	0.059	1.000		
Methionine	(-22.56979; 35.75848)	0.641	0.693	1.000		
Myoinositol	(-14.67927; 169.87984)	0.093	0.172	1.000		
N-Acetyl lysine	(64.2734; 121.16448)	0.000	0.000	0.000	*	↓
N-Acetyl tyrosine	(5.72187; 28.0312)	0.005	0.017	0.259	*	↓
Phenylalanine	(-23.67653; 7.401)	0.288	0.396	1.000		
Phosphatidycholine	(10.47407; 92.08581)	0.016	0.046	0.872	*	↓
PUFA 18.02	(-32.26536; 68.48863)	0.463	0.581	1.000		
PUFA not 18.02	(-22.64803; 50.76773)	0.436	0.560	1.000		
Saccharopine	(-45.94637; 26.57182)	0.585	0.672	1.000		
Serotonin	(-29.48701; 17.92615)	0.615	0.678	1.000		
Triglyceride	(-6.65987; 64.87148)	0.106	0.174	1.000		
Tryptophan	(8.14055; 33.88031)	0.003	0.012	0.146	*	↓
Tyrosine	(-57.15494; -6.62721)	0.016	0.046	0.851	*	↑
Valine	(-98.74416; 39.72032)	0.384	0.506	1.000		
VLDL	(-229.99386; -8.44643)	0.037	0.083	1.000		

Abbreviations and note: * indicates a significant change from pre- to post-training (Benjamini-Hochberg p-value of < 0.05); ↑ indicates a significant increase in a metabolite concentration; ↓ indicates a significant decrease in a metabolite concentration.

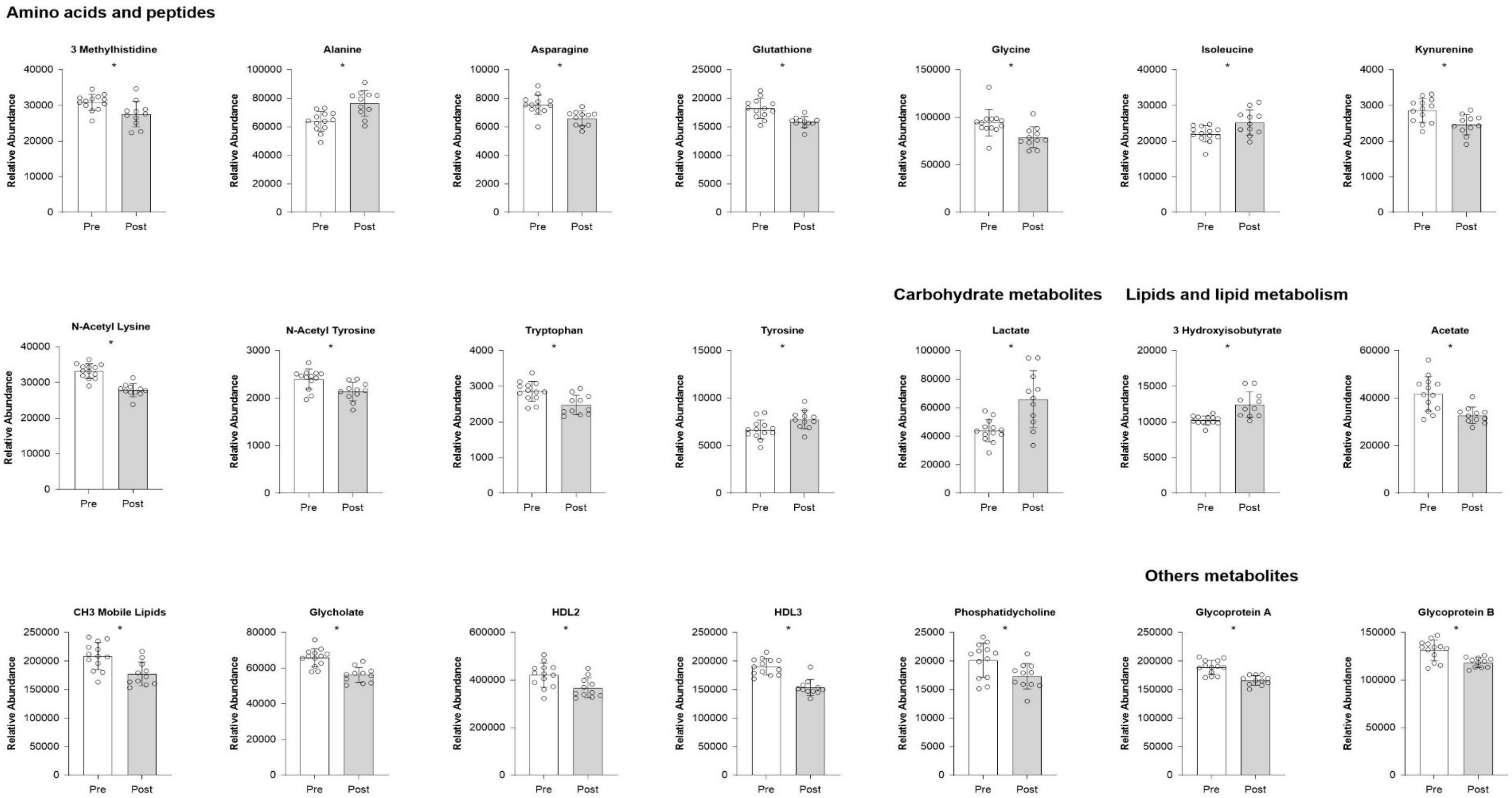

Figure 20. Acute changes in the relative abundance of the 21 serum metabolites significantly changed post-training in Italian Serie A youth soccer players (n = 13). White bars represent pre-training data, grey bars represent post-training data. Individual responses are depicted with dots. Abbreviations: * denotes significant change from pre- to post-training ($p < 0.05$).

6.5 Discussion

This study aimed to characterise the acute responses to a training session by combining multiple responses to load measures in Italian Serie A youth soccer players. While previous research has explored metabolite alterations in response to soccer training and match-play (Pedroso et al., 2025), this study is the first to integrate physical performance, metabolomic and perceptual measures to comprehensively characterise the responses in high-level youth soccer players. The main findings indicated that the training session did not induce substantial reductions in physical performance and perceptual status, except for significant decrements in CMJ force at zero velocity, CMJ eccentric and concentric peak force (*small* to *moderate* effect size). Conversely, metabolomics analysis revealed significant changes in 21 metabolites in the serum sample, indicating alterations in energy production, amino acid metabolism, and lipid metabolism, including glycolysis, the tricarboxylic acid cycle, and gluconeogenesis to meet the training demands. Additionally, we controlled the energy intake from the meal preceding the experimental session and quantified the training load to contextualise the results better. The quantification of training load suggested that players sustained a moderate-intensity session (sRPE: 3.3 ± 0.7 AU). The HR internal load highlighted that ~14% of training time was spent > 85% HR_{max}, with HR_{peak} reaching 183.0 ± 6.3 $b \cdot min^{-1}$. When compared with the typical match demands quantified in Study 1 (Chapter 3), the external training loads of the experimental session represented ~40% of total distance and HSR distance (> 20 $km \cdot h^{-1}$), and ~50% of acceleration and deceleration demands. Finally, the energy and macronutrient intake assumed in the meal before training met the energy recommendations for youth soccer players (Hannon, Close, et al., 2020).

The demands of the training session induced limited changes in most of the physical performance measures investigated. Only the CMJ concentric and eccentric peak force, and force at zero velocity showed significant alterations, with *small* to *moderate* effect sizes. The remaining CMJ outcome measures and movement strategy measures showed no change at post-training, with *trivial* to *small* effect sizes. The fact that outcome measures such as jump height were unchanged following the training session agrees with previous studies conducted with youth soccer players (Deely et al., 2022; Gantzer et al., 2024; Malone, Murtagh, et al., 2015; Ruf et al., 2022). For instance, Malone et al. (2015) demonstrated that CMJ height was unaffected following training sessions of an in-season microcycle in under-18 high-level youth soccer players, reporting mean changes of 0.5 cm (-2%) post-training. Similarly, Deely et al. (2022) observed no changes in CMJ height in response to a high-intensity training session in under-18 youth soccer players, whilst Ruf et al. (2022) recorded similar results in response to two days of training load accumulation in under-15 youth soccer players. Furthermore, CMJ height also demonstrated a poor relationship with daily fluctuations in training load in English Premier League soccer players, supporting the notion that jump height might not be a sensitive measure for capturing acute training-related fatigue (Thorpe et al., 2015).

Differently, the observed changes in the CMJ measures during the eccentric phase of the jump (eccentric peak force, eccentric peak velocity and force at zero velocity) provided a detailed insight into the acute response to training. Significant reductions were observed for eccentric peak force and force at zero velocity, with *moderate* reductions of ~7% compared to pre-training status. Previous research has shown that CMJ eccentric force is markedly reduced following soccer match-play in high-level youth soccer players from the English Premier League and Spanish La Liga (de Hoyo et al., 2016; Springham et al., 2024). In addition, in Study 2 (Chapter 4), eccentric phase measures (also known as the braking phase of the CMJ) were demonstrated to be more sensitive to change immediately after a youth soccer match-play compared to typically reported outcome measures. Moreover, Ellis et al. (2022) identified that braking phase force-time measures displayed a higher probability of change in response to pre-season training in youth soccer players than jump height. Overall, the analysis of the eccentric force-time components of the CMJ regularly displays reductions in force and alterations in time, which might be associated with the onset of acute neuromuscular fatigue and altered SSC function following moderate to intense activities (Gathercole et al., 2015).

