UNIVERSIDADE LUSÓFONA

Centro Universitário de Lisboa

Faculdade de Educação Física e Desporto

Doutoramento em Educação Física e Desporto

GROWTH, BIOLOGICAL MATURATION, AND PHYSICAL QUALITIES IN YOUNG SOCCER PLAYERS

Tese de Doutoramento apresentada a provas públicas para a obtenção do grau de Doutor em Educação Física e Desporto, na especialidade de Didática da Educação Física e Desporto, orientada pelo Professor Doutor João Alberto Valente dos Santos.

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VERSÃO FINAL

Tese defendida por Nuno Costa Ribeiro em provas públicas na Universidade Lusófona, Centro Universitário de Lisboa, no dia 18 de maio de 2026, perante o júri, nomeado pelo Despacho de Nomeação n.º 70/2025, de 30 de janeiro, com a seguinte composição:

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Resumo

A adolescência é um período crítico para jovens atletas, caracterizado por mudanças significativas no crescimento, na maturação biológica e no desempenho físico. Estas alterações influenciam de forma substancial a identificação de talentos, o risco de lesão, a gestão da carga de treino/jogo e a evolução do desenvolvimento atlético. Esta tese de doutoramento investiga o papel multifacetado da maturação biológica na modelação do desempenho e na gestão da carga de treino em jovens futebolistas, abordando as complexidades inerentes ao desenvolvimento desportivo a longo prazo.

A **Parte 1** estabelece uma base conceptual para compreender como o crescimento e a maturação influenciam jovens futebolistas. Destaca a relevância do futebol de formação enquanto plataforma estruturada para o desenvolvimento de talento e sublinha as complexidades associadas à adolescência, nomeadamente as interações dinâmicas entre fatores físicos, fisiológicos e psicológicos. São explorados temas centrais como o acompanhamento das características de maturação, a avaliação do risco de lesão e a gestão da carga de jogo, assegurando um desenvolvimento atlético otimizado. Esta secção também aborda os sistemas de classificação biológica e a sua aplicabilidade no treino e na competição. Nesta fase, são introduzidos os objetivos gerais da tese, com ênfase na integração das avaliações de crescimento e maturação nas estratégias de desenvolvimento desportivo a longo prazo, visando melhorar o acompanhamento, a gestão e a progressão dos jogadores.

A **Parte 2** apresenta três estudos inter-relacionados que constituem o núcleo desta investigação. O primeiro estudo foi uma revisão sistemática que investigou o impacto da maturação biológica no risco de lesão, particularmente durante o pico de velocidade de crescimento, fornecendo recomendações baseadas em evidências para a prevenção de lesões em atletas adolescentes. O segundo estudo analisou o efeito da maturação biológica no desempenho físico de jovens futebolistas de elite com idades entre 14 e 17 anos, revelando como as qualidades físicas evoluem ao longo de duas épocas e oferecendo insights críticos sobre as trajetórias de desempenho influenciadas pela maturação. O terceiro estudo explorou a relação entre a maturação biológica e a carga de jogo, analisando diferenças entre grupos de maturação. Foram estabelecidos valores de referência para métricas de carga e identificadas tendências de desenvolvimento, oferecendo parâmetros valiosos para a gestão

de jogadores no contexto de programas de desenvolvimento desportivo a longo prazo. O último estudo investigou as interações complexas entre crescimento, maturação biológica, carga de treino e risco de lesão em jovens jogadores de futebol do sexo masculino, particularmente em torno do pico de velocidade de crescimento em estatura. Tendo em conta a variabilidade individual nas taxas de crescimento e no estado de maturação, este estudo teve como objetivo identificar os principais fatores de risco e as suas relações com a suscetibilidade a lesões. Além disso, destaca a importância da disseminação deste conhecimento junto das partes interessadas e defende a realização de estudos longitudinais para aprofundar a compreensão e informar estratégias práticas de mitigação de lesões.

A **Parte 3** sintetiza os resultados dos estudos anteriores e contextualiza a sua relevância para as academias de futebol e os programas de formação de jovens atletas. Este segmento destaca o papel significativo da maturação biológica na modelação de atributos morfo-funcionais, padrões de carga de treino e variabilidade de desempenho. As implicações destes resultados para o planeamento do treino, da competição são discutidas, com foco em estratégias práticas que promovam o desenvolvimento otimizado dos jogadores. A tese enfatiza a importância de abordagens sensíveis à maturação no contexto do futebol de elite juvenil, fornecendo informações aplicáveis para apoiar o crescimento, o desempenho e o bem-estar de jovens jogadores de futebol.

Ao integrar fundamentos teóricos, evidências empíricas e aplicações práticas, esta tese avança o entendimento sobre o papel da maturação biológica no futebol juvenil. O estudo apresenta um enquadramento abrangente para orientar o desenvolvimento de talentos, a prevenção de lesões e a gestão da carga de treino em ambientes de treino de elite.

Palavras-chave: Maturação Biológica · Adolescência · Desempenho Físico · Risco de Lesão · Carga de Jogo · Desenvolvimento de Talento · Desenvolvimento Desportivo a Longo Prazo

Abstract

Adolescence is a critical period for young athletes characterized by significant changes in growth, biological maturation, and physical performance. These changes have substantially influenced talent identification, injury risk, workload management, and overall athletic development. This doctoral thesis investigates the multifaceted role of biological maturation in shaping performance and managing workload in young male soccer players, addressing the complexities inherent in long-term athlete development.

Part 1 establishes a framework for understanding how growth and maturation influence young male soccer players. This underscores the significance of academy soccer as a structured platform for fostering young talent and highlights the complexities of adolescent development, including the dynamic interactions between physical, physiological, and psychological factors. The central themes encompass monitoring maturity characteristics, assessing injury risk, and managing match workloads to ensure optimal athletic development. This section also discusses biological classification systems and their relevance to training and competition. This thesis introduced its overarching aims, emphasizing the integration of growth and maturation assessments into long-term athletic development strategies to enhance player monitoring, management, and progression.

Part 2 presents three interconnected studies that form the core of this study. The first was a systematic review that investigated the impact of biological maturation on injury risk, particularly during peak height velocity, and provided evidence-based recommendations for injury prevention in adolescent soccer players. The second study examined the effect of biological maturation on the physical performance of elite male soccer players aged 14–17 years. This analysis revealed how physical qualities evolve across the two seasons, providing critical insights into the influence of maturation on performance trajectories. The third study explored the relationship between biological maturation and match workload by analyzing differences across biological maturation groups. It establishes reference values for workload metrics and tracks developmental trends, offering valuable benchmarks for player management within long-term athlete development frameworks. The final study investigated intricate interactions among growth, biological maturation, workload, and injury risk in young male soccer players, particularly around peak height velocity (PHV). Considering the individual variability in growth rates and maturation status,

this study aimed to identify the key risk factors and their relationships with injury susceptibility. Furthermore, it underscores the importance of disseminating this knowledge to stakeholders and advocates for longitudinal studies to enhance understanding and inform practical injury mitigation strategies.

Part 3 synthesizes findings from previous studies and contextualizes their relevance to soccer academies and youth development programs. It highlights the significant role of biological maturation in influencing morpho-functional attributes, workload patterns, and performance variability. The implications of these findings for training and competition planning are discussed, focusing on practical strategies to optimize player development. This thesis emphasizes the importance of maturation-sensitive approaches in elite youth soccer and provides actionable insights to support the growth, performance, and well-being of young soccer players.

By integrating theoretical foundations, empirical evidence, and practical applications, this thesis advances the understanding of the role of biological maturation in youth soccer. This study provides a comprehensive framework to guide talent development, injury prevention, and workload management in elite training environments.

Keywords: Biological Maturation · Adolescence · Physical Performance · Injury Risk · Match Workload · Talent Development · Long-Term Athlete Development

List of Abbreviations

Abbreviation	Definition	Unit
ACC	accelerations	number (n)
ACWR	acute: chronic workload ratio	
APHV	age at peak height velocity	years (y)
BM	biological maturation	
CA	chronological age	years (y)
CMJ	countermovement jump	centimeters (cm)
COD	change of direction	seconds (s)
DCC	deceleration	number (n)
d-RPE	differentiated ratings of perceived exertion	arbitrary units (au)
GPS	global positioning system	
HR	heart rate	beats per minute (bpm)
HRV	Heart rate variability	beats per minute (bpm)
HSR	high speed running	meters (m)
IMTP	isometric mid-thigh pull	newtons (n)
LTDA	long-term athlete development	
MO	maturity offset	years (y)
PPAH	percentage of predicted adult height	
PHV	peak height velocity	years (y)
PWH	peak weight velocity	years (y)
RPE	ratings of perceived exertion	arbitrary units (au)
SA	skeletal age	years (y)
SD	sprint distance	meters (m)
s-RPE	session ratings of perceived exertion	arbitrary units (au)
TD	total distance	meters (m)
TRIMP	training impulse	arbitrary units (au)
U	under	

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PART 1

Introdução Geral

O desenvolvimento de jovens atletas em contextos desportivos de elite é moldado por uma interação complexa entre crescimento biológico, maturação e exposição ao treino, fatores que influenciam substancialmente os resultados de desempenho físico. No futebol, uma modalidade globalmente dominante que exige a integração de componentes físicas, técnicas, táticas e psicológicas de elevado nível, compreender estes processos de desenvolvimento é crucial para uma identificação eficaz de talento, para a definição de estratégias de treino individualizadas e para a implementação de programas de prevenção e mitigação do risco de lesão [1,2]. Neste contexto, as academias de futebol de elite têm assumido um papel cada vez mais relevante, proporcionando ambientes estruturados que promovem simultaneamente a melhoria do desempenho e o bem-estar a longo prazo dos atletas [3].

Do ponto de vista fisiológico e morfológico, a adolescência constitui um período crítico caracterizado por alterações substanciais na composição corporal, no desenvolvimento muscular e no controlo neuromuscular [4,5]. No entanto, esta janela de desenvolvimento apresenta uma ampla variabilidade interindividual na maturação biológica, sendo frequente que jovens com a mesma idade cronológica apresentem diferenças significativas no seu desenvolvimento biológico. No contexto da presente tese, a adolescência é entendida como um período transitório de desenvolvimento entre a infância e a idade adulta, caracterizado por marcadas alterações biológicas, psicológicas e sociais. Embora os intervalos de idade cronológica possam variar consoante as definições e os contextos, esta tese centra-se em jogadores de academias de futebol com idades compreendidas entre os 14 e os 17 anos, período durante o qual pode existir uma variabilidade interindividual substancial na maturação biológica. Estas discrepâncias podem influenciar o desempenho atlético, a resposta ao treino e a resiliência psicológica, evidenciando a importância da monitorização individualizada e de estratégias de acompanhamento adaptadas [6–8]. Consequentemente, a presente tese tem como objetivo explorar de que forma a maturação biológica, juntamente com o crescimento e a carga de trabalho, influencia o desenvolvimento das qualidades físicas em jovens jogadores de futebol.

No futebol de formação, a interação entre crescimento, maturação e desempenho físico tem sido amplamente investigada com o objetivo de otimizar os modelos de treino e de competição. Vaeyens et al. [1] salientaram a necessidade de considerar as diferenças associadas à maturação nos programas de desenvolvimento de talento, de forma a evitar enviesamentos de seleção que favoreçam atletas com maturação precoce e a promover um desenvolvimento mais equitativo. Estes estudos defendem abordagens de treino sensíveis à maturação, capazes de acomodar a interação dinâmica entre alterações hormonais, neuromusculares e morfológicas que ocorrem durante a adolescência. Adicionalmente, Buchheit e Mendez-Villanueva [10] investigaram a influência da maturação no desenvolvimento de capacidades físicas específicas do futebol, como a resistência intermitente e a capacidade de sprint, determinantes para o desempenho em competição. O seu trabalho fornece evidência relevante para a adaptação das cargas de treino e das exigências competitivas em função do estado maturacional do atleta, promovendo simultaneamente a progressão do desempenho e a redução do risco de lesão.

A interação entre maturação biológica e gestão da carga de treino constitui outra área temática de particular relevância. Gabbett [4] e Impellizzeri et al. [5] destacaram a necessidade de adaptar as estratégias de monitorização da carga e os modelos de prevenção de lesões ao estado maturacional dos atletas, de forma a assegurar um desenvolvimento seguro. Em particular, o período do pico de velocidade de crescimento em estatura (PVCA), caracterizado por um crescimento acelerado e potencialmente associado a períodos transitórios de maior vulnerabilidade a lesões, requer especial atenção na planificação do treino e da competição. A incorporação de avaliações da maturação nos processos de gestão da carga permite a treinadores e cientistas do desporto ajustar com maior precisão as prescrições de treino às capacidades e vulnerabilidades em desenvolvimento dos jovens atletas. Esta abordagem é consistente com o modelo de Desenvolvimento Desportivo a Longo Prazo proposto por Balyi et al. [6], que enfatiza a importância da idade biológica na estruturação de fases de treino adequadas ao desenvolvimento.

Uma abordagem cientificamente fundamentada que integre o estado de maturação biológica com a idade cronológica é essencial para orientar os percursos de desenvolvimento de talento no futebol [7,8]. A presente tese baseia-se no pressuposto de que a maturação constitui um determinante fundamental da capacidade física e da adaptação ao treino durante a adolescência. Ao considerar simultaneamente categorias etárias, qualidades físicas e fases de treino, este estudo pretende colmatar lacunas relevantes no conhecimento existente e fornecer ferramentas práticas para profissionais que trabalham em academias, com o objetivo de otimizar o desenvolvimento a longo prazo, minimizar o risco de lesão e personalizar o planeamento do desempenho no futebol de formação.

Crescimento e Maturação Biológica no Futebol de Formação

A maturação biológica é um processo individualizado e não linear que diverge da idade cronológica e que influencia significativamente a força, a velocidade, a agilidade e outras capacidades de desempenho essenciais no futebol [9]. Estas diferenças tornam-se particularmente evidentes durante o surto de crescimento pubertário e o PVCA, que representam um período de desenvolvimento acelerado do sistema esquelético e muscular [9]. Investigadores como Malina, Bouchard e Bar-Or [9] documentaram extensivamente os mecanismos fisiológicos subjacentes ao crescimento durante a adolescência, destacando o seu impacto em capacidades como força, potência, velocidade e agilidade, atributos determinantes para o desempenho no futebol. Figueiredo et al. [10] salientaram ainda que o estado maturacional influencia não apenas a capacidade física, mas também a participação competitiva e potenciais enviesamentos nos processos de seleção.

De forma significativa, a variação no estado de maturação biológica em jovens com a mesma idade cronológica pode distorcer a perceção de talento, favorecendo potencialmente jogadores com maturação precoce que podem, temporariamente, superar os seus pares menos maturados [11]. Esta situação levanta preocupações de natureza ética e prática nos sistemas de formação, tornando necessária a adoção de métodos mais sensíveis e sofisticados para avaliar e desenvolver jovens jogadores. Neste contexto, uma abordagem informada pela maturação revela-se simultaneamente mais justa e mais eficaz na promoção do desenvolvimento a longo prazo. A presente tese apoia-se nestas perspetivas ao investigar de que forma a maturação influencia o desempenho, a carga de jogo e o risco de lesão em jovens jogadores de futebol de elite, com o objetivo de otimizar estratégias individualizadas de treino e competição.

Identificação de Talento, Desempenho Físico e Viés de Maturação

Processos de identificação de talento que não considerem a maturação biológica correm o risco de excluir prematuramente atletas com maturação tardia, comprometendo assim o seu potencial de desenvolvimento a longo prazo [1,7]. As vantagens associadas à maturação precoce, como maior estatura, força e velocidade, podem criar um desfasamento de desenvolvimento que, se não for devidamente considerado, pode induzir em erro treinadores e observadores. De facto, Buchheit e Mendez-Villanueva [12] demonstraram que atletas com maturação precoce frequentemente apresentam melhores resultados em métricas de capacidade aeróbia e sprint; contudo, tal não constitui necessariamente um preditor fiável de desempenho na idade adulta ou de longevidade na carreira desportiva.

Carga de Treino, Risco de Lesão e Considerações de Maturação

A interação entre maturação biológica e carga de trabalho representa uma área crítica de investigação, particularmente devido às suas implicações na prevenção de lesões. Adolescentes que atravessam fases de crescimento acelerado frequentemente apresentam défices temporários de coordenação, flexibilidade e força, aumentando a suscetibilidade a lesões, especialmente durante o PVCA [13]. Gabbett [4] e Impellizzeri et al. [5] sublinharam a importância de estratégias de gestão da carga que considerem o estado maturacional, permitindo aos treinadores ajustar os protocolos de treino e recuperação de forma a proteger a saúde dos atletas.

Ferramentas de monitorização, como os sistemas de posicionamento global e unidades de medição inercial, permitem quantificar com precisão variáveis de carga externa, incluindo distância total percorrida, corrida de alta intensidade e acelerações. Estas métricas podem ser analisadas em relação ao estado maturacional para otimizar a prescrição da carga de treino [14]. Esta abordagem está alinhada com o modelo de Desenvolvimento Desportivo a Longo Prazo proposto por Balyi et al. [6], que recomenda estruturar o treino com base em janelas de desenvolvimento em vez de categorias etárias fixas. Neste enquadramento, a presente tese procura analisar de forma sistemática as variações nas cargas de jogo em diferentes estágios de maturação e em diferentes posições de jogo, permitindo estratégias de periodização mais informadas e individualizadas nas academias de futebol de elite.

1.1. Objetivos da Tese e Objetivos de Investigação

Tendo em consideração as relações complexas, multidimensionais e dinâmicas entre crescimento, maturação biológica e desenvolvimento das qualidades físicas, bem como o papel significativo da carga de trabalho na influência do risco de lesão em jovens jogadores de futebol de elite, torna-se evidente a necessidade de uma investigação abrangente e metodologicamente rigorosa destes fatores. Tal investigação visa otimizar os percursos de desenvolvimento e melhorar substancialmente as práticas atuais de treino. O objetivo principal desta tese de doutoramento é proporcionar uma compreensão aprofundada do impacto do crescimento, da maturação biológica e da carga de trabalho nas qualidades físicas e no risco de lesão em jovens jogadores de futebol de elite, bem como desenvolver estratégias eficazes de monitorização e intervenção em contextos de academia.

Para alcançar este objetivo principal de forma sistemática, esta tese aborda vários objetivos específicos claramente definidos, concebidos para esclarecer diferentes dimensões do complexo processo de desenvolvimento no futebol de formação de elite.

1.1.1. Objetivos da tese

1. Rever a literatura científica atual sobre a influência do crescimento, da maturação biológica e da carga de trabalho no risco de lesão em jovens jogadores de futebol do sexo masculino.

2. Avaliar o impacto longitudinal da maturação biológica na evolução do desempenho físico ao longo de duas épocas competitivas.

3. Avaliar de que forma a maturação biológica influencia as cargas de jogo em jovens jogadores de futebol de elite.

1.1.2. Objetivos de investigação

1. Analisar a influência do crescimento, da maturação e da carga de trabalho no risco de lesão. Este objetivo explora de que forma o desenvolvimento biológico interage com as exigências externas de treino e competição, identificando períodos de maior vulnerabilidade e informando estratégias de prevenção de lesões alinhadas com as diferentes fases de desenvolvimento.

2. Identificar estratégias eficazes de monitorização do crescimento, da maturação e da carga de trabalho em contextos de academia. Este objetivo visa desenvolver e validar protocolos práticos que possam ser implementados por treinadores e profissionais de performance, com vista à melhoria da prevenção de lesões, ao acompanhamento do desenvolvimento dos atletas e à individualização do treino.

3. Examinar a influência da maturação biológica no desempenho em testes físicos em jogadores de futebol do sexo masculino pertencentes a uma academia de futebol de elite. Este objetivo avalia o impacto do estado maturacional nos resultados de testes neuromusculares e de condição física, procurando melhorar a interpretação das avaliações de desempenho e promover um desenvolvimento de talento mais equitativo.

4. Fornecer recomendações etárias e referências de desempenho físico específicas para diferentes estados de maturação destinadas a profissionais que trabalham em academias. Com base em dados empíricos, este objetivo apresenta orientações práticas ajustadas a diferentes estados maturacionais, apoiando o desenvolvimento de intervenções de treino adequadas ao desenvolvimento e a critérios de avaliação apropriados.

5. Quantificar e comparar a carga de jogo (por exemplo, distância percorrida, sprints de alta intensidade e acelerações) em diferentes estados de maturação biológica em jovens jogadores de futebol de elite pertencentes a uma academia. Utilizando métricas derivadas de sistemas de posicionamento global, este objetivo investiga de que forma jogadores com diferentes estados maturacionais respondem às exigências físicas da competição, permitindo estratégias de gestão da carga mais informadas e individualizadas.

6. Avaliar as relações entre o estado maturacional e métricas de carga externa durante os jogos. Este objetivo procura investigar de que forma variações no estado maturacional influenciam as exigências físicas experimentadas durante a competição, fornecendo conhecimentos essenciais para a caracterização do desempenho e para o desenvolvimento de estratégias de treino individualizadas no futebol de formação de elite.

Ao prosseguir sistematicamente estes objetivos claramente definidos, esta tese pretende oferecer uma compreensão abrangente, empiricamente fundamentada e aprofundada dos fatores complexos que influenciam significativamente as qualidades físicas e o risco de lesão em jovens jogadores de futebol de elite. Espera-se que estes resultados forneçam contributos relevantes para cientistas do desporto, analistas de performance e treinadores de força e condicionamento no futebol, contribuindo para o desenvolvimento holístico dos jovens atletas. Este trabalho pretende ainda representar um contributo significativo para o conhecimento científico nas áreas da ciência do exercício pediátrico e do desenvolvimento desportivo jovem, apoiando o avanço de práticas baseadas na evidência na identificação de talento, no planeamento estratégico do treino e na promoção de percursos sustentáveis de desenvolvimento atlético a longo prazo em academias de futebol de elite.

General Introduction

The development of young athletes in elite sports settings is shaped by a complex interaction among biological growth, maturation, and training exposure, all of which substantially influence physical performance. In soccer, a globally dominant sport that integrates high-level physical, technical, tactical, and psychological components, understanding these developmental processes is crucial for effective talent identification, tailored training strategies, and injury prevention and mitigation programs [1,2]. Furthermore, psychological and psychosocial factors, including perceived stress, motivation, emotional well-being, coping strategies, and perceptions of recovery, may interact with biological maturation and workload responses. In the context of this thesis, adolescence is understood as a transitional developmental period between childhood and adulthood, broadly characterized by marked biological, psychological, and social changes. Although chronological age ranges may vary across definitions and contexts, this thesis focuses on youth academy players aged 14 to 17 years, a period in which substantial inter-individual variability in biological maturation may occur. These interactions can influence athletic development, training adaptation, and injury susceptibility during adolescence. Elite soccer academies have become increasingly relevant in this context, offering structured environments that promote performance enhancement and long-term athlete well-being [3].

From a physiological and morphological standpoint, adolescence is a critical period marked by substantial changes in body composition, muscular development, and neuromuscular control [4,5]. However, this developmental window features wide inter-individual variability in biological maturation, with youths of the same chronological age often differing significantly in their biological development. These discrepancies can influence athletic performance, training responsiveness, and psychological resilience, highlighting the importance of individualized monitoring and support [6–8]. Consequently, this thesis aims to explore how biological maturation, along with growth and workload, affects the development of physical qualities in young soccer players.

In youth soccer, the interaction among growth, maturation, and physical performance has been extensively studied to optimize training and competition frameworks. Vaeyens et al. [1] have emphasized the necessity of considering maturation-related differences in talent development programs to prevent selection biases that favor early maturers and promote equitable athlete development. These studies advocate for maturation-sensitive training approaches that accommodate the dynamic interplay of hormonal, neuromuscular, and morphological changes during adolescence. Furthermore, Buchheit and Mendez-Villanueva [10] investigated the influence of maturation on the development of soccer-specific physical capabilities such as intermittent endurance and sprint capacity, which are crucial for on-field performance. Their research provides insights into tailoring training loads and competition demands based on an athlete's maturation status, thereby fostering performance progression while mitigating injury risks.

The intersection of biological maturation and workload management constitutes a critical thematic area. Gabbett [4] and Impellizzeri et al. [5] highlighted the necessity of adapting load-monitoring strategies and injury prevention frameworks to maturation status to ensure safe development. Notably, the peak height velocity (PHV) period, characterized by rapid growth and potentially associated with transient periods of increased injury vulnerability, requires particular consideration in the formulation of training and competition schedules. Incorporating maturation assessments into load management allows coaches and sports scientists to refine training prescriptions corresponding to young athletes' developing capacities and vulnerabilities. This approach is consistent with the Long-Term Athlete Development (LTAD) model proposed by Balyi et al. [6], which emphasizes the significance of biological age in structuring age-appropriate training phases to sustainably optimize athletic potential.

A biologically informed and scientifically grounded approach that integrates biological maturation status with chronological age is essential for guiding talent development pathways in soccer [7,8]. This thesis is based on the premise that maturation is an important contributing factor influencing physical capacity and training adaptation during adolescence. By accounting for age categories, physical qualities, and training phases, this study aims to fill critical knowledge gaps and provide practical tools for academy practitioners to optimize long-term development, minimize injury risk, and personalize performance planning in youth soccer.

Growth and Biological Maturation in Youth Soccer

Biological maturation is a non-linear, individualized process that diverges from chronological age and significantly impacts strength, speed, agility, and other performance attributes essential in soccer [9]. These differences are particularly pronounced during the pubertal growth spurt and peak height velocity (PHV), which signify a period of accelerated skeletal and muscular development [9]. Researchers such as Malina, Bouchard, and Bar-Or [9] have extensively documented the physiological mechanisms underlying adolescent growth, emphasizing its impact on strength, power, speed, and agility, which are critical performance attributes in soccer. Figueiredo et al. [10] further highlighted that maturity status affects not only physical capacity but also competitive participation and selection biases.

Significantly, the variation in biological maturity at a given chronological age can distort perceptions of talent, potentially favoring early maturing players who may temporarily outperform their less-mature peers [11]. This issue raises ethical and practical concerns within academy systems, necessitating more nuanced methods to evaluate and train young players. Assert, a maturity-informed approach, is both fairer and more effective in fostering long-term development. This thesis builds upon such perspectives by investigating how maturation influences performance, match workload, and injury risk in young elite soccer players, to optimize individualized training and competition strategies.

Talent Identification, Physical Performance, and Maturity Bias

Talent identification processes that disregard biological maturity risk prematurely exclude late-maturing athletes, thereby compromising their long-term potential [1,7]. The advantages of early maturation in terms of size, strength, and speed can create a developmental gap that, if not accounted for, may mislead coaches and scouts. Indeed, Buchheit and Mendez-Villanueva [12] demonstrated that early maturers often excel in aerobic capacity and sprint metrics; however, this does not necessarily predict adult performance or career longevity.

Workload, Injury Risk, and Maturity Considerations

The interaction between biological maturation and workload is a critical area of investigation, particularly because of its implications for injury prevention. Adolescents experiencing rapid growth often encounter temporary deficits in coordination, flexibility, and strength, increasing their susceptibility to injuries, especially during the period of peak height velocity (PHV) [13]. Gabbett [4] and Impellizzeri et al. [5] underscored the significance of load management strategies that consider maturity status, thereby enabling coaches to adjust training and recovery protocols to safeguard athlete health.

Monitoring tools such as GPS and inertial measurement units (IMUs) facilitate the precise quantification of external load variables, including total distance (TD), high-speed running (HSR), and accelerations (ACC). These metrics can be correlated with the maturity status to optimize workload prescription [14]. This approach is consistent with the Long-

Term Athlete Development (LTAD) model proposed by Balyi et al. [6], which recommends structuring training based on developmental windows rather than fixed age categories. Within this framework, this thesis seeks to systematically analyze the variations in match workloads across different maturity stages and positional roles, thereby enabling more informed and individualized periodization strategies in elite soccer academies.

1.1. Thesis Aims and Research Objectives

Given the complex, multidimensional, and dynamic interrelationships between growth, biological maturation, and the development of physical attributes, as well as the significant role of workload in affecting injury risk among young elite soccer players, a comprehensive and methodologically rigorous investigation of these multifaceted factors is clearly warranted. Such an investigation aims to optimize developmental pathways and substantially enhance current coaching practices. The primary objective of this PhD thesis is to provide an in-depth understanding of the impact of growth, biological maturation, and workload on physical attributes and injury risk in young elite soccer players, and to develop strategies for effective monitoring and intervention within academy settings.

To achieve this primary objective systematically, this thesis rigorously addresses several well-defined specific objectives, each designed to elucidate distinct aspects of the complex developmental landscape in elite youth soccer.

1.1.1. Thesis aims

1. To review the current literature on the influence of growth, biological maturation, and workload on injury risk in young male soccer players.

2. To assess the longitudinal impact of biological maturation on the progression of physical performance across two competitive seasons.

3. To evaluate how biological maturation affects match workloads in elite male youth soccer players.

1.1.2. Research objectives

1. To analyze the influence of growth, maturation, and workload on injury risk.

This objective explores how biological development interacts with external training and match demands, identifying periods of heightened vulnerability and informing injury prevention strategies aligned with developmental phases.

2. To identify effective monitoring strategies for growth, maturation, and workload in academy environments. This objective aims to develop and validate practical protocols that can be implemented by coaches and performance staff to enhance injury prevention, player development tracking, and training individualization.

3. To examine the influence of biological maturation on physical test performance in elite male soccer players from an elite soccer academy. This objective assesses the impact of maturational status on neuromuscular and fitness test results, aiming to enhance the interpretation of performance assessments and promote equitable talent development.

4. To provide age recommendations and maturity-specific physical performance benchmarks for academy practitioners. Building upon empirical data, this objective delivers practical guidelines tailored to different maturity stages, aiding practitioners in designing developmentally appropriate training interventions and evaluation criteria.

5. To quantify and compare match workload (e.g., running distance, high-intensity sprints, and accelerations) across different stages of biological maturation in elite male soccer players from an elite soccer academy. Using GPS-derived metrics, this objective investigates how players at different maturational levels respond to the physical demands of competition, enabling more informed and individualized load management strategies.

6. The relationships among maturation status and external workload metrics during matches were evaluated. This objective aims to investigate how variations in maturity status influence the physical demands experienced during match play, providing critical insights into performance profiling and individualized training strategies in elite youth soccer.

By systematically pursuing these clearly defined objectives, this thesis aims to offer a comprehensive, empirically grounded, and nuanced understanding of the complex factors that significantly affect physical attributes and injury risk among young elite soccer players.

These findings are expected to provide valuable insights for sports scientists, performance analysts, and strength and conditioning coaches in soccer, ultimately benefiting the holistic development of young athletes. This research is expected to make a substantial contribution to the existing body of knowledge in pediatric exercise science and youth sports development, thereby informing the advancement of evidence-based practices in talent identification, strategic design of training programs, and cultivation of sustainable long-term athletic development pathways within elite soccer academies.

Literature Review

1.1. The Importance of Soccer Development Academies

The long-term development of young soccer players is a crucial area of research as it has significant implications for future success and well-being [15]. Elite soccer academies play a vital role in developing young athletes by providing specialized training and support [16]. However, the intense demands of such environments can also increase the risk of injury, particularly in the context of biological maturation (BM) and the development of physical qualities [17]. Understanding the impact of BM on the physical qualities of young elite soccer players is essential for optimizing their training and performance. This knowledge also informs the management of training and match loads, ensuring that young athletes are not subjected to excessive demands that could compromise their long-term development [18].

Soccer academies have emerged as pivotal institutions in shaping the future of the sport. Their primary function is to identify and nurture young talent with the potential to compete at a senior level and secure a professional contract [3]. These specialized training grounds provide a structured pathway for aspiring soccer players to refine their skills and progress professionally. This process involved a multidisciplinary approach considering technical abilities, tactical awareness, physical fitness, and psychological resilience. Through comprehensive assessment and training programs, academies can accurately identify individuals with the potential to excel at their highest levels.

Research has highlighted the significance of financial resources, educational support, philosophical and cultural alignment, and intensity of practice sessions within these academies [19,20]. These elements profoundly impact the ability of young elite players to thrive and reach their full potential [19,20]. These elements can profoundly impact the ability of young elite players to thrive and reach their full potential [20]. Addressing these structural issues is crucial to providing a conducive environment for player development. In addition to financial considerations, the provision of educational support to soccer academies is paramount. Young players face various personal and interpersonal challenges when navigating the demands of elite-level training and competition. Academies that prioritize holistic development—offering counseling, life skills workshops, and academic support–are more likely to foster well-rounded individuals who can thrive both on and off the field [21].

Beyond talent identification, soccer academies play a pivotal role in players' long-term development. Rather than focusing solely on the most talented individuals, academies should strive to support the overall growth and well-being of all participating players regardless of their current performance level. This approach not only fosters a broader base of active and healthy individuals but also strengthens the foundation for identifying and nurturing future talent [22–24]. The diverse roles and responsibilities of the involved staff exemplify the multifaceted nature of soccer academies [19]. Coaches, fitness specialists, performance analysts, and psychologists collaborate to create a comprehensive training and development program that addresses the physical, tactical, and mental aspects of the game [22]. Researchers have emphasized the need to critically examine existing practices and ensure that the pathway provides the most appropriate starting point for player development.

Soccer academies play a crucial role in identifying, developing, and nurturing young players, thereby contributing to the long-term success and sustainability of the sport. By addressing structural challenges, adopting a comprehensive, holistic approach to player development, and prioritizing the well-being and growth of young athletes, these academies can significantly influence and shape the future trajectory of the game. Soccer academies function as essential incubators, fostering the next generation of talented players and ensuring the continued strength and vitality of the sport.

1.2. The Complexity of Adolescent Development

The process of identifying and developing talented athletes is a complex endeavor, particularly during adolescence. Sustainability and consistency are the two primary components necessary for designing long-term plans to develop talented athletes [25]. Several historical models of athletic and talent development exist, each of which embodies unique methods, pedagogical approaches, and timing strategies that adapt to CA and BM. This complexity is further exacerbated by the multidimensional nature of identification and talent development, with physical, technical, tactical, psychological, and social factors contributing to long-term athletic development [26]. Over the past few decades, there has been a growing focus on supplementing subjective evaluations with data-driven talent identification methods to improve the likelihood of choosing successful athletes [26]. Despite attempts to establish a consensus regarding talent development processes [27–30] universal agreement remains elusive. This complexity arises from two primary sources: (a) distinguishing between domains driven by performance outcomes or participation and (b) the unpredictable and non-linear progression of BM, which challenges the applicability of conventional frameworks [29].

Although widely utilized, categorizing individuals based on their CA fails to adequately address substantial variations in BM. Research has demonstrated significant disparities within age groups; for instance, among soccer academy players aged 11 to 12 years, body mass ranges from 30 to 49 kg, height varies between 134 and 157 cm, and skeletal age (SA) spans from 9.6 to 14.1 years [10]. Hannon et al. [31] verified similar variations, highlighting the challenges of creating equitable and effective training protocols. Such disparities can introduce maturity-selection biases favoring early maturing individuals, as they may exhibit physical advantages perceived favorably by talent scouts [7,32]. Consequently, late-maturing athletes are at risk of being overlooked, excluded, or compelled to adopt compensatory measures to align themselves with their peers [33]. The long-term implications of BM on athletic success remain a contentious area of study. Some studies have identified a bias favoring early maturing players in retention processes [34], whereas others report inconclusive associations [35,36] or minimal correlations [37]. Notwithstanding these findings, robust evidence links adolescence with increased injury risk, particularly during growth spurts [38–41]. This vulnerability is exacerbated when inappropriate age-centric workloads are imposed on biologically immature individuals, potentially causing excessive physical strain and escalating injury incidence [42,43].

The risk of injury often increases when training workloads are not properly managed [4,41,44,45]. Therefore, ensuring well-calibrated exposure to training stressors is critical for safeguarding the physical, psychological, and developmental well-being of young athletes [46,47]. Moreover, the physical demands of sports coincide with broader developmental stressors such as academic pressure and personal growth. The teenage years represent a crucial period of personal growth, during which young people develop their sense of identity, interpersonal dynamics, and future goals in various life spheres, including athletics [48]. Psychosocial factors, such as emotional and hormonal fluctuations, influence coping mechanisms and stress responses [9,49]. When coupled with the high stakes and professionalized environments of elite sporting academies, these factors may contribute to heightened stress and the risk of maladaptive outcomes, including burnout. Hill [50] identified self-identity as being closely tied to sports performance as a vulnerability factor for young athletes. This dependency can magnify the impact of adverse events, such as injuries or deselection, leading to negative consequences, including reduced accomplishment, physical and emotional exhaustion, and sports devaluation [51].

Preventing burnout requires mitigating chronic stressors and balancing training loads with sufficient recovery periods [52,53]. Effective management of these stressors is essential for protecting the long-term physical and mental health of adolescent athletes, ensuring that developmental processes unfold within a supportive and adaptive environment. By fostering resilience and acknowledging the intricate interplay between biological, psychological, and social factors, athletic development strategies can address the multifaceted nature of adolescence and its impact on young athletes.