Along with the limited reduction observed in CMJ performance, hamstring isometric force capacity was not reduced following training, with *trivial* changes in all IPC peak force and torque measures of the dominant and non-dominant leg. The absence of significant changes in response to training likely reflects the low HSR (mean distance > 20 $km \cdot h^{-1}$: 310 m) and sprinting (mean distance > 25 $km \cdot h^{-1}$: 25 m) demands of the experimental training session compared to match demands and high-intensity training sessions. This outcome agrees with previous research conducted on youth soccer players, which observed no changes in hamstring function following a training session (Gantzer et al., 2024). A smaller magnitude of fatigue in hamstring muscles was observed following high-intensity intermittent training and sprinting training compared to simulated match-play (Massamba et al., 2024). In addition, Martínez-Serrano et al. (2022) showed a significant decrease in hamstring muscle function following a "high-load" HSR training session compared to a “low-load” session in youth soccer players. A systematic review of soccer players suggested that HSR was highly correlated with acute post-match fatigue of hamstring muscle function (Hader et al., 2019) and that hamstring neuromuscular function displayed more severe changes in maximal voluntary contraction and potentiated twitch force compared to the quadricep muscle group in response to youth soccer match-play (Massamba et al., 2024). Overall, a greater magnitude of changes in hamstring strength is typically observed up to 48-72 h following high-volume maximal sprinting speed protocols (Carmona et al., 2025) and competitive matches for both youth and senior soccer players (Carmona et al., 2024; Constantine et al., 2019), highlighting the acute effect of posterior-chain muscle force capacity in response to soccer activities with high involvement of hamstring muscles.

No significant changes were reported in perceived muscle soreness and fatigue following the training session, suggesting that the physical demands of the session did not alter the perceptual state of youth soccer players. Overall, the training load sustained by youth soccer players during the single experimental session was rated as “moderate” (sRPE: 3.3 ± 0.7 AU), with external training volume and intensities similar to the “medium load” days endured across the competitive microcycle by under-19 Italian youth soccer players as documented in Study 1 (Chapter 3) or to typical daily training loads in under-18 English youth soccer players (Malone, Murtagh, et al., 2015). In contrast with our results, Deely et al. (2022) reported significant alterations in perceived fatigue and muscle soreness immediately after and in the day following a youth soccer training session, before recovering 48 h post. However, these differences appear to be due to the greater training demands in Deely’s research, with youth players completing a 100-minute training session characterised by ~7500 m of total distance covered and an sRPE of 8 AU. Similarly, monitoring of subjective recovery status following youth soccer match-play demonstrated altered perceptions of perceived recovery from pre-match to post-match and a return to baseline within 24 h post-match (Paul et al., 2019). Despite the growing use of AROMs in competitive sports (Saw et al., 2016), it has been suggested that subjective measures may have limited sensitivity in quantifying fatigue response to training and match with variations in response to load within the day-to-day variability (Fitzpatrick, Akenhead, et al., 2019; Ruf et al., 2022). This may be due to the unique characteristics of adolescent players and to the additional stressors, including school commitment and social pressure, they experience in addition to sport-specific stress, which can potentially impact the perception of fatigue and recovery. Given the short-term relationship between load and subjective acute responses in soccer (Brauers et al., 2025), it has been recommended to establish the measurement characteristics of the athlete-reported outcome measures to evaluate their use within different sports populations (Jeffries et al., 2020).

In addition to the integration of multiple measures to assess training responses, this study introduces novel aspects, including the use of capillary blood sampling from the fingertips and the subsequent application of metabolomics in high-level youth soccer players. Capillary blood samples were analysed using ^{1}H-NMR spectroscopy, detecting 54 distinct metabolites and revealing significant perturbations to the serum metabolome following the training session in 21 metabolites. Furthermore, PCA analysis (Figure 19) indicated a possible separation between pre- and post-training samples. However, it should be noted that PCA is an exploratory technique that identifies patterns within the metabolomics data but does not provide inferential evidence of statistically significant group differences (Owens and Bennett, 2024). Indeed, this study represents one of the first attempts to use capillary rather than venous blood sampling in combination with metabolomics in this population, offering a less invasive and more accessible alternative. To date, only one pilot study has applied this method in the context of high-level youth soccer, underscoring its potential utility (Sullivan, 2022). Compared to conventional single-metabolite assays (e.g., lactate monitoring), metabolomics provides a more comprehensive understanding of the metabolic pathways activated in response to sport and exercise stimuli through the large-scale identification, quantification, and characterisation of metabolites in biological fluids (Owens and Bennett, 2024). However, the logistical challenges associated with collecting multiple measures in a real-world setting limited the feasibility of implementing more advanced study designs, such as the inclusion of a control group to account for circadian variation or comparisons across different training regimes.

The observed changes in metabolite concentrations collectively indicated the activation of muscle energy metabolisms, including both anaerobic and aerobic pathways. From a physiological standpoint, muscle glycogen, blood glucose, and fatty acids serve as the primary substrates for energy production. Their relative contribution is largely determined by exercise intensity and duration, with carbohydrate oxidation prevailing at higher intensities and fat oxidation at lower intensities (Hargreaves and Spriet, 2020). Additionally, influencing factors such as training status, nutrition and environmental conditions can also influence substrate utilisation and exercise metabolism (Bennett et al., 2023; Hudson et al., 2021). Increased concentrations at post-training were observed in carbohydrate metabolites (lactate), amino acids and peptides (alanine, isoleucine, tyrosine), and lipids (3-Hydroxyisobutyrate). Conversely, a range of amino acids and peptides, and other metabolites were significantly decreased post-training. These results suggest that soccer-specific activities cause a flux in many energy metabolism reactions, with subsequent alterations in the blood concentration of metabolites involved in these reactions. Therefore, the observed change reflects the mobilisation, utilisation and conversion of energy metabolites, including carbohydrates and lipids to meet the ATP demands (Schranner et al., 2020). Specifically, the energy demands of the experimental session stimulated glycolysis, tricarboxylic acid cycle and gluconeogenesis to maintain the required rates of ATP resynthesis during the session, with alterations in the concentration of metabolites involved in energy metabolism.

Lactate concentration significantly increased post-training, likely reflecting an accelerated rate of glycolysis and the consequent accumulation of this metabolite in the muscle and blood in response to high-intensity exercise (Hargreaves and Spriet, 2020). Although in soccer the majority of energy provision is derived from aerobic metabolism, the contribution of anaerobic pathways becomes substantial during high-intensity actions preceding goal opportunities (Faude et al., 2012; Stølen et al., 2005). Monitoring blood lactate concentrations represents a practical strategy for estimating the anaerobic metabolism of soccer, with peak concentrations of 10-12 $mmol \cdot L^{-1}$ documented during competitive matches (Krustrup et al., 2006). Elevated blood lactate levels were also observed in response to soccer match-play (Aslan et al., 2012) and speed endurance training sessions (Ade et al., 2020) in youth soccer players. Previous metabolomics investigations have reported increased concentrations of carbohydrate metabolites and tricarboxylic acid cycle intermediates following soccer activities, including increases in lactate, citrate and glucose concentrations (Hudson et al., 2021; Sullivan, 2022). In the present research, the observed rise in lactate concentration may be attributed to the high-intensity nature of the final drill in the experimental session, which consisted of 25 min of 7 vs 7 small-sided games. However, the session training load was lower than in prior research, potentially explaining the comparatively modest changes observed in other carbohydrate metabolites (e.g., glucose).

Apart from its role in substrate-level phosphorylation, lactate is also considered an important metabolic intermediate for oxidative metabolism, a gluconeogenic precursor and a signalling molecule (Brooks, 2020). In parallel with the rise of glycolytic metabolite abundance, alanine was also significantly increased post-training, likely reflecting enhanced gluconeogenesis to support glycolytic flux and meet the energy demand of the experimental session. Alanine plays a key role in muscle energy metabolism by transporting nitrogen to the liver, where it is converted into pyruvate and used to produce glucose (Hargreaves and Spriet, 2020). This glucose is then delivered back to the muscle to support the energy supply throughout the glucose-alanine cycle (Ishikura et al., 2013). Similar findings have been reported in applied exercise physiology research with metabolomic analysis of high-intensity soccer training and rugby match-play (Hudson et al., 2021; Sullivan, 2022), with acute increases of alanine abundance within serum samples.

Significant alterations to circulating amino acids were also observed at post-training, with metabolite changes occurring in different directions (e.g., an increase in isoleucine concentration and a decrease in valine concentration). A possible reason for these changes occurring in different directions could be related to the role of amino acids in multiple reactions (Schranner et al., 2020). For example, when amino acids are used as substrates for oxidative phosphorylation, gluconeogenesis and ketogenesis, their concentration will be lowered. Conversely, when proteins are ingested, concentrations of amino acids will increase (Schranner et al., 2020). Indeed, amino acids are frequently associated with aerobic energy production pathways, and various changes in circulating amino acids occur to meet the physiological demands of training or competition (Ishikura et al., 2013). Although amino acid oxidation and protein breakdown are enhanced during exercise, their contribution to energy production is typically low (Hargreaves and Spriet, 2020). Apart from alanine, increased concentrations of isoleucine and tyrosine were also observed. An increase in tyrosine indicates that muscle protein breakdown is typically observed following prolonged exercise, with the release of tyrosine into circulation (Ishikura et al., 2013). Similar to previous research outcomes, this rise in tyrosine can be associated with the conversion of phenylalanine into tyrosine during training, as a consequence of such protein breakdown (Hudson et al., 2021; Sullivan, 2022). Conversely, a number of amino acids and peptides decreased following training, including 3-Methylhistidine, asparagine, glutathione, glycine, kynurenine, N-Acetyl lysine, N-Acetyl tyrosine and tryptophan. Overall, these outcomes align with prior metabolomics research suggesting that essential amino acids can exhibit different directions of changes following exercise (Schranner et al., 2020). For example, a decrease in glutathione and glycine concentration following training was also reported in a similar study conducted with high-level youth soccer players (Sullivan, 2022), suggesting oxidative stress and their utilisation to meet the energetic demands of training. In addition, the decreased concentrations of lipids and lipid metabolism intermediates may suggest a shift toward using lipids and amino acids as energy sources.