1.3. Monitoring Injury Risk in Adolescent Soccer

Adolescent soccer players represent a unique subset of athletes whose physical, physiological, and psychological development are in transition. Consequently, injury prevention and monitoring remain central priorities for practitioners working in this domain, as injuries during this critical developmental period can profoundly affect long-term athletic careers and overall well-being [54,55]. Monitoring injury risk in adolescent soccer requires understanding not only the biomechanical and physiological demands placed on players but also how growth, maturation, and training load interact to influence susceptibility to injury [56]. Adolescence is generally considered a developmental period characterized by substantial biological, psychological, and social changes, although the specific age range may vary across definitions and contexts [57]. These developmental shifts are further complicated by variations in timing and progression across individuals. As players experience growth spurts and attain physiological maturity, their bodies undergo structural and functional transformations that may temporarily impair coordination, flexibility, and balance, which increases their vulnerability to injuries, particularly those affecting muscles, tendons, and ligaments [58]. For this reason, understanding how an adolescent’s developmental stage impacts both their performance and susceptibility to injury is essential for designing effective training programs that minimize these risks [3,59]. In addition to physical growth, BM plays a fundamental role in determining an athlete’s risk of injury. Maturation involves the transformation of various biological systems, including the skeletal, muscular, and nervous systems, into adult-like capacities [56,60]. However, this process is not uniform. Within a given age group, players can exhibit considerable variations in their maturation rate, which can lead to different injury vulnerabilities [10,57]. Thus, monitoring growth and maturation status is key to ensuring that training loads, rehabilitation, and match participation are tailored to the individual, reducing injury risk while optimizing long-term player development [10,61].

Another critical factor that influences injury risk in adolescent soccer players is training and matching workload. The cumulative stress experienced by players during training sessions and matches can impose significant physical demands, potentially leading to fatigue-related injuries [56,62]. Workload management strategies such as balancing training intensity, frequency, and rest periods are vital for mitigating this risk [14]. Both external workloads (e.g., distance covered, speed, and accelerations) and internal loads (e.g., physiological responses and perceived exertion) should be consistently monitored to ensure that players do not experience excessive strain relative to their physical condition, recovery status, psychosocial stressors, and maturational status [56,63]. Despite a growing body of research examining injuries in youth soccer players, there remains a gap in our understanding of the complex interplay between growth, maturation, training load, and injury risk [64,65]. Studies suggest that adolescents in more advanced stages of maturation are more prone to sustaining injuries owing to a combination of increased physical activity and the still-developing state of their muscles and joints [56,58]. At the same time, a higher workload and inadequate recovery strategies can exacerbate this risk [56].

The monitoring of injury risk in adolescent soccer players necessitates a comprehensive approach that accounts for biological maturity, growth trends, and nuances of individual workload demands. This approach should consider various factors, such as physical, physiological, and psychosocial changes that occur during adolescence, to develop tailored strategies for injury prevention and performance enhancement. As increased attention is directed toward these areas, more effective strategies can be developed to enhance player safety, performance, and career longevity [55,56]. This chapter examines these key factors and provides an overview of the methodologies utilized to track injury risk in young athletes, with a focus on how research and clinical practices can converge to promote safer and more effective training regimens that address the unique needs and challenges faced by adolescent soccer players [59,66].

1.3.1. Growth & Injury Risk

Body growth in adolescents involves changes in dimensions, physique, and composition, which significantly affect injury risk in young soccer players. Height, weight, and body composition, including muscle and fat mass, evolve substantially during development [67,68]. These changes occur at varying rates and are influenced by genetic (80%) and environmental factors (20%), including heredity, nutrition, physical activity, and overall environmental conditions [69–71].

During adolescence, puberty triggers a sharp increase in the growth rate, marking a critical phase for injury risk. The period of peak height velocity (PHV), observed in boys aged between 13 and 14 years, involves growth rates of approximately 10 cm/year [61]. Similarly, peak weight velocity (PWV) occurs approximately 14–15 years later, with average weight gains of 9-10 kg/year [9]. For boys, typically, PWV occurs about 18 months after PHV in males [30,60,72]. It is essential to assess these swift changes in height, weight, and body composition at various ages as they can lead to notable differences in height and weight among different age groups [73]. This dynamic growth results in structural and functional changes that affect neuromuscular control and increase susceptibility to overuse injuries [74,75]. Growth plate vulnerability during PHV is a critical injury mechanism. Growth plates are thicker and less mineralized during this period, making them prone to mechanical stress and injury [74,76]. Furthermore, the mismatch in the growth rates of skeletal, muscular, and connective tissues increases the tension on these structures, elevating the risk of apophyseal stress injuries, such as Osgood-Schlatter disease [77,78]. Rapid changes during adolescence can affect neuromuscular control and proprioception. The phenomenon of "adolescent awkwardness," characterized by transient declines in coordination and motor control, reflects the challenges of adapting to new body dimensions [79,80]. These biomechanical alterations contribute to increased joint stiffness and reduced flexibility in key muscle groups such as the hamstrings and lower back [81]. Consequently, adolescents are at a higher risk of acute and overuse injuries such as muscle tears and stress fractures [82,83].

Longitudinal studies have underscored the importance of monitoring growth patterns to effectively predict and manage injury risk. Frequent assessments of growth velocity, particularly during critical phases such as PHV, provide actionable insights into training adaptation [84]. Notably, a growth velocity exceeding 0.6 cm per month significantly increases injury risk, emphasizing the need for vigilant monitoring [84]. The relationship between rapid growth and injury risk extends the motor performance. Rommers et al. [83] demonstrated a causal link between growth velocity and injury incidence, revealing a 15% increase in the likelihood of injury per additional centimeter per year. These findings underscore the necessity for tailored interventions during high-risk periods, particularly for managing workloads and enhancing neuromuscular resilience.

To reduce the risk of injury during the PHV period, several crucial approaches should be employed. It is vital to conduct regular assessments of risk factors, preferably every 2–3 months, which should encompass the evaluation of growth and maturation data, particularly growth curves during PHV [85]. Professionals should follow the ISAK guidelines for anthropometric measurements. Identifying growth rates above 7.2 cm per year and BMI increases exceeding 0.3 kg/m² can help pinpoint players at elevated risk, enabling the implementation of tailored injury prevention plans [84]. Moreover, it is essential to develop a thorough risk profile for each player, taking into account factors such as injury history, biological age, and physical condition. Training programs should be customized to suit players' developmental stages and individual requirements. During rapid growth phases, monthly evaluations are advised to closely monitor growth rates and adjust training intensities accordingly [85]. Conversely, coaches can evaluate players' external workload using GPS-tracking devices and sports monitoring software [86]. By examining data on speed and distance, coaches can recognize patterns and trends that might suggest a higher risk of injury. For young soccer players, it is important to monitor external workload metrics, including total distance covered (TD) and high-speed running (HSR), to optimize training and match loads. By tracking these variables, coaches and medical personnel can make necessary adjustments to training regimens, thereby reducing the risk of injury [86,87]. Furthermore, measuring internal workload through heart rate variability (HRV) is essential for gauging fatigue levels and guiding recovery strategies.

1.3.2. Maturation & Injury Risk

BM is a critical factor influencing injury risk in adolescent soccer players, with growing evidence emphasizing its complex role in determining the susceptibility to various types of injuries. BM, a dynamic and individualized process beginning at conception and concluding in adulthood, involves distinct components such as maturity status, timing, and tempo. These components capture various dimensions of development, including how advanced an individual is in their maturation process (absolute maturity), categorization relative to peers (relative maturity), age at key maturational milestones (timing), and the rate at which these changes occur (tempo). Maturity status, evaluated as absolute or relative, provides valuable insights into players' proximity to physical development. Absolute maturity refers to how close an individual is to achieving their adult form, while relative maturity categorizes individuals as early, average, or late maturers compared to one-time matures [88]. Timing captures milestones such as PHV, the age at which adolescents experience their fastest growth spurt [9,67]. Tempo describes the pace of maturation, influencing how quickly an individual transitions through developmental phases [9,67].

Skeletal maturation has emerged as the gold standard for assessing biological maturity owing to its reliability and precision. This process involves monitoring ossification and bone morphology using imaging techniques such as hand-wrist radiography. Commonly employed methods include Greulich-Pyle, Fels, and Tanner-Whitehouse (TW), each of which offers unique criteria for assessing SA [7,60]. Although effective, these techniques often require significant resources and expose participants to ionizing radiation, limiting their practical applicability in sports contexts [89,90]. To address these limitations, noninvasive somatic assessments, such as the prediction of PHV age using anthropometric equations, have gained traction. Models, such as those developed by Mirwald et al. [91], Fransen et al. [92], and Moore et al. [93], used variables such as age, height, seated height, and body mass to estimate maturity status, making them well-suited for soccer academies [91–93].

The relationship between maturation and injury risk has garnered significant attention, with studies consistently highlighting players' vulnerability during the PHV period. During this phase, rapid physical changes, including the disproportionate growth of bones, muscles, and tendons, may contribute to biomechanical imbalances and an increased injury risk [94,95]. For example, research involving Spanish La Liga youth players revealed a higher incidence of growth-related injuries during the pre-PHV and circa-PHV phases, characterized by percentages of predicted adult height below 96% [40]. Growth-related injuries include apophysitis and osteochondritis, whereas the post-PHV phases have been associated with muscular, knee, and ankle joint injuries. Timing and tempo further modulate susceptibility to injury. Players reaching PHV earlier than their peers often experience different injury patterns compared with later maturers. Van Der Sluis et al. [43] observed higher rates of overuse injuries among later-maturing players during pre- and circa-PHV periods but no significant differences in traumatic injury incidence. Conversely, Bult et al. [54] reported peak injury incidence and burden within six months following PHV, illustrating the significance of the post-PHV adaptation period [54]. These studies underscore the importance of continuous monitoring during the years surrounding PHV to effectively mitigate injury risks. Relative maturity also plays a role in injury patterns. Studies using skeletal maturity indicators have revealed a nuanced relationship between maturation and risk of injury. For instance, Le Gall et al. [96] found no significant differences in overall injury incidence between early, average, and late maturers among elite U14 French soccer players. However, certain injury types showed clear trends; osteochondral disorders were more frequent among average and late maturers, whereas tendinopathies were predominant in early and average maturers. Similarly, Materne et al. [97] demonstrated that skeletal maturity levels correlate with injury likelihood, particularly for overuse injuries, highlighting the need for tailored training and recovery protocols based on the maturity status.

The researchers emphasize the complex influence of maturation on injury risk in adolescent soccer, highlighting PHV as a critical period for proactive monitoring and intervention. The integration of skeletal and somatic maturity assessments provides a comprehensive understanding of players' maturation profiles. This approach facilitates the implementation of targeted strategies to manage workload, optimize training adaptations, and reduce injury incidence, thereby supporting the long-term development and overall well-being of young athletes. Through careful monitoring of players' physical maturation and subsequent adaptation of training programs, coaches and sports medicine professionals can mitigate the elevated risk of injuries often associated with the rapid physical changes that occur during adolescence, ultimately fostering a safer and more sustainable trajectory for the long-term development of young soccer players.

1.3.2. Workload & Injury Risk

Monitoring workload is a critical component in evaluating young soccer players' responses and adaptations to training regimens as well as in managing fatigue, promoting recovery, and mitigating the risk of overtraining, injuries, and illnesses [14]. Both internal and external factors influence the incidence and prevalence of injuries in adolescent soccer players. Internal factors such as age, career length, and prior injury history are closely linked to the risk of injury [98–100]. During PHV, players often face performance plateaus or declines and are more susceptible to overuse injuries [75]. Hence, it is essential to regulate players' exposure to high and repetitive workloads during this period while ensuring adequate recovery to optimize performance and mitigate injury risk [101,102]. Additionally, match days are associated with significantly higher injury rates (18.2–24.1 injuries per 1000 hours) than training days (1.5–3.3 injuries per 1000 hours) [84]. Boys undergoing puberty frequently experience a swift growth phase, often termed "adolescent awkwardness." This period is marked by abrupt alterations in body dimensions and proportions, potentially impacting motor control, especially in certain athletes [11,79,80,103,104]. The rapid growth can also affect neuromuscular control and proprioceptive abilities [105]. Furthermore, when body mass development lags behind bone growth, it can result in motor control issues [75,106]. Athletes in their adolescent years may face stagnation or deterioration in performance during the PHV phase, coupled with an elevated risk of overuse injuries [75]. Considering that factors like workload can be modified, it is essential to implement more rigorous monitoring of young soccer players' exposure to intense and repetitive training and match demands during this crucial period [101].

Research has provided varying insights into the relationship between the internal workload and injury risk in young soccer players. Brink et al. [44] investigated stress recovery monitoring in 53 young elite players over two seasons using training logs and the Recovery Stress Questionnaire for Athletes (RESTQ-Sport). However, their findings showed no significant correlation among recovery, stress indices, and injury occurrence, particularly for traumatic or overuse injuries. Conversely, Raya-González et al. [107] explored internal workload markers, such as session ratings of perceived exertion (s-RPE), weekly internal workload, and acute:chronic workload ratios (A:C), in a cohort of twenty-two U19 players and concluded that these markers had limited predictive capacity for non-contact injuries. Mandorino et al. [108] provided further insights by examining internal workload indicators among U14 players categorized by maturity level. The study revealed associations between metrics such as RPE, A:C workload ratios, total quality recovery (TQR), and injury risk in players who had passed PHV.

Examination of the external workload has also revealed crucial findings. Studies utilizing GPS data have identified relationships between injury incidence and specific workload metrics. Bowen et al. (2017) demonstrated that high accelerations (ACC) and decelerations (DCC) over three weeks, along with high acute high-speed distance (HSD) paired with low chronic HSD, significantly increased the risk of non-contact injuries [87]. Similarly, cumulative high workload and elevated acute-to-chronic ratios for ACC were linked to an increased injury risk. Conversely, Bacon and Mauger [109] highlighted that the total distance (TD) covered during training and matches significantly predicted overuse injury incidence, although no significant correlation was observed for high-speed running meters. The disparities between these studies, including workload metrics, statistical methodologies, and GPS variable choices, underscore the complexity of drawing uniform conclusions.

Further research into external workload has revealed a strong link between excessive training volume and injury risk. Bell et al. [110] found that an annual training duration exceeding eight months was associated with a higher incidence of knee injuries among players aged 12–18 years. Supporting these findings, Zoellner et al. [111] reported that prolonged weekly sports participation among 10 to 15-year-olds increased the risk of gradual onset injuries. According to Rössler et al. [112], a greater proportion of matches compared to training sessions was linked to an elevated injury risk, indicating that training activities might offer a protective benefit in contrast to match participation. Existing evidence emphasizes the need for benchmark external workload metrics and a deeper understanding of how these metrics affect the injury risk across developmental stages. Longitudinal studies that monitor young players from younger age groups (< 16 years) and account for biological age, workload dynamics, and recovery protocols are essential to provide tailored injury prevention strategies [85]. Such investigations could support coaches, medical professionals, and technical staff in optimizing training and matching schedules, ensuring player health, and fostering athletic development.

Despite preliminary evidence linking workload parameters to injury risk, inconsistent methodologies and variations across studies present challenges for definitive conclusions. Future research endeavors should aim to harmonize research designs, integrate standardized workload metrics, and address population-specific nuances to provide actionable insights. Monitoring internal and external workloads, such as physiological responses and training load data, along with individualized training programs tailored to each athlete's needs, will remain fundamental for balancing performance enhancement and injury prevention in adolescent soccer players. Adopting a comprehensive approach that incorporates both quantitative and qualitative measures can assist coaches and sports medicine practitioners in developing more effective training strategies and mitigating injury risk in young soccer players.

1.4. Monitoring Maturity Characteristics

1.4.1. Maturity Characteristics

Biological development towards adult form and function is known as maturation, which exhibits considerable variability in both timing and pace among individuals and between sexes [9,67]. The chronological age at which specific developmental milestones are reached, such as the age of peak height velocity (APHV), is referred to as the timing, whereas the rate at which these changes occur is termed the tempo [9]. These concepts elucidate the nonlinear and highly individualized nature of growth and maturation processes.

In young athletes, particularly soccer athletes, understanding maturation is essential for talent identification, training adaptation, and injury prevention strategies [113]. Athletic performance is significantly influenced by physiological and morphological changes, including increases in stature, body mass, and lean tissue, as well as alterations in body composition. During growth, organ size, aerobic capacity, and muscle strength undergo changes that affect both immediate and long-term responses to training and competition [67]. Scammon [114] demonstrated that body systems develop at different rates, with the greatest variation occurring during puberty. This heterogeneity presents challenges, as individuals of the same chronological age may exhibit variations in their biological maturity by several years, thereby influencing their physical and physiological characteristics [115]. For instance, a 12-year-old male might have a biological age ranging from 9 to 15 years. Early maturers typically exhibit superior physical characteristics owing to advanced musculoskeletal and cardiorespiratory development, often conferring a competitive advantage. Conversely, later maturers are at higher risk of injury and faces disadvantages, particularly during the adolescent growth spurt [32,43]. Growth curves for height and weight provide valuable developmental reference models. Height growth decelerates from infancy to childhood until the adolescent growth spurt, which initiates a brief acceleration. In contrast, weight increases steadily after infancy, with significant changes occurring during puberty [9]. Males experience an adolescent growth spurt approximately two years later than females and achieve greater height gains, contributing to the average 12-13 cm height difference between sexes in adulthood [9].

The PHV, which represents the maximum rate of height increase during adolescence, is a critical maturation indicator. For male soccer players, PHV typically occurs between 13.8 and 14.2 years, coinciding with elevated injury risk during adolescence [9,11].

Continuous monitoring of growth patterns and maturity markers, such as age at PHV, helps professionals manage training loads, nutrition, and recovery to address growth and maturation challenges. Young athletes tend to have more advanced bone development and sexual maturation than their non-athletic peers [32]. This predisposition towards physical maturity is observed across multiple sports, with a higher prevalence of early development [10,115]. Early maturers often demonstrate greater increases in height, weight, and muscle mass, conferring an advantage in strength and power [115]. Conversely, later maturers may have superior long-term prospects due to extended skill acquisition periods and reduced injury risk upon physical maturation [35,115].

A comprehensive understanding of growth patterns and maturity indicators is essential to address the challenges and opportunities presented by varying maturation rates. Through the assessment of an athlete's maturity status, practitioners can implement strategies to mitigate disadvantages faced by late developers while ensuring optimal growth opportunities for all athletes [43,116]. Effective monitoring supports a comprehensive athlete management approach that considers the complex interactions between growth, maturation, and physical performance. This holistic approach facilitates a more nuanced understanding of the intricacies involved in athlete development, enabling tailored interventions and maximizing the potential of each athlete, irrespective of their maturation timeline.

1.4.2. Somatic Growth

Somatic growth, a fundamental aspect of human development, encompasses temporal changes in body dimensions. This process involves a progressive increase in physical measurements, including height, weight, and other bodily segments, which indicate biological development [9]. Although growth and maturation are often used interchangeably, growth refers to body enlargement, while maturation denotes progression towards physical or functional adulthood [9]. As an integral component of maturation, somatic growth can provide substantial information regarding an individual's developmental progress. Various factors, including genetics, nutrition, and the environment, contribute to physical development. Biologically, growth occurs through three primary mechanisms: hyperplasia (cell multiplication), hypertrophy (cell enlargement), and accretion (expansion of substances between cells) [9]. These processes contribute differentially to various developmental stages, making somatic growth a complex, phase-specific phenomenon.

Standardized anthropometric techniques can measure physical changes by using precise instruments to assess specific body points [9]. Key indicators of physical development include stature, weight, leg length, and trunk height [9]. Comprehensive evaluations may measure bone widths, limb circumferences, adipose tissue thickness, and cranial dimensions, providing insights into muscular development, adipose distribution, and skeletal structure [9]. Although numerous measurements exist, it is crucial to select the most appropriate ones based on the objectives of the evaluation. Accurate prediction of biological maturity can be achieved through longitudinal research observing physical characteristics over time and identifying developmental markers such as the onset of adolescent growth spurt and PHV [72]. Body size alone may not consistently indicate biological maturity precisely [60], but empirical research using a combination of body size measurements and age can estimate maturity status throughout development. One method for assessing the maturation status involves calculating the percentage of predicted adult height (PPAH), which can inform the timing of specific interventions.

Acquiring precise somatic growth data requires rigorous techniques to minimize measurement errors. Anthropometric evaluations must be conducted by trained professionals using standardized protocols. Without proper standardization, minor growth changes may go undetected because of random or systematic errors [9]. Repeated measurements over time are essential to capture genuine size changes. The measurement accuracy can be influenced by factors such as diurnal variations in the assessor technique, equipment calibration, and individual physiological fluctuations [117]. Inconsistencies in inter-rater reliability can result in measurement discrepancies that affect the consistency of growth data [117]. To address this, researchers emphasize replicating assessments to quantify inaccuracies and ensure the reliable interpretation of results. Measurement protocols should incorporate guidelines for determining significant changes in body size, such as the minimum clinically important difference (MCID) [117]. Statistical analyses have indicated that the measurement accuracy for common somatic growth indicators typically falls within 0.2-1.1% [118]. These error ranges highlight the need to consider potential data inaccuracies and to identify clinically significant changes. To effectively use somatic growth for evaluating maturity status, implementing precise measurement protocols and meticulously accounting for potential errors are imperative.

1.4.3. Musculoskeletal Growth

The adolescent growth spurt is a critical period for musculoskeletal system development and is marked by rapid changes in morphology and function. During this phase, the fundamental biological mechanisms governing musculoskeletal growth influence physical capabilities, injury susceptibility, and responsiveness to training stimuli. While a comprehensive examination of musculoskeletal tissue growth and maturation exceeds the scope of thesis, seminal works like [9] explore the subject extensively. This section contextualizes this thesis by elucidating key aspects of musculoskeletal growth.

Puberty initiates rapid growth, particularly in the bone tissue. This accelerated bone development elicits a corresponding adjustment in the muscular system, as the expanding skeletal framework requires muscles to adapt their length and force-generating capabilities [99]. However, the sequential nature of this process often results in a temporary mismatch between bone elongation and muscle adaptation, which creates a 'lag' period. During this interval, the musculoskeletal system exhibits increased susceptibility to mechanical imbalances, elevating the likelihood of overuse injuries due to bone fragility and joint rigidity [42,84]. Exacerbating these structural imbalances, the disproportionate growth of lower limb long bones relative to the torso strains connective tissues, particularly at attachment points, such as apophyses. This disproportion is most pronounced during the PHV phase, which is associated with increased stress on musculotendinous units. Such stress can manifest in conditions such as traction apophysitis, which occurs because of elevated tension in connective tissues that are not fully adapted to rapid bone growth [99].

Musculoskeletal growth affects physical structure and neuromuscular control and functional stability. Reduced muscle cross-sectional area and slower hypertrophic adaptation relative to increasing skeletal size result in suboptimal force generation, potentially compromising dynamic stability and altering movement patterns [81,119]. These neuromuscular challenges are exacerbated by 'adolescent awkwardness,' a phase where recent rapid growth interferes with established motor skills and coordination [42,99].

Research findings indicate an elevated susceptibility to injury among adolescents, particularly during high-intensity physical activities, such as soccer. Apophyseal- and joint-related injuries were frequent in this demographic. The combination of substantial mechanical stress from training and competition and instability in a developing musculoskeletal system underscores the need for judicious management of training loads for young athletes. Failure to account for the physiological and biomechanical constraints of this developmental stage may significantly increase acute and chronic injury risks [42,54]. Experts advocate the implementation of a tailored training regimen during this critical period, emphasizing injury prevention and sustainable athletic development. By modulating training intensities and continuously assessing growth and maturation indicators, it is possible to mitigate potential adverse effects on skeletal and muscular development while facilitating long-term athletic enhancement. This tailored strategy involves creating training regimens that consider the individual physical attributes, growth stages, and potential injury vulnerabilities of each young athlete. Through meticulous monitoring and adjustment of the training load, exercise selection, and recovery strategies, coaches and trainers can facilitate the safe and effective progression of young athletes toward their full potential [99,120].

1.4.4. Athletic Performance

The complex interplay of physical, biomechanical, and physiological systems significantly impacts athletic performance in young athletes, with these systems exhibiting nonlinear variations during growth. These characteristics are associated with an athlete's maturity level, which influences their capacity to withstand mechanical stress and meet neuromuscular requirements [121]. Young soccer players in training academies encounter substantial physical demands, including rapid sprints, abrupt accelerations and decelerations, and swift directional changes. These movements are heavily dependent on the efficacy of the stretch-shortening cycle (SSC) [122]. This section examines how maturity-related factors affect athletic performance, emphasizing the neuromuscular adaptations, musculoskeletal changes, and training considerations associated with biological development.

Athletic performance is heavily dependent on the stretch-shortening cycle (SSC), which combines eccentric and concentric muscle actions to generate efficient and powerful movements. The effectiveness of SSC is rooted in neuromuscular function, which involves the interplay of neural, muscular, and musculotendinous units (MTU) [122]. Studies indicate that neuromuscular performance, evaluated through activities such as jumping and hopping, exhibits nonlinear improvements throughout maturation. While neural changes contribute to these advancements, the adolescent growth spurt serves as a crucial catalyst, primarily because of associated hormonal fluctuations and growth factor alterations [123]. The muscle composition of children is distinct from that of adults, with a greater percentage of Type I fibers. These fibers are characterized by reduced force generation and slower contraction speeds than Type II fibers [122]. As children mature, muscle growth primarily occurs through hypertrophy with minimal fiber hyperplasia [124]. Improved motor unit activation is crucial for strength increase during this phase; however, less mature individuals experience challenges in motor unit recruitment and increased co-contraction, negatively impacting movement efficiency and force production [125]. These muscular and neural limitations, along with higher energy expenditure and inconsistent neural activation, improve as children mature, leading to optimized stretch-shortening cycle (SSC) and muscle-tendon unit (MTU) properties [122].

During growth, the musculoskeletal system undergoes adaptation, including alterations in muscle dimensions, tendon rigidity, and muscle-tendon unit (MTU) performance. Tendons play a critical role in the stretch-shortening cycle (SSC) functionality by maintaining a balance between flexibility and firmness to optimize force transmission. As individuals progress through maturation, tendon stiffness increases, approximating adult characteristics around PHV. Contractile tissue stiffness continues to develop, reducing injury susceptibility and enhancing athletic performance [122]. The developmental discrepancy between soft and hard tissues during adolescence, termed the "lag period," can result in strength disparities and elevated injury risk [126]. Comprehension of these maturity-related changes enables professionals to tailor load management approaches, balance performance enhancement, and prevent injury [127].

Improvements in athletic ability occur nonuniformly during maturation and are influenced by asynchronous growth patterns. Peak sprinting and jumping performance frequently occur at different times relative to PHV, emphasizing the relationship between neuromuscular and musculoskeletal development [11]. When normalized for body size, performance indicators, such as horizontal and vertical jumps, exhibit greater variability, suggesting that biomechanical and neural efficiency are crucial success factors [128]. During PHV, adolescent awkwardness often manifests and is characterized by a temporary reduction in movement quality. To mitigate these effects and enhance athletic potential, training interventions have focused on improving movement efficiency, particularly targeting neuromuscular control and SSC tasks [119]. The efficacy of sprint training interventions varies based on maturity status; pre-PHV individuals often demonstrate more substantial adaptations than circa- or post-PHV individuals [129]. Understanding the impact of maturity on athletic performance underscores the need for customized approaches. Standard training programs based on chronological age are inadequate for addressing the varied developmental trajectories in young athletes. Interventions tailored to maturity levels, informed by biological indicators such as PHV and growth rate, optimize training effectiveness and minimize injury potential [130].

In addition to BM-related adaptations, body proportionality and scaling considerations may also influence the interpretation of physical performance during adolescence [9]. Growth-related changes in body dimensions, body mass, limb length, and body composition may affect strength, power, sprinting, and COD performance independently of CA. During adolescence, improvements in physical performance may therefore partially reflect increases in body size and anthropometric characteristics rather than neuromuscular development alone [9].

Consequently, several authors have highlighted the importance of considering allometric approaches when interpreting physical performance in youth athletes. Traditional ratio scaling methods (e.g., strength relative to body mass) assume linear relationships between body size and performance, which may not accurately reflect the non-linear biological changes occurring during growth and maturation [9]. Allometric scaling approaches may therefore provide additional insight into the interpretation of physical performance by accounting for the complex interactions between body size, proportionality, and athletic performance throughout adolescence [9].

Nevertheless, although allometric approaches may offer methodological advantages in specific research contexts, the practical implementation of these methods in applied academy settings remains challenging because of their statistical complexity and the need for individualized interpretation. Therefore, practitioners should consider both biological maturation and body size characteristics when evaluating the physical development of young soccer players.

The plateau or reduction in neuromuscular characteristics, such as the reactive strength index and leg stiffness, proximal to the time of PHV, necessitates targeted training during this critical developmental stage [131]. The implementation of exercises that engage a rapid stretch-shortening cycle and enhance joint stability can augment an athlete's movement quality and maintain athletic performance [127]. The identification of mechanical and neuromuscular deficiencies during these crucial growth phases enables professionals to implement evidence-based interventions, thereby enhancing an athlete's preparedness for sport-specific requirements and mitigating the risks associated with underdeveloped motor control and a high relative workload. Addressing these neuromuscular changes through appropriate training strategies during this period of rapid growth can optimize an athlete's development and establish a foundation for long-term success in soccer.

1.5. Biological Classification of Soccer Players

Appropriate categorization of soccer players based on their biological development is essential for designing appropriate growth-specific training programs. Reliable techniques for evaluating maturity levels are crucial. Maturity can be assessed using skeletal, sexual, or somatic measurements, each with methodological and ethical implications [9].

The gold standard for assessing maturity is the evaluation of skeletal maturity. This method compares radiographs of the hand and wrist with standardized references, reflecting bone ossification during growth [9]. Maturity indicators were determined by examining bones in the hands and wrists. Three primary protocols are typically employed: Greulich-Pyle (1959), Tanner-Whitehouse (1966), and Fels (1989) [132–134]. Each protocol uses different reference samples from longitudinal studies, potentially resulting in variations in the reported SA [9]. SA is expressed as the difference between SA and chronological age (CA), indicating whether maturation is early, one-time, or late. Although accurate, skeletal maturity assessment is often unfeasible owing to practical limitations, necessitating alternative methods, such as sexual maturity evaluation. This approach relies on secondary sex characteristics and was classified into five stages by Tanner et al., [134]. Ethical concerns restrict direct observation in nonclinical settings. Self-assessment using standardized images is commonly employed, although correlations with expert-rated stages vary [135]. For females, menarche onset serves as an additional indicator [9].

In youth soccer, practical constraints have led to a focus on estimating somatic maturity. These methods utilize growth patterns to estimate developmental stages, such as APHV. Algorithms based on longitudinal data enable the prediction of growth spurts using anthropometric measurements [9]. By incorporating parental height, the percentage of predicted adult stature (PAH%) can be calculated as a biological maturity indicator. The maturity offset (MO), a widely accessible indicator of maturation, calculates the time before and after PHV. Introduced by Mirwald et al. [91], the method has subsequently undergone methodological modifications and validation studies, including those proposed by Moore et al. [[49], this], the method has subsequently undergone methodological modifications and validation studies, including those proposed by Moore et al. [93] and Kozieł and Malina [49]. These approaches employ regression equations based on anthropometric interaction. Despite a strong correlation with longitudinal data ($R^2 = 0.91$), the standard error of the estimate (0.49 years) necessitates the careful interpretation of maturity-specific interventions [9]. Accurate sitting height measurement is crucial because of its significant impact on the calculation [118]. Although modified equations and alternative approaches have attempted to reduce prediction errors and improve applicability, important limitations persist, particularly in early- and late-maturing individuals and in youth further from PHV [49,136]. These limitations reflect the nonlinear nature of biological maturation and the challenges associated with predicting individual growth trajectories using anthropometric models alone. The Fransen maturity ratio employs a polynomial regression model to reflect the nonlinear aspects of maturation better [92]. This method demonstrated increased reliability in adolescent soccer by integrating MO data with somatic variables, although additional validation across diverse groups is required. The PAH% is another common method used in youth soccer to differentiate genetically tall players from those who are advanced in maturity [9]. Techniques for calculating the PAH%, such as those proposed by Bayley and Pinneau [138] and Khamis and Roche [137], offer alternatives without skeletal assessments. However, including parental height estimates may introduce errors due to self-reported inaccuracies or the unavailability of biological parents [115]. PAH% forms the basis of bio-banding, which groups young athletes by biological rather than chronological age. This method has gained recognition for reducing maturity-related selection bias in youth sports [57]. Biobanding typically uses predetermined maturity ranges that correspond to key growth stages [115]. Research has highlighted its potential to foster equitable competitive environments and customize developmental strategies for adolescent athletes [57,139].

1.6. Monitoring Workload

Assessing and tracking the training load of young soccer players is essential for enhancing athletic performance and reducing the likelihood of injuries [140]. Proper training leads to short-term functional adaptations, whereas consistent stimuli can result in long-term improvements in fitness, performance, and overall health [5]. Effective load monitoring in youth soccer requires a comprehensive approach that incorporates both internal and external metrics. By combining these measures, coaches and trainers can acquire a thorough understanding of how athletes respond to specific workloads by considering factors such as fatigue, hydration, and training history [141]. This balanced approach is crucial for addressing developmental challenges during adolescence, because both excessive and insufficient loads can adversely affect growth and performance [56,142].

Workload is generally categorized into two components: internal load, which encompasses the physiological and psychological stress experienced by athletes; and external load, which represents the objective work completed [14,143]. Internal workload reflects physiological and psychological responses to exercise [14]. Internal load signifies an athlete's response to training and can be evaluated using metrics such as heart rate (HR), training impulse (TRIMP), and ratings of perceived exertion (RPE). S-RPE, which is calculated by multiplying perceived exertion by session duration, is frequently used because of its simplicity and efficacy [144,145]. Research has shown strong correlations between s-RPE and HR-based measures, validating their use in youth soccer [144]. Differentiated ratings of perceived exertion (d-RPE) offer enhanced precision by separately evaluating exertion in different physiological domains, such as breathlessness or muscle fatigue [146]. This approach enables practitioners to refine their training programs more effectively. Although internal load measures are reliable, their interpretation can be influenced by factors such as the athlete's fitness level, psychological state, and external conditions [5]. Combining internal metrics with external load data is advisable to account for these variations and optimize load management strategies [147]. External load quantifies the physical exertion of an athlete and is measured independently of their internal physiological responses [143]. Global positioning system (GPS) devices that measure distances calculated by positional differentiation are used to collect and analyze external workloads. However, speed can be derived from distance [14]. For instance, it can be quantified as the total distance (TD) covered, accelerations (ACC), deceleration (DCC), or metabolic power [148–150]. Using Inertial Measurement Units (IMU) technology and satellites, GPS devices use positional differentiation to evaluate external effort and cadence, calculate athlete locations with variable precision [151,152], and quantify sports and team activity metrics using accelerometers and power meters. GPS technology has been widely adopted in soccer, enabling detailed workload distribution analysis during training and matches [148]. Understanding these metrics is crucial for young players because of the variability in their physical and physiological responses during growth and maturation [44]. Accelerometers, gyroscopes, and magnetometers, particularly accelerometers, quantify external workload during low-speed, short-distance activities with high reliability and validity [153].

Nevertheless, monitoring the external load in youth soccer is often challenging because of the overlapping training schedules from schools, clubs, and representative teams [154]. This fragmented approach underscores the importance of effective communication among stakeholders to avoid overtraining or undertraining and minimize injury risk [155].

A more comprehensive understanding of an athlete's training response can be attained through the integration of internal and external load metrics. The external load represents the physical work performed, whereas the internal load reflects the physiological and psychological costs experienced by the athlete. This dual approach, considering both external demands and internal responses, is particularly pertinent for adolescent players, as developmental changes during this stage can significantly influence their capacity to manage and recover from workloads encountered during training and competition [44,56].

References

1. Vaeyens, R.; Lenoir, M.; Williams, A. M.; Philippaerts, R. M. Talent Identification and Development Programmes in Sport: Current Models and Future Directions. *Sports Medicine* **2008**, *38* (9), 703–714. https://doi.org/10.2165/00007256-200838090-00001.
2. Reilly, T.; Bangsbo, J.; Franks, A. Anthropometric and Physiological Predispositions for Elite Soccer. *Journal of Sports Sciences* **2000**, *18* (9), 669–683. https://doi.org/10.1080/02640410050120050.
3. le Gall, F.; Carling, C.; Williams, M.; Reilly, T. Anthropometric and Fitness Characteristics of International, Professional and Amateur Male Graduate Soccer Players from an Elite Youth Academy. *Journal of Science and Medicine in Sport* **2010**, *13* (1), 90–95. https://doi.org/10.1016/j.jsams.2008.07.004.
4. Gabbett, T. J. The Training—Injury Prevention Paradox: Should Athletes Be Training Smarter and Harder? *British Journal of Sports Medicine* **2016**, *50* (5), 273–280. https://doi.org/10.1136/bjsports-2015-095788.
5. Impellizzeri, F. M.; Marcora, S. M.; Coutts, A. J. Internal and External Training Load: 15 Years On. *International Journal of Sports Physiology and Performance* **2019**, *14* (2), 270–273. https://doi.org/10.1123/ijspp.2018-0935.
6. Balyi, I.; Way, R.; Higgs, C. *Long-Term Athlete Development*; Human Kinetics, 2013. https://doi.org/10.5040/9781492596318.
7. Malina, R. M.; Rogol, A. D.; Cumming, S. P.; Coelho e Silva, M. J.; Figueiredo, A. J. Biological Maturation of Youth Athletes: Assessment and Implications. *British Journal of Sports Medicine* **2015**, *49* (13), 852–859. https://doi.org/10.1136/bjsports-2015-094623.
8. Lloyd, R. S.; Oliver, J. L.; Faigenbaum, A. D.; Myer, G. D.; De Ste Croix, M. B. A. Chronological Age vs. Biological Maturation. *Journal of Strength and Conditioning Research* **2014**, *28* (5), 1454–1464. https://doi.org/10.1519/JSC.0000000000000391.
9. Robert M Malina; Claude Bouchard; Oded Bar-Or. *Growth, Maturation, and Physical Activity*, 2nd ed.; Human Kinetics: Champaign, IL, USA, 2004.
10. Figueiredo, A. J.; e Silva, M. J. C.; Cumming, S. P.; Malina, R. M. Size and Maturity Mismatch in Youth Soccer Players 11- to 14-Years-Old. *Pediatric Exercise Science* **2010**, *22* (4), 596–612. https://doi.org/10.1123/pes.22.4.596.
11. Philippaerts, R. M.; Vaeyens, R.; Janssens, M.; Van Renterghem, B.; Matthys, D.;

Craen, R.; Bourgois, J.; Vrijens, J.; Beunen, G.; Malina, R. M. The Relationship between Peak Height Velocity and Physical Performance in Youth Soccer Players. *Journal of Sports Sciences* **2006**, *24* (3), 221–230. https://doi.org/10.1080/02640410500189371.