These findings suggest the importance of meeting the daily energy requirements through appropriate fuelling and recovery practices, particularly before and after training. Given the well-documented role of energy and macronutrient availability in promoting performance (e.g., training intensity and volume) and development (e.g., growth and maturation), it is essential to avoid under-consumption of carbohydrate and protein often observed in high-level youth soccer players (Stables et al., 2024). Within this context, the application of biomarker monitoring may reveal individual recovery and nutritional needs in adolescent soccer players during rapid periods of growth. Considering the small sample size and the exploratory nature of this chapter, it is important to further explore this area to understand the specific nutritional and recovery considerations within this population.

Despite the attempt to integrate multiple measures to profile acute responses to soccer training in high-level youth soccer players, this study has several limitations that must be acknowledged. Firstly, we assessed acute responses to a single training session in a small sample of players. It is important to acknowledge that the mismatch in the timing of capillary blood sampling (~10 minutes post-training) and physical performance testing (~30 minutes post-training) may have influenced the study outcomes. This temporal discrepancy may partially explain the greater magnitude of alterations detected in the serum metabolome relative to the limited variations observed in physical performance. While this simple design provided valuable information, the practical constraints of collecting a range of measures (e.g., physiological, performance and subjective) limited our ability to explore responses across sessions with varying training loads or post-match conditions. These comparisons would have offered a more comprehensive profiling and understanding of how different soccer demands affect metabolic stress, physical performance capacity, and perceptual responses within this population. In addition, including a control group could have helped account for naturally occurring circadian variations (Ayala et al., 2021) and should be considered in future research to strengthen the interpretation of results. Secondly, blood samples were collected using the capillary technique rather than the more commonly used venous sampling method. While this approach was more feasible within the applied context of the study, its validity for metabolite identification remains to be fully established. In our study, 54 metabolites were identified from the serum samples, whereas other studies employing venous sampling have reported a higher number of detectable metabolites (Alzharani et al., 2020). This discrepancy highlights the need for further investigation into the validity, reliability and sensitivity of capillary sampling for metabolomic profiling. Thirdly, metabolite analysis was performed using untargeted NMR metabolomics, which is considered less sensitive than the MS-based technique and may fail to detect very low concentrations (Owens and Bennett, 2024). Finally, as nutritional and hydration status greatly influence metabolomic responses to training, it is critical to quantify and control energy intake. Although we quantified energy intake, it was not standardised across all players, which may have impacted, to a certain degree, the acute changes in serum metabolome (e.g., changes in glucose abundance).

6.6 Conclusion

This study demonstrated that a moderate-intensity soccer training session elicited limited changes in physical performance and perceptual responses, whilst inducing significant perturbations in the serum metabolome in high-level youth soccer players. The integration of multiple measures of training response revealed that physical performance, perceptual fatigue and muscle soreness remained stable, with only minor reductions observed in CMJ eccentric peak force, force at zero velocity, and concentric peak force. However, alterations in metabolite concentrations were observed, particularly in metabolic pathways related to energy production, including glycolysis, tricarboxylic acid cycle and gluconeogenesis. Understanding how training affects internal responses whilst not resulting in changes in performance capacity helps to elucidate the dose-response relationship and inform more effective training and recovery strategies in high-level youth soccer.

7.1 Synthesis

The purpose of this chapter is to synthesise the main findings of this thesis in relation to the original aim and objectives outlined in Chapter 1. It presents a general discussion of the key outcomes, including the integrated monitoring of external and internal load, the multifaceted nature of fatigue and recovery responses, and the use of training load manipulation as a key intervention to support the recovery process in the days post-match. Finally, it highlights limitations, offers recommendations for future research and outlines practical applications, with a particular focus on how these findings enhance the understanding of training load and its responses in Italian Serie A youth soccer players.

7.2 Accomplishment of Aims and Objectives

This thesis aimed to investigate training load, acute fatigue and post-match recovery responses of Italian Serie A youth soccer players. It was hoped that the findings and information derived from this thesis would assist towards a greater understanding of how high-level youth soccer players from the Italian Serie A train, respond acutely to training and match load, and recover in the days following match-play. Ultimately, this work aimed to improve sporting performance using applied research that addresses relevant performance-related questions (Bishop, 2008). This aim was achieved through the completion of four applied research studies conducted in Chapters 3, 4, 5 and 6. An overview of each objective is provided in this section, whilst a summary of the experimental methods employed in the thesis is reported in Table 23.

Objective 1: To quantify external and internal training and match loads in multiple age groups throughout a competitive season in Italian Serie A youth soccer players.

This objective was achieved through the completion of Study 1 (Chapter 3). Weekly accumulated training loads exhibited a progressive increase along the academy development pathway. Late-stage youth soccer players (under-19 and under-17) trained with higher session frequency, greater external load and sRPE-TL in comparison to their younger counterparts (under-16 and under-15) ($p < 0.05$). Conversely, under-15 players displayed higher HR training loads ($p < 0.05$). Periodisation of daily load across the microcycle was evident in late-stage youth soccer players, contrasting with the less pronounced loading distribution observed in the younger counterparts. On MD Italian Serie A youth soccer players experienced the greatest load of the microcycle, while on the last training session before competition (MD-1 or MD-2), the lowest load of the microcycle ($p < 0.05$). MD-5 and MD-3 sessions emerged as the most physically demanding training days compared to all the other ones of the microcycle ($p < 0.05$). During congested microcycles, under-19 players' training loads decreased on MD-2 compared to non-congested weekly microcycles ($p < 0.05$). The quantification of training and match load served as the foundation for better contextualising fatigue and recovery in the subsequent studies.

Objective 2: To quantify reliability and examine sensitivity to change in physical performance measures used to assess fatigue and recovery following match-play in Italian Serie A youth soccer players.

This objective was achieved through the completion of Study 2 (Chapter 4). Most of the physical performance measures demonstrated acceptable levels of absolute reliability (CVs ranged from 1.5 to 8.8%), and *moderate* to *excellent* levels of relative reliability (ICCs ranged from 0.70 to 0.98). Although a wide range of IPC and CMJ measures showed significant alterations from pre- to post-match ($p < 0.05$; g: *small* to *moderate*), our findings showed that IPC peak force and torque, CMJ RSI-modified, CMJ eccentric measures (mean braking force, mean deceleration force, peak force and force at zero velocity) and CMJ mean power displayed post-match changes greater than their typical variation (i.e., > 1.5 TE). Conversely, typically reported CMJ measures such as jump height and peak power showed limited sensitivity in detecting post-match changes. The assessment of reliability alongside the examination of sensitivity to change permitted the identification of suitable measures for monitoring fatigue and recovery responses in physical performance in the subsequent studies.

Objective 3: To describe the time course of recovery post-match and examine the effects of manipulating training volume 48 hours following match-play in Italian Serie A youth soccer players.

This objective was achieved through the completion of Study 3 (Chapter 5). Having described the acute post-match changes in Chapter 4, Study 3 provided information on the time course of recovery following match-play using physical performance and subjective measures. The analysis of the time course of recovery revealed that an 80-minute youth soccer match significantly impaired physical performance and perceptual recovery both immediately and in the subsequent days, with variations in recovery patterns among indicators. CMJ performance and perceived fatigue returned to baseline levels 48 h post-match ($p > 0.05$), whereas hamstring muscle force capacity and perceived muscle soreness had not fully recovered by that time ($p < 0.001$). Given the results on the periodisation of training load observed in Study 1, the second analysis of Study 3 examined the impact of training load applied 48 h post-match by comparing the effects of a CT session (100-minute; high training volume) and an RT session (70-minute; moderate training volume). A significant interaction was observed for CMJ height and IPC measures ($p < 0.05$), with reductions in physical performance observed in the CT group from 48 h to 72 h post-match ($p < 0.05$). Conversely, no changes were observed in the RT group ($p > 0.05$). A high-volume training session administered 48 h post-match may negatively influence physical performance, whilst a moderate training session may support the recovery process without further impairment of performance. These findings suggested the importance of monitoring readiness to train and managing players' training load in the days following a match.

Objective 4: To characterise the acute responses to training in physical performance, metabolic and perceptual measures in Italian Serie A youth soccer players.

This objective was achieved through the completion of Study 4 (Chapter 6). Building on the previous chapters, where acute fatigue and recovery responses were examined following match-play, Study 4 described acute fatigue responses to a typical training session in Italian Serie A youth soccer players by integrating physical performance, metabolic and perceptual measures. The results showed that a moderate-intensity training session elicited minimal changes in physical performance, perceptual fatigue and muscle soreness at post-training ($p > 0.05$), with reductions limited to CMJ eccentric and concentric peak forces. However, metabolomics analysis using capillary blood revealed significant alterations in 21 metabolites ($p < 0.05$), with increased concentration of lactate, alanine, isoleucine, tyrosine and 3-hydroxisobutyrate, alongside decreased abundance in 16 other metabolites, including markers related to amino acid and lipid metabolism. This metabolic shift indicated activation of key energy pathways, including glycolysis, tricarboxylic acid cycle and gluconeogenesis. These findings suggested that integrating multiple measures may enhance the understanding of physiological and neuromuscular responses to training.