12. Buchheit, M.; Mendez-Villanueva, A. Effects of Age, Maturity and Body Dimensions on Match Running Performance in Highly Trained under-15 Soccer Players. *Journal of Sports Sciences* **2014**, *32* (13), 1271–1278. https://doi.org/10.1080/02640414.2014.884721.
13. Maffulli, N.; Longo, U. G.; Gougoulias, N.; Caine, D.; Denaro, V. Sport Injuries: A Review of Outcomes. *British Medical Bulletin* **2011**, *97* (1), 47–80. https://doi.org/10.1093/bmb/ldq026.
14. Bourdon, P. C.; Cardinale, M.; Murray, A.; Gastin, P.; Kellmann, M.; Varley, M. C.; Gabbett, T. J.; Coutts, A. J.; Burgess, D. J.; Gregson, W.; Cable, N. T. Monitoring Athlete Training Loads: Consensus Statement. *International Journal of Sports Physiology and Performance* **2017**, *12* (s2), S2-161-S2-170. https://doi.org/10.1123/IJSPP.2017-0208.
15. Hermassi, S.; Hayes, L. D.; Bartels, T.; Schwesig, R. Differences in Body Composition, Static Balance, Field Test Performance, and Academic Achievement in 10–12-Year-Old Soccer Players. *Frontiers in Physiology* **2023**, *14*. https://doi.org/10.3389/fphys.2023.1150484.
16. Figueiredo, A. J.; Coelho-E-Silva, M. J.; Sarmento, H.; Moya, J.; Malina, R. M. Adolescent Characteristics of Youth Soccer Players: Do They Vary with Playing Status in Young Adulthood? *Research in Sports Medicine* **2020**, *28* (1), 72–83. https://doi.org/10.1080/15438627.2019.1586704.
17. Read, P.; Oliver, J. L.; De Ste Croix, M. B. A.; Myer, G. D.; Lloyd, R. S. Injury Risk Factors in Male Youth Soccer Players. *Strength & Conditioning Journal* **2015**, *37* (5), 1–7. https://doi.org/10.1519/SSC.0000000000000171.
18. Ginés, H. J.; Huertas, F.; García Calvo, T.; Ponce-Bordón, J. C.; Figueiredo, A. J.; Ballester, R. Age and Maturation Matter in Youth Elite Soccer, but Depending on Competitive Level and Gender. *International Journal of Environmental Research and Public Health* **2023**, *20* (3), 2015. https://doi.org/10.3390/ijerph20032015.
19. Figueiredo, A. J.; Gonçalves, C. E.; Tessitore, A. Bridging the Gap Between Empirical Results, Actual Strategies, and Developmental Programs in Soccer. *International Journal of Sports Physiology and Performance* **2014**, *9* (3), 540–543.

https://doi.org/10.1123/ijspp.2014_0023.
20. Reeves, M. J.; Roberts, S. J.; McRobert, A. P.; Littlewood, M. A. Factors Affecting the Identification of Talented Junior-Elite Footballers: A Case Study. *Soccer & Society* **2018**, 1–16. https://doi.org/10.1080/14660970.2018.1432383.
21. Richardson, D.; Gilbourne, D.; Littlewood, M. Developing Support Mechanisms for Elite Young Players in a Professional Soccer Academy: Creative Reflections in Action Research. *European Sport Management Quarterly* **2004**, *4* (4), 195–214. https://doi.org/10.1080/16184740408737477.
22. Raya-Castellano, E. P.; Uriondo., L. F. A Review of the Multidisciplinary Approach to Develop Elite Players at Professional Football Academies: Applying Science to a Professional Context. *International Journal of Performance Analysis in Sport* **2015**, *15* (1), 1–19. https://doi.org/10.1080/24748668.2015.11868773.
23. Sweeney, L.; Horan, D.; MacNamara, Á. Premature Professionalisation or Early Engagement? Examining Practise in Football Player Pathways. *Frontiers in Sports and Active Living* **2021**, *3*. https://doi.org/10.3389/fspor.2021.660167.
24. Faude, O. Back to the Roots in Football Science. Why It Might Be Smart to Invest in the Youngest Players. *Science and Medicine in Football* **2018**, *2* (3), 171–172. https://doi.org/10.1080/24733938.2018.1493047.
25. Till, K.; Baker, J. Challenges and [Possible] Solutions to Optimizing Talent Identification and Development in Sport. *Frontiers in Psychology* **2020**, *11*. https://doi.org/10.3389/fpsyg.2020.00664.
26. Bergkamp, T. L. G.; Niessen, A. S. M.; den Hartigh, R. J. R.; Frencken, W. G. P.; Meijer, R. R. Methodological Issues in Soccer Talent Identification Research. *Sports Medicine* **2019**, *49* (9), 1317–1335. https://doi.org/10.1007/s40279-019-01113-w.
27. Bailey, R.; Collins, D.; Ford, P.; Macnamara, Á.; Toms, M.; Pearce, G. Participant Development in Sport. *Leeds: Sports Coach UK* **2010**, No. March, 1–134.
28. Côté, J.; Vierimaa, M. The Developmental Model of Sport Participation: 15 Years after Its First Conceptualization. *Science & Sports* **2014**, *29*, S63–S69. https://doi.org/10.1016/j.scispo.2014.08.133.
29. Ford, P.; De Ste Croix, M.; Lloyd, R.; Meyers, R.; Moosavi, M.; Oliver, J.; Till, K.; Williams, C. The Long-Term Athlete Development Model: Physiological Evidence and Application. *Journal of Sports Sciences* **2011**, *29* (4), 389–402. https://doi.org/10.1080/02640414.2010.536849.
30. Lloyd, R. S.; Oliver, J. L. The Youth Physical Development Model. *Strength &*

Conditioning Journal **2012**, *34* (3), 61–72. https://doi.org/10.1519/SSC.0b013e31825760ea.

31. Hannon, M. P.; Carney, D. J.; Floyd, S.; Parker, L. J. F.; McKeown, J.; Drust, B.; Unnithan, V. B.; Close, G. L.; Morton, J. P. Cross-Sectional Comparison of Body Composition and Resting Metabolic Rate in Premier League Academy Soccer Players: Implications for Growth and Maturation. *Journal of Sports Sciences* **2020**, *38* (11–12), 1326–1334. https://doi.org/10.1080/02640414.2020.1717286.
32. Malina, R. M. Growth and Maturity Status of Young Soccer Players. In *Science and Soccer*; Routledge, Ed.; 2003; pp 287–306.
33. Cobley, S. Talent Identification And Development In Youth Sport. In *Routledge Handbook of Youth Sport*; Routledge, Ed.; 2016; pp 506–521.
34. Johnson, A.; Farooq, A.; Whiteley, R. Skeletal Maturation Status Is More Strongly Associated with Academy Selection than Birth Quarter. *Science and Medicine in Football* **2017**, *1* (2), 157–163. https://doi.org/10.1080/24733938.2017.1283434.
35. Hill, M.; Scott, S.; Malina, R. M.; McGee, D.; Cumming, S. P. Relative Age and Maturation Selection Biases in Academy Football. *Journal of Sports Sciences* **2020**, *38* (11–12), 1359–1367. https://doi.org/10.1080/02640414.2019.1649524.
36. Noon, M. R.; Eyre, E. L. J.; Ellis, M.; Myers, T. D.; Morris, R. O.; Mundy, P. D.; Penny, R.; Clarke, N. D. The Influence of Recruitment Age and Anthropometric and Physical Characteristics on the Development Pathway of English Academy Football Players. *International Journal of Sports Physiology and Performance* **2021**, *16* (2), 199–207. https://doi.org/10.1123/ijspp.2019-0534.
37. Grendstad, H.; Nilsen, A.; Rygh, C. B.; Hafstad, A.; Kristoffersen, M.; Iversen, V. V.; Nybakken, T.; Vestbøstad, M.; Algrøy, E. A.; Sandbakk, Ø.; Gundersen, H. Physical Capacity, Not Skeletal Maturity, Distinguishes Competitive Levels in Male Norwegian U14 Soccer Players. *Scandinavian Journal of Medicine & Science in Sports* **2020**, *30* (2), 254–263. https://doi.org/10.1111/sms.13572.
38. Bowerman, E.; Whatman, C.; Harris, N.; Bradshaw, E.; Karin, J. Are Maturation, Growth and Lower Extremity Alignment Associated with Overuse Injury in Elite Adolescent Ballet Dancers? *Physical Therapy in Sport* **2014**, *15* (4), 234–241. https://doi.org/10.1016/j.ptsp.2013.12.014.
39. Johnson, A.; Doherty, P. J.; Freemont, A. Investigation of Growth, Development, and Factors Associated with Injury in Elite Schoolboy Footballers: Prospective Study. *BMJ* **2009**, *338* (feb26 1), b490–b490. https://doi.org/10.1136/bmj.b490.

40. Monasterio, X.; Gil, S. M.; Bidaurrazaga-Letona, I.; Lekue, J. A.; Santisteban, J. M.; Diaz-Beitia, G.; Martin-Garetxana, I.; Bikandi, E.; Larruskain, J. Injuries According to the Percentage of Adult Height in an Elite Soccer Academy. *Journal of Science and Medicine in Sport* **2021**, *24* (3), 218–223. https://doi.org/10.1016/j.jsams.2020.08.004.
41. Ribeiro, N.; Martinho, D. V.; Pereira, J. R.; Rebelo, A.; Monasterio, X.; Gonzalo-Skok, O.; Valente-dos-Santos, J.; Tavares, F. Injury Risk in Elite Young Male Soccer Players: A Review on the Impact of Growth, Maturation, and Workload. *Journal of Strength & Conditioning Research* **2024**. https://doi.org/10.1519/JSC.0000000000004889.
42. Van der Sluis, A.; Elferink-Gemser, M.; Coelho-e-Silva, M.; Nijboer, J.; Brink, M.; Visscher, C. Sport Injuries Aligned to Peak Height Velocity in Talented Pubertal Soccer Players. *International Journal of Sports Medicine* **2013**, *35* (04), 351–355. https://doi.org/10.1055/s-0033-1349874.
43. Van der Sluis, A.; Elferink-Gemser, M.; Brink, M.; Visscher, C. Importance of Peak Height Velocity Timing in Terms of Injuries in Talented Soccer Players. *International Journal of Sports Medicine* **2015**, *36* (04), 327–332. https://doi.org/10.1055/s-0034-1385879.
44. Brink, M. S.; Nederhof, E.; Visscher, C.; Schmikli, S. L.; Lemmink, K. A. P. M. Monitoring Load, Recovery, and Performance in Young Elite Soccer Players. *Journal of Strength and Conditioning Research* **2010**, *24* (3), 597–603. https://doi.org/10.1519/JSC.0b013e3181c4d38b.
45. Drew, M. K.; Purdam, C. Time to Bin the Term 'Overuse' Injury: Is 'Training Load Error' a More Accurate Term? *British Journal of Sports Medicine* **2016**, *50* (22), 1423–1424. https://doi.org/10.1136/bjsports-2015-095543.
46. Forsdyke, D.; Smith, A.; Jones, M.; Gledhill, A. Psychosocial Factors Associated with Outcomes of Sports Injury Rehabilitation in Competitive Athletes: A Mixed Studies Systematic Review. *British Journal of Sports Medicine* **2016**, *50* (9), 537–544. https://doi.org/10.1136/bjsports-2015-094850.
47. Gledhill, A.; Harwood, C.; Forsdyke, D. Psychosocial Factors Associated with Talent Development in Football: A Systematic Review. *Psychology of Sport and Exercise* **2017**, *31*, 93–112. https://doi.org/10.1016/j.psychsport.2017.04.002.
48. Evans, D. W. Self-Complexity and Its Relation to Development, Symptomatology and Self-Perception during Adolescence. *Child Psychiatry and Human Development*

1994, *24* (3), 173–182. https://doi.org/10.1007/BF02353194.
49. Malina, R. M.; Kozieł, S. M. Validation of Maturity Offset in a Longitudinal Sample of Polish Boys. *Journal of Sports Sciences* **2014**, *32* (5), 424–437. https://doi.org/10.1080/02640414.2013.828850.
50. Hill, A. P. Perfectionism and Burnout in Junior Soccer Players: A Test of the 2 × 2 Model of Dispositional Perfectionism. *Journal of Sport and Exercise Psychology* **2013**, *35* (1), 18–29. https://doi.org/10.1123/jsep.35.1.18.
51. Smith, E. P.; Hill, A. P.; Hall, H. K. Perfectionism, Burnout, and Depression in Youth Soccer Players: A Longitudinal Study. *Journal of Clinical Sport Psychology* **2018**, *12* (2), 179–200. https://doi.org/10.1123/jcsp.2017-0015.
52. Cresswell, S. L.; Eklund, R. C. Athlete Burnout: A Longitudinal Qualitative Study. *The Sport Psychologist* **2007**, *21* (1), 1–20. https://doi.org/10.1123/tsp.21.1.1.
53. Williams, S.; Trewartha, G.; Cross, M. J.; Kemp, S. P. T.; Stokes, K. A. Monitoring What Matters: A Systematic Process for Selecting Training-Load Measures. *International Journal of Sports Physiology and Performance* **2017**, *12* (s2), S2-101-S2-106. https://doi.org/10.1123/ijspp.2016-0337.
54. Bult, H. J.; Barendrecht, M.; Tak, I. J. R. Injury Risk and Injury Burden Are Related to Age Group and Peak Height Velocity Among Talented Male Youth Soccer Players. *Orthopaedic journal of sports medicine* **2018**, *6* (12), 1–7. https://doi.org/10.1177/2325967118811042.
55. Jones, S.; Almousa, S.; Gibb, A.; Allamby, N.; Mullen, R.; Andersen, T. E.; Williams, M. Injury Incidence, Prevalence and Severity in High-Level Male Youth Football: A Systematic Review. *Sports Medicine* **2019**, *49* (12), 1879–1899. https://doi.org/10.1007/s40279-019-01169-8.
56. Gabbett, T. J.; Whyte, D. G.; Hartwig, T. B.; Wescombe, H.; Naughton, G. A. The Relationship Between Workloads, Physical Performance, Injury and Illness in Adolescent Male Football Players. *Sports Medicine* **2014**, *44* (7), 989–1003. https://doi.org/10.1007/s40279-014-0179-5.
57. Malina, R. M.; Cumming, S. P.; Rogol, A. D.; Coelho-e-Silva, M. J.; Figueiredo, A. J.; Konarski, J. M.; Kozieł, S. M. Bio-Banding in Youth Sports: Background, Concept, and Application. *Sports Medicine* **2019**, *49* (11), 1671–1685. https://doi.org/10.1007/s40279-019-01166-x.
58. Malina, R. M. Skeletal Age and Age Verification in YouthSport. *Sports Medicine* **2011**, *41* (11), 925–947. https://doi.org/10.2165/11590300-000000000-00000.

59. Swain, M.; Kamper, S. J.; Maher, C. G.; Broderick, C.; McKay, D.; Henschke, N. Relationship between Growth, Maturation and Musculoskeletal Conditions in Adolescents: A Systematic Review. *British Journal of Sports Medicine* **2018**, *52* (19), 1246–1252. https://doi.org/10.1136/bjsports-2017-098418.
60. Beunen, G. P.; Rogol, A. D.; Malina, R. M. Indicators of Biological Maturation and Secular Changes in Biological Maturation. *Food and Nutrition Bulletin* **2006**, *27* (4_suppl5), S244–S256. https://doi.org/10.1177/15648265060274S508.
61. Malina, R. M. Top 10 Research Questions Related to Growth and Maturation of Relevance to Physical Activity, Performance, and Fitness. *Research Quarterly for Exercise and Sport* **2014**, *85* (2), 157–173. https://doi.org/10.1080/02701367.2014.897592.
62. Windt, J.; Gabbett, T. J. How Do Training and Competition Workloads Relate to Injury? The Workload—Injury Aetiology Model. *British Journal of Sports Medicine* **2017**, *51* (5), 428–435. https://doi.org/10.1136/bjsports-2016-096040.
63. Hannon, M. P.; Coleman, N. M.; Parker, L. J. F.; McKeown, J.; Unnithan, V. B.; Close, G. L.; Drust, B.; Morton, J. P. Seasonal Training and Match Load and Micro-Cycle Periodization in Male Premier League Academy Soccer Players. *Journal of Sports Sciences* **2021**, *39* (16), 1838–1849. https://doi.org/10.1080/02640414.2021.1899610.
64. Robles-Palazón, F. J.; López-Valenciano, A.; De Ste Croix, M.; Oliver, J. L.; García-Gómez, A.; Sainz de Baranda, P.; Ayala, F. Epidemiology of Injuries in Male and Female Youth Football Players: A Systematic Review and Meta-Analysis. *Journal of Sport and Health Science* **2022**, *11* (6), 681–695. https://doi.org/10.1016/j.jshs.2021.10.002.
65. Lehnert, M.; De Ste Croix, M.; Šťastný, P.; Maixnerová, E.; Zaatar, A.; Botek, M.; Vařeková, R.; Hůlka, K.; Petr, M.; Elfmark, M.; Lipinska, P. *The Influence of Fatigue on Injury Risk in Male Youth Soccer*; Univerzita Palackého v Olomouci: Křížkovského 8, 771 47 Olomouc, 2019. https://doi.org/10.5507/ftk.19.24455587.
66. Webborn, N. Lifetime Injury Prevention: The Sport Profile Model. *South African Journal of Sports Medicine* **2012**, *24* (4). https://doi.org/10.7196/sajsm.356.
67. Baxter-Jones, A. D. G.; Eisenmann, J. C.; Sherar, L. B. Controlling for Maturation in Pediatric Exercise Science. *Pediatric Exercise Science* **2005**, *17* (1), 18–30. https://doi.org/10.1123/pes.17.1.18.
68. Lloyd, R. S.; Cronin, J. B.; Faigenbaum, A. D.; Haff, G. G.; Howard, R.; Kraemer,

W. J.; Micheli, L. J.; Myer, G. D.; Oliver, J. L. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *Journal of Strength and Conditioning Research* **2016**, *30* (6), 1491–1509. https://doi.org/10.1519/JSC.0000000000001387.

69. Macgregor, S.; Cornes, B. K.; Martin, N. G.; Visscher, P. M. Bias, Precision and Heritability of Self-Reported and Clinically Measured Height in Australian Twins. *Human Genetics* **2006**, *120* (4), 571–580. https://doi.org/10.1007/s00439-006-0240-z.

70. McEvoy, B. P.; Visscher, P. M. Genetics of Human Height. *Economics & Human Biology* **2009**, *7* (3), 294–306. https://doi.org/10.1016/j.ehb.2009.09.005.

71. Silventoinen, K.; Sammalisto, S.; Perola, M.; Boomsma, D. I.; Cornes, B. K.; Davis, C.; Dunkel, L.; de Lange, M.; Harris, J. R.; Hjelmborg, J. V. B.; Luciano, M.; Martin, N. G.; Mortensen, J.; Nisticò, L.; Pedersen, N. L.; Skytthe, A.; Spector, T. D.; Stazi, M. A.; Willemsen, G.; Kaprio, J. Heritability of Adult Body Height: A Comparative Study of Twin Cohorts in Eight Countries. *Twin Research* **2003**, *6* (5), 399–408. https://doi.org/10.1375/136905203770326402.

72. Beunen, G.; Malina, R. M. Growth and Physical Performance Relative to the Timing of the Adolescent Spurt. *Exercise and Sport Sciences Reviews* **1988**, *16*, 503–540.

73. MacMaster, C.; Portas, M.; Parkin, G.; Cumming, S.; Wilcox, C.; Towlson, C. The Effect of Bio-Banding on the Anthropometric, Physical Fitness and Functional Movement Characteristics of Academy Soccer Players. *PLoS ONE* **2021**, *16* (11 November), 1–16. https://doi.org/10.1371/journal.pone.0260136.

74. Hawkins, D.; Metheny, J. Overuse Injuries in Youth Sports: Biomechanical Considerations. *Medicine & Science in Sports & Exercise* **2001**, *33* (10), 1701–1707. https://doi.org/10.1097/00005768-200110000-00014.

75. Corso, M. Developmental Changes in the Youth Athlete: Implications for Movement, Skills Acquisition, Performance and Injuries. *Journal of the Canadian Chiropractic Association* **2018**, *62* (3), 150–160.

76. Caine, D. Physeal Injuries in Children's and Youth Sports: Reasons for Concern? *British Journal of Sports Medicine* **2006**, *40* (9), 749–760. https://doi.org/10.1136/bjsm.2005.017822.

77. Bezuglov, E. N.; Tikhonova, A. A.; Chubarovskiy, P. V.; Repetyuk, A. D.; Khaitin, V. Y.; Lazarev, A. M.; Usmanova, E. M. Conservative Treatment of Osgood-

Schlatter Disease among Young Professional Soccer Players. *International Orthopaedics* **2020**, *44* (9), 1737–1743. https://doi.org/10.1007/s00264-020-04572-3.

78. Hanada, M.; Takahashi; Matsuyama. Relationship between the Clinical Findings and Radiographic Severity in Osgood&Ndash;Schlatter Disease. *Open Access Journal of Sports Medicine* **2012**, 17. https://doi.org/10.2147/OAJSM.S29115.

79. Quatman-Yates, C. C.; Quatman, C. E.; Meszaros, A. J.; Paterno, M. V.; Hewett, T. E. A Systematic Review of Sensorimotor Function during Adolescence: A Developmental Stage of Increased Motor Awkwardness? *British Journal of Sports Medicine* **2012**, *46* (9), 649–655. https://doi.org/10.1136/bjsm.2010.079616.

80. Bisi, M. C.; Stagni, R. Development of Gait Motor Control: What Happens after a Sudden Increase in Height during Adolescence? *BioMedical Engineering Online* **2016**, *15* (1), 1–12. https://doi.org/10.1186/s12938-016-0159-0.

81. Ford, K. R.; Myer, G. NIH Public Access. **2010**, No. September. https://doi.org/10.1177/0363546510367425.

82. Blimkie, C. J. R.; Lefevre, J.; Beunen, G. P.; Renson, R.; Dequeker, J.; Van Damme, P. Fractures, Physical Activity, and Growth Velocity in Adolescent Belgian Boys. *Medicine & Science in Sports & Exercise* **1993**, *25* (7), 801–808. https://doi.org/10.1249/00005768-199307000-00008.

83. Rommers, N.; Rössler, R.; Goossens, L.; Vaeyens, R.; Lenoir, M.; Witvrouw, E.; D'Hondt, E. Risk of Acute and Overuse Injuries in Youth Elite Soccer Players: Body Size and Growth Matter. *Journal of Science and Medicine in Sport* **2020**, *23* (3), 246–251. https://doi.org/10.1016/j.jsams.2019.10.001.

84. Kemper, G. L. J.; Van Der Sluis, A.; Brink, M. S.; Visscher, C.; Frencken, W. G. P.; Elferink-Gemser, M. T. Anthropometric Injury Risk Factors in Elite-Standard Youth Soccer. *International Journal of Sports Medicine* **2015**, *36* (13), 1112–1117. https://doi.org/10.1055/s-0035-1555778.

85. McBurnie, A. J.; Dos'santos, T.; Johnson, D.; Leng, E. Training Management of the Elite Adolescent Soccer Player throughout Maturation. *Sports* **2021**, *9* (12), 1–21. https://doi.org/10.3390/sports9120170.

86. Torres-Ronda, L.; Beanland, E.; Whitehead, S.; Sweeting, A.; Clubb, J. Tracking Systems in Team Sports: A Narrative Review of Applications of the Data and Sport Specific Analysis. *Sports Medicine - Open* **2022**, *8* (1), 1–22. https://doi.org/10.1186/s40798-022-00408-z.

87. Bowen, L.; Gross, A. S.; Gimpel, M.; Li, F. X. Accumulated Workloads and the Acute: Chronic Workload Ratio Relate to Injury Risk in Elite Youth Football Players. *British Journal of Sports Medicine* **2017**, *51* (5), 452–459. https://doi.org/10.1136/bjsports-2015-095820.
88. Wik, E. H. Growth, Maturation and Injuries in High-Level Youth Football (Soccer): A Mini Review. *Frontiers in Sports and Active Living* **2022**, *4*, 1–9. https://doi.org/10.3389/fspor.2022.975900.
89. Engebretsen, L.; Steffen, K.; Bahr, R.; Broderick, C.; Dvorak, J.; Janarv, P.-M.; Johnson, A.; Leglise, M.; Mamisch, T. C.; McKay, D.; Micheli, L.; Schamasch, P.; Singh, G. D.; Stafford, D. E. J.; Steen, H. The International Olympic Committee Consensus Statement on Age Determination in High-Level Young Athletes. *British Journal of Sports Medicine* **2010**, *44* (7), 476–484. https://doi.org/10.1136/bjsm.2010.073122.
90. Huda, W.; Gkanatsios, N. A. Radiation Dosimetry for Extremity Radiographs. *Health Physics* **1998**, *75* (5), 492–499. https://doi.org/10.1097/00004032-199811000-00005.
91. Mirwald, R. L.; G Baxter-jones, A. D.; Bailey, D. A.; Beunen, G. P.; Baxter-jones, D. G.; Bailey, D. A.; Beunen, G. P. An Assessment of Maturity from Anthropometric Measurements. *Med. Sci. Sports Exerc* **2002**, *34* (4), 689–694.
92. Fransen, J.; Bush, S.; Woodcock, S.; Novak, A.; Baxter-Jones, A. D. G.; Deprez, D.; Vaeyens, R.; Lenoir, M. Improving the Prediction of Maturity from Anthropometric Variables Using a Maturity Ratio. *Pediatric Exercise Science* **2018**, *30* (2), 296–307. https://doi.org/10.1123/pes.2017-0009.
93. Moore, S. A.; McKay, H. A.; Macdonald, H.; Nettlefold, L.; Baxter-Jones, A. D. G.; Cameron, N.; Brasher, P. M. A. Enhancing a Somatic Maturity Prediction Model. *Medicine and Science in Sports and Exercise* **2015**, *47* (8), 1755–1764. https://doi.org/10.1249/MSS.0000000000000588.
94. Johnson, D. M.; Williams, S.; Bradley, B.; Sayer, S.; Murray Fisher, J.; Cumming, S. Growing Pains: Maturity Associated Variation in Injury Risk in Academy Football. *European Journal of Sport Science* **2020**, *20* (4), 544–552. https://doi.org/10.1080/17461391.2019.1633416.
95. Van Der Sluis, A.; Elferink-Gemser, M. T.; Coelho-E-Silva, M. J.; Nijboer, J. A.; Brink, M. S.; Visscher, C. Sport Injuries Aligned to Peak Height Velocity in Talented Pubertal Soccer Players. *International Journal of Sports Medicine* **2014**, *35*

(4), 351–355. https://doi.org/10.1055/s-0033-1349874.

96. Gall, F. Le; Carling, C.; Reilly, T. Biological Maturity and Injury in Elite Youth Football. **2007**, 564–572. https://doi.org/10.1111/j.1600-0838.2006.00594.x.
97. Materne, O.; Chamari, K.; Farooq, A.; Weir, A.; Hölmich, P.; Bahr, R.; Greig, M.; McNaughton, L. R. Association of Skeletal Maturity and Injury Risk in Elite Youth Soccer Players: A 4-Season Prospective Study With Survival Analysis. *Orthopaedic Journal of Sports Medicine* **2021**, *9* (3), 1–11. https://doi.org/10.1177/2325967121999113.
98. Kucera, K. L.; Marshall, S. W.; Kirkendall, D. T.; Marchak, P. M.; Garrett, W. E. Injury History as a Risk Factor for Incident Injury in Youth Soccer. *British Journal of Sports Medicine* **2005**, *39* (7), 462–466. https://doi.org/10.1136/bjsm.2004.013672.
99. Read, P. J.; Oliver, J. L.; De Ste Croix, M. B. A.; Myer, G. D.; Lloyd, R. S. Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players. *Sports Medicine* **2016**, *46* (8), 1059–1066. https://doi.org/10.1007/s40279-016-0479-z.
100. Renshaw, A.; Goodwin, P. C. Injury Incidence in a Premier League Youth Soccer Academy Using the Consensus Statement: A Prospective Cohort Study. *BMJ Open Sport & Exercise Medicine* **2016**, *2* (1), 1–6. https://doi.org/10.1136/bmjsem-2016-000132.
101. Hirtz, P.; Starosta, W. Sensitive and Critical Periods of Motor Co-Ordination Development and Its Relation To Motor Learning. *Journal of Human Kinetics* **2002**, *7*, 19–28.
102. Calleja-González, J.; Mielgo-Ayuso, J.; Miguel-Ortega, Á.; Marqués-Jiménez, D.; Del Valle, M.; Ostojic, S. M.; Sampaio, J.; Terrados, N.; Refoyo, I. Post-Exercise Recovery Methods Focus on Young Soccer Players: A Systematic Review. *Frontiers in Physiology* **2021**, *12*, 1–12. https://doi.org/10.3389/fphys.2021.505149.
103. Frisch, A.; Urhausen, A.; Seil, R.; Croisier, J. L.; Windal, T.; Theisen, D. Association between Preseason Functional Tests and Injuries in Youth Football: A Prospective Follow-Up. *Scandinavian Journal of Medicine & Science in Sports* **2011**, *21* (6), e468–e476. https://doi.org/10.1111/j.1600-0838.2011.01369.x.
104. Wachholz, F.; Tiribello, F.; Mohr, M.; van Andel, S.; Federolf, P. Adolescent Awkwardness: Alterations in Temporal Control Characteristics of Posture with Maturation and the Relation to Movement Exploration. *Brain Sciences* **2020**, *10* (4),

1–15. https://doi.org/10.3390/brainsci10040216.

105. Viel, S.; Vaugoyeau, M.; Assaiante, C. Adolescence: A Transient Period of Proprioceptive Neglect in Sensory Integration of Postural Control. *Motor Control* **2009**, *13* (1), 25–42. https://doi.org/10.1123/mcj.13.1.25.

106. Kanehisa, H.; Yata, H.; Ikegawa, S.; Fukunaga, T. A Cross-Sectional Study of the Size and Strength of the Lower Leg Muscles during Growth. *European Journal of Applied Physiology and Occupational Physiology* **1995**, *72* (1), 150–156. https://doi.org/10.1007/BF00964130.

107. Raya-González, J.; Nakamura, F. Y.; Castillo, D.; Yanci, J.; Fanchini, M. Determining the Relationship between Internal Load Markers and Noncontact Injuries in Young Elite Soccer Players. *International Journal of Sports Physiology and Performance* **2019**, *14* (4), 421–425. https://doi.org/10.1123/ijspp.2018-0466.

108. Mandorino, M.; J. Figueiredo, A.; Condello, G.; Tessitore, A. The Influence of Maturity on Recovery and Perceived Exertion, and Its Relationship with Illnesses and Non-Contact Injuries in Young Soccer Players. *Biology of Sport* **2022**, *39* (4), 839–848. https://doi.org/10.5114/biolsport.2022.109953.

109. Bacon, C. S.; Mauger, A. R. Prediction of Overuse Injuries in Professional U18-U21 Footballers Using Metrics of Training Distance and Intensity. *Journal of Strength and Conditioning Research* **2017**, *31* (11), 3067–3076. https://doi.org/10.1519/JSC.0000000000001744.

110. Bell, D. R.; Lang, P. J.; Valovich McLeod, T. C.; McCaffrey, K. A.; Zaslow, T. L.; McKay, S. D. Sport Specialization Is Associated With Injury History in Youth Soccer Athletes. *Athletic Training & Sports Health Care* **2018**, *10* (6), 241–246. https://doi.org/10.3928/19425864-20180813-01.

111. Zoellner, A.; Whatman, C.; Sheerin, K.; Read, P. Prevalence of Sport Specialisation and Association with Injury History in Youth Football. *Physical Therapy in Sport* **2022**, *58*, 160–166. https://doi.org/10.1016/j.ptsp.2022.10.013.

112. Rössler, R.; Junge, A.; Jiri Chomiak; Němec, K.; Dvorak, J.; Lichtenstein, E.; Faude, O. Risk Factors for Football Injuries in Young Players Aged 7 to 12 Years. *Scandinavian Journal of Medicine & Science in Sports* **2018**, *28* (3), 1176–1182. https://doi.org/10.1111/sms.12981.

113. Wrigley, R.; Drust, B.; Stratton, G.; Scott, M.; Gregson, W. Quantification of the Typical Weekly In-Season Training Load in Elite Junior Soccer Players. *Journal of Sports Sciences* **2012**, *30* (15), 1573–1580.

https://doi.org/10.1080/02640414.2012.709265.

114. Scammon, R. E. The Ponderal Growth of the Extremities of the Human Fetus. *American Journal of Physical Anthropology* **1930**, *15* (1), 111–121. https://doi.org/10.1002/ajpa.1330150104.
115. Cumming, S. P.; Lloyd, R. S.; Oliver, J. L.; Eisenmann, J. C.; Malina, R. M. Bio-Banding in Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of Youth Athletes. *Strength & Conditioning Journal* **2017**, *39* (2), 34–47. https://doi.org/10.1519/SSC.0000000000000281.
116. Malina, R. M.; Coelho E Silva, M. J.; Figueiredo, A. J.; Carling, C.; Beunen, G. P. Interrelationships among Invasive and Non-Invasive Indicators of Biological Maturation in Adolescent Male Soccer Players. *Journal of Sports Sciences* **2012**, *30* (15), 1705–1717. https://doi.org/10.1080/02640414.2011.639382.
117. Buchheit, M. Chasing the 0.2. *International Journal of Sports Physiology and Performance* **2016**, *11* (4), 417–418. https://doi.org/10.1123/ijspp.2016-0220.
118. Massard, T.; Fransen, J.; Duffield, R.; Wignell, T.; Lovell, R. Comparison of Sitting Height Protocols Used for the Prediction of Somatic Maturation. *Sport Performance Science Reports* **2019**, *66*, 1–4.
119. Ryan, D.; Mccall, A.; Fitzpatrick, G. F.; Hennessy, L.; Meyer, T.; McCunn, R. The Influence of Maturity Status on Movement Quality among English Premier League Academy Soccer Players. *Sport Peformance Science Reports* **2018**, *32* (1), 1–3.
120. Kalkhoven, J. T.; Watsford, M. L.; Coutts, A. J.; Edwards, W. B.; Impellizzeri, F. M. Training Load and Injury: Causal Pathways and Future Directions. *Sports Medicine* **2021**, *51* (6), 1137–1150. https://doi.org/10.1007/s40279-020-01413-6.
121. Beato, M.; Bianchi, M.; Coratella, G.; Merlini, M.; Drust, B. Effects of Plyometric and Directional Training on Speed and Jump Performance in Elite Youth Soccer Players. *Journal of Strength and Conditioning Research* **2018**, *32* (2), 289–296. https://doi.org/10.1519/JSC.0000000000002371.
122. Radnor, J. M.; Oliver, J. L.; Waugh, C. M.; Myer, G. D.; Moore, I. S.; Lloyd, R. S. The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth. *Sports Medicine* **2018**, *48* (1), 57–71. https://doi.org/10.1007/s40279-017-0785-0.
123. McNarry, M.; Barker, A.; Lloyd, R. S.; Buchheit, M.; Craig, P.; Fbases, W.; Oliver, J. The BASES Expert Statement on Trainability during Childhood and Adolescence. *The Sport and Exercise Scientist* **2014**, No. 41, 22–23.

124. Tonson, A.; Ratel, S.; Fur, Y. Le; Cozzone, P.; Bendahan, D. Effect of Maturation on the Relationship between Muscle Size and Force Production. *Medicine & Science in Sports & Exercise* **2008**, *40* (5), 918–925. https://doi.org/10.1249/MSS.0b013e3181641bed.
125. Grosset, J. F.; Mora, I.; Lambertz, D.; Pérot, C. Voluntary Activation of the Triceps Surae in Prepubertal Children. *Journal of Electromyography and Kinesiology* **2008**, *18* (3), 455–465. https://doi.org/10.1016/j.jelekin.2006.11.002.
126. Dotan, R.; Mitchell, C.; Cohen, R.; Klentrou, P.; Gabriel, D.; Falk, B. Child—Adult Differences in Muscle Activation — A Review. *Pediatric Exercise Science* **2012**, *24* (1), 2–21. https://doi.org/10.1123/pes.24.1.2.
127. De Ste Croix, M.; Lehnert, M.; Maixnerova, E.; Ayala, F.; Psotta, R. The Influence of Age and Maturation on Trajectories of Stretch-Shortening Cycle Capability in Male Youth Team Sports. *Pediatric Exercise Science* **2021**, *33* (1), 16–22. https://doi.org/10.1123/pes.2020-0063.
128. Read, P.; Oliver, J.; De Ste Croix, M.; Myer, G.; Lloyd, R. Hopping and Landing Performance in Male Youth Soccer Players: Effects of Age and Maturation. *International Journal of Sports Medicine* **2017**, *38* (12), 902–908. https://doi.org/10.1055/s-0043-114009.
129. Moran, J.; Parry, D. A.; Lewis, I.; Collison, J.; Rumpf, M. C.; Sandercock, G. R. H. Maturation-Related Adaptations in Running Speed in Response to Sprint Training in Youth Soccer Players. *Journal of Science and Medicine in Sport* **2018**, *21* (5), 538–542. https://doi.org/10.1016/j.jsams.2017.09.012.
130. Towlson, C.; Cobley, S.; Parkin, G.; Lovell, R. When Does the Influence of Maturation on Anthropometric and Physical Fitness Characteristics Increase and Subside? *Scandinavian Journal of Medicine & Science in Sports* **2018**, *28* (8), 1946–1955. https://doi.org/10.1111/sms.13198.
131. Lloyd, R. S.; Oliver, J. L.; Hughes, M. G.; Williams, C. A. The Influence of Chronological Age on Periods of Accelerated Adaptation of Stretch-Shortening Cycle Performance in Pre and Postpubescent Boys. *Journal of Strength and Conditioning Research* **2011**, *25* (7), 1889–1897. https://doi.org/10.1519/JSC.0b013e3181e7faa8.
132. Chumela, W. C.; Roche, A. F.; Thissen, D. *The FELS Method of Assessing the Skeletal Maturity of the Hand-wrist*; 1989; Vol. 1. https://doi.org/10.1002/ajhb.1310010206.

133. Iannaccone, G. W. W. Greulich and S. I. Pyle: Radiographic Atlas of Skeletal Development of the Hand and Wrist. 2nd Edition. I Volume-Atlante Di 256 Pagine. Stanford University Press, Stanford, California, 1959. *Acta geneticae medicae et gemellologiae* **1959**, *8* (4), 513–513. https://doi.org/10.1017/S1120962300018680.

134. Tanner, J. M.; Whitehouse, R. H.; Takaishi, M. Standards from Birth to Maturity for Height, Weight, Height Velocity, and Weight Velocity: British Children, 1965. I. *Archives of Disease in Childhood* **1966**, *41* (219), 454–471. https://doi.org/10.1136/adc.41.219.454.

135. Matsudo, S. M. M.; Matsudo, V. K. R. Self-assessment and Physician Assessment of Sexual Maturation in Brazilian Boys and Girls: Concordance and Reproducibility. *American Journal of Human Biology* **1994**, *6* (4), 451–455. https://doi.org/10.1002/ajhb.1310060406.

136. Rogol, A. D.; Clark, P. A.; Roemmich, J. N. Growth and Pubertal Development in Children and Adolescents: Effects of Diet and Physical Activity. *The American Journal of Clinical Nutrition* **2000**, *72* (2), 521S-528S. https://doi.org/10.1093/ajcn/72.2.521S.

137. Khamis, H. J.; Roche, A. F. Predicting Adult Stature without Using Skeletal Age: The Khamis-Roche Method. *Pediatrics* **1994**, *94* (4 Pt 1), 504–507.

138. Bayley, N.; Pinneau, S. R. Tables for Predicting Adult Height from Skeletal Age: Revised for Use with the Greulich-Pyle Hand Standards. *The Journal of Pediatrics* **1952**, *40* (4), 423–441. https://doi.org/10.1016/S0022-3476(52)80205-7.

139. Abbott, W.; Williams, S.; Brickley, G.; Smeeton, N. Effects of Bio-Banding upon Physical and Technical Performance during Soccer Competition: A Preliminary Analysis. *Sports* **2019**, *7* (8), 193. https://doi.org/10.3390/sports7080193.

140. Drew, M. K.; Finch, C. F. The Relationship Between Training Load and Injury, Illness and Soreness: A Systematic and Literature Review. *Sports Medicine* **2016**, *46* (6), 861–883. https://doi.org/10.1007/s40279-015-0459-8.

141. Burgess, D. J. The Research Doesn’t Always Apply: Practical Solutions to Evidence-Based Training-Load Monitoring in Elite Team Sports. *International Journal of Sports Physiology and Performance* **2017**, *12* (s2), S2-136-S2-141. https://doi.org/10.1123/ijspp.2016-0608.

142. Mountjoy, M.; Armstrong, N.; Bizzini, L.; Blimkie, C.; Evans, J.; Gerrard, D.; Hangen, J.; Knoll, K.; Micheli, L.; Sangenis, P.; Van Mechelen, W. IOC Consensus Statement: “Training the Elite Child Athlete.” *British Journal of Sports Medicine*

2008, *42* (3), 163–164. https://doi.org/10.1136/bjsm.2007.044016.

143. Halson, S. L. Monitoring Training Load to Understand Fatigue in Athletes. *Sports Medicine* **2014**, *44* (S2), 139–147. https://doi.org/10.1007/s40279-014-0253-z.
144. Impellizzeri, F. M.; Rampinini, E.; Coutts, A. J.; Sassi, A.; Marcora, S. M. Use of RPE-Based Training Load in Soccer. *Medicine & Science in Sports & Exercise* **2004**, *36* (6), 1042–1047. https://doi.org/10.1249/01.MSS.0000128199.23901.2F.
145. Foster, C. Monitoring Training in Athletes with Reference to Overtraining Syndrome. *Medicine & Science in Sports & Exercise* **1998**, *30* (7), 1164–1168. https://doi.org/10.1097/00005768-199807000-00023.
146. McLaren, S. J.; Smith, A.; Spears, I. R.; Weston, M. A Detailed Quantification of Differential Ratings of Perceived Exertion during Team-Sport Training. *Journal of Science and Medicine in Sport* **2017**, *20* (3), 290–295. https://doi.org/10.1016/j.jsams.2016.06.011.
147. Gabbett, T. J.; Whiteley, R. Two Training-Load Paradoxes: Can We Work Harder and Smarter, Can Physical Preparation and Medical Be Teammates? *International Journal of Sports Physiology and Performance* **2017**, *12* (s2), S2-50-S2-54. https://doi.org/10.1123/ijspp.2016-0321.
148. Akenhead, R.; Nassis, G. P. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. *International Journal of Sports Physiology and Performance* **2016**, *11* (5), 587–593. https://doi.org/10.1123/ijspp.2015-0331.
149. Castagna, C.; Varley, M.; Póvoas, S. C. A.; D'Ottavio, S. Evaluation of the Match External Load in Soccer: Methods Comparison. *International Journal of Sports Physiology and Performance* **2017**, *12* (4), 490–495. https://doi.org/10.1123/ijspp.2016-0160.
150. Cummins, C.; Orr, R.; O'Connor, H.; West, C. Global Positioning Systems (GPS) and Microtechnology Sensors in Team Sports: A Systematic Review. *Sports Medicine* **2013**, *43* (10), 1025–1042. https://doi.org/10.1007/s40279-013-0069-2.
151. Scott, M. T. U.; Scott, T. J.; Kelly, V. G. The Validity and Reliability of Global Positioning Systems in Team Sport. *Journal of Strength and Conditioning Research* **2016**, *30* (5), 1470–1490. https://doi.org/10.1519/JSC.0000000000001221.
152. Varley, M. C.; Jaspers, A.; Helsen, W. F.; Malone, J. J. Methodological Considerations When Quantifying High-Intensity Efforts in Team Sport Using Global Positioning System Technology. *International Journal of Sports Physiology*

and Performance **2017**, *12* (8), 1059–1068. https://doi.org/10.1123/ijspp.2016-0534.

153. Rowell, A. E.; Aughey, R. J.; Clubb, J.; Cormack, S. J. A Standardized Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in Professional A-League Football Players. *Frontiers in Physiology* **2018**, *9*, 1–13. https://doi.org/10.3389/fphys.2018.01011.
154. Phibbs, P. J.; Roe, G.; Jones, B.; Read, D. B.; Weakley, J.; Darrall-Jones, J.; Till, K. Validity of Daily and Weekly Self-Reported Training Load Measures in Adolescent Athletes. *Journal of Strength and Conditioning Research* **2017**, *31* (4), 1121–1126. https://doi.org/10.1519/JSC.0000000000001708.
155. Scantlebury, S.; Till, K.; Sawczuk, T.; Phibbs, P.; Jones, B. Navigating the Complex Pathway of Youth Athletic Development: Challenges and Solutions to Managing the Training Load of Youth Team Sport Athletes. *Strength & Conditioning Journal* **2020**, *42* (6), 100–108. https://doi.org/10.1519/SSC.0000000000000564.

PART 2

Chapter 1

STUDY I

Injury Risk in Elite Young Male Soccer Players: A Review on the Impact of Growth, Maturation, and Workload

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Injury Risk in Elite Young Male Soccer Players: A Review on the Impact of Growth, Maturation, and Workload

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1. Abstract

The long-term development of young male soccer players involves a prolonged period of significant adjustments, highlighting the importance of studying the complex interaction between dynamic variables, including workload, and inherent elements like growth and maturity. This analysis examines the intricate connections involving the development, maturity, workload, and susceptibility to injuries among adolescent male soccer players. Significantly, these connections become prominent at the peak height velocity (PHV) period, a crucial moment in maturation. Growth rates vary among individuals, and higher rates have been associated with an increased risk of injury in young soccer players, particularly during periods of rapid growth. Identifying possible risk factors and understanding the complex connections between them is crucial to developing specific methods for reducing the risk of injury. Sharing this valuable information with essential stakeholders is crucial for guaranteeing young athletes' comprehensive growth and maturation process. Furthermore, this review emphasizes the immediate need for long-term studies and thorough injury analyses to comprehend better the dynamic interactions that influence injury patterns in young male soccer players. This review will allow practitioners to better understand the main modifiable and nonmodifiable risk factors for injury and provide essential information focusing on practical strategies, facilitating more informed decision making by all stakeholders. The review aims to clarify these complexities and offer crucial insights that can assist in designing and implementing efficient strategies to reduce the risk of injury, specifically for the challenges faced during PHV and within the broader framework of long-term athletic development in young soccer.

Keywords: long-term athletic development; intrinsic factors; extrinsic factors; assessment; monitoring

2. Introduction

Soccer academies aim to identify and nurture young talent with the potential to compete at a senior level and secure a professional contract [1]. Consequently, these institutions' medical and performance teams prioritize reducing injury risk among these young athletes [2–4]. Increased injury incidence can diminish training and match participation availability, potentially impeding development across technical, tactical, physical, and psychological domains [5]. Over recent years, a significant increase in scientific studies investigating injuries among young soccer players has been noted [6–9]. A recent systematic review and meta-analysis of injury epidemiology in young male soccer players (≤ 19 years) indicated that the overall injury incidence rate was 5.70 per 1000 hours, with match and training injuries contributing 14.43 and 2.80 injuries per 1000 hours, respectively [10]. Predominantly, the injuries observed were muscular and tendon-related, affecting the lower extremities, with a higher incidence rate compared with other locations of injuries (trunk, upper extremity, head, and neck). A systematic review and meta-analysis also found that injury incidence increased with chronological age among male participants and was higher in elite players than in non-elite players [10]. A significant issue concerning injuries in young soccer players is their increased susceptibility to future injuries, which potentially affects their adult health and their chances of optimizing global performance, as identified in a systematic review by Swain et al. [11]. Thus, searching for training strategies to minimize injury risk and to detect periods where young soccer players are more sensitive to injury would be necessary.

Youth and young athletes are children, typically up to 11 girls and 13 boys [12]. In contrast, adolescence, typically defined as the second decade of life, is often identified as a critical phase of player development, typically including boys aged 14–18 and girls aged 12–18 [12,13]. Owing to variability in the timing of the beginning and end of adolescence, it becomes more difficult to define the term exclusively based on chronological age [14]. However, in the early stages of adolescence, there are usually noticeable changes in body structure, particularly a rapid increase in height (the start of accelerated growth throughout adolescence) [14]. For example, during pubertal development, secondary center ossification begins to merge around the age of 15 years and reaches full fusion by 21 years of age [15]. It is essential to recognize that, during childhood and adolescence, different systems in the body, such as the skeletal, circulatory, respiratory, and endocrine systems, develop nonlinearly at different speeds [12,14]. Adolescence is characterized by significant body size and compositional changes resulting from the underlying cellular accretion and growth of adipose tissue, bone, and skeletal muscle [14]. As a result, adolescents of the same age may have significantly different levels of physical development [12,16,17]. Changes in size are a consequence of three cellular processes: hyperplasia (increase in cell number, e.g., adipocytes), hypertrophy (increase in cell size, e.g., adipocytes and myocytes), and accretion (increase in intercellular substances) [14]. Although the preference for one process over the other is tissue- and age-dependent, three distinct cellular processes are involved in bone development [14]. Examples include the number of neurons (brain cells) and muscle fibers. In contrast to the first instance, which occurs at the midpoint of pregnancy, muscle fiber establishment occurs rapidly following birth [14]. Both cases showed a pattern in which the initial phase consisted primarily of hypertrophy followed by hyperplasia [14].

Factors such as growth and maturation can be influenced by nutrition [18–20], socioeconomic status variables [21–24], training [14], and the environment [14], which play a significant role during this period. Firstly, growth can be defined as changes in the body size as a whole or of specific parts [16,25,26]. Growth can be classified in terms of status and tempo, with status referring to the height or weight of an adolescent at a specific time point and tempo relating to the rate of change over time (Baxter-Jones et al., 2005; Malina et al., 2019). The highest height gain during adolescence is referred to as peak height velocity (PHV) [14,26]. Between the ages of 13 and 14 years, especially among boys, a period of market acceleration of growth occurs, commonly referred to as the growth spurt [14]. Common indicators of somatic maturation include the age at peak height velocity (APHV) and PHV [14]. While body mass undergoes notable changes throughout life, particularly during adolescence, there is a specific period around 14 to 15 years old (1.5 years after PHV for boys), during which a notable increase in weight is typically observed, known as peak weight velocity (PWV) [27]. Furthermore, maturation refers to transitioning from childhood to adulthood and can be studied in each biological system (e.g., sexual, skeletal, somatic, and dental) [28]. Moreover, maturation can be studied in terms of status (maturation level at a specific date), timing (when particular maturational events occur), and tempo (maturation rate over time) [14,29]. Status corresponds to the maturation level at a specific date; timing refers to when particular maturational events occur; and tempo corresponds to the maturation rate over time. Maturation timing and tempo vary considerably within a group of adolescents of the same age [14,30,31], leading to inter-individual differences in maturity status. Thus, monitoring and evaluating these factors (i.e., growth and maturation) is vital for thoroughly understanding their impact on player development.

Workload represents the cumulative stress imposed on an individual through repeated training sessions (i.e., practices) and matches over time [32]. A cumulative amount of stress is imposed on an individual through repeated training sessions (i.e., practices) and matches over time, represented as workload [33]. External and internal workloads are commonly reported in studies on professional [34] and young [35] soccer players. External load is defined as the work done by an athlete, measured independently of its internal characteristics [36]. Global positioning system (GPS) devices that measure distances calculated by positional differentiation are used to collect and analyze external workloads. However, the speed can be derived from distance [37]. It can be quantified, for instance, as the total distance (TD) covered, accelerations (ACC), deceleration (DCC), or metabolic power [38–40]. Using IMU technology and satellites, GPS devices use positional differentiation to evaluate external effort and cadence, calculate athlete locations with variable precision [41,42], and quantify sports and team activity metrics using accelerometers and power meters. Accelerometers, gyroscopes, and magnetometers, particularly accelerometers, quantify external workload during low-speed, short-distance activities with high reliability and validity [43]. Conversely, internal workload reflects physiological and psychological responses to exercise [37]. Most frequently, subjective self-report measures are used to quantify internal workload-related information [36,44], as the rating of perceived exertion (RPE) is measured using the Foster 0–10 scale after each training session or match [45]. However, there is a growing trend towards utilizing monitoring instruments such as heart rate variability (HRV), which enables the measurement of internal workload [46].

Scientific evidence associating workload with injury risk primarily focuses on adult players and may not be generalizable to young [33,47]. Furthermore, understanding that training induces different biological and psychological training adaptations in young soccer players compared to their adult counterparts (42) is crucial for understanding how fatigue is related to [33] an increased risk of injury [48]. Wik [49] emphasized the importance of forthcoming research to bridge lacunae in the literature on growth, maturation, and injuries among young soccer players. Such endeavors are crucial for delineating more comprehensive associations between the growth-maturation continuum and injury susceptibility [49]. However, the principal focus of this review is to delineate non-modifiable risk factors (e.g., growth and maturation) and their interplay with modifiable risk factors (e.g., workload). Clarifying the dichotomy between modifiable and non-modifiable elements is pivotal because it aids in formulating individual and team injury risk profiles. Consequently, this review is driven by the available scientific literature that links growth, maturation, and workload to injury risk.

Therefore, the primary aim of this review is to present a narrative review of the current literature and to understand the impact of growth, maturation, and workload on injury risk in young soccer players. Secondary objectives include: (a) understanding the theoretical rationale for each of the factors analyzed in this review and their association with increased risk of injury, (b) identifying "red flags" to mitigate injury risk during different stages of long-term athletic development [12]; (c) providing essential information that focuses on practical strategies, facilitating more informed decision-making by all stakeholders, and (d) presenting a guide for practitioners of sports science and medicine that work mainly with these age-related groups.

3. Methods

3.1. Experimental Approach to the Problem

Search Strategy. A literature review was conducted using electronic searches of SPORTDiscus, Web of Science, MEDLINE/PubMed, PubMed, and Cochrane databases, encompassing studies published up to February 2023. The following keywords comprised the search strategy devised by the investigators: “young" OR “youth” AND “male soccer players” OR “male football players” AND “maturation” AND “growth” AND “injury risk” AND “training load” OR “workload”. The references listed in the articles were subsequently examined to identify additional pertinent articles that were not found during the initial search.

3.2. Eligibility Criteria

The inclusion criteria were stringent, limiting the studies to those published in (1) English, (2) articles identified in a digital database and published up to February 2023, (3) published original data, (4) elite and non-elite male young soccer players, and (5) publication in a scientific journal subject to peer review to ensure the most current and pertinent information. Studies that (1) were written and published in a language other than English, (2) were devoted to the study of sports other than soccer; (3) had a sample of young female soccer players; (4) featured a sample of individuals aged 19 years or older chronologically; and (5) were case reports and case series were excluded from the present narrative review.

3.3. Study Selection

The initial screening of titles and abstracts was conducted by one author (N.R.), with a subsequent review of full texts and the final selection of included studies conducted by two other authors (D.V.M. and A.R.). This process ensured that the inclusion of studies was based not only on validation but also on agreement among the authors responsible for study selection. All included studies were agreed upon by the authors, representing a subset of the research team. Additional papers, known to the authors or identified indirectly (e.g., through citations within relevant articles), were also considered for inclusion to ensure thorough coverage of the topic. Each of the indirectly identified studies underwent the same rigorous evaluation process as those found directly through the search strategy. This approach helped to mitigate potential selection bias, allowing for a more balanced and inclusive review. All studies, whether identified directly or indirectly, were reassessed by another author, who maintained a high level of scrutiny and adherence to the inclusion criteria. Only those studies that passed this two-tier review process were included for further analysis.

4. Results

Data were abstracted from the included studies by one author (N.R.) and reviewed for accuracy and consistency by 2 other authors (D.V.M. and A.R.). The synthesis of the extracted data in the Results section involved all authors to ensure consensus. To ensure coverage and validity of the information, the data were extracted primarily from the original peer-reviewed research articles. Some of the studies included in our review were derived from systematic reviews and meta-analyses, which were used to enhance the understanding of broader trends and conclusions within the topic. However, we carefully evaluated these reviews to ensure that our interpretations were based on consensus from multiple primary studies rather than the summarized outcomes of secondary sources alone (Tables 2 and 3). Synthesized data from the included studies were described using a combination of qualitative and quantitative approaches. This approach allowed the authors to discuss variability measures, such as standard deviations, within the context of each specific result discussed in the article rather than applying a uniform measure of variability across all results (Table 4).

5. Discussion

5.1 Growth & Injury Risk

Body growth involves changes in dimensions, physique, and composition, with height, weight, and body composition (e.g., fat and muscle mass) increasing in players [12,16]. Players grow taller and heavier during development with varying maturation rates in different body sections [16]. Hyperplasia, hypertrophy, and cellular accretion all contribute to cell growth [14]. Genetic factors account for 80% of adult height variations, while environmental factors make up the remaining 20%, influenced by heredity, nutrition, physical activity, diseases, and the environment [50–53].

Growth can be defined by tempo - the rate of change over time–or by status–how tall or heavy a player is at a specific time, compared to the average height and weight of a player's gender and age [25,26]. During puberty, physical and biological changes often occur with an increase in growth rate, which is lower than that observed during the first year of life [16]. The start of the growth spurt (takeoff) occurs around the age of 10 to 12 years for boys, according to mean values from longitudinal studies [14,26]. In this context, peak height velocity is observed in boys aged 13–14 years, with average growth rates of approximately

10 cm/year [14,26]. After PHV, male growth slows until the adult height is approximately 18 years; however, some males may only reach their final height in their early twenties [26], demonstrating the magnitude of the aforementioned inter-individual variability. Owing to significant inter-individual variability in the rate and intensity of growth, this model requires an appropriate answer to many questions, such as estimating the final height or describing growth during periods of accelerated development [54]. In this regard, it is imperative to comprehend the potential deleterious effects on the growth plate centers of long bones resulting from repeated loading associated with training and matches, notwithstanding the challenges in evaluating and monitoring such impacts.

During the adolescent growth spurt, adolescents undergo increases in height and weight, with PWV typically marking the most significant weight gain period [14]. Weight gain slows during infancy (first year, reaching its lowest rate between 2 and 3 years of age) before consistently accelerating throughout childhood, especially during middle childhood (6 years until adolescence), at approximately 2-3 kg per year [14]. Thus, evaluating body mass growth rate (kg/year) during adolescence is crucial for determining the moment of maximum weight gain. The mean age at PWV is 14–15 years for boys (standard deviations (SD) from 0.9–1.5), with mean weight velocities of 9–10 kg/year [14]. On average, PWV follows the PHV in boys approximately 18 months later [27,55,56]. Consequently, evaluating these relatively rapid changes in height, weight, and body composition at different ages is critical because they can result in significant differences in height and weight between age groups [57].

Throughout puberty, boys may undergo a swift growth spurt, often leading to what is commonly referred to as "adolescent awkwardness." This phase is marked by rapid changes in size and proportion, potentially causing alterations in motor control, particularly in some athletes. [58–62]. In addition, neuromuscular control and proprioceptive capacity may be affected by this period of rapid growth and increased size [63]. In addition, delayed body mass development in bone size and growth often leads to disturbances in motor control disturbances [64,65]. During PHV, it is logical to anticipate that adolescent athletes could encounter a plateau or decline in performance and a heightened risk of common overuse injuries [64]. Considering the modifiable risk factors for injury, such as workload, it is essential that during this period, there is stricter control over the exposure of young soccer players to the high and repetitive workloads of training and matches [66].

Growth-related injuries, such as growth plate fractures, apophysitis, apophyseal avulsion fractures, and greenstick fractures, are uncommon in adults, but are frequent in athletes with immature skeletons. Adolescent athletes are prone to several problems associated with the primary and secondary sites of bone formation (osteochondrosis), such as Sever's (apophysitis of the calcaneus) and Osgood-Schlatter (apophysitis of the tibial tubercle) diseases [67,68]. During periods of accelerated skeletal growth, the growth plates show an increase in thickness, making them more vulnerable to growth-related injuries [69]. As athletes grow, their cartilage and joint surfaces undergo mechanical change. Tissues and structures are vulnerable points in the muscle, tendon, and skeletal connection chains. In younger players, the skeletal attachment site (apophysis) tends to be weaker, whereas in more mature players, the muscles, ligaments, and tendons are more prone to giving way first [49,70]. Adolescent athletes with less-developed growth plates are more prone to traction and shear stress [67,71]. Athletes have a notable change in limb mass, moments of inertia, and length throughout the substantial and fast somatic growth phase during adolescence [14].

It is essential to discuss the potential underlying mechanisms proposed to explain the relationship between growth and injury. In this regard, Wik (2022) listed four potential mechanisms in a review [49]: 1) during rapid growth, growth plates are typically thicker and more vulnerable, making them more susceptible to injury [72]; 2) slower adaptation of tendons and apophyses to a lengthening skeleton can increase tension on weakened structures and the force needed to move them, thereby increasing apophyseal stress [69]; 3) during rapid growth, delayed bone mineralization and increased fracture rates have been observed, suggesting a period of relative bone fragility [73,74]; and 4) alterations in body proportions have been linked to temporarily diminished neuromuscular control, which may be a risk factor for injury [59,61]. Due to the difficulty distinguishing between the effects of growth and maturation, higher growth rates have been associated with a greater risk of injury among elite young soccer players. Kemper et al. (2015) aimed to determine whether frequent anthropometric measurements could help identify young soccer players at a higher risk of injury [75]. The study involved 101 elite male standard young soccer players aged between 11 and 19 years. Odds ratios (OR) and 95% confidence intervals (CI) were computed for each injury risk factor. The OR, which compares the odds of an event occurring in one group to the odds of the same event occurring in another group, is a widely used statistical concept in epidemiological studies to assess the strength of the association between exposures and outcomes [76,77]. These findings support the conclusion that faster growth rates, explicitly exceeding 0.6 cm per month, are associated with an increased risk of injury, particularly among players around the age of their PHV [75]. This means that, compared to players who maintain the same height, those who grow at least 0.6 cm per month have an OR of 1.63-fold higher risk of injury. An estimated value of height growth velocity less than or equal to 7.2 centimeters per year was proposed to indicate that a player had entered the growth phase by extrapolating the average monthly height gain over a year [75]. This information is critical for calculating the annual growth rate, as exceeding a height increase of 7.2 cm per year raises the risk of injury. The study also revealed a higher risk of injury among young players who experienced a monthly body mass index (BMI) increase of ≥ 0.3 kg/m2, with an odds ratio of 1.61. This indicates that the group with an increased BMI had a 1.61-fold increased risk of injury compared to players without an increase. To estimate minimal detectable changes (MDC), anthropometric assessment specialists should be cautious when defining distinct growth rates. The MDC shows the smallest change in a variable required to reflect a true change and is derived from the standard error of measurement [78]. Further research is needed to understand the impact of BMI increase on injury risk. However, this aspect holds significant importance, particularly in the months following PHV (0.2–0.4 years after PHV), as weight gain, primarily driven by lean mass gains, is more substantial during this period [14]. Rommers et al. (2020) investigated the relationship between anthropometric measures, growth, and the risk of overuse and acute injuries in young elite soccer players (U10 to U15) over a sporting season. The study produced varied results for each of the groups evaluated. The younger group (U10 to U12) increased their limb length during the season, which correlated with a higher risk of overuse injuries, especially in the thigh (27.5%), hip/groin (25.0%), and knee (22.5%). Younger age was also associated with an increased risk of acute injury. In contrast, longer leg length was correlated with an increased risk of overuse injuries in the older group (U13 to U15). Furthermore, greater weight and slower growth rates were associated with an increased risk of acute injuries in the older group [79]. In a subsequent study, Rommers et al. (2021) examined the mediating effects of motor performance on the relationship between growth velocity and injury risk in elite young soccer players. The study included 378 young male soccer players aged U13–U15. The authors proposed hypotheses regarding the causal connection between the growth rate, injuries, and motor performance. Using maturity offset as a conditioning variable, the causal effect of growth velocity on injury risk was determined. Growth velocity was computed by dividing the difference in body height between the two measurements by the exact time interval between measurements. Medical professionals from the academies continuously recorded injuries during the initial two months. The results demonstrated that 105 athletes with faster growth rates suffered injuries (56 overuse injuries versus 49 acute injuries) and the likelihood of injury risk was 15% per centimeter/year of growth velocity. With each additional 1 cm/year of annual growth velocity, the likelihood of injury increases by 15%, as denoted by odds ratios (1.15, 95% CI: 1.05-1.26). Regarding the type of injury, muscle rupture/tear/strain/cramps had a higher incidence (33.3 %). Concerning the injury location, the thigh was the structure that presented the most significant number of injuries (21.9%). Consequently, this study demonstrated a causal relationship between growth velocity and injury risk in elite young soccer players [80]. Regularly monitoring growth and associated growth rates is vital for effectively reducing injury risk in young soccer players, particularly during periods of accelerated height growth [30,81,82]. Therefore, it is necessary to devise strategies with practical implications to mitigate the impact of growth on injury risks.

In analyzing various studies that aimed to verify the causal relationship between growth and injury risk, it was found that most studies used results from relatively broad injury categories, such as combined injuries or all overuse injuries [49]. However, a study by Monasterio et al. [83] demonstrated that the effects of rapid growth are type-dependent, with exceptionally high injury rates in areas of skeletal growth during the PHV period [83]. While the abovementioned risk factors are not modifiable, it is crucial to understand that growth varies significantly from an individual perspective, necessitating regular monitoring. Identifying the periods of the most significant injury risk allows coaches to be informed and enables academies to manage injury risk effectively.

There appears to be consensus in the literature regarding the association between injury risk and growth. Higher growth rates have been linked with an increased likelihood of injuries [75,79,80,84]. Rommers et al. [79] found that among young soccer players (U10–U12), an increase in leg length variation was associated with a higher incidence of injuries [79]. On the other hand, players in the U13–U15 age bracket who had longer legs early in the season were at a higher risk of overuse injuries. An SD increase in the growth rate of stature is also associated with a higher risk of bone and growth plate injuries [84]. Leg length growth rate is also related to the overall injury risk, bone injuries, and growth plate injuries [84]. Meticulous attention to assessment methods is imperative when examining studies that seek to establish an association between growth and heightened injury risk. This scrutiny extends to details such as the duration of the studies, frequency of assessments conducted throughout their execution, and whether these studies provide values for the short-term reliability of each anthropometric characteristic employed in indicator calculations. A comprehensive understanding of these methodological intricacies is crucial for discerning the robustness and applicability of the association findings, ensuring a nuanced interpretation of the relationship between growth and injury risk in the context of available scientific evidence. For example, the limitation arises from data collection spanning only a single season, rendering it infeasible to observe individuals over a sufficiently extended period to construct growth curve models that can effectively capture the nonlinear nature of growth [85]. This abbreviated timeframe restricts the ability to determine nuanced patterns and trajectories of growth, potentially limiting the depth and accuracy of analyses [85]. This constraint underscores the importance of acknowledging the temporal constraints inherent in the study design when interpreting and generalizing the findings related to growth dynamics.

In conclusion, growth in young players is a complex and dynamic process involving numerous factors such as genetic predisposition, nutrition, physical activity, and environmental influences. It involves significant changes in body dimensions, physique, and composition, such as increases in height, weight, muscle mass, and organ size. Nonetheless, the maturation process can lead to particular difficulties. Aside from the frequent "adolescent awkwardness" caused by the rapid growth spurt, specific sensory-motor mechanisms may even regress during this period. For instance, younger individuals may encounter difficulties in landing tasks owing to incomplete sensorimotor function development. Furthermore, rapid growth is associated with increased injury risk, particularly in areas of skeletal growth and growth plate vulnerability. This information can guide strength and conditioning coaches in adjusting their training processes according to injury risk. Thus, it is imperative to ensure that understanding and monitoring growth patterns and their impact on injury risk are central to effective injury reduction and management strategies in young players (Table 1).

5.2. Maturation & Injury Risk

Distinct from growth, maturation has a definite beginning (at conception) and end (in adulthood). It is worth noting that the maturation process is composed of status, timing, and tempo. Regarding the status of maturity, it is crucial to specify which of the two main approaches is more commonly employed: 1) an approach based on the absolute status of maturity, which reflects how far a player has progressed in maturation; and 2) an approach that categorizes athletes who mature earlier or later than what is considered normal based on their relative maturity status [49]. Hence, absolute maturity refers to the proximity of a player to reach maturity, whereas relative maturity categorizes players as maturing earlier or later than others (early, average, or late maturers) [49]. In this context, timing refers to the age at which specific maturational events occur (e.g., the age at which the peak growth rate is achieved during the adolescent growth spurt) [14,16]. In contrast, tempo is the maturation rate, or how rapidly or slowly a person advances from the early phases of sexual maturation to the mature state [14,16].

Maturation occurs in all body tissues, organs, and systems, which means that various indicators are needed to assess maturation in different biological systems, making this task challenging [14]. Maturation assessment can be complex because each biological system requires unique indicators and maturation is defined differently for each system [28]. Skeletal maturation is considered the most accurate and reliable indicator of maturity. Given the available commencement (cartilage skeleton) and endpoint (mature bone skeleton) of the process, accurate estimates can be obtained throughout the maturation process [28,86]. The most common method uses a single X-ray of the hand-wrist complex, which mirrors the maturation of the entire skeleton [81]. The level of ossification, bone morphology, and union of epiphyses (growth plates) follow a regular sequence, and skeletal age (bone age) can be estimated by comparing an image with the criteria from reference samples [81,86]. There are three primary methods [30]: Greulich-Pyle (GP) [87], Fels [88], and Tanner-Whitehouse (TW 1-3) [89–91]. Three notable techniques were used to evaluate pediatric skeletal age. Skeletal Age (SA) is determined using the GP method, which was created for American White children born between 1917 and 1942 [14,86]. Although this method adheres to standards for both boys and girls, it has been criticized for ignoring bone variation. Originating in Ohio, United States of America, the Fels method utilizes particular ratios and indicators in conjunction with a computational program that supplies SA and standard error to improve precision. The TW method, specifically TW3, is predicated on bone maturation status scores, emphasizing RUS and CARPAL Sas [14,86]. In contrast to TW1 and TW2, which were derived from British children, TW3 underwent evolutionary refinement to accommodate age verification in specific competitions using diverse samples [14,86]. Collectively, these approaches make valuable contributions to the intricate domain of skeletal age determination, providing distinct advantages and factors to be considered. It is important to note that each method varies in the attribution of scores [14,86].

However, sexual maturation is based on the reproductive system. Puberty represents the transition from childhood to adulthood, and sexual maturity is achieved when an individual reaches maximum reproductive capacity [26]. Therefore, its evaluation is based on secondary sexual characteristics such as genital development in boys [26,28]. Secondary sex characteristics are easy to use, but are limited by their invasive nature, exclusive applicability to puberty, and arbitrary discrete categories [28]. Moreover, assessing skeletal age or secondary sex characteristics is impractical in most practical and scientific sports contexts [92]. Based on growth curve parameters (age at onset and age at peak velocity), somatic maturity assessment is confined to the adolescent period and considers only one or two biological events [28]. Thus, assessment of somatic maturation represents a noninvasive and cost-effective alternative [92]. Soccer academies commonly use somatic equations derived from anthropometric measurements to estimate maturation status age at PHV and predict adult height, particularly for the latter two purposes, as per the study by Salter et al. [93].

In contrast, somatic maturity assessment has fewer significant resources and logistical or ethical requirements (e.g., ionizing radiation dose with a left-hand radiograph) [94,95], allowing it to be more applicable in various academic contexts. Specifically, Mirwald et al. [96] devised a method for predicting age at PHV, referred to as maturity offset, using age, height, seated height, and body mass as variables [96]. Individuals were classified into pre-PHV, circa-PHV, and post-PHV periods based on their negative, zero, and positive values. Two modified equations derived from Moore et al. [97] and Fransen et al. [98] were created for boys. These equations estimate the maturity offset and age at PHV by subtracting the predicted age offset from chronological age [97,98]. Another approach involves utilizing the maturity ratio, which divides the chronological age by the maturity ratio to ascertain the age of the PHV. Nevertheless, recent evidence indicates that these newly adapted versions of maturity offset prediction still share limitations with the original method [99,100]. One primary limitation is the potential discrepancy between the predicted chronological age at the time of assessment and the actual age at PHV, especially for boys far from PHV [100]. Furthermore, the Khamis-Roche method (61) uses reference data from American children in the Fels Longitudinal Study to predict adult height [101]. Midparent height (the average height of both parents) was incorporated to predict adult height at a given chronological age. Concerning parents' height, it should be noted that this can either be explicitly measured or self-reported. Unfortunately, it is typical for the height of the parents to be overestimated. To account for this overestimation, Epstein et al. [102] provided corrective equations for self-reported height [102]. The percentage of predicted adult height was used to categorize the athletes according to their maturity level. At 18 years of age, reference values for adult height have been established [103]. The equation can estimate the period around PHV, typically observed around 91-92% of adult height, and occurs in most athletes between 88-96% [103,104]. However, this approach requires accurate anthropometric measurements, and some degree of error (1-3% depending on age and growth percentile) should be expected [92,103]. To compare these two methods of assessing somatic maturation, Parr et al. [104] compared three protocols to the observed age at PHV: An estimate of 13.8 ±1.0 years, an estimate based on the maturity offset equation, age at PHV ± 1.0 year, and a window based on 85-96% of predicted adult height [104]. The authors found that generic age and predicted age at PHV accurately predicted the observed age at PHV for 14 participants (61%). Conversely, the percentage of adult-height windows correctly predicted 22 participants (96%). The accuracy of this study's results was within 2%, consistent with the error values reported by the validation authors, Khamis and Roche [101]. Therefore, somatic maturation may be most effectively evaluated using the Khamis-Roche method.