Table 23. Summary of the studies completed for this thesis, outlining the experimental methods used and the link between studies.

Study (Chapter)	Title	Training	Match	Training loads and energy intakes			Fatigue and recovery responses		Type of fatigue and recovery measures		
				External load	Internal load	Energy intake	Fatigue	Recovery	Perf.	Phys.	Subj.
Study 1 (Chapter 3)	Training loads and microcycle periodisation in Italian Serie A youth soccer players	×	×	×	×						
Study 2 (Chapter 4)	Reliability and sensitivity to change of post-match physical performance measures in Italian Serie A youth soccer players		×	×	×		×		×		
Study 3 (Chapter 5)	Post-match fatigue and recovery responses in Italian Serie A youth soccer players: effects of manipulating training volume 48 hours after a match		×	×	×		×	×	×		×
Study 4 (Chapter 6)	Acute fatigue responses to training in physical performance, metabolic and perceptual measures in Italian Serie A youth soccer players	×		×	×	×	×		×	×	×

Abbreviations and notes: Fatigue responses include measurements performed pre and immediately post-training or match (e.g., 0.5 h post); Recovery responses also include measurements performed in the days following training or match (e.g., 48h post, 72h post); Perf.: Performance measures; Phys.: Physiological measures; Subj.: Subjective measures

7.3 General Discussion

This thesis investigated training loads, acute fatigue and post-match recovery responses in Italian Serie A youth soccer players. This is the first research project to concurrently examine training load and its associated responses within this cohort of high-level adolescent soccer players. In this section, the main findings of this thesis are discussed in the context of the conceptual framework of physical training presented in the literature review (Figure 2), with particular emphasis on how these findings inform the construct of training load (i.e., external and internal components), the responses to load (i.e., acute and chronic training effects) and performance outcomes (i.e., increase, decrease or no change) in Italian Serie A youth soccer players.

7.3.1 External and internal training load characteristics of Italian Serie A youth soccer players

Before exploring acute responses to training and match load in this thesis, the examination of the habitual external and internal load sustained and experienced by Italian Serie A youth soccer players was needed. Training load monitoring enables practitioners to control training and competition stimuli and determine if internal responses are progressing as intended, or adjustments to the program are required (Coutts et al., 2018; Impellizzeri et al., 2019; Jeffries et al., 2022). Given the youth soccer context, systematic planning, monitoring and manipulation of the training stimulus is recommended to support performance development and reduce the likelihood of negative outcomes (McBurnie et al., 2021). Despite the widespread use of training monitoring systems among professional academies (Salter et al., 2021), prior to the completion of Study 1 (Chapter 3), limited research investigated the typical training and match demands using both external and internal load measures within this population.

In Study 1, we therefore quantified training and match demands in Italian Serie A youth soccer players across multiple academy age groups, integrating the most commonly utilised methods of monitoring external (duration and GNSS) and internal (HR and RPE) loads in adolescent athletes (Dudley et al., 2023). The findings on the weekly accumulated training loads revealed progressive increases along the academy pathway, with late-stage youth soccer players (under-19 and under-17) training with higher session frequency, greater external load and sRPE-TL in comparison to their younger counterparts (under-16 and under-15) (Figure 5). When comparing our absolute weekly training volumes for total distance and sprinting distance (> 25 km·h^{-1}), it emerges that Italian Serie A youth soccer players accumulated higher loads across the microcycle than in other European academies (Bowen et al., 2017; Hannon et al., 2021; Houtmeyers et al., 2021). Conversely, younger players exhibited higher weekly HR-based internal load (Table 10). This is in contrast with previous research documenting higher time spent at high HR intensity in older academy players compared to younger counterparts (Wrigley et al., 2012). Based on these findings, it appears that, despite a progressively increasing weekly external load, late-stage youth soccer players spent less time at high HR intensities throughout the microcycle. With the recent advancements in technology, there has been a noticeable shift in practitioners' focus towards monitoring external load, often at the expense of internal load (Impellizzeri et al., 2019). Considering the critical role of internal load in driving physiological adaptation, it is essential to design training sessions that not only deliver appropriate external demands but also elicit sufficient internal responses, such as elevated HR intensity, reflective of the physiological demands encountered during competitions for maximising physical performance development.

Additionally, Study 1 also explored the periodisation of loading across the competitive microcycle with varying distributions of load among age groups and training days. Late-stage youth soccer players (under-19 and under-17) trained with marked fluctuations of daily load as opposed to a less evident loading distribution in the younger counterparts (Figures 6, 7, 8), emphasising the diversified training approaches among academy squads. Despite this result agreeing with previous research conducted with English Premier League and Portuguese national-level academy players during a typical microcycle (Coutinho et al., 2015; Hannon et al., 2021; Wrigley et al., 2012), particular characteristics of the microcycle periodisation emerged within our cohort. Firstly, Italian Serie A youth soccer players experienced their highest load on MD across the competitive microcycle across all age groups and for all external and internal load measures (Figures 6, 7, 8; Table 11). Consequently, similar to adult players, this finding suggests that high-level youth soccer players likely experience the largest daily energy expenditure and the largest magnitude of fatigue of the microcycle (Hannon et al., 2021; Springham et al., 2024). Secondly, MD-5 and MD-3 sessions emerged as the most physically demanding training days compared to all the other ones of the microcycle, whereas the last training session before competition (MD-1 or MD-2, depending on the weekly schedule) had the lowest load of the microcycle. Whilst previous studies revealed higher load in the central days of the microcycle (e.g., MD-4 and MD-3) and lower training demands in the two days preceding official matches in both adult and youth soccer players (Hannon et al., 2021;

Silva et al., 2023), our results differed on MD-5 session with multiple external and internal load measures peaking on the session occurring two days after match-play (Figures 6, 7, 8; Table 11). Thirdly, we examined the influence of congested microcycles in under-19 players, observing that training loads are lower on MD-2 compared to typical microcycles. Given that this competitive scenario required youth players to play successive matches with limited recovery time (e.g., 2 or 3 days between matches), effective management of training load and recovery becomes particularly important during congested periods of competition (Buchheit et al., 2023; Cross et al., 2019; Field et al., 2021; Noor et al., 2021). These periods of competition in high-level youth soccer provide valuable opportunities for adolescent players to experience competition schedules that closely resemble those faced by professional players. When supported by appropriate load planning and periodisation strategies (e.g., nutritional, regeneration and load management strategies), such scenarios may facilitate the progressive exposure to elevated physical demands.

Ultimately, these periods may enhance players' capacity to tolerate higher training and match loads during the transition from the academy to the first-team environment, where elite players are required to participate in congested schedules with associated travel demands and subsequent disturbance of sleep and recovery (Gualtieri et al., 2024). In addition, the greater training loads observed in this thesis compared to previously published research in the youth soccer population evidence a trend to improve players' ability to develop robustness and physical preparedness. This approach contrasts with the more conservative load management practices commonly reported in the literature, which may restrict opportunities for exposing players to higher training stimuli necessary for developing maximal performance capacity (West et al., 2024).

Whilst the training and match loads of adult soccer players are well documented, the completion of Study 1 expands existing research in this area with detailed training characteristics of an Italian Serie A academy across multiple age groups. Specifically, this study outlines the importance of simultaneously integrating and monitoring both external and internal loads in adolescent players to ensure they are exposed to appropriate training stimuli throughout the academy pathway. As outlined in the conceptual framework for physical training (Jeffries et al., 2022), the characterisation and quantification of training load constituted a fundamental component of the training process for better understanding the acute responses to load (e.g., fatigue and recovery) in the subsequent studies of this thesis. Therefore, in Studies 2, 3 and 4, we described both external and internal load of the experimental training and match-play used to examine acute fatigue and recovery responses (Tables 15, 16 and 19). Additionally, the real-world loading patterns observed in Study 1 influenced the experimental design of subsequent studies, particularly with the examination of different training loads in Study 3.

7.3.2 Acute fatigue responses to training and match load in Italian Serie A youth soccer players

Assessing responses to training and match demands constitutes another fundamental component of the training process, as it enables the description of the various effects caused and occurring after a single or multiple training sessions (i.e., acute and chronic, positive and negative) (Jeffries et al., 2022; Vanrenterghem et al., 2017). This practice is critical for understanding how players are coping and adapting to the cumulative stimuli imposed by training and competition, thereby supporting practitioners to inform training optimisation strategies at the individual level (Coutts et al., 2018; Impellizzeri et al., 2019). Within the scope of this thesis, acute responses were examined following match-play (Study 2, Study 3) and training (Study 4) using performance, physiological and subjective measures (Table 23). Given that the manifestation of fatigue is shaped by the interplay between performance and perceived fatigability, and is influenced by both the sport demands and the players' capacity to tolerate a given training load (Grainger et al., 2024; Skorski et al., 2019), it was crucial to assess acute responses by incorporating multiple measures and accounting for the external and internal training load sustained to better contextualise the findings of this work.