The relationship between maturation and injury risk in young soccer players has been recently investigated [6,9,11,105–107]. However, scientific research must be advanced to reach a consensus on this issue and provide more practical solutions. Therefore, based on the concepts outlined in this chapter, we present various scientific articles that examine the relationship between maturation and injury risk in young soccer players. It is categorized according to the distinction between absolute and relative maturity. Moreover, differentiation was performed based on the system used to evaluate maturation. Thus, only articles evaluating skeletal and somatic maturation were included in this review. Concerning absolute maturity, utilizing somatic indicators, a recent study collected information on growth and maturation from 1998 to 2019 from 63 elite male soccer players from the academy of a Spanish La Liga club in at least the U12 category [9]. This study defined the injury pattern as the percentage of adult height attained and the categorization of injuries according to somatic maturity status bands. Over the 21 years of data collection, a stadiometer measured each participant's height every 3-4 months. According to a study by Roche and Davila, the maximum height was achieved when the annual development rate was 1 cm for one year [108]. As suggested by an earlier study, the following categories were established for categorizing injuries according to maturity bands: pre-PHV 88%, circa-PHV 88-96%, and post-PHV >96% of predicted adult height [103]. The study recorded 509 injuries and determined injury patterns based on the adult height percentage. The results revealed a distinct pattern of injuries, based on the percentage of adult height. When the height percentage was lower, more growth-related injuries occurred during the pre-PHV and circa-PHV periods. Conversely, during the post-PHV period, muscular, knee, and joint ankle injuries were more prevalent when a higher percentage was significant.

Maturation, particularly maturity status, has been extensively studied, with the PHV period and periods near this maturational event showing a strong association with the risk of injury [105,109]. A recent study found that the PHV period had a greater incidence and burden [105]. Injury burden is the product of injury incidence and mean severity [110] and is typically reported as days' absence per 1000 player hours. Additionally, it should be noted that Bult et al. (2018) found a higher incidence of injury six months after the occurrence of PHV [6]. The study assessed injury risk and burden in 170 young male soccer players over three seasons, calculated the incidence and burden per 1000 hours of participation for five PHV periods and seven age categories, and compared the results with those of the entire cohort [6]. The age of the PHV was determined using an algorithm developed by Mirwald et al. [96]. The incidence of injuries peaked in the first six months post-PHV (10.92/1000 hours) and returned to pre-PHV levels approximately six months later (8.69/1000 hours) [6], that is, one year after PHV. In contrast, Van Der Sluis et al. [111] analyzed the same data to identify disparities in the incidence of traumatic and overuse injuries among soccer players whose adolescent growth spurts occurred during various periods [111]. The maturation offset was calculated using the Mirwald method, as described by Bult et al. [6]. Thirteen players had their PHV at an earlier age (moment of PHV between 12.85 and 13.91), and 13 players had their PHV at an older age (moment of PHV between 13.92 and 15.41). Both groups were observed for three years around PHV, with the year of PHV calculated by subtracting six months from the predicted and actual ages. Pre-PHV and post-PHV refer to the 12 months preceding and following the PHV outbreak, respectively. Later maturing Dutch soccer players (below the sample median APHV) were also at a greater risk of medical attention overuse injuries, but only in the pre-and circa-PHV periods, without differences in the incidence of traumatic injuries [111].

Concerning relative maturity, using the skeletal indicators, Le Gall et al. [112] investigated the injury incidence and severity of biological maturity in 233 elite U14 soccer players over a ten-season period [112]. In this study, the skeletal evaluation method (i.e., the

Greulich–Pyle method) was used to determine the maturation of each player and establish three cohorts (early, average, and late matures) based on their relative skeletal maturity status. However, the primary findings of this study indicate that the level of biological maturity did not significantly influence the overall incidence of injuries among elite French male soccer players. Notably, the authors were discernible only when examining specific categories of injuries. For instance, osteochondral disorders are more prevalent in players with average and late maturation, whereas tendinopathies are more prevalent in players with average and early maturation. Van Der Sluis et al. [109] conducted a 3-year longitudinal study to identify differences in traumatic and overuse injuries among soccer players before, during, and after PHV [109]. First, the authors applied the Mirwald method [96] to calculate maturity offset. Next, the predicted age at the maximal height velocity was computed using the chronological age plus the maturity offset. The authors found that during the PHV period, significantly more players sustained traumatic injuries than in the previous year (1.41 vs 0.81) [109]. According to the authors, PHV years increase the risk of traumatic injuries [109]. Furthermore, the moderate effect size for the difference in training injury incidence and days missed due to injury between the previous year and the PHV year indicated that players were more susceptible to sustaining injuries during the PHV period. In contrast, a study conducted by Johnson et al. [113] involving 292 schoolboy players (9.0–16.0 years old) was conducted over six seasons to assess the impact of skeletal relative maturity status, anthropometric data, and soccer-related variables to explain injury statistics and determine the differences between skeletal and chronological age [113]. The Fels method [114], which employs bone-by-bone comparisons with the addition of ratios between the epiphysis and diaphysis, was used to assess skeletal maturation [115]. This study categorizes maturity as early, average, or late. Early and late matures were categorized as such if their skeletal age was greater than one year or younger than their chronological age, respectively. Those with a skeletal age within one year of their chronological age were considered to be mature on average. According to the findings of this study, young soccer players designated as early mature suffered more injuries than those who were late or average mature. Nevertheless, upon analyzing the mean playing time, mean training time, mean height, and position performed, the authors found no statistically significant variations based on skeletal age. Materne et al. [107] investigated injury patterns and the incidence of skeletal maturity in 283 elite academy soccer players aged U13 to U19 over four consecutive seasons [107]. A modified Cox regression model was employed to ascertain the likelihood of injury. Using the Fels method, the authors determined the skeletal maturity status of 454 players based on the difference between their skeletal and chronological age. They found that musculoskeletal injury patterns and risks varied based on the skeletal maturity status, with the highest overall adjusted injury risk occurring at early maturity [107]. Additionally, they observed that players who had reached skeletal maturity at the wrist had the lowest incidence of apophyseal injuries to the lower extremities, but remained susceptible to apophyseal injuries to the hip and pelvis. Monasterio et al. [83] explored the injury burden of male academy soccer players relative to their growth curve-derived maturity status and chronology. Injury and growth data were collected between 2000 and 2020. In line with other research, the authors found that the overall injury burden increased with an advanced maturity status. Specifically, pre-PHV players exhibited 3.2-, 3.7-, and 5.5-fold lower injury burdens than circa-PHV, post-PHV, and adult players, respectively. For post-PHV and adult players, muscle and joint/ligament injuries were significantly more burdensome than growth-related injuries [83]. Furthermore, relative maturity, evaluated using somatic indicators, was investigated by Johnson et al. [101]. Researchers have investigated how differences in somatic maturity status (pre-, circa-, and post-PHV) and maturity timing (early, average, and late) influence injury risk in academy soccer players. During the two competitive seasons, 76 young soccer players, aged U11 to U16, participated in the study. The authors predicted each player's adult height using the player's height, weight, chronological age, and mid-parent height [101]. The primary finding of this study was that there were no statistically significant differences among early, average, and late maturers in terms of injury burden. However, the circa-PHV period was associated with a greater injury incidence and burden concerning somatic maturity status. Notably, no statistically significant differences in injury risk were observed between the maturity groups. The interaction between maturity status and timing revealed a circa-PHV risk period independent of maturity timing [105].

Concerning the relationship between maturation and injury risk, it is essential to note some contradictory results in the available data, which may be due to methodological differences and limitations [11]. The non-invasive methods used in various studies, such as the Khamis-Roche equation (which predicts adult height using the player's height and weight, along with the height of the parents) and the Mirwald equation (which relies on anthropometric measurements), are less accurate than the gold standard for growth adaptation techniques [85,104]. Furthermore, most studies have a cross-sectional or longitudinal design with a duration of fewer than four years. Therefore, individuals must be followed for a longer duration (from prepubescence to maturity) to model individual growth curves and estimate the age of PHV [85]. Analyzing these studies makes it possible to determine the need for more rigorous scientific research on the relationship between maturation and injury risk (Tables 2 and 3). From a detailed analysis of the presented studies, the following consensus points arise: early maturing athletes tend to have a higher incidence of injuries in general, and the period circa- and post-PHV are associated with a greater injury incidence and burden. Concerning maturity status, there appears to be a consensus that growth-related injuries predominantly occur in the pre-PHV and circa-PHV periods, whereas muscle injuries mainly occur post-PHV.

5.3. Workload & Injury Risk

Monitoring workload is crucial for assessing players' responses and adaptations to training programs, investigating fatigue parameters, aiding recovery, and reducing the risk of nonfunctional overreach, injuries, and illnesses [37]. Internal and external factors largely determine the incidence and prevalence of the injuries. Within the internal factors, age, career length, and history of injuries have been associated with injury risk [116–118]. Throughout PHV, adolescent players are likely to experience a plateau or decline in performance and an increased risk of prevalent overuse injuries [64]. Considering the modifiable risk factors for injury, such as workload, it is crucial to exercise greater control over young soccer players’ exposure to high and repetitive workloads during training and matches during this period [66]. However, ensuring adequate recovery time by implementing strategies that maximize soccer performance is equally critical, as reported in a systematic review by Calleja-González [119]. The highest injury rates were reported on match days (18.2–24.1 injuries per 1000 hours) compared to training days (1.5–3.3 injuries per 1000 hours) [75].

Three studies investigated the relationship between the internal workload and injury risk in young male soccer players. Brink et al. [120] aimed to determine how monitoring stress and recovery can contribute to injury and disease prevention in 53 young elite soccer players [120]. Using daily training logs, the authors employed various methodologies, including recording the duration of training and matches and the session's rate of perceived exertion classification for two competitive seasons [45]. Moreover, the authors used the Dutch version of the Recovery Stress Questionnaire for Athletes (RESTQ-Sport) every month to evaluate athletes’ psychosocial stress recovery status [121]. Injury occurrence with recovery and stress was not established in the RESTQ-Sport analysis, particularly for those who sustained traumatic or overuse injuries. In a subsequent study, Raya-González et al.

(2019) examined the relationship and predictive capacity of internal workload markers regarding noncontact injuries in young elite soccer players [122]. This study involved twenty-two soccer players (aged 18.6 years) who competed in the Spanish U19 League. Throughout the season, a session rating of perceived exertion, internal weekly workload (sum of all training sessions and matches per week), and acute:chronic workload ratio (typically acute = current week and chronic = rolling four-week average) were calculated to determine the internal workload. The authors concluded that internal workload markers were not related to noncontact injuries in young soccer players and had a limited ability to predict these injuries. More recently, Mandorino et al. [47] examined how young soccer players with varying maturity levels related internal workload indicators to their recovery status, risk of illnesses, and noncontact injuries [47]. Twenty-three U14 soccer players were observed throughout the season with PHV-year-based categorization. A multinomial regression analysis assessed the relationship between internal workload indicators and the risk of sickness and noncontact injuries. The authors observed that RPE, acute-to-chronic workload ratio for four weeks (A:C4), total quality recovery (TQR), and Z-TQR-RPE (z-score transformation was used to calculate the difference between TQR and RPE values) were associated with noncontact injuries post-PHV.

Four studies investigated the relationship between external workload and injuries in young soccer players. Two of these four studies prospectively collected GPS data and analyzed their relationship with injury incidence. Bowen et al. [123] studied specific GPS and accelerometer-derived variables, including TD, high-speed distance (HSD), ACC, and total workload [123]. Multiple regression analysis was employed to compare the cumulative workload and acute:chronic (A:C) workload ratios of injured and non-injured players. The A:C ratio evaluation compares the one-week absolute workload with the four-week chronic workload [124,125]. The acute workload was compared with the chronic workload using a workload index [125,126] to determine whether the acute workload was higher or lower. By dividing the acute workload by the chronic workload, the A:C ratio was calculated; a value greater than one indicates that the acute workload is greater than the chronic workload [101]. The injury-workload relationships between the A:C ratios and high and low chronic workloads were examined using z-scores. The workloads were classified into discrete ranges, and the relative risk (RR) was calculated. RR is the proportion of the likelihood of an event occurring in a particular group (such as the exposed group) compared with the likelihood of the same event occurring in another group (such as the non-exposed group)

[76,77]. The authors found that a very high number of ACC (9254) over three weeks was associated with the highest overall (RR = 3.84) and noncontact injury (RR = 5.1) risk. The study also found that the risk of noncontact injury increased substantially when a high acute HSD was combined with a low chronic HSD (RR = 2.55). On the other hand, the authors observed that the relative risk was lower when a high acute HSD was combined with a high chronic HSD (RR = 0.47). The highest contact injury risk was associated with higher A:C TD and ACC ratios (1.76 and 1.76, respectively) (RR = 4.98). In summary, the authors discovered that a high cumulative workload at one and four weeks and a high A:C ACC were related to an increased risk of injury. Bacon and Mauger [127] conducted a second study to determine the predictability of overuse injuries using GPS variables in 48 young professional soccer players aged between 16.7 years and 18.9 years across two seasons [127]. Again, linear regression was used to test the predictability of the injury based on workload using loading groups calculated from weekly squad averages. Players' workload was categorized into three groups: low workload (1 SD) below the mean squad score), average workload (within ± 1 SD of the squad mean), and high workload (1 SD above the squad mean). The study found that TD significantly predicted overuse injury incidence rates (F 1.39 = 6.482, $p = 0.015$), but high-speed running (HSR) meters could not (F 1.39 = 1.003, $p = 0.323$). According to the study, the incidence rates of overuse injury were significantly predicted by TD covered (F 1.39 = 6.482, $p = 0.015$) but not by HSR meters (F 1.39 = 1.003, $p = 0.323$). Therefore, the authors found that young soccer players' susceptibility to overuse injuries may be influenced by the distance covered during training and matches, and on the other hand, noted that a higher accumulation of TD, HSR, and ACC was linked to a greater likelihood of injury [127].

Comparing the two studies [123,127] is complex because of disparities in statistical methods, metrics, and workload calculation. Bacon and Mauger find a correlation between overuse injuries and TD insurance. In contrast, Bowen et al. found a correlation between many high ACC/DCC-content ACC/DCC events over three weeks, an increased risk of all-cause and noncontact injury, and a combination of high acute HSD and low chronic HSD. There is insufficient evidence to support a correlation between TD and ACC and an increased risk of injury in young soccer players, as determined by an analysis of multiple indicators. Similarly, preliminary evidence supports a link between various HSD exposures and the development of general damage.

Two additional studies analyzed the relationship between external workload and injuries in young soccer players, recognizing that the volume of training and matches can affect the risk of injury. Bell et al. [128] investigated the relationship between sports specialization and self-reported knee injury history among young soccer players [128]. This study included 761 soccer participants (mean age: 14.7 ± 1.8 years) between the ages of 12 and 18 who completed an online questionnaire. In addition, they examined the associations between specialization, participation volume, and history of knee injury ($P \leq .05$). The authors found that an annual training volume exceeding eight months increased the risk of knee overload injuries. According to Zoellner et al. [129], among 340 young soccer players (10–15 years) in New Zealand, a history of gradual onset injury was also associated with playing soccer for more than eight months per year and increasing the weekly volume of participation in categorized sports, regardless of skill level [129]. Finally, covering two seasons, Rössler et al. (2018) analyzed prospective injury risk factors in players aged 7–12 years (106). Online registration allows coaches to report player exposure (in hours), absence, and injury information. Time-to-injury data were analyzed using extended Cox models that accounted for intra-team and intra-person correlations. By observing the match-to-training ratio, Rössler et al. [130] confirmed that young soccer players with greater exposure to training suffered fewer match injuries. However, non-injured players had a match-training ratio of 1:7, while injured players had a ratio of 1:5.

Given the early evidence supporting the relationship between workload and injury risk, future research should establish benchmarks for critical external workload metrics. Doing so will provide more reliable references for optimizing training and recovery procedures. In addition, research should target younger training levels based on biological age to identify and mitigate injury risk factors. This approach can promote safer and more efficient athletic development. In examining the association between workload impact and injury risk in young soccer players, akin to the considerations made for growth and maturation, it is imperative to conduct a detailed analysis of all factors contributing to potentially mixed findings across studies. Accurately examining differences in research design, sample characteristics, and metrics employed. For instance, in studies by Bowen et al. [123] and Bacon and Mauger [127], when scrutinizing two articles that explored the relationship between external load (collected by GPS) and injury risk in young soccer players, disparities became evident, such as variations in selected GPS metrics precisely distances covered at specific velocity bands (e.g., HSR). Recognizing these discrepancies underscores the need to consider diverse factors that could result in inaccurate or biased conclusions when synthesizing insights from different articles in this domain. This methodical approach ensures a more nuanced interpretation of the intricate relationship between workload and injury risk among young soccer players.

Regarding the association between the risk of injury and workload, there is a lack of evidence of an association between internal and external workload parameters and the risk of injury in young elite soccer players. Therefore, it is crucial to highlight some critical aspects of the available literature. First, there is a need for younger age groups to contribute more to scientific production, enabling the research community to examine studies that present data on external workload, including prospectively collected GPS data, and relate them to injury incidence. The age range of the samples examined was 16.7 to 18.9 years. There is a need for additional published data concerning the longitudinal training demands (≤ 16 years) of young soccer academies [131]. Although the scientific literature calls for the design of longitudinal studies and the continuous monitoring of players to evaluate the injury workload, there are few studies on this topic in soccer, especially in younger players. Therefore, it is essential to advance knowledge regarding workload and its relationship with the risk of injury and performance degradation. This can only be achieved by providing robust, objective, and reliable measures of external and internal workloads across different age groups of young soccer players. Understanding how different workloads are associated with the risk of injury may be fundamental for coaches, technical staff, and medical professionals to control and manage the training and match workloads of young soccer players, intending to keep them as healthy as possible, optimize their performance, and enhance their talent development (Table 4).

The association between injury risk and growth and maturation has been a topic of great interest among researchers with a growing consensus on the importance of the PHV period. Considering some of the limitations of the current body of research presented throughout the article, such as the different methods of assessing growth and maturation applied, as well as the different periods of study, statistical methods, metrics, and workload calculation disparities, the entire analysis process between some of the studies becomes complex. Future research should consider several essential criteria to enhance our understanding of this relationship: (1) because the methods of estimating maturity offset may have lower validity, longitudinal investigations are necessary to ensure a more accurate analysis and evaluation of the PHV period; (2) further studies are needed to examine a variety of injuries and proportions for different body regions and injury categories, enabling a more comprehensive assessment of injury risk. Addressing these criteria will allow for a more thorough investigation of the relationship between growth, maturation, and injury risk, ultimately contributing to the development of effective strategies to reduce the risk of injury.

Several internal and external factors affect the incidence and burden of injuries in young soccer players. Although some studies suggest that increased workload may be the primary cause, it is crucial to accurately classify injury burden by determining the instant of injury, whether during training or competition. Furthermore, it is essential to include an analysis of each individual's positional profile regarding the variables of growth and maturation and the effects of their internal and external workloads.

In conclusion, future research must delve into the intricate dynamics among workload, recovery, and performance, while also examining how the composition of training sessions influences workload responses throughout various growth and maturation status. Comprehending the theoretical framework and scientific insights presented in this article is essential for effectively using knowledge to develop practical guides for coaching and managing young soccer players. A summary of helpful strategies is presented for consideration.

Comprehending the theoretical framework and scientific insights presented in this article is essential for effectively using knowledge to develop practical guides for coaching and managing young soccer players. A summary of helpful strategies is presented for consideration.

<u>1. Tracking Injury Risk Factors:</u> Regular (e.g., 2–3 months) monitoring of risk factors is essential and can be accomplished by collecting growth and maturity data (e.g., growth curves), particularly during PHV [131]. Practitioners must follow the International Society for the Advancement of Kinanthropometry (ISAK) recommendations for anthropometric assessment. Consideration of growth rates exceeding 7.2 cm per year and a BMI increase of ≥ 0.3 kg/m2 can help identify players at higher risk, facilitating tailored injury prevention strategies [75].

<u>2. Tracking Player Information:</u> It is essential to establish a risk analysis for each player to reference crucial aspects such as the history of injury throughout the sporting career. Regarding biological age, injury history, and physical condition, individualized training

programs are crucial for young players to tailor programs according to their needs and developmental stages. During periods of faster growth, it is important to carry out monthly assessments, allowing the growth rate to be analyzed in more detail [131].

3. Create an Athlete Profile: Develop each athlete's individualized athletic program quality, matching the status and timing of maturity. It is essential to promote a stimulus related to the period of development that the athlete is in, seeking, on the one hand, to enhance their physical performance and mitigate any risk of injury.

4. Assessment of Biological Maturation: Sports practitioners can refine their assessment of athletes' maturity levels by incorporating the percentage of predicted adult height, utilizing the Khamis-Roche method [101,103]. This quantitative measurement tool empowers coaches to tailor training programs and strategies to individual developmental stages. By accurately estimating the timing of peak height velocity within the range of 88-96% of adult height, coaches can implement a personalized approach to athletic development [103]. Recognizing that PHV typically occurs around 91-92% of the predicted adult height [25,132] provides crucial insights for sports professionals, enabling them to anticipate periods of rapid growth and potential performance fluctuations among athletes. to anticipate periods of rapid growth and potential performance fluctuations among athletes.

5. Management Workload: To reduce noncontact injury risk, gradual workload progression should be implemented for young soccer players, especially post-PHV. Monitoring training intensity, volume, and recovery periods ensures a well-balanced and progressively increasing workload [133]. One possible strategy to help quantify workload may involve using the acute:chronic workload ratio (ACWR) [123,134]. It measures the difference between the acute workload completed in the last seven days and the weekly average workload carried out in the previous 28 days (e.g., the exponentially weighted moving average model (EWMA)) [134,135]. It is essential to control young players’ exposure to high and repetitive workloads during the PHV period to reduce the risk of overuse injuries. When managing the training load, it is essential to establish an association between the data collected regarding external and internal workloads and possible symptoms related to "typical" growth injuries. If any symptomatology is reported, it is vital to ensure an adjustment in the dynamics of the microcycle workload and to modify the involvement during specific sessions of the modality (e.g., adjustment in the volume of intense accelerations and decelerations). It is advisable to implement readiness monitoring as a

strategic approach. For instance, utilizing wellness questionnaires, such as the Recovery-Stress Questionnaire for Athletes (RESTQ-Sport) [121], before field or gym training sessions could be highly beneficial. Managing the internal workload and evaluating heart rate and variability changes are fundamental [136]. Heart rate recovery and variability (HRV) improvements during and after exercise show beneficial physiological changes [46]. Monitoring sports training programs have used HRV to identify the ideal daily workout intensity or the anaerobic threshold, as shown by HRV minutes.

6. Analysis of Tracking Systems and Workload: Incorporating GPS tracking devices and sports monitoring software allows coaches to evaluate players' external workload [137]. By adequately analyzing data to measure distance and speed, coaches can discern trends and patterns, indicating a higher likelihood of athletes being prone to injuries. Coaches and medical staff should use external workload metrics, such as total distance covered and high-speed running, to monitor training and match workloads in young soccer players. Tracking these metrics helps to identify injury risk and adjust training programs accordingly [123,137]. Measuring the internal workload by measuring heart rate variability is essential for understanding fatigue levels.

7. Collaborative Approach: Effective implementation of injury reduction strategies requires essential collaboration among coaches, strength and conditioning coaches, medical departments, and other stakeholders [138,139]. A comprehensive approach to injury reduction can be developed by exchanging knowledge and insights from the developmental dynamics and technological breakthroughs. Consistent communication and collaboration across different departments guarantee that the distinct requirements of every player are thoroughly addressed [140].

8. Education and Awareness: Educating players, parents, and coaching staff on the significance of injury reduction and the various elements that affect growth and development is crucial [140]. By cultivating a climate that promotes consciousness and comprehension, those with vested interests can actively participate in endeavors to avoid harm. Offering information and guidance on nutrition, hydration, sleep, and recovery measures enhances young soccer players’ overall well-being.

6. Practical Applications

Integrating these tangible uses into coaching strategies and athlete supervision methods promotes a proactive strategy for reducing injury risk and enhancing the performance of young soccer players. By integrating scientific expertise and effective tactics, coaches and stakeholders can provide a nurturing atmosphere that optimizes young athletes' capabilities, while ensuring their long-term physical and mental welfare.

Table 1 - Synthesis of studies that relate growth to injuries in young soccer players, presenting the identified risk factors and considerations on evaluation and monitoring.

Study	Year of Study	Study Duration	Sample Size	Under/ Age	Assessment and Monitoring Considerations	Risk Factor Identified
Kemper et al. [76]	2015	One season	101 male young soccer players	U12 to U19	Regular evaluation of growth and body composition (e.g., every month)	1. Monthly growth rates of at least 0.6 cm (7.2 cm/year) 2. A monthly increase in body mass index of > 0.3 kg/m2 3. A decrease in body mass index of at least 0.4 kg/m2
Rommers et al. [75]	2020	One season	314 male young soccer players	U10 to U15	Regular evaluation of the growth of standing height and lower limb (e.g., every month)	1. U10 to U12 increased lower limb length during the season, correlated with a higher risk of overuse injuries. 2. U13 to U15's longer lower limb correlated with an increased risk of overuse injuries in the older group. 3. Greater weights and slower growth rates were linked with an increased risk of acute injuries in the older group.
Rommers et al. [150]	2021	One season	378 male young soccer players	U13 to U15	Identification of the group of players with the highest growth rates over the entire season (e.g., creation of a "red flags" list)	1. 15% increase in injury risk per centimetre of growth per year.

Key: U = under; PHV = peak height velocity

Table 2 - Synthesis of studies that relate maturity (absolute maturity) to injuries in young soccer players, presenting the identified risk factors and considerations on evaluation and monitoring.

Study	Year of Study	Study Duration	Sample Size	Under/ Age	Assessment and Monitoring Considerations	Risk Factor Identified
Monasterio et al. [151]	2021	Twenty-one seasons	63 elite male young soccer players	U11 to U19	Identify each player's maturation status and timing	1. The results revealed a distinct pattern of injuries based on the adult height percentage. 2. Growth-related injuries occur during the pre-PHV and circa-PHV periods. 3. During the post-PHV period, muscular, knee, and joint ankle injuries are more prevalent when the higher percentage is significant.
Johnson et al. [152]	2021	Two seasons	76 male young soccer players	U11 to U16	Regular monitoring of players is essential	1. Circa-PHV period had a greater injury incidence and burden. 2. There were no statistically significant differences in injury risk between maturity timing groups (early, on-time, late)
Van Der Sluits et al. [87]	2014	Three seasons	26 male young soccer players	-	Regular monitoring of players is essential	1. Higher incidence of injuries circa-PHV
Butl et al., [45]	2018	Three seasons	170 male young soccer players	U12 to U19	Regular monitoring of players during the PHV period is essential	1. Six months following PHV, the injury incidence was significantly higher. 2. During period PHV 1 (>12 months before PHV), the injury incidence decreased significantly.
Van Der Sluits et al. [153]	2015	Three seasons	26 male young soccer players	-	Regular monitoring of maturity status and timing is essential	1. Late maturers had a greater incidence of overuse injuries pre-PHV. 2. The incidence of overuse injuries circa-PHV was greater in early maturers

Key: U = under; PHV = peak height velocity

Table 3 - Synthesis of studies that relate maturity (relative maturity) to injuries in young soccer players, presenting the identified risk factors and considerations on evaluation and monitoring.

Study	Year of Study	Study Duration	Sample Size	Under/ Age	Assessment and Monitoring Considerations	Risk Factor Identified
Le Gall et al. [154]	2007	Ten seasons	233 elite male young soccer players	U14	Regular monitoring of maturity status and timing is essential	1. The level of biological maturation had no significant effect on the incidence of injuries among elite male French soccer players. 2. Osteochondral disorders were more common among players with average and late maturation, whereas tendinopathies were more common among players with average and early maturation.
Johnson et al. [155]	2009	Six seasons	292 schoolboy players	9 to 16 years	Information sharing between various departments (e.g., medical, performance) Identification of the somatic status and timing of maturation and the respective framework with possible symptoms	1. Young soccer players designated as early mature suffered more injuries than late or average mature players. 2. Adjusted for playing time, average training time, average height, and playing position, the analysis revealed no significant differences in injury incidence between categories of maturity status.
Materne et al. [89]	2021	Four seasons	283 male elite soccer	U13 to U19	-	1. Musculoskeletal injury patterns and risks varied based on skeletal maturity status, with the highest overall adjusted injury risk occurring at early maturity. 2. Players who had reached skeletal maturity at the wrist had the lowest incidence of apophyseal injuries to the lower extremities but remained susceptible to apophyseal injuries to the hip and pelvis
Monasterio et al. [156]	2021	Twenty seasons	110 male young soccer players	U11 to U19	Identify each player's maturation status and timing	1. Pre-PHV players exhibited a lower injury burden than circa-PHV, post-PHV, and adult players. 2. Post-PHV and adult players, muscle and joint/ligament injuries were significantly more burdensome than growth-related injuries.

Key: U = under; PHV = peak height velocity

Table 4 - Synthesis of studies that relate workload to injuries in young soccer players, presenting the identified risk factors and considerations on evaluation and monitoring.

Study	Year of Study	Study Duration	Sample Size	Under/ Age	Assessment and Monitoring Considerations	Risk Factor Identified
Brink et al. [157]	2010	Two seasons	53 elite male young soccer players	15 to 18 years	Regular assessment and monitoring of internal workload (e.g., Daily RPE Questionnaires)	1. Association between internal workload (S-RPE), monotony, and strain with traumatic injuries.
Raya-González et al. [100]	2019	One season	22 male young soccer players	18 to 19,2 years		1. Internal workload markers were not associated with non-contact injuries in young soccer players and had a low predictive capacity for these injuries.
Mandorino et al. [101]	2022	One season	23 male young soccer players	U14	Quantify volume, intensity, frequency, type, and response to training and relate to the RPE and well-being questionnaires.	1. RPE, acute to chronic workload ratio for four weeks (A:C4), total quality recovery (TQR), and Z-TQR-RPE (z-score transformation was used to calculate the difference between TQR and RPE values) were substantially linked with non-contact injuries in post-PHV. 2. A rapid increase in workload and a decrease in recovery state could result in heightened vulnerability to illnesses and non-contact injuries.
Bowen et al. [79]	2017	Two seasons	32 male young soccer players	16,4 to 18,2 years	Monitoring acute and chronic workloads (e.g., TD, HSR, ACC)	1. A very high number of accelerations (ACC) over three weeks was associated with the highest overall (RR) = 3.84) and non-contact injury risk (RR = 5.1). 2. The risk of non-contact injury increased substantially when a high acute high-speed distance (HSD) was combined with a low chronic HSD (RR = 2.55) but not when a high chronic HSD was present (RR = 0.47). 3. The highest contact injury risk was associated with higher acute:chronic (A:C) total distance (TD) and ACC ratios (1.76 and 1.76, respectively) (RR = 4.98). 4. High cumulative workload at 1 and 4 weeks and a high A:C ACC were related to an increased risk of injury.

Bacon & Mauger [102]	2017	Two seasons	41 male young soccer players	U18 to U21	Monitoring acute and chronic workloads (e.g., TD, HSR, ACC)	1. TD significantly predicted overuse injury incidence rates, but HSR meters could not. 2. The incidence rates of overuse injury were significantly predicted by TD covered but not by the meters of HSR 3. The distance covered during training and matches could affect overuse injury in young soccer players. 4. A significant relationship exists between the total distance, the cumulative workload of two weeks of high-speed running, and overuse injuries.
Bell et al. [103]	2018	Not available	761 young soccer players (330 males and 431 females)	12 to 18 years	Monitor the training volume and correlate it with exposure to extracurricular training, specific to soccer, gymnasiums, and multi-sports.	1. An annual training volume exceeding eight months increases the risk of knee overload injuries.
Rössler et al. [105]	2018	Two seasons	6038 young soccer players	7 to 12 years	Workload monitoring and management, taking into account the training:match ratio Monitoring and management of the workload during periods of PHV framing possible symptomatology on the part of the players	1. Young soccer players with greater exposure to training suffered fewer match injuries. 2. Non-injured players had a match-training ratio of 1:7, while injured players had a ratio of 1:5.

Key: S-RPE = session rate of perceived exertion; PHV = peak height velocity; A:C = acute to chronic workload ratio; A:C4 = acute to chronic workload ratio for four weeks; TQR = total quality recovery; Z-TQR-RPE = z-score transformation was used to calculate the difference between TQR and RPE values; ACC = accelerations; RR = Relative Risk; HSD = high-speed distance; TD = total distance; RPE = rate of perceived exertion

7. References

1. le Gall, F.; Carling, C.; Williams, M.; Reilly, T. Anthropometric and Fitness Characteristics of International, Professional and Amateur Male Graduate Soccer Players from an Elite Youth Academy. *J. Sci. Med. Sport* **2010**, *13* (1), 90–95. https://doi.org/10.1016/j.jsams.2008.07.004.

2. Larruskain, J.; Lekue, J. A.; Martin-Garetxana, I.; Barrio, I.; McCall, A.; Gil, S. M. Injuries Are Negatively Associated with Player Progression in an Elite Football Academy. *Sci. Med. Footb.* **2022**, *6* (4), 405–414. https://doi.org/10.1080/24733938.2021.1943756.

3. Finch, C. A New Framework for Research Leading to Sports Injury Prevention. *J. Sci. Med. Sport* **2006**, *9* (1–2), 3–9. https://doi.org/10.1016/j.jsams.2006.02.009.

4. Brien, J. O.; Finch, C. F.; Pruna, R.; Mccall, A.; Brien, J. O.; Finch, C. F.; Pruna, R.; A, A. M. A New Model for Injury Prevention in Team Sports : The Team-Sport Injury Prevention (TIP) Cycle A New Model for Injury Prevention in Team Sports : The Team-Sport Injury Prevention. *Sci. Med. Footb.* **2018**, *00* (00), 1–4. https://doi.org/10.1080/24733938.2018.1512752.

5. Price, R. J.; Hawkins, R. D.; Hulse, M. A.; Hodson, A. The Football Association Medical Research Programme: An Audit of Injuries in Academy Youth Football. *Br. J. Sports Med.* **2004**, *38* (4), 466–471. https://doi.org/10.1136/bjsm.2003.005165.

6. Bult, H. J.; Barendrecht, M.; Tak, I. J. R. Injury Risk and Injury Burden Are Related to Age Group and Peak Height Velocity Among Talented Male Youth Soccer Players. *Orthop. J. Sport. Med.* **2018**, *6* (12), 1–7. https://doi.org/10.1177/2325967118811042.

7. Jones, S.; Almousa, S.; Gibb, A.; Allamby, N.; Mullen, R.; Andersen, T. E.; Williams, M. Injury Incidence, Prevalence and Severity in High-Level Male Youth Football: A Systematic Review. *Sport. Med.* **2019**, *49* (12), 1879–1899. https://doi.org/10.1007/s40279-019-01169-8.

8. Monasterio, X. Relative Skeletal Maturity Status Affects Injury Burden in U14 Elite Academy Football Players : A 9-Season Prospective Study. *Scand. J. Med. Sci. Sports* **2022**. https://doi.org/10.1111/sms.14204.

9. Monasterio, X.; Gil, S. M.; Bidaurrazaga-Letona, I.; Lekue, J. A.; Santisteban, J.; Diaz-Beitia, G.; Martin-Garetxana, I.; Bikandi, E.; Larruskain, J. Injuries According to

the Percentage of Adult Height in an Elite Soccer Academy. *J. Sci. Med. Sport* **2021**, *24* (3), 218–223. https://doi.org/10.1016/j.jsams.2020.08.004.

10. Robles-Palazón, F. J.; López-Valenciano, A.; De Ste Croix, M.; Oliver, J. L.; García-Gómez, A.; Sainz de Baranda, P.; Ayala, F. Epidemiology of Injuries in Male and Female Youth Football Players: A Systematic Review and Meta-Analysis. *J. Sport Heal. Sci.* **2022**, *11* (6), 681–695. https://doi.org/10.1016/j.jshs.2021.10.002.

11. Swain, M.; Kamper, S. J.; Maher, C. G.; Broderick, C.; McKay, D.; Henschke, N. Relationship between Growth, Maturation and Musculoskeletal Conditions in Adolescents: A Systematic Review. *Br. J. Sports Med.* **2018**, *52* (19), 1246–1252. https://doi.org/10.1136/bjsports-2017-098418.

12. Lloyd, R. S.; Cronin, J. B.; Faigenbaum, A. D.; Haff, G. G.; Howard, R.; Kraemer, W. J.; Micheli, L. J.; Myer, G. D.; Oliver, J. L. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *J. Strength Cond. Res.* **2016**, *30* (6), 1491–1509. https://doi.org/10.1519/JSC.0000000000001387.

13. Istvan Balyi, B.; Simon -Nobel Laureate, H. Long-Term Athlete Development: Trainability in Children and Adolescents. Windows of Opportunity. Optimal Trainability. *Victoria, BC Natl. Coach. Inst. Br. Columbia Adv. Train. Perform. Ltd* **2004**.

14. Robert M Malina; Claude Bouchard; Oded Bar-Or. *Growth, Maturation, and Physical Activity*, 2nd ed.; Human Kinetics: Champaign, IL, USA, 2004.