Fatigue is an integral component of exercise and is required to elicit both acute responses and chronic adaptations (Pyne and Martin, 2011). In applied sport science, fatigue is commonly observed as a state characterised by a reduction in physical or mental performance (Hauswirth and Mujika, 2013), and also as the inability to complete a task previously achievable within a recent timeframe (Halson, 2014). Within this context, it has been suggested that a suitable measure used for effectively monitoring acute responses should be valid, reliable, sensitive to change and practical (Impellizzeri and Marcora, 2009; Thorpe et al., 2017). Therefore, quantifying both reliability and sensitivity to change of post-match fatigue measures has been recommended to interpret individual responses in elite sports (Howarth et al., 2022; Mercer et al., 2022). However, prior to the completion of Study 2 (Chapter 4), despite the widespread use of physical performance tests, limited evidence existed within the youth soccer population. Hence, in Study 2, we described acute responses following match-play, quantified test-retest reliability and sensitivity to change in Italian Serie A youth soccer players using the IPC and CMJ tests. These physical performance measures showed significant acute alterations at post-match. The magnitude of change post-match was greater than the typical variation (1.5 times the TE), with reductions in IPC measures and alterations in CMJ measures (e.g., force at zero velocity, RSI-modified). However, typically reported CMJ measures such as jump height and peak power showed limited changes within their typical variation (Table 14, Figures 12, 13). Additionally, in Studies 3 and 4 (Chapters 5 and 6), CMJ performance showed similar changes following match-play (Figure 15, Table 15) and limited variations following a moderate training session, except for CMJ eccentric forces such as force at zero velocity (Figure 18, Table 21). Similar variations were also observed in previous research following match-play, pre-season and in-season training sessions (de Hoyo et al., 2016; Ellis et al., 2022; Malone, Murtagh, et al., 2015; Ruf et al., 2022; Springham et al., 2024; Thorpe et al., 2017).

Taken together, these findings on the acute effects of training and match load on CMJ performance suggest that these alterations in CMJ eccentric forces may be representative of altered SSC and linked to the onset of neuromuscular fatigue following exercise (Gathercole et al., 2015; Komi, 2000; Nicol et al., 2006). This is particularly relevant given the growing match demands, including intense acceleration and deceleration actions observed during match and training. Consequently, the selection and adoption of CMJ eccentric phase force measures (e.g., eccentric peak force, force at zero velocity) may be valuable to longitudinally monitor fatigue responses and readiness to train in the real world. Nonetheless, emerging trends in some soccer environments also advocate for the use of "invisible" monitoring approaches, which avoid direct player testing weekly to monitor fitness and fatigue (Leduc and Weaving, 2025). These methods rely instead on advanced analyses of training data and the integration of artificial intelligence techniques throughout the microcycle to generate insights into players' fitness and fatigue status (Mandorino et al., 2025; Shushan et al., 2023).

The same physical performance measures were subsequently used in Study 3 and Study 4 in combination with other subjective and physiological measures to characterise acute responses to match and training. A synthesis of the acute changes in physical performance following match and training demands across the experimental studies of this thesis is reported in Table 24. Across studies, significant acute decrements in physical performance were more accentuated following match-play (Study 2 and Study 3) compared to a moderate intensity training session (Study 4). Specifically, the demands of an 80-minute youth soccer match-play caused signs of acute fatigue with significant reductions in both IPC and CMJ measures (Tables 14, 15), whilst the lower training loads associated with the experimental session of Study 4 induced limited and less accentuated changes in these measures (Table 21). Interestingly, the accentuated HSR and SPR demands of match-play documented in Study 2 and Study 3 resulted in acute alterations of hamstring muscle force-generating capacity at post-match, with moderate reductions of IPC peak force and torque (from -17 to -10% compared to pre). Conversely, the lower HSR and SPR training demands observed in Study 4 (Table 19) did not cause changes (from -3 to 0 % compared to pre) in all IPC peak force and torque measures of the dominant and non-dominant leg. These findings are consistent with previous literature reporting substantial reductions in hamstring muscle function following competition and intense training sessions (Barreira et al., 2024; Constantine et al., 2019; Martínez-Serrano et al., 2022; Massamba et al., 2024; Springham et al., 2024; Wollin et al., 2017), and limited changes following moderate to low soccer training in high-level youth soccer players (Gantzer et al., 2024). Given that neuromuscular fatigue is one of the factors associated with hamstring strain injury (Huygaerts et al., 2020), it is important to consider acute fatigue and recovery responses in hamstring muscle strength to optimise the periodisation of loading (e.g., recovery session in the days after competition, HSR and SPR sessions on the pitch or strength sessions in the gym across the microcycle). Collectively, these findings from Studies 2, 3 and 4 suggest that high-level youth soccer players, when exposed to high-load HSR and SPR activities such as match-play and intense training, experience significant acute reductions in hamstring muscle strength.

Table 24. Synthesis of the acute mean changes in physical performance following match-play and training in this thesis.

	Acute changes to match-play		Acute changes to training
	Study 2 (n = 13)	Study 3 (n = 48)	Study 4 (n = 13)
Countermovement jump test			
Jump height (cm)	-3.1 % $*^{S}$	-4.6 % $*^{S}$	-1.7 %
Peak power (W)	-0.8 %	-2.7 % $*^{S}$	0.7 %
Force at zero velocity (N)	-8.1 % $*^{M}$	-6.5 % $*^{S}$	-7.1 % $*^{M}$
RSI-modified ($m \cdot s^{-1}$)	-6.1 % $*^{S}$	-5.7 % $*^{S}$	-2.3 % ^{S}
Isometric posterior chain lower-limb muscle test			
Peak force dominant leg (N)	-10.0 % $*^{M}$	-15.1 % $*^{M}$	3.1 %
Peak force non-dominant leg (N)	-10.6 % $*^{M}$	-17.1 % $*^{M}$	-0.3 %
Peak torque dominant leg (Nm)	-10.0 % $*^{M}$	-15.0 % $*^{M}$	3.0 %
Peak torque non-dominant leg (Nm)	-10.6 % $*^{M}$	-17.1 % $*^{M}$	-0.2 %

Abbreviations and notes: Relative acute changes are calculated based on the measurements performed pre- and immediately post-training or match (e.g., 0.5 h post); RSI: reactive strength index; * significant change from pre-match or pre-training condition ($p < 0.05$). S: small; M: moderate effect sizes compared with Pre. Trivial effect sizes are not reported.

Despite the acute changes in physical performance observed in Study 2 and Study 3, these responses reflect the bodily systems contributing to the force-generating capacity of the muscles. Given that soccer activities impose both neuromuscular and metabolic demands, it was important to characterise players' responses, including physiological measures. These indicators refer to the myriads of biomarkers that can be found in biological samples (e.g., blood, urine and saliva) and have the potential to provide objective information regarding the homeostatic disturbances occurring in response to exercise (Pedlar et al., 2019). However, biomarker monitoring is often invasive, requires high associated costs, technical expertise and also several measurement points to provide insights beyond the high degree of variability of these indicators (Pérez-Castillo et al., 2023; Twist and Highton, 2013). More recently, technological advancements in both collection (e.g., capillary samples) and associated analyses (e.g., multiple markers monitoring) have allowed for more frequent monitoring of biological measures in elite soccer (Daniels et al., 2025; Pedroso et al., 2025). Therefore, in Study 4, we integrated multiple measures of fatigue and recovery, including metabolic, performance and subjective indicators, to fully characterise acute responses to training in Italian Serie A youth soccer players.

In Study 4, the analysis of capillary blood serum fractions via untargeted ^{1}H-NMR metabolomics revealed significant perturbations in the serum metabolome, with modest clustering of pre- and post-training samples (Figure 19). This analytical technique allowed the identification and characterisation of 54 metabolites from a capillary blood sample and revealed 21 metabolite concentrations altered following a moderate-intensity training session in high-level youth players (Figure 20; Table 22). Perturbations in metabolite concentrations suggested the activation of energy-muscle metabolism via glycolysis, tricarboxylic acid cycle and gluconeogenesis to meet the training demands of the session, enhancing our understanding of the complex changes occurring to maintain the required rates of ATP resynthesis during the session. In addition, these results are similar to those observed in a pilot research study conducted by Sullivan (2022), which described metabolomic responses to a training session in English Premier League youth soccer players. Before the completion of Study 4, published research failed to concurrently describe training-related changes using physical performance, metabolic and subjective indicators within this population. To our knowledge, only one research study by Romagnoli et al. (2016) described changes following a competitive match in high-level youth soccer players using multiple measures, including performance, physiological and subjective measures. However, we adopted more comprehensive approaches by analysing physical performance measures using multiple force-time curve indicators and metabolic markers via untargeted ^{1}H-NMR metabolomics. Interestingly, our findings on the metabolic perturbations were accompanied by limited changes in performance and subjective fatigue measures as described earlier in this section, supporting the notion of separate physiological and biomechanical load-adaptation pathways presented by Vanrenterghem et al. (2017). Apart from the varied responses observed in Study 4, these combined approaches hold potential for informing training, recovery and nutritional strategies at the individual level.