15. Cardoso, H. F. V.; Pereira, V.; Rios, L. Chronology of Fusion of the Primary and Secondary Ossification Centers in the Human Sacrum and Age Estimation in Child and Adolescent Skeletons. *Am. J. Phys. Anthropol.* **2014**, *153* (2), 214–225. https://doi.org/10.1002/ajpa.22422.

16. Baxter-Jones, A. D. G.; Eisenmann, J. C.; Sherar, L. B. Controlling for Maturation in Pediatric Exercise Science. *Pediatr. Exerc. Sci.* **2005**, *17* (1), 18–30. https://doi.org/10.1123/pes.17.1.18.

17. Lloyd, R. S.; Oliver, J. L.; Faigenbaum, A. D.; Myer, G. D.; De Ste Croix, M. B. A. Chronological Age vs. Biological Maturation. *J. Strength Cond. Res.* **2014**, *28* (5), 1454–1464. https://doi.org/10.1519/JSC.0000000000000391.

18. North, M.; Kelly, A. L.; Ranchordas, M. K.; Cole, M. Nutritional Considerations in High Performance Youth Soccer: A Systematic Review. *J. Sci. Sport Exerc.* **2022**, *4* (3), 195–212. https://doi.org/10.1007/s42978-022-00171-3.

19. Desbrow, B.; Cox, G.; Desbrow, B.; Burke, L. M.; Cox, G. R.; Sawyer, S. M. Sports Dietitians Australia Position Statement : Sports Nutrition for the Adolescent Athlete Sports Dietitians Australia Position Statement : Sports Nutrition for the Adolescent Athlete. *Int. J. Sport Nutr. Exerc. Metab.* **2014**, *24* (5), 570–584.

20. Marcus P Hannon, Lloyd J F Parker, Daniel J Carney, John McKeown, John R Speakman, Catherine Hambly, Barry Drust, Viswanath B Unnithan, Graeme L Close, J. P. M. Energy Requirements of Male Academy Soccer Players from the English Premier League. *Med. Sci. Sport. Exerc.* **2021**, *53* (1), 200–210. https://doi.org/10.1249/MSS.0000000000002443.

21. Schell, L. M.; Knutson, K. L.; Bailey, S. Environmental Effects on Growth. In *Human Growth and Development*; Elsevier, 2012; pp 245–286. https://doi.org/10.1016/B978-0-12-383882-7.00010-6.

22. Baxter-Jones, A. D. G. Physical Growth and Development in Young Athletes: Factors of Influence and Consequence. *Kinesiol. Rev.* **2019**, *8* (3), 211–219. https://doi.org/10.1123/kr.2019-0024.

23. Stojanoska, B. B. Impact of Socioeconomic Factors on Somatotype Components in Macedonian Adolescents. *MOJ Anat. Physiol.* **2016**, *2* (4). https://doi.org/10.15406/mojap.2016.02.00050.

24. Mekonnen, T.; Papadopoulou, E.; Arah, O. A.; Brantsæter, A. L.; Lien, N.; Gebremariam, M. K. Socioeconomic Inequalities in Children's Weight, Height and BMI Trajectories in Norway. *Sci. Rep.* **2021**, *11* (1), 1–9. https://doi.org/10.1038/s41598-021-84615-w.

25. Malina, R. M.; Cumming, S. P.; Rogol, A. D.; Coelho-e-Silva, M. J.; Figueiredo, A. J.; Konarski, J. M.; Kozieł, S. M. Bio-Banding in Youth Sports: Background, Concept, and Application. *Sport. Med.* **2019**, *49* (11), 1671–1685. https://doi.org/10.1007/s40279-019-01166-x.

26. Malina, R. M. Top 10 Research Questions Related to Growth and Maturation of Relevance to Physical Activity, Performance, and Fitness. *Res. Q. Exerc. Sport* **2014**, *85* (2), 157–173. https://doi.org/10.1080/02701367.2014.897592.

27. Lloyd, R. S.; Oliver, J. L. The Youth Physical Development Model. *Strength Cond. J.* **2012**, *34* (3), 61–72. https://doi.org/10.1519/SSC.0b013e31825760ea.

28. Beunen, G. P.; Rogol, A. D.; Malina, R. M. Indicators of Biological Maturation

and Secular Changes in Biological Maturation. *Food Nutr. Bull.* **2006**, *27* (4 SUPPL.), 244–256. https://doi.org/10.1177/15648265060274s508.

29. Malina, R. M.; Eisenmann, J. C.; Cumming, S. P.; Ribeiro, B.; Aroso, J. Maturity-Associated Variation in the Growth and Functional Capacities of Youth Football (Soccer) Players 13?15 years. *Eur. J. Appl. Physiol.* **2004**, *91* (5–6), 555–562. https://doi.org/10.1007/s00421-003-0995-z.

30. Malina, R. M. Skeletal Age and Age Verification in Youth Sport. *Sport. Med.* **2011**, *41* (11), 925–947. https://doi.org/10.2165/11590300-000000000-00000.

31. Figueiredo, A. J.; e Silva, M. J. C.; Cumming, S. P.; Malina, R. M. Size and Maturity Mismatch in Youth Soccer Players 11- to 14-Years-Old. *Pediatr. Exerc. Sci.* **2010**, *22* (4), 596–612. https://doi.org/10.1123/pes.22.4.596.

32. Windt, J.; Gabbett, T. J. How Do Training and Competition Workloads Relate to Injury? The Workload—Injury Aetiology Model. *Br. J. Sports Med.* **2017**, *51* (5), 428–435. https://doi.org/10.1136/bjsports-2016-096040.

33. Gabbett, T. J.; Whyte, D. G.; Hartwig, T. B.; Wescombe, H.; Naughton, G. A. The Relationship between Workloads, Physical Performance, Injury and Illness in Adolescent Male Football Players. *Sport. Med.* **2014**, *44* (7), 989–1003. https://doi.org/10.1007/s40279-014-0179-5.

34. Pereira, L. A.; Freitas, T. T.; Zanetti, V.; Loturco, I. Variations in Internal and External Training Load Measures and Neuromuscular Performance of Professional Soccer Players during a Preseason Training Period. *J. Hum. Kinet.* **2022**, *81* (1), 149–162. https://doi.org/10.2478/hukin-2022-0012.

35. Hannon, M. P.; Coleman, N. M.; Parker, L. J. F.; McKeown, J.; Unnithan, V. B.; Close, G. L.; Drust, B.; Morton, J. P. Seasonal Training and Match Load and Micro-Cycle Periodization in Male Premier League Academy Soccer Players. *J. Sports Sci.* **2021**, *39* (16), 1838–1849. https://doi.org/10.1080/02640414.2021.1899610.

36. Halson, S. L. Monitoring Training Load to Understand Fatigue in Athletes. *Sport. Med.* **2014**, *44*, 139–147. https://doi.org/10.1007/s40279-014-0253-z.

37. Bourdon, P. C.; Cardinale, M.; Murray, A.; Gastin, P.; Kellmann, M.; Varley, M. C.; Gabbett, T. J.; Coutts, A. J.; Burgess, D. J.; Gregson, W.; Cable, N. T. Monitoring Athlete Training Loads: Consensus Statement. *Int. J. Sports Physiol. Perform.* **2017**, *12*, 161–170. https://doi.org/10.1123/IJSPP.2017-0208.

38. Castagna, C.; Varley, M.; Póvoas, S. C. A.; D'Ottavio, S. Evaluation of the Match External Load in Soccer: Methods Comparison. *Int. J. Sports Physiol. Perform.* **2017**, *12* (4), 490–495. https://doi.org/10.1123/ijspp.2016-0160.

39. Akenhead, R.; Nassis, G. P. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. *Int. J. Sports Physiol. Perform.* **2016**, *11* (5), 587–593. https://doi.org/10.1123/ijspp.2015-0331.

40. Cummins, C.; Orr, R.; O'Connor, H.; West, C. Global Positioning Systems (GPS) and Microtechnology Sensors in Team Sports: A Systematic Review. *Sport. Med.* **2013**, *43* (10), 1025–1042. https://doi.org/10.1007/s40279-013-0069-2.

41. Varley, M. C.; Jaspers, A.; Helsen, W. F.; Malone, J. J. Methodological Considerations When Quantifying High-Intensity Efforts in Team Sport Using Global Positioning System Technology. *Int. J. Sports Physiol. Perform.* **2017**, *12* (8), 1059–1068. https://doi.org/10.1123/ijspp.2016-0534.

42. Scott, M. T. U.; Scott, T. J.; Kelly, V. G. The Validity and Reliability of Global Positioning Systems in Team Sport. *J. Strength Cond. Res.* **2016**, *30* (5), 1470–1490. https://doi.org/10.1519/JSC.0000000000001221.

43. Rowell, A. E.; Aughey, R. J.; Clubb, J.; Cormack, S. J. A Standardized Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in Professional A-League Football Players. *Front. Physiol.* **2018**, *9*, 1–13. https://doi.org/10.3389/fphys.2018.01011.

44. Coyne, J. O. C.; Gregory Haff, G.; Coutts, A. J.; Newton, R. U.; Nimphius, S. The Current State of Subjective Training Load Monitoring—a Practical Perspective and Call to Action. *Sport. Med. - Open* **2018**, *4* (1), 1–10. https://doi.org/10.1186/s40798-018-0172-x.

45. Foster, C. Monitoring Training in Athletes with Reference to Overtraining Syndrome. *Med. Sci. Sports Exerc.* **1988**, *30* (7), 1164–1168. https://doi.org/10.1097/00005768- 199807000-00023.

46. Bricout, V.-A.; DeChenaud, S.; Favre-Juvin, A. Analyses of Heart Rate Variability in Young Soccer Players: The Effects of Sport Activity. *Auton. Neurosci.* **2010**, *154* (1–2), 112–116. https://doi.org/10.1016/j.autneu.2009.12.001.

47. Mandorino, M.; J. Figueiredo, A.; Condello, G.; Tessitore, A. The Influence of Maturity on Recovery and Perceived Exertion, and Its Relationship with Illnesses and

Non-Contact Injuries in Young Soccer Players. *Biol. Sport* **2022**, *39* (4), 839–848. https://doi.org/10.5114/biolsport.2022.109953.

48. Lehnert, M.; De Ste Croix, M.; Šťastný, P.; Maixnerová, E.; Zaatar, A.; Botek, M.; Vařeková, R.; Hůlka, K.; Petr, M.; Elfmark, M.; Lipinska, P. *The Influence of Fatigue on Injury Risk in Male Youth Soccer*; 2019. https://doi.org/10.5507/ftk.19.24455587.

49. Wik, E. H. Growth, Maturation and Injuries in High-Level Youth Football (Soccer): A Mini Review. *Front. Sport. Act. Living* **2022**, *4*, 1–9. https://doi.org/10.3389/fspor.2022.975900.

50. Macgregor, S.; Cornes, B. K.; Martin, N. G.; Visscher, P. M. Bias, Precision and Heritability of Self-Reported and Clinically Measured Height in Australian Twins. *Hum. Genet.* **2006**, *120* (4), 571–580. https://doi.org/10.1007/s00439-006-0240-z.

51. McEvoy, B. P.; Visscher, P. M. Genetics of Human Height. *Econ. Hum. Biol.* **2009**, *7* (3), 294–306. https://doi.org/10.1016/j.ehb.2009.09.005.

52. Perola, M.; Sammalisto, S.; Hiekkalinna, T.; Martin, N. G.; Visscher, P. M.; Montgomery, G. W.; Benyamin, B.; Harris, J. R.; Boomsma, D.; Willemsen, G.; Hottenga, J. J.; Christensen, K.; Kyvik, K. O.; Sørensen, T. I. A.; Pedersen, N. L.; Magnusson, P. K. E.; Spector, T. D.; Widen, E.; Silventoinen, K.; Kaprio, J.; Palotie, A.; Peltonen, L. Combined Genome Scans for Body Stature in 6,602 European Twins: Evidence for Common Caucasian Loci. *PLoS Genet.* **2007**, *3* (6), 1019–1028. https://doi.org/10.1371/journal.pgen.0030097.

53. Silventoinen, K.; Sammalisto, S.; Perola, M.; Boomsma, D. I.; Cornes, B. K.; Davis, C.; Dunkel, L.; De Lange, M.; Harris, J. R.; Hjelmborg, J. V. B.; Luciano, M.; Martin, N. G.; Mortensen, J.; Nisticò, L.; Pedersen, N. L.; Skytthe, A.; Spector, T. D.; Stazi, M. A.; Willemsen, G.; Kaprio, J. Heritability of Adult Body Height: A Comparative Study of Twin Cohorts in Eight Countries. *Twin Res.* **2003**, *6* (5), 399–408. https://doi.org/10.1375/136905203770326402.

54. Molinari, L.; Gasser, T.; Largo, R. A Comparison of Skeletal Maturity and Growth. *Ann. Hum. Biol.* **2012**, No. October, 1–9. https://doi.org/10.3109/03014460.2012.756122.

55. Beunen, G.; Malina, R. M. Growth and Biologic Maturation: Relevance to Athletic Performance. In *The Young Athlete*; Wiley, 2007; pp 3–17. https://doi.org/10.1002/9780470696255.ch1.

56. Beunen, G.; Malina, R. M. Growth and Physical Performance Relative to the Timing of the Adolescent Spurt. *Exerc. Sport Sci. Rev.* **1988**, *16*, 503–540.

57. MacMaster, C.; Portas, M.; Parkin, G.; Cumming, S.; Wilcox, C.; Towlson, C. The Effect of Bio-Banding on the Anthropometric, Physical Fitness and Functional Movement Characteristics of Academy Soccer Players. *PLoS One* **2021**, *16* (11 November), 1–16. https://doi.org/10.1371/journal.pone.0260136.

58. Bisi, M. C.; Stagni, R. Development of Gait Motor Control: What Happens after a Sudden Increase in Height during Adolescence? *Biomed. Eng. Online* **2016**, *15* (1), 1–12. https://doi.org/10.1186/s12938-016-0159-0.

59. Frisch, A.; Urhausen, A.; Seil, R.; Croisier, J. L.; Windal, T.; Theisen, D. Association between Preseason Functional Tests and Injuries in Youth Football: A Prospective Follow-Up. *Scand. J. Med. Sci. Sports* **2011**, *21* (6), e468–e476. https://doi.org/10.1111/j.1600-0838.2011.01369.x.

60. Philippaerts, R. M.; Vaeyens, R.; Janssens, M.; Van Renterghem, B.; Matthys, D.; Craen, R.; Bourgois, J.; Vrijens, J.; Beunen, G.; Malina, R. M. The Relationship between Peak Height Velocity and Physical Performance in Youth Soccer Players. *J. Sports Sci.* **2006**, *24* (3), 221–230. https://doi.org/10.1080/02640410500189371.

61. Quatman-Yates, C. C.; Quatman, C. E.; Meszaros, A. J.; Paterno, M. V.; Hewett, T. E. A Systematic Review of Sensorimotor Function during Adolescence: A Developmental Stage of Increased Motor Awkwardness? *Br. J. Sports Med.* **2012**, *46* (9), 649–655. https://doi.org/10.1136/bjsm.2010.079616.

62. Wachholz, F.; Tiribello, F.; Mohr, M.; van Andel, S.; Federolf, P. Adolescent Awkwardness: Alterations in Temporal Control Characteristics of Posture with Maturation and the Relation to Movement Exploration. *Brain Sci.* **2020**, *10* (4), 1–15. https://doi.org/10.3390/brainsci10040216.

63. Viel, S.; Vaugoyeau, M.; Assaiante, C. Adolescence: A Transient Period of Proprioceptive Neglect in Sensory Integration of Postural Control. *Motor Control* **2009**, *13* (1), 25–42. https://doi.org/10.1123/mcj.13.1.25.

64. Corso, M. Developmental Changes in the Youth Athlete: Implications for Movement, Skills Acquisition, Performance and Injuries. *J. Can. Chiropr. Assoc.* **2018**, *62* (3), 150–160.

65. Kanehisa, H.; Yata, H.; Ikegawa, S.; Fukunaga, T. A Cross-Sectional Study of the

Size and Strength of the Lower Leg Muscles during Growth. *Eur. J. Appl. Physiol. Occup. Physiol.* **1995**, *72* (1), 150–156. https://doi.org/10.1007/BF00964130.

66. Hirtz, P.; Starosta, W. Sensitive and Critical Periods of Motor Co-Ordination Development and Its Relation To Motor Learning. *J. Hum. Kinet.* **2002**, *7*, 19–28.

67. Landry, M. Brukner & Khan's Clinical Sports Medicine. *Physiother. Canada* **2014**, *66* (1), 109–110. https://doi.org/10.3138/ptc.66.1.rev2.

68. Atanda, A.; Shah, S. A.; O'Brien, K. Osteochondrosis: Common Causes of Pain in Growing Bones. *Am. Fam. Physician* **2011**, *83* (3), 285–291.

69. Hawkins, D.; Metheny, J. Overuse Injuries in Youth Sports: Biomechanical Considerations. *Med. Sci. Sport. Exerc.* **2001**, *33* (10), 1701–1707. https://doi.org/10.1097/00005768-200110000-00014.

70. Brukner P; Khan KM. *Clinical Sports Medicine*, 4th ed.; Elsevier: New York, NY: McGraw-Hill Medical, 2006. https://doi.org/10.1016/B978-0-323-02588-1.X5001-5.

71. Caine, D. Physeal Injuries in Children's and Youth Sports: Reasons for Concern? *Br. J. Sports Med.* **2006**, *40* (9), 749–760. https://doi.org/10.1136/bjsm.2005.017822.

72. Caine, D.; DiFiori, J.; Maffulli, N. Physeal Injuries in Children's and Youth Sports: Reasons for Concern? *Br. J. Sports Med.* **2006**, *40* (9), 749–760. https://doi.org/10.1136/bjsm.2005.017822.

73. Blimkie, C. J. R.; Lefevre, J.; Beunen, G. P.; Renson, R.; Dequeker, J.; Van Damme, P. Fractures, Physical Activity, and Growth Velocity in Adolescent Belgian Boys. *Med. Sci. Sport. Exerc.* **1993**, *25* (7), 801–808. https://doi.org/10.1249/00005768-199307000-00008.

74. Faulkner, R. A.; Davison, K. S.; Bailey, D. A.; Mirwald, R. L.; Baxter-Jones, A. D. Size-Corrected BMD Decreases During Peak Linear Growth: Implications for Fracture Incidence During Adolescence. *J. Bone Miner. Res.* **2006**, *21* (12), 1864–1870. https://doi.org/10.1359/jbmr.060907.

75. Kemper, G. L. J.; Van Der Sluis, A.; Brink, M. S.; Visscher, C.; Frencken, W. G. P.; Elferink-Gemser, M. T. Anthropometric Injury Risk Factors in Elite-Standard Youth Soccer. *Int. J. Sports Med.* **2015**, *36* (13), 1112–1117. https://doi.org/10.1055/s-0035-1555778.

76. Ranganathan, P.; Aggarwal, R.; Pramesh, C. Common Pitfalls in Statistical Analysis: Odds versus Risk. *Perspect. Clin. Res.* **2015**, *6* (4), 222.

https://doi.org/10.4103/2229-3485.167092.

77. Monaghan, T. F.; Rahman, S. N.; Agudelo, C. W.; Wein, A. J.; Lazar, J. M.; Everaert, K.; Dmochowski, R. R. Foundational Statistical Principles in Medical Research: A Tutorial on Odds Ratios, Relative Risk, Absolute Risk, and Number Needed to Treat. *Int. J. Environ. Res. Public Health* **2021**, *18* (11), 1–11. https://doi.org/10.3390/ijerph18115669.

78. Furlan, L.; Sterr, A. The Applicability of Standard Error of Measurement and Minimal Detectable Change to Motor Learning Research—A Behavioral Study. *Front. Hum. Neurosci.* **2018**, *12*, 1–10. https://doi.org/10.3389/fnhum.2018.00095.

79. Rommers, N.; Rössler, R.; Goossens, L.; Vaeyens, R.; Lenoir, M.; Witvrouw, E.; D'Hondt, E. Risk of Acute and Overuse Injuries in Youth Elite Soccer Players: Body Size and Growth Matter. *J. Sci. Med. Sport* **2020**, *23* (3), 246–251. https://doi.org/10.1016/j.jsams.2019.10.001.

80. Rommers, N.; Rössler, R.; Shrier, I.; Lenoir, M.; Witvrouw, E.; D'Hondt, E.; Verhagen, E. Motor Performance Is Not Related to Injury Risk in Growing Elite-Level Male Youth Football Players. A Causal Inference Approach to Injury Risk Assessment. *J. Sci. Med. Sport* **2021**, *24* (9), 881–885. https://doi.org/10.1016/j.jsams.2021.03.004.

81. Malina, R. M.; Rogol, A. D.; Cumming, S. P.; Coelho E Silva, M. J.; Figueiredo, A. J. Biological Maturation of Youth Athletes: Assessment and Implications. *Br. J. Sports Med.* **2015**, *49* (13), 852–859. https://doi.org/10.1136/bjsports-2015-094623.

82. Dvorak, J.; George, J.; Junge, A.; Hodler, J. Age Determination by Magnetic Resonance Imaging of the Wrist in Adolescent Male Football Players. *Br. J. Sports Med.* **2007**, *41* (1), 45–52. https://doi.org/10.1136/bjsm.2006.031021.

83. Monasterio, X.; Gil, S. M.; Bidaurrazaga-Letona, I.; Lekue, J. A.; Santisteban, J. M.; Diaz-Beitia, G.; Lee, D. J.; Zumeta-Olaskoaga, L.; Martin-Garetxana, I.; Bikandi, E.; Larruskain, J. The Burden of Injuries According to Maturity Status and Timing: A Two-Decade Study with 110 Growth Curves in an Elite Football Academy. *Eur. J. Sport Sci.* **2021**, *0* (0), 1–11. https://doi.org/10.1080/17461391.2021.2006316.

84. Wik, E. H.; Lolli, L.; Chamari, K.; Materne, O.; Salvo, V. Di; Gregson, W.; Bahr, R. Injury Patterns Differ with Age in Male Youth Football : A Four- - Season Prospective Study of 1111 Time- - Loss Injuries in an Elite National Academy. **2020**, 1–8. https://doi.org/10.1136/bjsports-2020-103430.

85. Teunissen, J. W.; Rommers, N.; Pion, J.; Cumming, S. P.; Rössler, R.; D'Hondt, E.; Lenoir, M.; Savelsbergh, G. J. P.; Malina, R. M. Accuracy of Maturity Prediction Equations in Individual Elite Male Football Players. *Ann. Hum. Biol.* **2020**, *47* (4), 409–416. https://doi.org/10.1080/03014460.2020.1783360.

86. Malina, R. M.; Peña Reyes, M. E.; Figueiredo, A. J.; Coelho E Silva, M. J.; Horta, L.; Miller, R.; Chamorro, M.; Serratosa, L.; Morate, F. Skeletal Age in Youth Soccer Players: Implication for Age Verification. *Clin. J. Sport Med.* **2010**, *20* (6), 469–474. https://doi.org/10.1097/JSM.0b013e3181f827ea.

87. Greulich, W. W., & Pyle, S. I. *Radiographic Atlas of Skeletal Development of the Hand and Wrist*; Stanford University Press, Ed.; 1959.

88. Chumela, W. C.; Roche, A. F.; Thissen, D. *The FELS Method of Assessing the Skeletal Maturity of the Hand-wrist*; 1989; Vol. 1. https://doi.org/10.1002/ajhb.1310010206.

89. Tanner JM, Healy MJR, Goldstein H, C. N. *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 Method)*, 3rd editio.; London, U. S., Ed.; 2001.

90. Tanner JM, Whitehouse RH, Marshall WA, Healy MJR, G. H. *Assessment of Skeletal Maturity and Prediction of Adult Height (TW2 Method)*; New York, N. A. P., Ed.; 1975.

91. Tanner JM, Whitehouse RH, H. M. *A New System for Estimating Skeletal Maturity from the Hand and Wrist, with Standards Derived from a Study of 2,600 Healthy British Children*; Paris, FR: Centre, I. C., Ed.; 1962.

92. Towlson, C.; Salter, J.; Ade, J. D.; Enright, K.; Harper, L. D.; Page, R. M.; Malone, J. J. Maturity-Associated Considerations for Training Load, Injury Risk, and Physical Performance in Youth Soccer: One Size Does Not Fit All. *J. Sport Heal. Sci.* **2021**, *10* (4), 403–412. https://doi.org/10.1016/j.jshs.2020.09.003.

93. Salter, J.; De Ste Croix, M. B. A.; Hughes, J. D.; Weston, M.; Towlson, C. Monitoring Practices of Training Load and Biological Maturity in Uk Soccer Academies. *Int. J. Sports Physiol. Perform.* **2021**, *16* (March), 395–406. https://doi.org/10.1123/IJSPP.2019-0624.

94. Huda, W.; Gkanatsios, N. A. Radiation Dosimetry for Extremity Radiographs. *Health Phys.* **1998**, *75* (5), 492–499. https://doi.org/10.1097/00004032-199811000-00005.

95. Engebretsen, L.; Steffen, K.; Bahr, R.; Broderick, C.; Dvorak, J.; Janarv, P. M.; Johnson, A.; Leglise, M.; Mamisch, T. C.; Mckay, D.; Micheli, L.; Schamasch, P.; Singh, G. D.; Stafford, D. E. J.; Steen, H. The International Olympic Committee Consensus Statement on Age Determination in High-Level Young Athletes. *Br. J. Sports Med.* **2010**, *44* (7), 476–484. https://doi.org/10.1136/bjsm.2010.073122.

96. Mirwald, R. L.; G. Baxter-Jones, A. D.; Bailey, D. A.; Beunen, G. P. An Assessment of Maturity from Anthropometric Measurements. *Med. Sci. Sport. Exerc.* **2002**, *34* (4), 689–694. https://doi.org/10.1097/00005768-200204000-00020.

97. Fransen, J.; Bush, S.; Woodcock, S.; Novak, A.; Baxter-Jones, A. D. G.; Deprez, D.; Vaeyens, R.; Lenoir, M. Improving the Prediction of Maturity from Anthropometric Variables Using a Maturity Ratio. *Pediatr. Exerc. Sci.* **2018**, *30* (2), 296–307. https://doi.org/10.1123/pes.2017-0009.

98. Moore, S. A.; McKay, H. A.; Macdonald, H.; Nettlefold, L.; Baxter-Jones, A. D. G.; Cameron, N.; Brasher, P. M. A. Enhancing a Somatic Maturity Prediction Model. *Med. Sci. Sports Exerc.* **2015**, *47* (8), 1755–1764. https://doi.org/10.1249/MSS.0000000000000588.

99. Nevill, A.; Burton, R. F. Commentary on the Article “Improving the Prediction of Maturity From Anthropometric Variables Using a Maturity Ratio.” *Pediatr. Exerc. Sci.* **2018**, *30* (2), 308–310. https://doi.org/10.1123/pes.2017-0201.

100. Kozieł, S. M.; Malina, R. M. Modified Maturity Offset Prediction Equations: Validation in Independent Longitudinal Samples of Boys and Girls. *Sport. Med.* **2018**, *48* (1), 221–236. https://doi.org/10.1007/s40279-017-0750-y.

101. Khamis, H. J.; Roche, A. F. Predicting Adult Stature without Using Skeletal Age: The Khamis-Roche Method. *Pediatrics* **1994**, *94* (4 Pt 1), 504–507.

102. Epstein, L. H.; Valoski, A. M.; Kalarchian, M. A.; McCurley, J. Do Children Lose and Maintain Weight Easier Than Adults: A Comparison of Child and Parent Weight Changes From Six Months to Ten Years. *Obes. Res.* **1995**, *3* (5), 411–417. https://doi.org/10.1002/j.1550-8528.1995.tb00170.x.

103. Cumming, S. P.; Lloyd, R. S.; Oliver, J. L.; Eisenmann, J. C.; Malina, R. M. Bio-Banding in Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of Youth Athletes. *Strength Cond. J.* **2017**, *39* (2), 34–47. https://doi.org/10.1519/SSC.0000000000000281.

104. Parr, J.; Winwood, K.; Hodson-Tole, E.; Deconinck, F. J. A.; Parry, L.; Hill, J. P.; Malina, R. M.; Cumming, S. P. Predicting the Timing of the Peak of the Pubertal Growth Spurt in Elite Male Youth Soccer Players: Evaluation of Methods. *Ann. Hum. Biol.* **2020**, *47* (4), 400–408. https://doi.org/10.1080/03014460.2020.1782989.

105. Johnson, D. M.; Williams, S.; Bradley, B.; Sayer, S.; Murray Fisher, J.; Cumming, S. Growing Pains: Maturity Associated Variation in Injury Risk in Academy Football. *Eur. J. Sport Sci.* **2020**, *20* (4), 544–552. https://doi.org/10.1080/17461391.2019.1633416.

106. Materne, O.; Chamari, K.; Farooq, A.; Tabben, M.; Weir, A.; Holmich, P.; Bahr, R.; Greig, M.; McNaughton, L. R. Shedding Light on Incidence and Burden of Physeal Injuries in a Youth Elite Football Academy: A 4-season Prospective Study. *Scand. J. Med. Sci. Sports* **2022**, *32* (1), 165–176. https://doi.org/10.1111/sms.14059.

107. Materne, O.; Chamari, K.; Farooq, A.; Weir, A.; Hölmich, P.; Bahr, R.; Greig, M.; McNaughton, L. R. Association of Skeletal Maturity and Injury Risk in Elite Youth Soccer Players: A 4-Season Prospective Study With Survival Analysis. *Orthop. J. Sport. Med.* **2021**, *9* (3), 1–11. https://doi.org/10.1177/2325967121999113.

108. Roche, A. F.; Davila, G. H. Late Adolescent Growth in Stature. *Pediatrics* **1972**, *50* (6), 874–880.

109. Van Der Sluis, A.; Elferink-Gemser, M. T.; Coelho-E-Silva, M. J.; Nijboer, J. A.; Brink, M. S.; Visscher, C. Sport Injuries Aligned to Peak Height Velocity in Talented Pubertal Soccer Players. *Int. J. Sports Med.* **2014**, *35* (4), 351–355. https://doi.org/10.1055/s-0033-1349874.

110. Bahr, R.; Clarsen, B.; Ekstrand, J. Why We Should Focus on the Burden of Injuries and Illnesses, Not Just Their Incidence. *Br. J. Sports Med.* **2018**, *52* (16), 1018–1021. https://doi.org/10.1136/bjsports-2017-098160.

111. Van Der Sluis, A.; Elferink-Gemser, M. T.; Brink, M. S.; Visscher, C. Importance of Peak Height Velocity Timing in Terms of Injuries in Talented Soccer Players. *Int. J. Sports Med.* **2015**, *36* (4), 327–332. https://doi.org/10.1055/s-0034-1385879.

112. Le Gall, F.; Carling, C.; Reilly, T. Biological Maturity and Injury in Elite Youth Football. *Scand. J. Med. Sci. Sport.* **2007**, *17* (5), 564–572. https://doi.org/10.1111/j.1600-0838.2006.00594.x.

113. Johnson, A.; Doherty, P. J.; Freemont, A. Investigation of Growth, Development,

and Factors Associated with Injury in Elite Schoolboy Footballers: Prospective Study. *BMJ* **2009**, *338*, 1–4. https://doi.org/10.1136/bmj.b490.

114. Roche, AF., Chumlea, WC., Thissen, D. *Assessing the Skeletal Maturity of the Hand-Wrist: Fels Method*; Springfield: CC Thomas, 1988.

115. Malina, R. M.; Chamorro, M.; Serratosa, L.; Morate, F. TW3 and Fels Skeletal Ages in Elite Youth Soccer Players. *Ann. Hum. Biol.* **2007**, *34* (2), 265–272. https://doi.org/10.1080/03014460701207601.

116. Kucera, K. L.; Marshall, S. W.; Kirkendall, D. T.; Marchak, P. M.; Garrett, W. E. Injury History as a Risk Factor for Incident Injury in Youth Soccer. *Br. J. Sports Med.* **2005**, *39* (7), 462–466. https://doi.org/10.1136/bjsm.2004.013672.

117. Read, P. J.; Oliver, J. L.; De Ste Croix, M. B. A.; Myer, G. D.; Lloyd, R. S. Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players. *Sport. Med.* **2016**, *46* (8), 1059–1066. https://doi.org/10.1007/s40279-016-0479-z.

118. Renshaw, A.; Goodwin, P. C. Injury Incidence in a Premier League Youth Soccer Academy Using the Consensus Statement: A Prospective Cohort Study. *BMJ Open Sport Exerc. Med.* **2016**, *2* (1), 1–6. https://doi.org/10.1136/bmjsem-2016-000132.

119. Calleja-González, J.; Mielgo-Ayuso, J.; Miguel-Ortega, Á.; Marqués-Jiménez, D.; Del Valle, M.; Ostojic, S. M.; Sampaio, J.; Terrados, N.; Refoyo, I. Post-Exercise Recovery Methods Focus on Young Soccer Players: A Systematic Review. *Front. Physiol.* **2021**, *12*, 1–12. https://doi.org/10.3389/fphys.2021.505149.

120. Brink, M. S.; Visscher, C.; Arends, S.; Zwerver, J.; Post, W. J.; Lemmink, K. A. P. M. Monitoring Stress and Recovery: New Insights for the Prevention of Injuries and Illnesses in Elite Youth Soccer Players. *Br. J. Sports Med.* **2010**, *44* (11), 809–815. https://doi.org/10.1136/bjsm.2009.069476.

121. Kallus, W.; Kellmann, M. *The Recovery-Stress Questionnaires: User Anual*; Champaign, Illinois, USA: Human Kinetics, 2001.

122. Raya-González, J.; Nakamura, F. Y.; Castillo, D.; Yanci, J.; Fanchini, M. Determining the Relationship between Internal Load Markers and Noncontact Injuries in Young Elite Soccer Players. *Int. J. Sports Physiol. Perform.* **2019**, *14* (4), 421–425. https://doi.org/10.1123/ijspp.2018-0466.

123. Bowen, L.; Gross, A. S.; Gimpel, M.; Li, F. X. Accumulated Workloads and the

Acute: Chronic Workload Ratio Relate to Injury Risk in Elite Youth Football Players. *Br. J. Sports Med.* **2017**, *51* (5), 452–459. https://doi.org/10.1136/bjsports-2015-095820.

124. Hulin, B. T.; Gabbett, T. J.; Blanch, P.; Chapman, P.; Bailey, D.; Orchard, J. W. Spikes in Acute Workload Are Associated with Increased Injury Risk in Elite Cricket Fast Bowlers. *Br. J. Sports Med.* **2014**, *48* (8), 708–712. https://doi.org/10.1136/bjsports-2013-092524.

125. Hulin, B. T.; Gabbett, T. J.; Lawson, D. W.; Caputi, P.; Sampson, J. A. The Acute: Chronic Workload Ratio Predicts Injury: High Chronic Workload May Decrease Injury Risk in Elite Rugby League Players. *Br. J. Sports Med.* **2016**, *50* (4), 231–236. https://doi.org/10.1136/bjsports-2015-094817.

126. Calvert, T. W.; Banister, E. W.; Savage, M. V.; Bach, T. A Systems Model of Training for Athletic Performance. *Aust J Sport. Med* **1976**, *SMC-6* (2), 94–102.

127. Bacon, C. S.; Mauger, A. R. Prediction of Overuse Injuries in Professional U18-U21 Footballers Using Metrics of Training Distance and Intensity. *J. Strength Cond. Res.* **2017**, *31* (11), 3067–3076. https://doi.org/10.1519/JSC.0000000000001744.

128. Bell, D. R.; Lang, P. J.; Valovich McLeod, T. C.; McCaffrey, K. A.; Zaslow, T. L.; McKay, S. D. Sport Specialization Is Associated With Injury History in Youth Soccer Athletes. *Athl. Train. Sport. Heal. Care* **2018**, *10* (6), 241–246. https://doi.org/10.3928/19425864-20180813-01.

129. Zoellner, A.; Whatman, C.; Sheerin, K.; Read, P. Prevalence of Sport Specialisation and Association with Injury History in Youth Football. *Phys. Ther. Sport* **2022**, *58*, 160–166. https://doi.org/10.1016/j.ptsp.2022.10.013.

130. Rössler, R.; Junge, A.; Jiri Chomiak; Němec, K.; Dvorak, J.; Lichtenstein, E.; Faude, O. Risk Factors for Football Injuries in Young Players Aged 7 to 12 Years. *Scand. J. Med. Sci. Sports* **2018**, *28* (3), 1176–1182. https://doi.org/10.1111/sms.12981.

131. McBurnie, A. J.; Dos'santos, T.; Johnson, D.; Leng, E. Training Management of the Elite Adolescent Soccer Player throughout Maturation. *Sports* **2021**, *9* (12), 1–21. https://doi.org/10.3390/sports9120170.

132. Sanders, J. O.; Qiu, X.; Lu, X.; Duren, D. L.; Liu, R. W.; Dang, D.; Menendez, M. E.; Hans, S. D.; Weber, D. R.; Cooperman, D. R. The Uniform Pattern of Growth and Skeletal Maturation during the Human Adolescent Growth Spurt. *Sci. Rep.* **2017**, *7* (1), 1–9. https://doi.org/10.1038/s41598-017-16996-w.

133. Gabbett, T. J.; Ullah, S. Relationship Between Running Loads and Soft-Tissue Injury in Elite Team Sport Athletes. *J. Strength Cond. Res.* **2012**, *26* (4), 953–960. https://doi.org/10.1519/JSC.0b013e3182302023.