Given the nature of fatigue, subjective measures can be used to characterise the perceived fatigability associated with its onset. The importance of subjective measures is particularly relevant given the role of individuals' perceptions within the fatigue and recovery mechanisms (Kellmann et al., 2018). In the applied setting, subjective measures showed better sensitivity to change in acute and chronic training loads than objective measures (Saw et al., 2016). However, these AROMs often lack methodological studies supporting their use in research and practice (Jeffries et al., 2020) and may have limitations within youth sporting populations. In this thesis, subjective fatigue and recovery were assessed in Study 3 and Study 4, alongside objective indicators of physical performance and physiological state. Before the completion of these studies, limited research described acute fatigue and recovery responses using multiple measures (Table 4). Therefore, we integrated perceived measures of fatigue and muscle soreness using VAS. In Study 3, we observed acute alterations in the perception of fatigue and muscle soreness immediately post-match (Figure 15, Table 15); however, in Study 4, no variations were observed following a moderate training session in both measures (Figure 18, Table 21). Similar to the results of hamstring muscle strength, the perceptual state of youth soccer players was not impaired following moderate training load, but demonstrated substantial alterations following 80-minute match-play. This response may reflect the high load of MD sessions across the microcycle in Italian Serie A youth soccer players (Study 1), and it is in line with the subjective responses documented in adult professional players from different European Leagues (Di Salvo et al., 2023). When comparing these findings with previous works conducted with high-level youth soccer players, it emerges that a worsened subjective state can be expected following competitive match-play and high-intensity training sessions (Deely et al., 2022; Paul et al., 2019). Recently, the results of a systematic review on the topic suggested that there appears to be a short-term relationship between load and acute responses of fatigue, muscle soreness, sleep and stress in soccer players (Brauers et al., 2025). However, it is also important to understand that these subjective measures may have limited sensitivity in quantifying fatigue response to training and match with variations in response to load within the day-to-day variability (Fitzpatrick, Akenhead, et al., 2019; Ruf et al., 2022). Therefore, it is suggested to examine the measurement characteristics of these measures before implementation in the applied setting for effective monitoring of athletes' responses to load (Jeffries et al., 2020).

7.3.3 Profiling post-match recovery responses in Italian Serie A youth soccer players

It is well understood that the demands of competitive match-play cause fatigue in professional soccer players, with evidence of reduced performance capacity, alterations in physiological and biochemical balance, and worsened perception of recovery up to 48-72 h (Goulart et al., 2022; Silva et al., 2018). Prior to the completion of Study 3 (Chapter 5), the evidence regarding the time course of recovery in youth soccer players remained limited. However, during the completion of this thesis, new studies have reported information on the time course of recovery in English Premier League and Portuguese national-level youth soccer players following 90-minute competitions (Barreira et al., 2024; Springham et al., 2024). Existing studies on youth players rarely reported both external and internal load of the match, and few investigated post-match responses using multiple measures (Table 4). Given the unique physical characteristics of adolescent athletes and shorter youth soccer matches of 80 or 70 minutes (Palucci Vieira et al., 2019), it was therefore important to examine the time-course of recovery in the subsequent days within this context to better understand recovery needs and readiness to train post-match.

Building on the findings from Study 1, which identified MD as the session with the highest load in the microcycle, and Study 2, which demonstrated acute reductions in physical performance immediately post-match, Study 3 investigated acute fatigue and the time course of recovery following match-play in Italian Serie A youth soccer players using physical performance and subjective measures. The findings revealed that an 80-minute youth soccer match significantly impaired physical performance and perceptual recovery both immediately and in the subsequent days, with variation in recovery patterns 48 h post-match (Table 15). The selected recovery measures were chosen not only for their measurement properties (e.g., reliability, sensitivity to change, practicability), but also because they reflect the elements of performance fatigability and perceived fatigability of the definition of fatigue (Enoka and Duchateau, 2016). The fact that variations in recovery responses were observed 48 h post-match aligns with the complex and multifaceted nature of the recovery process previously described elsewhere (Gabbett and Oetter, 2024; Skorski et al., 2019). Specifically, our results indicate that CMJ performance (both outcome and movement strategy measures) and perceived fatigue returned to baseline levels 48 h post-match (Table 15, Figure 15). This recovery kinetics is consistent with recent results observed in under-18 English Premier League youth players (Springham et al., 2024) and also aligns with measures of central and peripheral fatigue, which showed a return to baseline values 48 h after the match in adult soccer players (Brownstein et al., 2017). Moreover, these findings suggest that the time of restoration of CMJ appears to be shorter in youth soccer players than those observed in the adult population (Silva et al., 2018), likely due to match duration and physical demands.

Additionally, the findings of Study 3 showed that hamstring muscle force capacity and perceived muscle soreness had not fully recovered 48 h post-match in Italian Serie A youth soccer players (Table 15, Figure 15). Moderate reductions were observed in IPC peak force and torque of both the dominant and non-dominant leg, alongside the altered perception of muscle soreness, underscoring the major involvement of hamstring muscles during high-intensity actions and eccentric activities (Carmona et al., 2024). When comparing these results with previous similar studies, research outcomes are mixed: some reported prolonged recovery (Barreira et al., 2024) and others' complete regeneration (Constantine et al., 2019; Springham et al., 2024; Wollin et al., 2017) of hamstring muscle strength 48 h post-match. However, these discrepancies may result from the different tests or measures used to profile the recovery of IPC muscles and the varied levels of the players involved. As recovery is defined as the time during which biological responses to training load occur, our result suggests that youth players competing in 80-minute match-play likely require a longer recovery period for hamstring muscle strength, similar to professional adult players who exhibited prolonged recovery times up to 72 h post-match (Silva et al., 2018). Taken together, the findings on the post-match recovery responses examined in Study 3 highlight the importance of understanding recovery profiles in youth soccer players using multiple measures. These measures can reflect the main characteristics of the match demands and consequently can be used to evaluate recovery modalities and training strategies administered post-match. Additionally, given the characteristics of the training load sustained and the nature of the time course of recovery, this study provides evidence to better inform training periodisation strategies used with youth soccer players.

7.3.4 Manipulation of training load at post-match as a fundamental recovery intervention in Italian Serie A youth soccer players

Given the prolonged recovery following soccer match-play and the growing competitive demands of modern soccer at both senior and youth levels, the application of effective recovery strategies represents an essential element to optimise players' performance within the training process (Field et al., 2021; Reilly and Ekblom, 2005; Wiewelhove et al., 2024). These interventions can include nutritional, regeneration and training modalities which aim to mitigate the magnitude of fatigue, accelerate the recovery process, increase training quality and tolerance and ultimately support match-play performance (Cross et al., 2019; Field et al., 2021; Thorpe, 2021; Wiewelhove et al., 2024). For example, in elite adult soccer, a multi-club study examined the association between the programming of days off and injury rate, showing that the inclusion of a day off on MD+2 was associated with a lower non-contact injury rate compared to other scheduling sequences (Buchheit et al., 2023). Prior to the completion of Study 3 (Chapter

5), research examining the effects of recovery strategies in youth soccer players was mainly limited to nutritional and recovery modalities (Table 8), with little emphasis on the effects of training load interventions applied in the days following match-play. However, the application of nutritional strategies, active recovery or water immersion modalities at post-match may not always be available in a youth academy setting (e.g., logistical challenges when playing away matches). Therefore, after having explored habitual training and match loads (Study 1), acute responses to training and match (Study 2, Study 4), and the time course of recovery following match-play (Study 3), the second analysis of Study 3 examined the effects of manipulating training volume 48 h post-match in Italian Serie A youth soccer players. This intervention has been proposed to be a fundamental strategy alongside sleep and nutrition (Driller and Leabeater, 2023; Mujika et al., 2018) to facilitate recovery in the first days after match-play.

For the first time, we examined the manipulation of training load following match-play as a fundamental intervention applied to optimise recovery and performance capacity (Driller and Leabeater, 2023; Slattery et al., 2012; Thorpe et al., 2017). In Study 3, we compared the effects of two training load interventions administered 48 h post-match, on MD+2: 1) a CT session (100 minutes; high volume and high intensity); or 2) an RT session (70 minutes; moderate intensity). The findings of this research revealed that physical performance was further reduced from 48h to 72h post-match in the CT condition, whereas physical performance was not significantly altered across the same period in the RT condition (Figure 16; Table 18). Compared to previous research investigating the effects of active recovery modalities on MD+2 in high-level youth soccer players (Springham et al., 2024; Trecroci et al., 2020, 2021), this work evidences that a moderate soccer-specific training session prescribed 48 h post-match may support recovery without further impairing performance capacity. This new information appears to be a key aspect for practitioners working with high-level youth soccer players, as it allows the maintenance of a training stimulus 48 h post-match without impairing the recovery process. Specifically, it appears promising for coaches and sports scientists, as it enables exposure to sport-specific training as opposed to regeneration strategies performed in the gym (e.g., active recovery, stretching) or in the physiotherapy room (e.g., massage, water immersion). Consequently, this strategy would maximise training time across the microcycle and potentially expose players to tolerate moderate training load in conditions of incomplete recovery, which may ultimately improve players' robustness over the long-term development process. Finally, given the increased awareness of the importance of training load monitoring, this field-based strategy may also increase cooperation between technical coaches and sports scientists in designing effective training sessions on MD+2 in youth players. Collectively, these results support the periodisation and manipulation of training load in the days following match-play as a practical tool to affect acute performance and recovery responses across the microcycle in line with previous research conducted with team sport athletes (Douchet et al., 2022, 2024; Slattery et al., 2012).

This thesis presents an updated version of the conceptual framework for physical training, originally proposed by Jeffries et al. (2022) and introduced earlier in the literature review (Figure 2). Based on the findings from this thesis and on the applied context of monitoring physical performance in youth soccer, the revised framework (Figure 21) incorporated two main modifications: 1) the measurable component of the responses to load (i.e., training effects) has been redefined as either acute fatigue or recovery responses; and 2) a new component, 'recovery interventions' has been added to encompass the training, recovery and nutritional strategies typically used after training or competition to return to pre-exercise status. While the original classification of the training effects remains applicable for physical performance and subjective measures (e.g., positive or negative, acute or chronic training effects), its utility in interpreting physiological responses is more limited. This categorisation may oversimplify the multifaceted and complex nature of physiological responses and key pathways highlighted in Study 4, which can manifest across various biological levels (e.g., cellular, tissue and systemic levels) (Balagué et al., 2020). Therefore, it appears important to contextualise observed physiological changes by evaluating whether they align with the specific pathways stimulated and the intended adaptive outcomes. In the revised framework, the terminology has been refined to distinguish between acute fatigue responses (i.e., changes observed acutely post-training or match) and recovery responses (i.e., changes observed in the days following training or match, such as 48 h post or 72h post). Although the measurement properties of the response to load measures are not explicitly represented within the framework, it remains critical to determine their measurement characteristics (e.g., reliability and sensitivity to change) to ensure that detected variations represent meaningful changes.

Moreover, the inclusion of the 'recovery interventions' aims to provide a more comprehensive evaluation of how training, regeneration and nutritional strategies can be prescribed according to the type and magnitude of fatigue, as well as individual and contextual factors (e.g., season periods, microcycle structure, fitness level) (Thorpe, 2021). This updated schematic may serve as a hypothetical model for monitoring training, fatigue and recovery in high-level youth soccer players. Finally, this work can help sports scientists in supporting technical coaches while refining training and recovery strategies across the microcycle, especially in the days following competition.

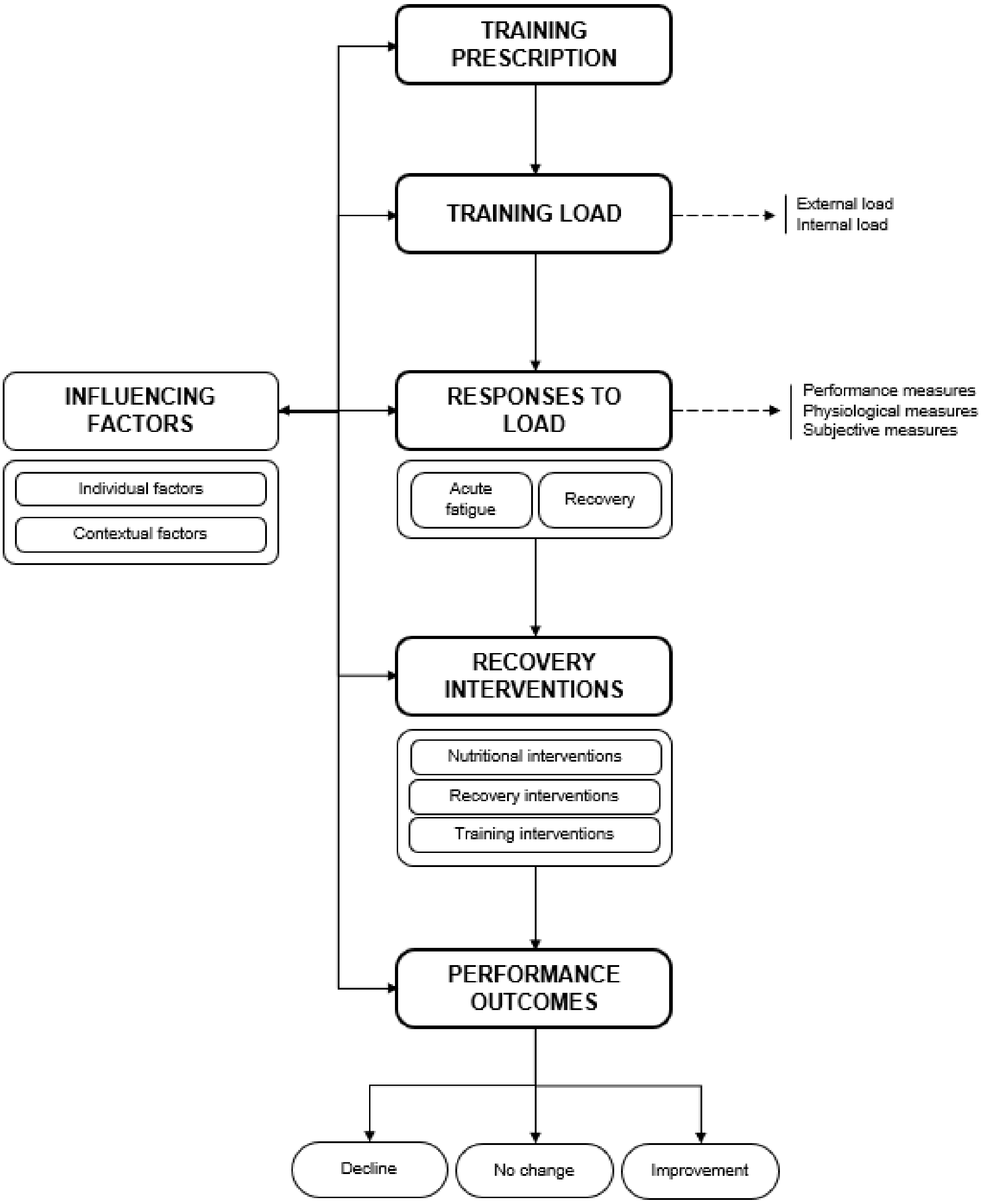

Figure 21. A theoretical framework for monitoring and optimising training and recovery in high-level youth soccer players. Originating from the work of Jeffries et al. (2022), it integrates elements investigated within this thesis. The dotted arrows indicate the type of training load and training response measures. Acute fatigue refers to measurements performed pre- and immediately post-training or match (e.g., 0.5 h post), while recovery

refers to measurements performed in the days following training or match (e.g., 48 h post, 72h post). Recovery interventions refer to the training, recovery and nutritional strategies commonly administered following training or competition to support the recovery process before returning to the next training session.

7.4 Limitations and Recommendations for Future Research

While this thesis has generated novel findings, it remains essential to critically acknowledge the limitations of this series of applied research studies. Although the specific limitations of each study have been discussed within their respective chapters, this section presents the overarching limitations and also outlines recommendations for future research to advance the understanding and application of training and recovery within this population.

A recurring limitation across the different studies concerns the restricted generalisability of the findings, as all the investigations were conducted within a single-club youth academy. Although such a limitation is common in applied soccer science projects (Warmenhoven et al., 2025), it must be recognised that these data, derived from male youth players within one Italian Serie A academy, may not be representative of female cohorts, other Italian academies, or other first division academies worldwide. Indeed, variations in cultural contexts, training methodologies, logistics and available resources across clubs and leagues are likely to influence coaching programmes and sport science support, thereby affecting both training and recovery practices (Pass et al., 2022). To enhance the generalisability of the findings, future research should seek to replicate these investigations within female youth soccer populations. Within this context, the integration of external load and internal responses should also be investigated during the maximal intensity periods occurring in training and competition (Kim et al., 2023). Furthermore, the adoption of multi-club or multi-nation study designs is warranted to provide more solid evidence on the training profiles of high-level youth players (Myhill et al., 2022; Ramírez-López et al., 2020). Although these approaches can certainly offer more robust evidence compared to a single-club study, conducting multi-club research in high-level sports presents substantial methodological and practical challenges (e.g., financial and logistical constraints, issues concerning data ownership and the protection of competitive advantage).

A second common limitation concerned the use of arbitrary speed thresholds for quantifying HSR and SPR distance across studies. Although this monitoring approach may support long-term monitoring and comparison between groups, it may not accurately reflect the individual differences in players' physical capacities (e.g., maximal sprinting speed). The adoption of relative speed zone thresholds, tailored to each player's maximal running speed, would allow for a more precise quantification of high-speed and sprinting efforts and, consequently better understanding of the associated internal responses. Future investigations should consider reporting external load using individualised thresholds and also report relative data (e.g., meters per minute) to improve the interpretation of training demands within youth soccer.

An additional general limitation, particularly evident in the chapters examining fatigue and recovery responses (Studies 2, 3 and 4), relates to the methodological choices of the study design. Specifically, fatigue and recovery were assessed following ad hoc training sessions and friendly match-play. Although this methodological choice offered several advantages (e.g., increased sample size through friendly match participation, greater control during the experimental procedures in an ecologically valid environment), it also introduced certain limitations. The absence of responses following official competitions and the lack of longitudinal monitoring (e.g., repeated measures design) limit the applicability of our findings, particularly given the high variability of match demands (Di Salvo et al., 2009; Palucci Vieira et al., 2019). At the time of data collection, systematic monitoring of fatigue and recovery was not fully integrated into the club's sport science practices across all age groups, rendering longitudinal approaches impractical. This exemplifies a fundamental trade-off in applied sport science research, whereby efforts to maximise ecological validity often necessitate methodological approaches that deviate from the more controlled conditions of laboratory studies. Future research should aim to overcome these limitations by employing crossover and repeated measures designs to examine the effects of both recovery- and training-based strategies in the days following match-play, with particular interest in congested fixture scenarios (Hecksteden et al., 2022; Springham et al., 2025). Additionally, conducting survey research studies may help bridge the gap between science and practice by elucidating the real-world strategies adopted within youth soccer academies and informing the design of future applied research projects (Field et al., 2021; Loturco and Bishop, 2025).