134. Arazi, H.; Asadi, A.; Khalkhali, F.; Boullosa, D.; Hackney, A. C.; Granacher, U.; Zouhal, H. Association Between the Acute to Chronic Workload Ratio and Injury Occurrence in Young Male Team Soccer Players: A Preliminary Study. *Front. Physiol.* **2020**, *11*, 608. https://doi.org/10.3389/fphys.2020.00608.

135. Williams, S.; West, S.; Cross, M. J.; Stokes, K. A. Better Way to Determine the Acute:Chronic Workload Ratio? *Br. J. Sports Med.* **2017**, *51* (3), 209–210. https://doi.org/10.1136/bjsports-2016-096589.

136. Borresen, J.; Lambert, M. I. Changes in Heart Rate Recovery in Response to Acute Changes in Training Load. *Eur. J. Appl. Physiol.* **2007**, *101* (4), 503–511. https://doi.org/10.1007/s00421-007-0516-6.

137. Torres-Ronda, L.; Beanland, E.; Whitehead, S.; Sweeting, A.; Clubb, J. Tracking Systems in Team Sports: A Narrative Review of Applications of the Data and Sport Specific Analysis. *Sport. Med. - Open* **2022**, *8* (1), 1–22. https://doi.org/10.1186/s40798-022-00408-z.

138. O'Brien, J.; Finch, C. F.; Pruna, R.; McCall, A. A New Model for Injury Prevention in Team Sports: The Team-Sport Injury Prevention (TIP) Cycle. *Sci. Med. Footb.* **2019**, *3* (1), 77–80. https://doi.org/10.1080/24733938.2018.1512752.

139. Donaldson, A.; Lloyd, D. G.; Gabbe, B. J.; Cook, J.; Finch, C. F. We Have the Programme, What next? Planning the Implementation of an Injury Prevention Programme. *Inj. Prev.* **2017**, *23* (4), 273–280. https://doi.org/10.1136/injuryprev-2015-041737.

140. Johnson, D.; Williams, S.; Bekker, S.; Bradley, B.; Cumming, S. English Academy Football Practitioners' Perceptions of Training Load, Maturation and Injury Risk: A Club Case Study. *Int. J. Sports Sci. Coach.* **2024**, *19* (1), 417–428. https://doi.org/10.1177/17479541231188071.

Chapter 2

STUDY II

Impact of Biological Maturation on Physical Tests Performance in Portuguese Elite Male Academy Soccer Players

Biology of Sport

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Impact of Biological Maturation on Physical Tests Performance in Portuguese Elite Male Academy Soccer Players

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1. Abstract

Aims: Soccer academies serve as pivotal platforms for identifying and nurturing promising young talent, which is crucial for achieving success at the professional level. This study investigated the impact of biological maturation on the physical performance of U-14 to U-17 highly talented young male soccer players. By employing a myriad of tests, including evaluations of somatic maturation, this study sought to elucidate how maturity status impacts various facets of physical performance tests, such as sprinting ability, jumping height, and aerobic capacity.

Methods: A total of 67 male soccer players from a professional academy in Portugal participated in the study, which spanned two consecutive sports seasons (2021-22 and 2022-23). Physical performance and maturation assessments were conducted at six time points, with three evaluations per season spaced three months apart. Players were divided into two groups based on their biological maturation status: Pre- and circa-peak height velocity (PHV), and post-PHV. Owing to the small sample size in the pre-PHV group (n=4), these players were combined with the circa-PHV group for analysis. Key physical qualities were measured and biological maturity was assessed using the predicted adult height percentage.

Result: Mixed-effects linear models revealed that chronological age significantly influenced the physical performance of young soccer players. Older players showed better COD speed ($p < 0.001$) and sprint performance ($p < 0.001$), with maturity status having no additional effects. In contrast, maturity status significantly interacted with age in the jumping height test ($p = 0.001$), with post-PHV players showing greater improvement. Both age and maturity status significantly affected endurance ($p = 0.001$) and maximal strength ($p = 0.020$), with post-PHV players experiencing greater gains on both measures.

Conclusions: This study found that both chronological age and biological maturation significantly affect the physical performance of young soccer players. Relying only on age may overlook the key developmental factors, highlighting the need for more tailored training and assessment strategies.

Keywords: Maturation, Physical performance tests, Performance indicators, Field testing, Young athletes, Long-term athletic development.

2. Introduction

Soccer academies play a critical role in identifying and developing young talent with the potential to compete at senior levels and secure professional contracts [1–3]. These academies provide essential resources, training, and guidance to help clubs cultivate promising players [4]. A key phase in this process is the selection and rejection of players, which frequently occurs between the ages of 14 and 15 [5]. At these ages, significant variations in maturity levels among players can heavily influence talent selection decisions [6–9]. Research has shown that elite youth soccer academies observe differences of five to six years between the biological and chronological ages of players [10]. Such disparities in biological maturation can lead to substantial variations in size and performance individuals [11,12]. These differences in maturity status profoundly affect physical qualities crucial for soccer performance, including strength, power, speed, agility, and endurance [6–9,13]. Therefore, accurate assessment of players' biological age is paramount given the potential discrepancies between their chronological and biological ages [14–16].

Physical quality refers to the abilities an individual possesses or develops, allowing them to participate in physical activities [17]. Assessments of fitness components, such as strength, power, endurance, and speed, are considered measures of physical quality [18]. The most frequently examined physical qualities in soccer are cardiorespiratory fitness, muscular power, maximal strength, movement speed, agility, balance, and body composition [19]. While evaluating these qualities is essential, it is equally important to understand their relationship with maturation status [20,21], as this can influence talent identification and performance optimization [2]. On the other hand, biological maturation, distinct from simple growth, is a complex and ongoing process that begins at conception and culminates in adulthood [5,9,22]. It varies widely between individuals in terms of timing, tempo, and sequence of developmental events [5,22]. Maturity status represents an individual's level of maturation at a given time, whereas the timing and tempo of maturation refer to the occurrence and rate of specific developmental milestones, respectively [15]. Consequently, consistent monitoring and evaluation of growth and maturation are critical to understanding their effects on player development. However, evaluating biological maturation is challenging because of the need for specific indicators for each biological system and different definitions of maturation across systems [23]. Skeletal maturation is widely regarded as the most accurate and reliable measure of biological maturation, aiding in the understanding of players' developmental trajectories [14]. Soccer academies often use somatic equations derived from anthropometric measurements to estimate age at peak height velocity (PHV) and predict adult height [24]. Despite the utility of these methods, there are concerns about discrepancies between predicted and actual chronological age at PHV, particularly for boys far from their PHV [25,26]. The Khamis-Roche method, which utilizes reference data from the Fels Longitudinal Study [27], is used to forecast adult height and categorize youth into bands based on the percentage of predicted adult height (PAH), such as ≥

85.0% and < 90.0% or ≥ 90.0% and < 95.0% [15,28,29]. These bands are intended to capture the adolescent growth spurt, but can be adjusted as needed, with adult height reference values set for age 18 [15,28]. Despite some expected errors (approximately 2%) in anthropometric measurements, the Khamis-Roche method has shown promise for evaluating somatic maturation, aligning with the error values reported in previous studies [29,30].

Longitudinal studies that track the evolution of physical qualities over two or more athletic seasons are particularly valuable from a long-term athlete development (LTAD) perspective. These studies allowed for the observation of developmental progression by consistently monitoring the same group of athletes (pre-PHV/PHV vs. post-PHV) throughout the intervention period. Therefore, this study aimed to investigate the influence of biological maturation on physical performance in young male soccer players. Specifically, it involves a longitudinal examination of physical qualities over two consecutive soccer seasons, focusing on U14 and U17 players in a high-level soccer academy. The primary objective is to assess the impact of biological maturation on physical performance, with secondary objectives focused on establishing reference values for various physical performance tests. These findings may assist stakeholders in identifying physical performance tests that are most influenced by biological maturation.

3. Materials and Methods

3.1. Experimental Approach to the Problem

This study utilized a longitudinal approach involving repeated measurements of the same entities. In this study, sixty-seven young male soccer players from a professional soccer academy in Portugal were enrolled. This study aimed to investigate various aspects of development, maturation, and a range of physical qualities, including muscular strength, change of direction, linear speed, and aerobic capacity. The assessment of biological maturity and physical qualities took place during the initial evaluation of the 2021-22 season, starting in the first week of training and concluding in the first week of May 2023 (Table 1). The research involved six assessment points spanning the 2021-22 and 2022-23 sports seasons, with three evaluations carried out per season, each three months apart (Table 1). Players were categorized into two groups based on their biological maturation status (Khamis-Roche method) [130]: Group 1 comprised athletes in the pre-and circa-PHV periods (<95.0% PAH), whereas Group 2 consisted of athletes in the post-PHV period (≥95.0% PAH). Owing to the limited number of players during the pre-PHV period (n=4), the analysis was conducted by combining the pre-PHV and PHV classification groups.

Table 1 - Assessment during the two sports seasons.

Season	**2021-22**			**2022-23**		
Year	**2021**	**2022**	**2022**	**2022**	**2023**	**2023**
Month	August	January	May	August	January	May
Week	1st	1st	1st	1st	1st	1st
Assessment Number	1st	2nd	3rd	4th	5th	6th

3.2. Subjects

Sixty-seven young male soccer players born between 2002 and 2007 from a professional soccer academy in Portugal were assessed. Players had an average age of 15.1 years (±1.1 years), with ages ranging from 12.0 to 18.1 years, mean height was 174.9 cm (±8.0 cm), and their average body mass was 64.1 kg (±8.5 kg) (Table 2). Participants were from the U14, U15, U16, and U17 age groups, and this evaluation marked the first assessment of the 2020-21 season. All players participated in the study with no dropouts or missing data during the assessment period. The inclusion criteria were as follows: (1) at least three years of experience playing soccer, (2) registered in the present academy/club for at least two seasons, and (3) did not use any supplement that could affect growth and maturation. The exclusion criteria were as follows: (1) players injured during the off-season period and (2) players who did not participate in the medical study. Players had an average training/match experience of 5.5 ± 1.1 years at the national, and international levels. Before beginning the investigation, the Ethics Committee of the Faculty of Physical Education and Sports at the University of Lusófona granted sanctions. The purpose of the study, research procedures, requirements, benefits, and hazards were communicated to the parents/custodians of the participants, who then provided written informed consent. The study adhered to the ethical standards of the Helsinki Declaration for human subject research.

Table 2 - Anthropometric, Body Composition and Maturity characteristics from under-14 to under-17.

Assessment	N	Chronological Age (y)	Height (cm)	Leg Length (cm)	Body Mass (kg)	Body Mass Index (BMI)	Σ 8 skinfolds (mm)	% Predicted Adult Height (%)
1	67	14.3 ± 0.93	172.0 ± 8.53	84.0 ± 4.28	59.6 ± 8.88	20.0 ± 1.73	49.9 ± 9.61	94.7 ± 3.17
2	67	14.7 ± 0.91	173.6 ± 8.08	84.5 ± 4.18	62.1 ± 8.57	20.5 ± 1.70	51.0 ± 8.53	95.9 ± 2.81
3	67	14.9 ± 0.94	174.4 ± 7.93	84.8 ± 4.34	63.1 ± 8.26	20.7 ± 1.73	51.9 ± 8.64	96.5 ± 2.68
4	67	15.3 ± 0.93	175.9 ± 7.58	85.2 ± 4.19	64.9 ± 7.86	20.9 ± 1.65	51.1 ± 7.25	97.3 ± 2.32
5	67	15.6 ± 0.93	176.4 ± 7.42	85.5 ± 4.19	66.7 ± 7.43	21.4 ± 1.56	51.2 ± 7.76	98.0 ± 2.02
6	67	15.9 ± 0.91	177.1 ± 7.32	85.7 ± 4.29	67.9 ± 7.29	21.6 ± 1.51	53.9 ± 10.10	98.5 ± 1.81

3.3. Procedures

The following sequence was consistently used throughout all assessments: (1) Anthropometry and Body Composition; (2) Countermovement Jump (CMJ); (3) Isometric Mid-Thigh Pull (IMTP); (4) Change of Direction Ability ("L-Test"); (5) Sprint Test (30 meters) and (6) aerobic fitness test, 1200 m shuttle run test (also refered to as The Bronco Test). It is essential to highlight that all athletes were familiar with all the physical tests. A comprehensive overview of these examinations was provided. Controlling for learning effects is of utmost importance, particularly for assessments that involve complex technical requirements. Tests were carried out over a week on different days and each day of the microcycle. Therefore, 24 h was provided between physical performance assessments. This sequence was planned from the least physically demanding test to the most physically demanding test in an attempt to minimize the potential fatigue impact of a test on subsequent assessments. Before each physical performance test, general and specific warm-up was performed, both involving body movements, such as those involved in the physical performance test, to increase the reliability of the physical performance tests [31]. As a general warm-up, all players completed 10 min of light jogging, followed by 5 min of dynamic stretching, including lunges, diver stretching, and lateral squats, and 5 min of moderate to high-intensity movements, such as high knees, butt kicks, cariocas, accelerations, decelerations, straight-line sprints, and changes in direction. For the Bronco test, players completed a standardized warm-up procedure consisting of 3 minutes of interspersed submaximal activity (jogging) and later combined with dynamic stretching and one practice lap of each respective test at approximately 50% of maximal effort [32]. In the remaining physical performance tests, the players performed two warm-up repetitions in each test, seeking to direct the warm-up's specificity toward the test's objective. For physical performance tests (2), (3), (4), (5), and (6), three attempts were made, considering the best results of the three attempts. Between each attempt, a three-minute rest interval was considered. When performing all physical performance tests, players had consistent verbal encouragement to produce maximal effort [33] for all tests provided by the strength and conditioning coaches.

Anthropometry and Body Composition. This evaluation was conducted by an experienced Level I ISAK-certified technician who performed anthropometric measurements (body mass, standing height, and sitting height) following the guidelines of the International Society for the Advancement of Kinanthropometry [34]. During all assessments, the following instructions were provided: (1) consumption of the usual evening meal the night before the test, according to their individual nutritional habits; (2) empty their bladders before arriving at the assessment site; (3) wearing soccer uniforms with their shoes removed; and (4) remain throughout. Height, seated height, and body mass were measured using instruments accurate to within 0.1 cm and 0.1 kg, respectively, and the arithmetic mean of the measurements was calculated. Height was measured with an anthropometer (SECA 206) to an accuracy of 0.1 cm, and weight was measured with an electronic scale (TANITA BC-601) to an accuracy of 0.1 kg. The inter- and intra-observer technical error of measurement for standing and seated height was 5%, whereas for weight, it was less than 5%. Body Mass Index (BMI) (kg/m2) was calculated using BM/HT2. An ISAK-certified technician conducted measurements of eight skinfold sites (triceps, subscapular, biceps, suprailiac, abdominal, supraspinal, thigh, and calf) using a Harpenden skinfold caliper (British Indicators, Ltd., London, UK). Each site was measured twice, with a precision of 0.1 mm. Double anthropometric measurements were obtained for each site, and the mean of the two measurements was used to compute the eight skinfolds (8SKF). A 5% intra-observer measurement error was considered acceptable for SKF; otherwise, a third measurement was performed.

Microcycle Structure. Players aged 14–17 years had a weekly training schedule during the competitive season that included one match designed by a match day (MD), followed by a day off (MD+1/-6), and a regeneration session (MD+2/-5). The training sessions leading up to the match were structured as follows: MD+3/-4, emphasized through positional drills and small-sided games. MD+4/-3 concentrated on tactical preparation for the upcoming match, featuring moderate-intensity positional exercises. MD+5/-2 incorporated activation drills that mimicked certain technical and tactical aspects, concluding with practice on set pieces. MD+6/-1 was the day off for all squads. Training sessions included physical, technical, and tactical components. The microcycle or weekly training schedule may be modified based on any developments on the day of the match. Young soccer players participated in four 90-minute training sessions weekly, with matches typically held on weekends. Matches for U14-U15 lasted 80 minutes, while those for U16-U17 lasted 90 minutes and were conducted on outdoor artificial turf fields with 11 players per side. The players in the academy participated in an average of 12 hours of combined training per week, which included four to five sessions of soccer, strength and power exercises (one to two sessions), speed and change-of-direction training (one to two sessions) drills, along with one competitive match per week.

Playing Position. In total, 67 highly young male players were categorized as goalkeepers (n = 7), central center-back players (n = 11), winger-back players (n = 10), central midfielders (n = 19), wingers (n = 13), or forwards (n = 7). While it is acknowledged that young soccer players between the ages of 12 and 18 may adopt various positions [35], the criterion for defining the position of each player was the highest volume of sessions in that position.

Biological Maturation. The Khamis-Roche method was used to define the biological maturation of each player, the Khamis-Roche method was used (pre-, circa-, and post-PHV) [29]. The percentage of observed adult height was used to indicate maturity status [5,9,15]. Height, body mass, chronological age, and average parent height were used to predict the adult height of each player and ascertain their biological maturity [29]. The heights of the biological parents of each player were self-reported and adjusted for over-estimation using the equations in Epstein, Valenki, Kalarchian, and McCurley (1995) [36]. Using the Khamis-Roche method, it is possible to predict the final adult height of men between 4.0 and 17.5 years old, considering a median error associated with the use of the 2.2 cm method, that is, an average error that can vary between 0.8 and 2.8 cm [29]. As indicated earlier, players were divided into three groups according to their maturity status using the percentage of their PAH. Thus, circa-PHVs accounted for 88–95% of the expected adult stature. Subsequently, pre-PHV was <88% and post-PHV was >95% [15,22,37]. Two groups were considered based on biological maturation (maturity status) for data analysis. Group 1 comprised young soccer players with a predicted adult height percentage of up to 95% (<95.0% PAH), and Group 2 comprised players with a predicted adult height percentage of ≥ 95% (≥95.0% PAH). The composition of each group was adjusted during the assessment period. Regarding the sample distribution between the two groups (pre-PHV/PHV and post-PHV), at the first evaluation, group 1 consisted of 32 players and group 2 consisted of 35 players.

Countermovement Jump Test. The CMJ tests were conducted immediately after the IMTP test. The players freely chose the countermovement speed and depth (velocity and depth were self-selected), maintaining an erect stance with hands placed on the hips. They were instructed to exert maximum effort to achieve the greatest possible vertical jump height [38,39]. Each participant completed three separate repetitions of the jump, with a one-minute rest interval between each attempt [40]. It has been reported that this protocol is a valid and reliable evaluation of neuromuscular performance in adolescents with an intraclass correlation coefficient (ICC) of 0.83 [41]. A contact platform (Chronopic®, Chronojump Boscosystem, Barcelona, Spain) was used to measure jump height, and specialized software was used to determine the height achieved [42]. The highest recorded jump in centimeters was selected for further analysis.

IMTP Test. The IMTP test was conducted with the athlete stooding on a 1000 Hz force platform (Pasco, Rosedale, USA; data analyzed using NMP ForceDecks, London, UK) with a fixed, immovable bar at mid-thigh height. The body position should closely resemble the second pull of the clean and clean grip mid-thigh pull, with the trunk upright, knee flexion, shoulder girdle retracted, shoulders above or slightly behind the vertical plane, feet centered under the barbell, knees under and in front of the barbell, and thighs in contact with the barbell. Specifically, the knee (125–145º) and hip (140–150º) joint angles [197,198]**.** The IMPT test evaluation procedure involved athletes performing a standard warm-up with specific components, including 3 seconds each of 50% maximal, 75% maximal, and 90% maximal exertion, with a 60 seconds pause between sets [199]. The athlete repeated the test in three sets with a 60-second break between each set, as in the warm-up. The athlete repeated the test three times with a 60-second break between each repetition, as in the warm-up. Players were directed to exert maximum effort for a duration of 3 seconds until signaled to stop. The peak force was determined by identifying the highest force value recorded on the force-time graph during the 3-second IMTP assessment. A countdown of “3, 2, 1, PULL!” provides the athlete with sufficient time to prepare for maximal effort [199,200]. All measurements were recorded in newtons (N), with the best repetition of the three trials recorded. Relative force was measured by dividing the net peak force (peak force – body mass) in N by the player’s body mass in kg.

Change of Direction Ability. The "L-Test" assessment was conducted on an artificial field following a previously established protocol to measure speed and directional change ability. This protocol adhered to the original method [47], which was used in subsequent studies [48,49]. An "L"-shaped configuration was created using three cones, each 5m long and 5m wide. Players navigated around the first cone towards the second cone, with the option to curve around either side before returning to the starting point. A photocell (Witty Gate, Microgate, Italy) was set up 1 m above ground and 2 m from the receiver. Players began in an "athletic stance" with their front foot 0.30 meters behind the initial photocell. The test required three repetitions with a two-minute rest period between attempts. All subjects were instructed to perform the test three times on each side, maintaining a two-minute interval between trials. The final "L-Run" score was determined by selecting the fastest time out of three attempts, recorded to the nearest 0.01 seconds.

Sprint Test. Sprinting times were assessed over 30 meters using two photocells (Witty Gate, Microgate, Italy). The test was conducted in an interior synthetic field, with photoelectric cells mounted at 1 m on a tripod. The photocells were positioned 0 and 30 m from the center of the tripod, where the photoelectric cells were affixed. The photoelectric cell was positioned 1.5 meters away from the receiver. The player's front foot must be 0.30 meters behind the first photoelectric cell when in an "athletic position," and no countermovement was permitted. Throughout each trial, the participants were verbally encouraged. Between the three trials, a minimum of four minutes of passive recovery was provided [50]. The best time out of the three trials was recorded for each player at 30 meters. The sprint score was based on the fastest recorded three times to the nearest 0.01 second.

Maximal Aerobic Speed Test. To evaluate the lowest running speed at which VO2max occurs, which is commonly denoted as the "velocity at VO2max," each player conducted a 1200 m shuttle run test (also refered to as The Bronco Test). The players began the assessment at the start line, sprinting 20 m forward before returning to the initial position. They then proceeded to cover a distance of 40 m, returning to the starting point. Finally, the athletes completed a 60-meter run, once they returned to the baseline. (i.e., 20 m and back, 40 m and back, 60 m and back) [51]. This sequence was repeated five times at maximal effort, resulting in a total distance of 1200 m. It was ensured that participants fully crossed or touched each line. Throughout the test, the players were instructed to maintain maximal running intensity to optimize performance outcomes. Players were acquainted with the test before taking it, increasing their tempo precision during the examination [51,52]. The total time to complete the test was recorded, and the maximal aerobic speed (MAS) score was calculated by dividing the distance by the recorded time. The time recorded for each player was corrected using the equation MAS = 1200 / (time in seconds – 20.3) [53,54].

3.4. Statistical Analysis

Initial zero-order Pearson correlations were conducted to inspect the potential overlap between the performance metrics. The correlations ranged from 0.19 to 0.61, indicating moderate relationships and suggesting that each test retains some level of independent properties relevant to short-term performance. Descriptive statistics for all performance measures are reported as the mean ± standard deviation. To examine changes in performance metrics power [CMJ Test], Maximal Strength [IMTP Test]), Change of Direction (COD) [L-Test], sprint ability [30-m Test], and Maximal Aerobic Speed Test [Bronco Test] as a function of chronological age and maturity status (pre- and circa-PHV players were coded as 0, and post-PHV players were coded as 1), a two-level growth model was employed. At Level 1, each athlete's successive measurements over time were modeled to capture individual changes at each time point, accounting for random errors. These individual changes were expressed as centered values (grand-mean centering) to improve interpretability and reduce multicollinearity. At Level 2, differences in growth trajectories between groups defined by maturity status were examined. To make inferences regarding the true (population) values of the effects of age and maturity status on physical performance, the 95% confidence limit (CI) for each effect was also calculated.

Mixed-effects linear models were used to investigate the impact of chronological age and maturity status on performance. We constructed three models for each dependent variable: (1) chronological age as the only fixed effect; (2) age and maturity status as fixed effects; and (3) age, maturity status, and their interaction as fixed effects. Player ID was included as a random effect in all models to account for repeated measures within subjects. The residuals from each model were assessed for normality using histograms and QQ plots, and homoscedasticity was evaluated using residual plots. Multicollinearity among predictors was checked using Variance Inflation Factors (VIFs). Model fit was compared using log-likelihood values and the Akaike Information Criterion (AIC). Statistical analyses were performed using the Statistical Package for the Social Sciences, version 28.0 (SPSS Inc., Chicago, IL, USA). The threshold for statistical significance was set at $p < 0.05$.

4. Results

The correlations ranged from 0.19 to 0.61, indicating moderate relationships and suggesting that each test retains some level of independent properties relevant to short-term performance. The results of the countermovement jump (CMJ) test highlight the importance of chronological age and maturity status. The interaction between these two variables was significant ($p = 0.001$), indicating that players' maturity status modulated the effect of age on explosive strength. Post-PHV players showed greater improvements in jumping height with age than their pre- and circa-PHV counterparts did. As measured by the IMTP test, the maximal strength also showed significant effects of age, maturity status, and their interaction ($p = 0.020$). The interaction revealed that strength gains were more substantial in post-PHV players, indicating that biological maturation enhances the rate of strength development beyond the effect of age alone. Chronological age emerged as a significant predictor of COD speed, as measured using the L-test, with older players generally exhibiting better COD speed scores ($p < 0.001$). The inclusion of maturity status and its interaction with age did not significantly improve model fit ($p = 0.420$ and $p = 0.305$, respectively). Similarly, for the 30-meter sprint test, age was the primary determinant of sprint performance, with older players running faster ($p < 0.001$). The addition of maturity status and its interaction with age did not significantly contribute to sprint performance ($p = 0.891$ and $p = 0.500$, respectively). This suggests that like change of direction capabilities, sprint ability in young soccer players is primarily influenced by age alone. Endurance performance, assessed using the Bronco test, was significantly influenced by age and maturity status, with a notable interaction between these factors ($p = 0.001$). Post-PHV players demonstrated more pronounced endurance improvement over time.

The analysis revealed that age alone could significantly explain the variance in the L-test and 30-m test, as indicated by the best fit for the model that included only age. In contrast, the best-fitting models for the CMJ, Bronco, and IMTP tests included the interaction between age and maturity status, highlighting the significant interaction effects. The detailed mixed-effects model results, including the coefficients, log-likelihood values, and fit statistics, are presented in Tables 3, 4, and 5.

Table 3 - Mixed-Effects Model Results for All Metrics.

Test	Model	Intercept (p-value)	Age (p-value)	Maturity (p-value)	Interaction (p-value)	AIC	Log-Likelihood	Random Effect Variance
L-Test	1	0.773 (0.001)	-0.511 (0.001)	-	-	-368.437	-372.437	0.025
	2	-0.870 (0.001)	-0.055 (0.001)	-0.019 (0.420)	-	-363.520	-367.520	0.025
	3	1.332 (0.007)	-0.088 (0.009)	-0.415 (0.282)	0.028 (0.305)	-359.199	-363.199	0.024
30-m Sprint	1	0.610 (0.001)	-0.040 (0.001)	-	-	-499.238	-502.238	0.040
	2	0.623 (0.001)	-0.041 (0.001)	-0.002 (0.891)	-	-493.222	-497.252	0.040
	3	0.869 (0.029)	-0.581 (0.033)	-0.212 (0.495)	0.0148 (0.500)	-487.913	-491.913	0.040
CMJ Test	1	-42.139 (0.001)	2.786 (0.001)	-	-	2175.834	2171.834	17.918
	2	-29.533 (0.001)	2.166 (0.001)	-2.636 (0.001)	-	2154.276	2150.276	18.055
	3	12.024 (0.277)	-0.738 (0.329)	-38.529 (0.001)	2.542 (0.001)	2136.997	2132.997	19.430
Bronco Test	1	163.674 (0.001)	-10.823 (0.001)	-	-	3364.837	3360.837	239.082
	2	141.510 (0.001)	-9.742 (0.001)	4.755 (0.072)	-	3357.860	3353.860	248.691
	3	-62.001 (0.223)	4.472 (0.199)	180.659 (0.001)	-12.448 (0.001)	3335.472	3331.472	272.518
IMTP Test	1	-78.024 (0.001)	5.159 (0.001)	-	-	2253.672	2249.672	18.708
	2	-73.683 (0.001)	4.949 (0.001)	-0.954 (0.142)	-	2250.575	22456.575	19.377
	3	-46.431 (0.001)	3.045 (0.001)	-24.403 (0.016)	1.660 (0.020)	2244.043	2240.043	19.741

*(1) age as the only fixed effect; (2) age and maturity status as fixed effects; and (3) age, maturity status, and their interaction as fixed effects.

Key: L-Test = Change of Direction Ability; 30-m Sprint = Sprint Test - 30 meters; CMJ Test = Countermovement Jump; Bronco Test = Maximal Aerobic Speed (vVO_{2max}); IMTP Test = Isometric Mid-Thigh Pull

Table 4 - Results of the L-Test, 30-m Sprint Test; CMJ Test, Bronco Test, and IMTP Test.

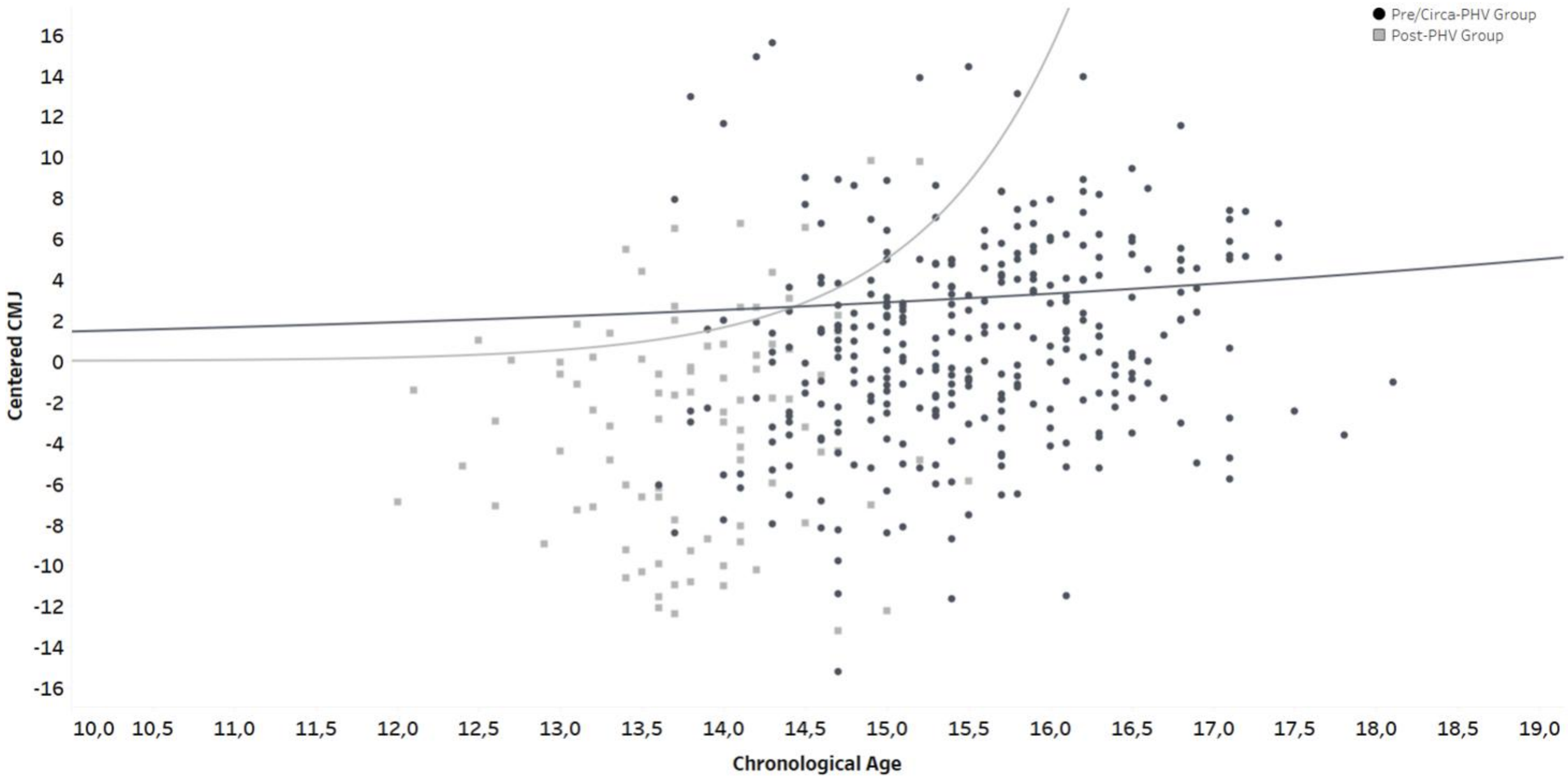
Assessment	N	L-Test (s)	30-m Sprint Test (s)	CMJ Test (cm)	Bronco Test (s)	IMTP Test (N/kg)
1	67	6.08 ± 0.23	4.61 ± 0.25	34.9 ± 5.8	310.2 ± 27.4	23.1 ± 4.3
2	67	5.97 ± 0.20	4.47 ± 0.22	36.5 ± 5.5	292.8 ± 18.2	25.4 ± 4.9
3	67	5.96 ± 0.23	4.67 ± 0.22	37.4 ± 5.4	293.3 ± 19.7	28.3 ± 4.8
4	67	5.96 ± 0.17	4.48 ± 0.21	38.3 ± 4.6	289.9 ± 15.8	30.2 ± 5.3
5	67	5.93 ± 0.18	4.49 ± 0.22	39.6 ± 3.7	287.9 ± 16.5	30.8 ± 5.1
6	67	5.97 ± 0.17	4.50 ± 0.20	40.0 ± 4.3	284.4 ± 14.4	33.0 ± 6.0

Key: L-Test = Change of Direction Ability; 30-m Sprint = Sprint Test - 30 meters; CMJ Test = Countermovement Jump; Bronco Test = Maximal Aerobic Speed (vVO_{2max}); IMTP Test = Isometric Mid-Thigh Pull

Table 5 - Results of the L-Test, 30-m Sprint Test, CMJ Test, Bronco Test, and IMTP Test Group (Pre-PHV/PHV) and Group (Post-PHV) throughout the six assessments (two sports seasons).