A further common limitation across all studies was the lack of examination of the role of biological maturation on training load, acute fatigue, and recovery. Although players' maturation status and timing were reported within the participants' section of each chapter, this information was not incorporated in the statistical analyses of the studies. Specifically, in Study 1 (n = 90) and Study 3 (n = 48), the inclusion of biological maturation as an independent variable could have yielded additional insights beyond age group comparisons. Given the substantial inter-individual variability in growth and maturation among youth soccer players, future research should integrate measures of biological maturation into analyses to better contextualise individual responses to training and match-play within this population (Towlson et al., 2021).

A final limitation of this thesis relates to the inherent complexities associated with the investigation of post-exercise fatigue and recovery in an applied setting. This area necessitates strict control over the exercise stimulus, the acute and chronic adaptive responses, recovery interventions, and influencing factors. Recovery is recognised as a topic of considerable interest in exercise physiology and applied sport science research, yet it also remains among the least understood components of the exercise-adaptation cycle due to its multifaceted nature (Peake et al., 2017; Peake and Gandevia, 2017). Despite the efforts to quantify training load through both external and internal measures (Dudley et al., 2023) and to account for energy intake (Costello et al., 2017), other influencing factors remained uncontrolled due to the nature of the applied research environment. Future research studies aiming to examine the effects of training and recovery strategies may benefit from employing more controlled environments (e.g., laboratory-based settings) and standardised experimental designs (e.g., match simulation protocols) to better isolate and understand the determinants of recovery (Field et al., 2022).

Conversely, from an applied research perspective, the application of "invisible monitoring" approaches to assess response to load within the soccer environment may represent a promising frontier for better understanding fatigue and fitness status in high-level soccer players (Leduc and Weaving, 2025; Mandorino et al., 2024). An example of this approach is the use of submaximal fitness tests within the weekly microcycle as part of the warmup activities in team sports players to examine how players are responding to the demands of training and competition (Shushan et al., 2022, 2023, 2024). However, the implementation of such monitoring practices demands considerable time, technological resources, and seamless integration within existing infrastructure, which can limit their feasibility in youth academy settings. From an analytical standpoint, adopting individualised adaptive reference ranges when evaluating responses to exercise may better assist with the identification of substantial changes from the typical responses in elite soccer (Daniels et al., 2025). Finally, the integration of artificial intelligence offers promising potential for the detection of deviations from individual normative patterns, enabling early identification of movement behaviours that may signal fatigue or fitness (Mandorino et al., 2025).

7.5 Practical Applications

These findings offer evidence-informed recommendations for practitioners working with adolescent soccer players. The main practical applications are synthesised in Figure 22.

Implications for physical performance monitoring in high-level youth soccer players:

- Monitoring training and match demands using a combination of external and internal load measures is essential for profiling players' responses to load. In addition, practitioners working with adolescent players should also consider the influence of individual and contextual factors that may modulate load tolerance and responses.
- When assessing post-match fatigue, IPC and CMJ tests represent reliable and sensitive tools for identifying changes in physical performance. It is recommended to incorporate eccentric phase measures (e.g., force at zero velocity) and movement strategy indices (e.g., RSI-modified) for monitoring acute responses, alongside the conventional outcome measures such as jump height and peak power.
- Profiling post-match recovery using assessments of hamstring strength and perception of muscle soreness is of primary importance due to the substantial magnitude of fatigue and prolonged time course of regeneration. These measures can inform readiness to train and post-match recovery requirements in youth soccer players.

Implications for optimising training and recovery in high-level youth soccer players:

- As training and match demands increase progressively across the academy pathway, sport scientists and coaches should seek exposure to more accentuated periodisation of loading (i.e., high, moderate and low load days) and greater weekly training volume and intensity with late-stage youth soccer players (> 16 years old).
- Practitioners should consider the multifaceted responses of training and match to physical performance capacity, metabolic homeostasis, and perceived fatigue. While youth soccer match-play leads to substantial and prolonged impairments, moderate-intensity sessions can elicit significant metabolic disturbances. Therefore, training and recovery strategies should be planned accordingly to optimise training exposure, load tolerance and regeneration.
- Manipulating training volume on MD+2 may represent a fundamental strategy to influence the recovery process and readiness to train in line with the desired training effects of the microcycle. This training-based strategy can support practitioners in optimising training programs that balance recovery needs with sport-specific preparation.

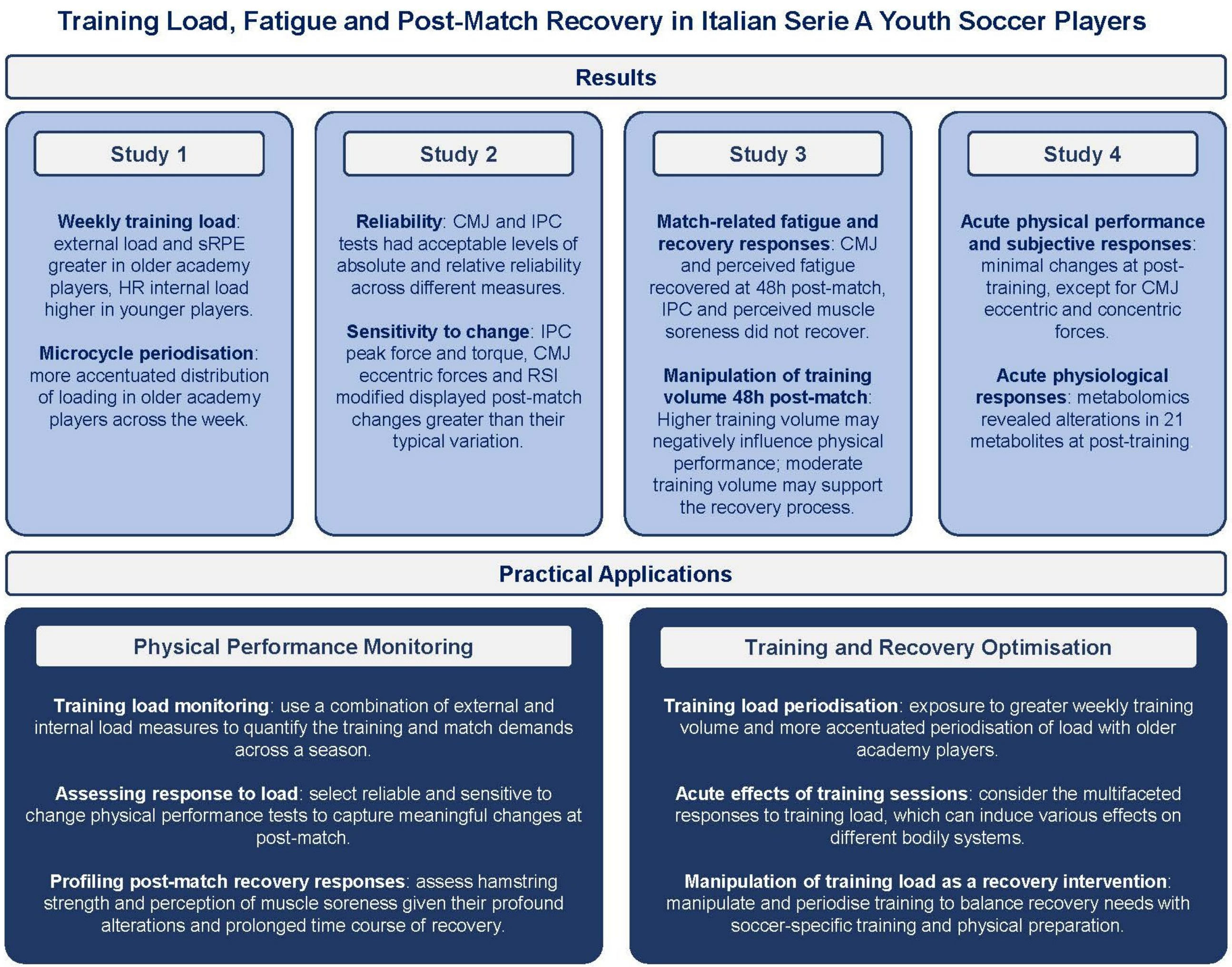

Figure 22. Schematic synthesis of the results and practical applications from the present thesis.

7.6 Conclusion

In summary, this thesis offers novel evidence on the training load characteristics, acute fatigue responses and post-match recovery profiles of Italian Serie A youth soccer players. Training demands were shown to progressively increase across the development pathway, with late-stage youth players exhibiting higher training frequency, greater weekly accumulated training loads, and more structured load periodisation throughout the microcycle compared to their younger counterparts. MD represented the highest loading day within the microcycle across all age groups. When assessing acute responses to load, IPC and CMJ tests demonstrated robust reliability and sensitivity in detecting post-match fatigue changes in physical performance. Among CMJ measures, eccentric forces (force at zero velocity) and RSI-modified exhibited superior measurement properties compared to more traditional measures such as jump height and peak power. Match-play elicited acute fatigue responses, manifesting with decrements in physical performance (reduced IPC and CMJ) and impairments of subjective recovery (increased perceived fatigue and muscle soreness). Conversely, a typical training session induced minimal alterations in physical performance and perceptual responses, yet was associated with a substantial shift in serum metabolite concentrations, suggestive of metabolic fatigue related to energy production pathways. Post-match recovery showed multifaceted responses, with CMJ performance and perceived fatigue returning to baseline within 48 h, whilst IPC and perceived muscle soreness remained unrecovered at the same time point. Finally, when resuming training on MD+2, a moderate-intensity training session supported the recovery process without further impairment of performance capacity, whereas exposure to high-volume and high-intensity training negatively influenced performance recovery. Taken together, these findings advance current knowledge and understanding of training, fatigue and recovery within high-level youth soccer players.

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