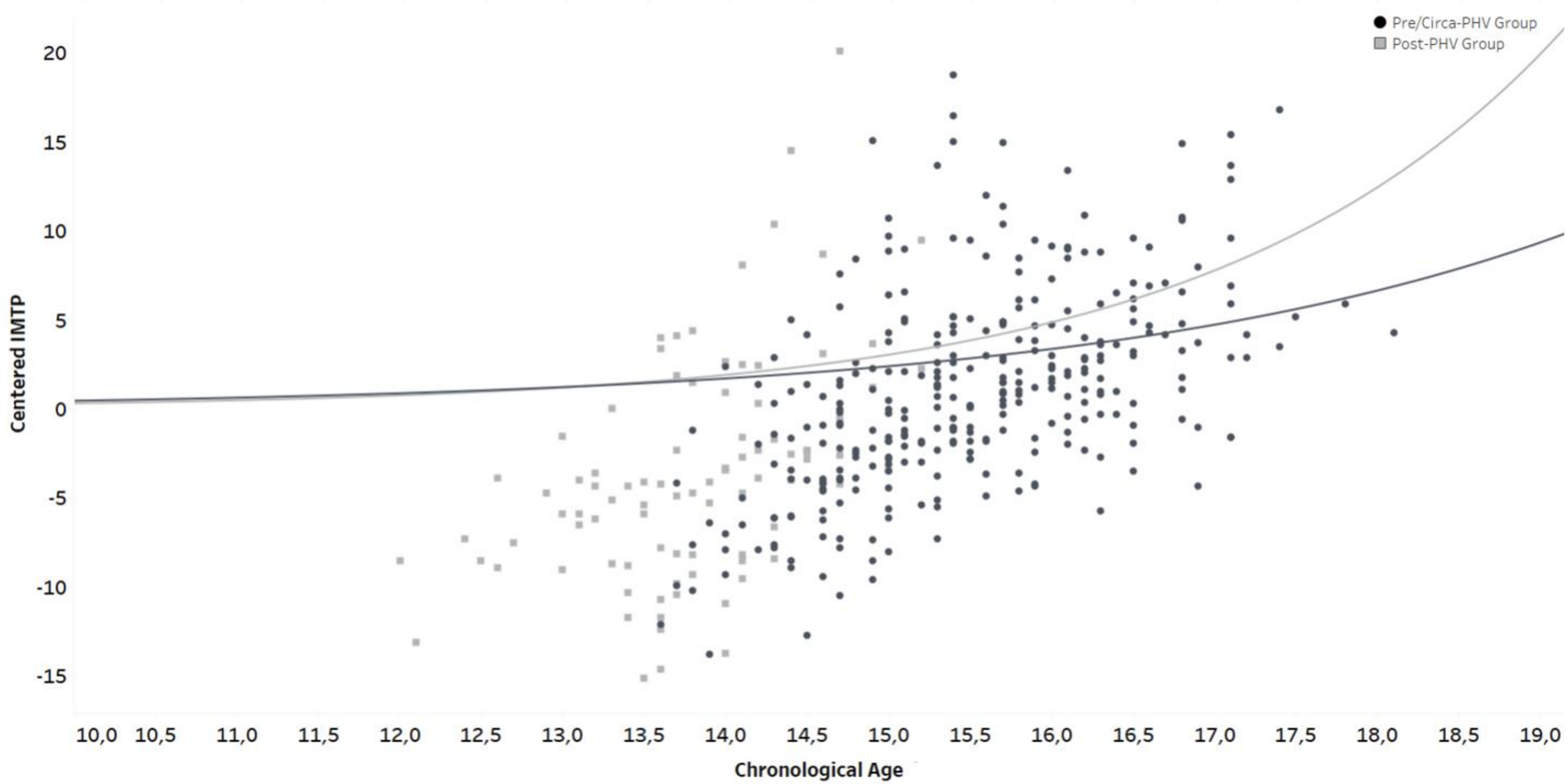
Assessment	Maturity Group	L-Test (s)	30-m Sprint Test (s)	CMJ Test (cm)	Bronco Test (s)	IMTP Test (N/kg)
1	Pre/Circa-PHV	6.04 ± 0.20	4.60 ± 0.24	32.35 ± 5.11	315.24 ± 27.44	21.40 ± 4.36
	Post-PHV	6.10 ± 0.25	4.60 ± 0.25	37.13 ± 5.56	395.51 ± 27.07	24.63 ± 3.68
2	Pre/Circa-PHV	5.97 ± 0.17	4.54 ± 0.24	33.24 ± 5.63	296.88 ± 17.52	22.80 ± 4.19
	Post-PHV	5.96 ±0.20	4.44 ± 0.19	38.10 ± 4.84	290.76 ± 18.40	26.61 ± 4.78
3	Pre/Circa-PHV	5.95 ± 0.25	4.50 ± 0.23	36.12 ± 4.25	291.53 ± 15.16	25.98 ± 4.75
	Post-PHV	5.96 ± 0.21	4.45 ± 0.22	37.77 ± 5.75	293.75 ± 20.94	28.93 ± 4.70
4	Pre/Circa-PHV	6.01 ± 0.23	4.50 ± 0.21	38.09 ± 3.72	290.76 ± 10.84	29.09 ± 4.46
	Post-PHV	5.94 ± 0.16	4.47 ± 0.20	38.34 ± 4.84	289.78 ± 16.55	30.31 ± 5.45
5	Pre/Circa-PHV	5.90 ± 0.18	4.53 ± 0.31	38.88 ± 3.42	284.36 ± 9.67	31.33 ± 7.98
	Post-PHV	5.93 ± 0.17	4.48 ± 0.20	39.62 ± 3.77	288.19 ± 17.12	30.73 ± 4.91
6	Pre/Circa-PHV	5.92 ± 0.20	4.53 ± 0.31	38.11 ± 4.05	278.83 ± 9.66	24.68± 7.47
	Post-PHV	5.97 ± 0.16	4.49 ± 0.19	40.22 ± 4.32	284.90 ± 14.82	32.80 ± 5.91

Key: L-Test = Change of Direction Ability; 30-m Sprint = Sprint Test - 30 meters; CMJ Test = Countermovement Jump; Bronco Test = Maximal Aerobic Speed (vVO_{2max}); IMTP Test = Isometric Mid-Thigh Pull; Pre-PHV = Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;



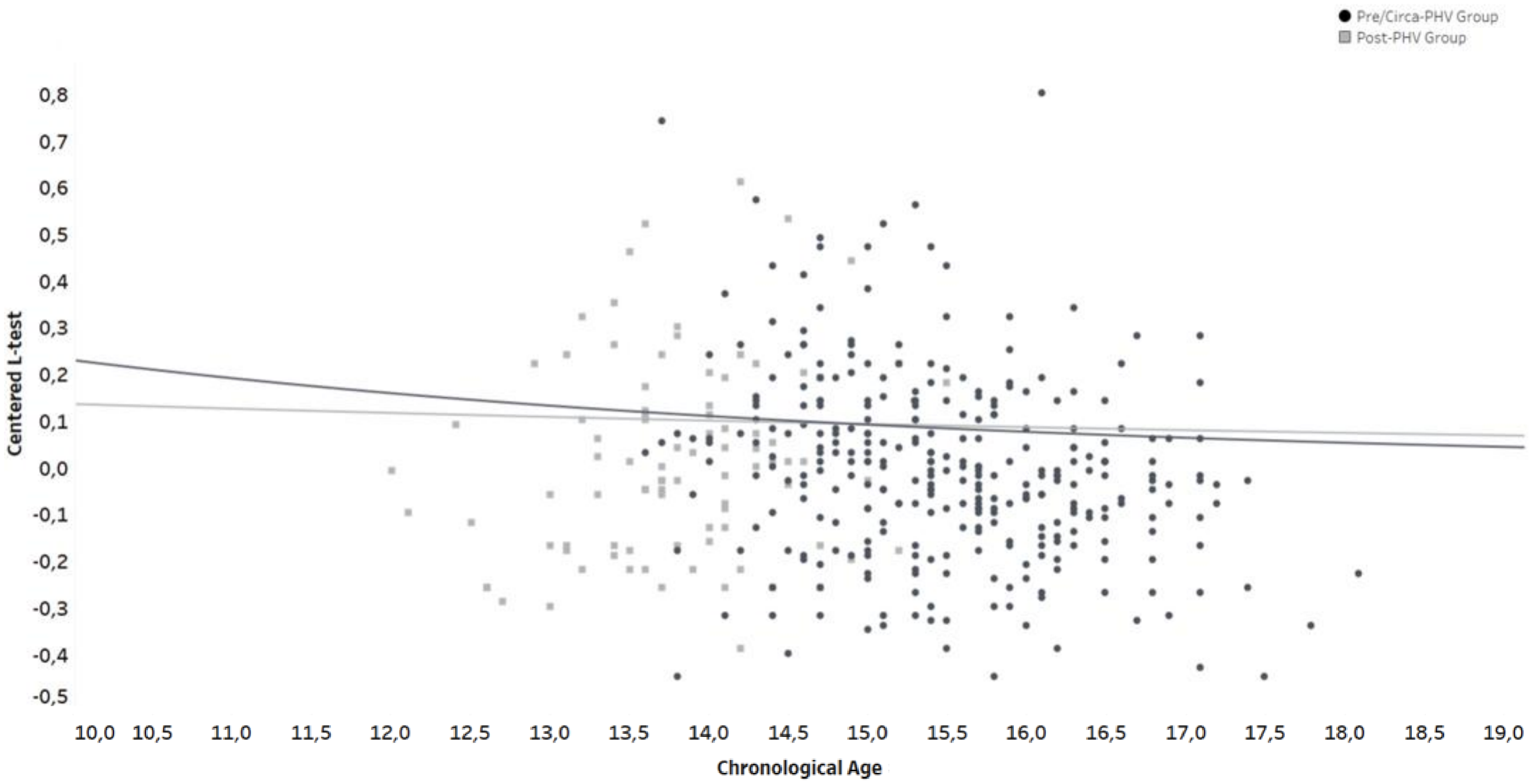
Key: CMJ Test = Countermovement Jump; Pre-PHV = Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity

Figure 1 - Representation of the CMJ in terms of chronological age evolution according to maturity status.



Key: IMTP Test = Isometric Mid-Thigh Pull; Pre-PHV = Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity

Figure 2 - Representation of the IMTP in terms of chronological age evolution according to maturity status.



Key: L Test = Change of Direction Ability; Pre-PHV = Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 3 - Representation of the L-Test in terms of chronological age evolution according to maturity status.

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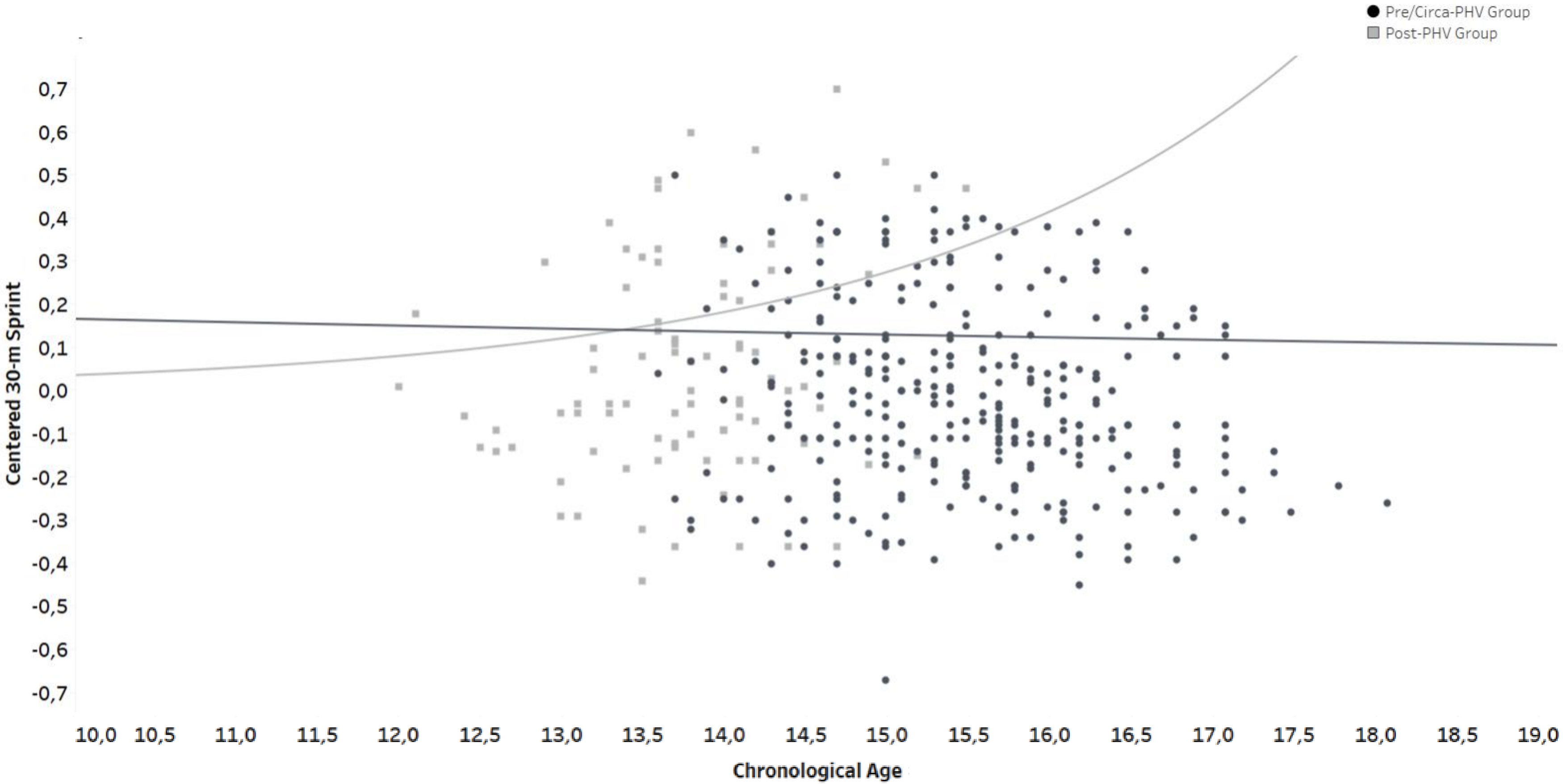

Key: 30-m Sprint = Sprint Test - 30 meters; Pre-PHV = Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 4 - Representation of the 30-m Sprint in terms of chronological age evolution according to maturity status.

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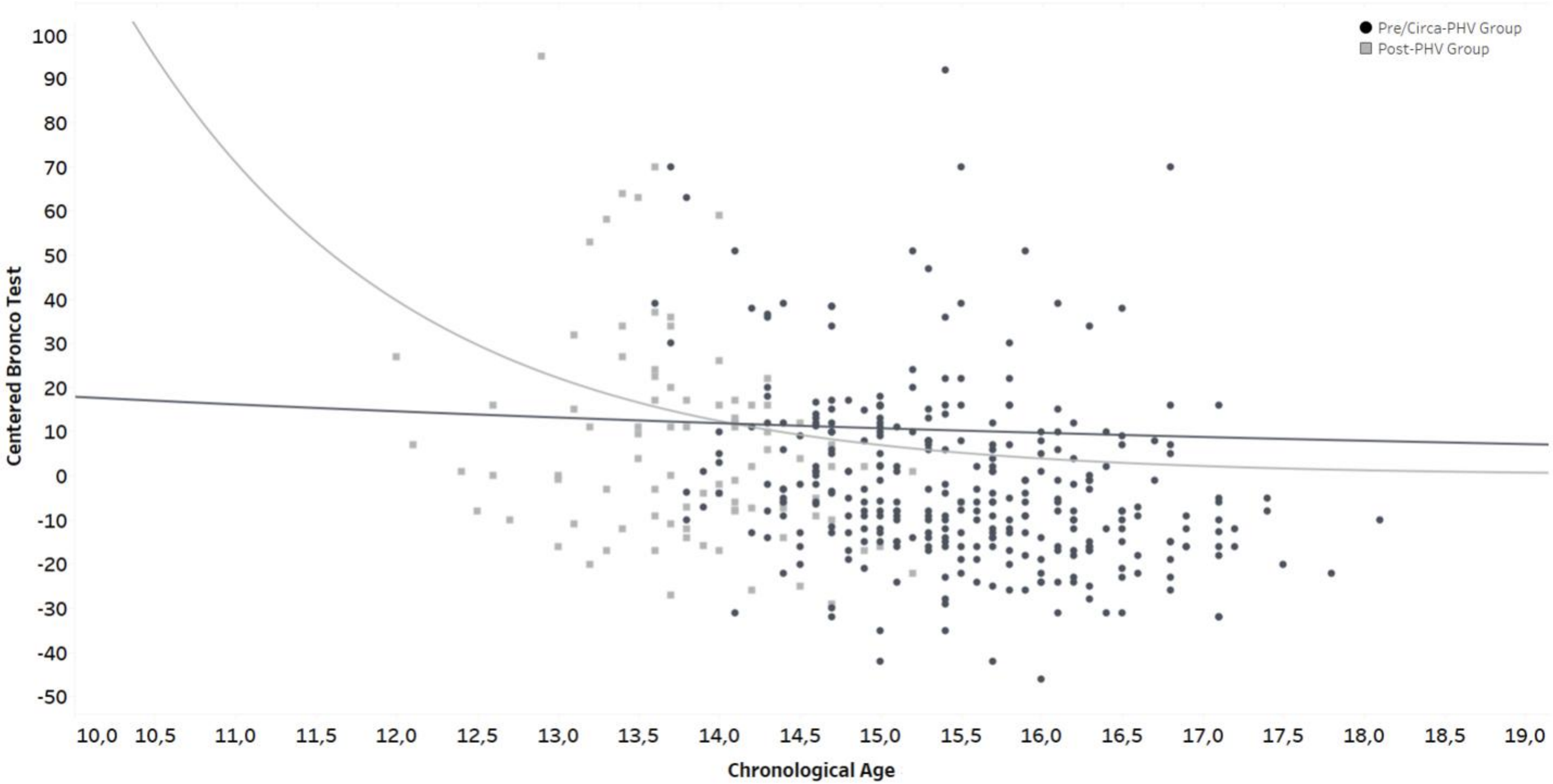

Key: Bronco Test = Maximal Aerobic Speed (vVO2max); Pre-PHV = Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 5 - Representation of the Bronco Test in terms of chronological age evolution according to maturity status.

5. Discussion

This study's primary objective was to examine biological age's influence on performance metrics, including jumping height, maximal strength, change of direction ability, sprint speed ability, and endurance across two consecutive soccer seasons. The main findings were as follows: 1) biological maturation proved crucial for performance in the jumping height test, with post-PHV players demonstrating significant improvements over time; 2) maximal strength [IMTP Test], which was directly influenced by biological maturation (maturity status), highlighting notable differences among maturation groups, particularly in post-PHV players; 3) linear and multidirectional speed showed that chronological age emerged as the primary predictor, with old-er players demonstrating superior performance in specific tests (for example, L-Test and 30-m sprint); and 4) endurance [1200 m shuttle run test], where biological maturation had a marked impact, with post-PHV players showing substantial gains over time.

Our analysis revealed a significant interaction between these two factors ($p = 0.001$), indicating that a player's maturity level modulated the impact of age on power. Specifically, post-PHV players demonstrated significantly greater improvements in jumping height than their pre- and circa-PHV counterparts, highlighting the enhanced power development that occurs during the post-PHV period. Recent studies have investigated the relationship between biological maturation and jumping ability. A study by Perroni et al. [55] found a strong correlation ($r = 0.63$) between CMJ performance and the pubertal development scale (PDS), as measured by a self-administered questionnaire in young soccer players aged approximately 13 years. Similarly, Hermassi et al. [56] observed a significant association between maturation, assessed through PHV, and CMJ performance in soccer players aged 8–12. In a more recent investigation, Amatori et al. [57] examined the connections between CMJ, soccer category, chronological age, relative age, and PDS to determine which factor best predicted jumping performance. The authors found that chronological age and pubertal development significantly influence CMJ performance, although they emphasized the importance of considering anthropometric variables when evaluating jumping abilities in youth. Although it has been suggested that the ability to perform quick movements (such as jumping high) may not be significantly affected by body size in adults, power is influenced by biological maturation, which is linked to sex hormones that increase during puberty [56]. It is noteworthy to emphasize that the aforementioned studies employed methodologies for assessing biological maturation that differed (Moore et al. 2015 and PDS) from those utilized in our investigation (Khamis and Roche, 1994) [29,58,59].

Strength development in boys during puberty significantly increases due to neuromuscular adaptations and muscle morphological changes during this period [60,61]. The findings from the IMTP test further underscored the significance of age and maturation in strength development. The interaction between these factors was significant ($p = 0.020$), demonstrating that post-PHV players achieved greater strength gains than their pre-PHV peers, highlighting that maturation plays a pivotal role in enhancing strength capabilities beyond chronological age effects. It reinforces the notion that biological maturation influences the rate at which young athletes can develop their maximal strength, consistent with the findings of Philippaerts et al. [62]. Our findings align with some previous investigations, which demonstrated maturation impacts on both peak force in elite youth male soccer players and those who are more mature and achieve superior results [63,64]. The IMTP serves as a valuable tool for practitioners, as it allows them to assess not only the absolute strength of players, but also to track changes in strength as they progress through different maturation status. Understanding these dynamics can aid in creating targeted strength-training regimens that optimize performance while reducing the injury risk, as athletes often experience varying responses to strength training based on their maturation status.

In team sports such as soccer, rapidly change direction is a crucial component of physical fitness [65,66], particularly COD speed [L-Test]. The ability to differentiate between top- and second-tier soccer players can be determined by COD speed, making it a potentially valuable metric for identifying and selecting talented athletes [65,67]. Prior to puberty, the COD speed performance of young males exhibited steady growth. However, after puberty, these males experience more substantial improvements, with the most significant gains typically occurring around ages 13-14, which aligns with PHV [68]. This trend reflected a two-phase maturation process. Initially, COD gains in young males were largely due to neural development, which enhances motor control through improved muscle coordination [69,70]. During puberty, hormonal shifts, including elevations in growth hormones, testosterone, and IGF-1, trigger structural changes in the body. These changes include muscle development, differentiation of fiber types, and modifications in muscle structure, all of which contribute to improved strength and physical capabilities in adolescent males [67,69,71]. Our analysis of COD speed indicated that chronological age was the primary determinant of performance in this test, with older players consistently outperforming their younger counterparts ($p < 0.001$). Maturation status and its interaction with age did not yield significant improvements in the predictive model ($p = 0.420$ and $p = 0.305$, respectively), suggesting that, while maturation may play a role, the influence of age alone is predominant in determining COD speed in young soccer players. Mathisen and Pettersen (2015) found no notable disparities in COD performance between groups before and after PHV [72]. However, Yang and Chen (2022) observed significantly superior COD performance among early-maturing soccer players aged 13 to 15 years compared to their late-maturing counterparts. This indicates that early maturation might provide a temporary edge in COD ability [73]. These contradictory results underscore the need for additional studies to elucidate the effect of maturation on COD in young soccer players [74]. It is essential to emphasize two aspects of this analysis about previous studies. First, the methodology employed to assess biological maturation differed from that used in our study. Second, and equally importance, the selection of tests to evaluate COD performance varies among the studies.

In the 30-meter sprint test, age was identified as the primary predictor of sprint performance, with older players generally outperforming younger players ($p < 0.001$). Our findings suggest that while both maturity status and its interaction with age did not contribute significantly to the predictive model ($p = 0.891$ and $p = 0.500$, respectively), sprint performance in young soccer players is strongly linked to chronological age rather than biological maturation. Current research has increasingly highlighted the significance of top sprint velocity in youth soccer, especially during the crucial growth period of the PHV [72,75]. Research indicates that the maximum sprint speed substantially improves during PHV, implying a notable influence of maturation on speed enhancement [75,76]. However, Radnor et al. [77] observed that maturation significantly affects peak speed development during PHV, underscoring the intricate nature of maturation's role in sprint velocity and the potential for maximum speed gains as players progress through key developmental stages [77]. Understanding these dynamics is crucial for creating sprint training regimens that respond to the diverse developmental phases of young athletes. Strength and Conditioning Coaches can use this information by concentrating on age-appropriate speed training exercises, particularly during and after PHV, to optimize sprint development potential and enhance players' readiness for soccer's physical demands.

Thus, it is vital to standardize the methods for assessing biological maturation and the protocol for testing maximal speed (e.g., distance determined).

The Bronco test revealed that age and maturity status significantly affected the results, with a substantial interplay between these variables ($p = 0.001$). Young soccer players who passed their PHV exhibited more substantial improvements in endurance over time. The growth and maturation processes lead to physiological changes that affect energy metabolism. These changes include an enlargement of the heart, increased blood volume, higher levels of hemoglobin, a possible increase in the proportion of type II muscle fibers, and improved activity of anaerobic enzymes [78]. Consequently, maturation leads to significant changes in absolute peak oxygen consumption and the ability to produce power through anaerobic energy systems, with the most notable improvements occurring during periods of rapid growth [9,62,70]. These physiological developments are likely to contribute to improved performance in endurance and high-intensity activities in young athletes through a natural progression. However, it is important to note that maturation tends to result in more substantial gains in anaerobic energy production than in aerobic energy production. Extensive research has been conducted on the natural development of aerobic fitness during maturation using both cross-sectional and longitudinal studies [79]. Research suggests that males experience a yearly increase in VO2max of about 200 $ml \cdot min^{-1}$ from pre-puberty to approximately 16 years of age due to the growth of cardiac, pulmonary, and muscular tissues [79]. In our investigation, players who had passed their PHV showed significantly greater Bronco test distances than those in the pre-PHV and mid-PHV stages ($p<0.01$). This observation aligns with Deprez et al. (2015), who reported that the most notable improvements occurred during the PHV period, marking a shift from pre- to post-PHV [80]. Our findings corroborate those of previous studies, which demonstrated that young soccer players who surpassed their PHV exhibited more pronounced enhancements in endurance over time.

There are certain limitations to this research. One notable constraint is that the study focused on players from a single club. To address this, future investigations should employ a broader approach by including multiple clubs in their analysis. In addition, this analysis did not include specific training load parameters that may have influenced player development. Considering a sample comprising players at different stages of biological maturation, specifically individuals in the pre-PHV, PHV, and post-PHV periods, is essential. This approach enables a detailed examination of primary differences across various physical performance tests, illuminating the most significant variations. Future investigations should continue exploring biological maturation's impact on young soccer players' physical performance while considering other variables, such as training load and soccer-specific exposure time. Finally, this study focused exclusively on male soccer players. With the growing development of female soccer, there is a pressing need for more research on talent development in female athletes.

6. Conclusions

Chronological age plays a significant role in predicting performance in COD and sprinting ability. At the same time, the impact of biological maturation is particularly notable in areas related to power, maximal strength, and endurance. Specifically, age alone emerged as the primary predictor of COD speed and sprinting ability, with older players generally exhibiting superior performance. However, maturation status plays a crucial role in modulating explosive strength, maximal strength, and endurance performance, particularly in post-PHV players, who showed greater gains in these areas over time.

7. Practical Applications

These findings provide actionable insights for sports scientists, coaches, and young soccer practitioners seeking to optimize the training and development of young soccer players. By considering chronological age and biological maturation, professionals can more effectively individualize training programs to align themselves with each player's developmental profile. For instance, power, strength, and endurance training could be intensified in post-PHV players, who demonstrated more substantial improvements in physical qualities than their pre- and circa-PHV counterparts. Such tailored approaches can maximize gains in power, endurance, and maximal strength, ensuring that training efforts are congruent with each athlete's maturation status.

The integration of biological maturation assessments can also enhance talent identification processes. By accurately assessing maturation status, programs can mitigate the risk of misidentifying late-maturing players, ensuring that talent potential is evaluated more comprehensively than solely relying on chronological age. Furthermore, practitioners can utilize the study results to design long-term athlete development plans and adjust training load and competition demands according to each player's growth stage, which may reduce injury risks and support sustained performance improvements over time.

This study further supports the development of a comprehensive battery of longitudinal tests for tracking performance in young soccer programs. This data-driven approach enables academies to monitor players' progress, compare results across teams or academies, and establish benchmarks to inform individualized training strategies. The analytical models derived from this study's findings can also aid in predicting performance outcomes, allowing soccer academies to make informed, evidence-based decisions in player development. Integrating maturation status into talent identification and development processes is essential for accurately evaluating young athletes and mitigating the potential biases linked to developmental timing.

8. References

1. Carling, C.; Le Gall, F.; Reilly, T.; Williams, A. M. Do Anthropometric and Fitness Characteristics Vary According to Birth Date Distribution in Elite Youth Academy Soccer Players? *Scand. J. Med. Sci. Sports* **2009**, *19* (1), 3–9. https://doi.org/10.1111/j.1600-0838.2008.00867.x.

2. le Gall, F.; Carling, C.; Williams, M.; Reilly, T. Anthropometric and Fitness Characteristics of International, Professional and Amateur Male Graduate Soccer Players from an Elite Youth Academy. *J. Sci. Med. Sport* **2010**, *13* (1), 90–95. https://doi.org/10.1016/j.jsams.2008.07.004.

3. Reilly, T.; Williams, A. M.; Nevill, A.; Franks, A. A Multidisciplinary Approach to Talent Identification in Soccer. *J. Sports Sci.* **2000**, *18* (9), 695–702. https://doi.org/10.1080/02640410050120078.

4. Hammami, M. A.; Ben Abderrahmane, A.; Nebigh, A.; Le Moal, E.; Ben Ounis, O.; Tabka, Z.; Zouhal, H. Effects of a Soccer Season on Anthropometric Characteristics and Physical Fitness in Elite Young Soccer Players. *J. Sports Sci.* **2013**, *31* (6), 589–596. https://doi.org/10.1080/02640414.2012.746721.

5. Malina, R. M.; Rogol, A. D.; Cumming, S. P.; Coelho e Silva, M. J.; Figueiredo, A. J. Biological Maturation of Youth Athletes: Assessment and Implications. *Br. J. Sports Med.* **2015**, *49* (13), 852–859. https://doi.org/10.1136/bjsports-2015-094623.

6. Buchheit, M.; Mendez-Villanueva, A. Effects of Age, Maturity and Body Dimensions on Match Running Performance in Highly Trained under-15 Soccer Players. *J. Sports Sci.* **2014**, *32* (13), 1271–1278. https://doi.org/10.1080/02640414.2014.884721.

7. Malina, R. M.; Cumming, S. P.; Kontos, A. P.; Eisenmann, J. C.; Ribeiro, B.; Aroso, J. Maturity-Associated Variation in Sport-Specific Skills of Youth Soccer Players Aged 13 – 15 Years. *J. Sports Sci.* **2005**, *23* (5), 515–522. https://doi.org/10.1080/02640410410001729928.

8. Monasterio, X.; Gil, S. M.; Bidaurrazaga-Letona, I.; Cumming, S. P.; Malina, R. M.; Williams, S.; Lekue, J. A.; Santisteban, J.; Diaz-Beitia, G.; Larruskain, J. Estimating

Maturity Status in Elite Youth Soccer Players: Evaluation of Methods. *Med. Sci. Sport. Exerc.* **2024**. https://doi.org/10.1249/MSS.0000000000003405.

9. Robert M Malina; Claude Bouchard; Oded Bar-Or. *Growth, Maturation, and Physical Activity*; 2004.

10. Johnson, A.; Farooq, A.; Whiteley, R. Skeletal Maturation Status Is More Strongly Associated with Academy Selection than Birth Quarter. *Sci. Med. Footb.* **2017**, *1* (2), 157–163. https://doi.org/10.1080/24733938.2017.1283434.

11. Valente-dos-Santos, J.; Coelho-e-Silva, M. J.; Simões, F.; Figueiredo, A. J.; Leite, N.; Elferink-Gemser, M. T.; Malina, R. M.; Sherar, L. Modeling Developmental Changes in Functional Capacities and Soccer-Specific Skills in Male Players Aged 11-17 Years. *Pediatr. Exerc. Sci.* **2012**, *24* (4), 603–621. https://doi.org/10.1123/pes.24.4.603.

12. Vandendriessche, J. B.; Vaeyens, R.; Vandorpe, B.; Lenoir, M.; Lefevre, J.; Philippaerts, R. M. Biological Maturation, Morphology, Fitness, and Motor Coordination as Part of a Selection Strategy in the Search for International Youth Soccer Players (Age 15–16 Years). *J. Sports Sci.* **2012**, *30* (15), 1695–1703. https://doi.org/10.1080/02640414.2011.652654.

13. Malina, R. M.; Figueiredo, A. J.; Coelho-e-Silva, M. J. Body Size of Male Youth Soccer Players: 1978–2015. *Sport. Med.* **2017**, *47* (10), 1983–1992. https://doi.org/10.1007/s40279-017-0743-x.

14. Lloyd, R. S.; Oliver, J. L.; Faigenbaum, A. D.; Myer, G. D.; De Ste Croix, M. B. A. Chronological Age vs. Biological Maturation. *J. Strength Cond. Res.* **2014**, *28* (5), 1454–1464. https://doi.org/10.1519/JSC.0000000000000391.

15. Malina, R. M.; Cumming, S. P.; Rogol, A. D.; Coelho-e-Silva, M. J.; Figueiredo, A. J.; Konarski, J. M.; Kozieł, S. M. Bio-Banding in Youth Sports: Background, Concept, and Application. *Sport. Med.* **2019**, *49* (11), 1671–1685. https://doi.org/10.1007/s40279-019-01166-x.

16. Mujika, I.; Vaeyens, R.; Matthys, S. P. J.; Santisteban, J.; Goiriena, J.; Philippaerts, R. The Relative Age Effect in a Professional Football Club Setting. *J. Sports Sci.* **2009**, *27* (11), 1153–1158. https://doi.org/10.1080/02640410903220328.

17. Farley, J. B.; Stein, J.; Keogh, J. W. L.; Woods, C. T.; Milne, N. The Relationship Between Physical Fitness Qualities and Sport-Specific Technical Skills in Female, Team-Based Ball Players: A Systematic Review. *Sport. Med. - Open* **2020**, *6* (1), 18. https://doi.org/10.1186/s40798-020-00245-y.

18. Dudley, C.; Johnston, R.; Jones, B.; Till, K.; Westbrook, H.; Weakley, J. Methods of Monitoring Internal and External Loads and Their Relationships with Physical Qualities, Injury, or Illness in Adolescent Athletes: A Systematic Review and Best-Evidence Synthesis. *Sport. Med.* **2023**, *53* (8), 1559–1593. https://doi.org/10.1007/s40279-023-01844-x.

19. Ortega, F. B.; Ruiz, J. R.; Castillo, M. J. Physical Activity, Physical Fitness, and Overweight in Children and Adolescents: Evidence from Epidemiologic Studies. *Endocrinol. y Nutr. (English Ed.* **2013**, *60* (8), 458–469. https://doi.org/10.1016/j.endoen.2013.10.007.

20. Sarmento, H.; Anguera, M. T.; Pereira, A.; Araújo, D. Talent Identification and Development in Male Football: A Systematic Review. *Sport. Med.* **2018**, *48* (4), 907–931. https://doi.org/10.1007/s40279-017-0851-7.

21. Till, K.; Cobley, S.; O’Hara, J.; Chapman, C.; Cooke, C. An Individualized Longitudinal Approach to Monitoring the Dynamics of Growth and Fitness Development in Adolescent Athletes. *J. Strength Cond. Res.* **2013**, *27* (5), 1313–1321. https://doi.org/10.1519/JSC.0b013e31828a1ea7.

22. Cumming, S. P.; Lloyd, R. S.; Oliver, J. L.; Eisenmann, J. C.; Malina, R. M. Bio-Banding in Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of Youth Athletes. *Strength Cond. J.* **2017**, *39* (2), 34–47. https://doi.org/10.1519/SSC.0000000000000281.

23. Beunen, G. P.; Rogol, A. D.; Malina, R. M. Indicators of Biological Maturation and Secular Changes in Biological Maturation. *Food Nutr. Bull.* **2006**, *27* (4_suppl5), S244–S256. https://doi.org/10.1177/15648265060274S508.

24. Towlson, C.; Salter, J.; Ade, J. D.; Enright, K.; Harper, L. D.; Page, R. M.; Malone, J. J. Maturity-Associated Considerations for Training Load, Injury Risk, and Physical Performance in Youth Soccer: One Size Does Not Fit All. *J. Sport Heal. Sci.*

2021, *10* (4), 403–412. https://doi.org/10.1016/j.jshs.2020.09.003.

25. Kozieł, S. M.; Malina, R. M. Modified Maturity Offset Prediction Equations: Validation in Independent Longitudinal Samples of Boys and Girls. *Sport. Med.* **2018**, *48* (1), 221–236. https://doi.org/10.1007/s40279-017-0750-y.

26. Nevill, A.; Burton, R. F. Commentary on the Article "Improving the Prediction of Maturity From Anthropometric Variables Using a Maturity Ratio." *Pediatr. Exerc. Sci.* **2018**, *30* (2), 308–310. https://doi.org/10.1123/pes.2017-0201.

27. Roche, A. F. *Growth, Maturation, and Body Composition*; Cambridge University Press, 1992. https://doi.org/10.1017/CBO9780511661655.

28. Cumming, S. P.; Brown, D. J.; Mitchell, S.; Bunce, J.; Hunt, D.; Hedges, C.; Crane, G.; Gross, A.; Scott, S.; Franklin, E.; Breakspear, D.; Dennison, L.; White, P.; Cain, A.; Eisenmann, J. C.; Malina, R. M. Premier League Academy Soccer Players' Experiences of Competing in a Tournament Bio-Banded for Biological Maturation. *J. Sports Sci.* **2018**, *36* (7), 757–765. https://doi.org/10.1080/02640414.2017.1340656.

29. Khamis, H. J.; Roche, A. F. Predicting Adult Stature without Using Skeletal Age: The Khamis-Roche Method. *Pediatrics* **1994**, *94* (4 Pt 1), 504–507.

30. Parr, J.; Winwood, K.; Hodson-Tole, E.; Deconinck, F. J. A.; Parry, L.; Hill, J. P.; Malina, R. M.; Cumming, S. P. Predicting the Timing of the Peak of the Pubertal Growth Spurt in Elite Male Youth Soccer Players: Evaluation of Methods. *Ann. Hum. Biol.* **2020**, *47* (4), 400–408. https://doi.org/10.1080/03014460.2020.1782989.

31. Baumgartner, TA, and Jackson, A. *Measurement for Evaluation in Physical Education and Exercise Science*, 8th ed.; 2007.

32. McCunn, R.; Devlin, P. The 1.2km Shuttle Run Test: Reliability and Comparison with the Yo-Yo Intermittent Recovery Level 1 Test in Young Elite Rugby Union Players. *J. Aust. Strength Cond.* **2019**, *27* (4), 14–20.

33. Selmi, O.; Jelleli, H.; Bouali, S.; Aydi, B.; Hindawi, O.; Muscella, A.; Bouassida, A.; Weiss, K.; Knechtle, B. The Impact of Verbal Encouragement during the Repeated Agility Speed Training on Internal Intensity, Mood State, and Physical Enjoyment in

Youth Soccer Players. *Front. Psychol.* **2023**, *14*. https://doi.org/10.3389/fpsyg.2023.1180985.

34. Marfell-Jones, M. J., Stewart, A. D., & de Ridder, J. H. *International Standards for Anthropometric Assessment*; International Society for the Advancement of Kinanthropometry, Ed.; 2012.

35. Sweeney, L.; Cummin, S.; MacNamara, Á.; Horan, D. The Selection Advantages Associated with Advanced Biological Maturation Vary According to Playing Position in National-Level Youth Soccer. *Biol. Sport* **2023**, *40* (3), 715–722. https://doi.org/10.5114/biolsport.2023.119983.

36. Epstein, L. H.; Valoski, A. M.; Kalarchian, M. A.; McCurley, J. Do Children Lose and Maintain Weight Easier Than Adults: A Comparison of Child and Parent Weight Changes From Six Months to Ten Years. *Obes. Res.* **1995**, *3* (5), 411–417. https://doi.org/10.1002/j.1550-8528.1995.tb00170.x.

37. Johnson, D. M.; Cumming, S. P.; Bradley, B.; Williams, S. The Influence of Exposure, Growth and Maturation on Injury Risk in Male Academy Football Players. *J. Sports Sci.* **2022**, *40* (10), 1127–1136. https://doi.org/10.1080/02640414.2022.2051380.

38. Glatthorn, J. F.; Gouge, S.; Nussbaumer, S.; Stauffacher, S.; Impellizzeri, F. M.; Maffiuletti, N. A. Validity and Reliability of Optojump Photoelectric Cells for Estimating Vertical Jump Height. *J. Strength Cond. Res.* **2011**, *25* (2), 556–560. https://doi.org/10.1519/JSC.0b013e3181ccb18d.

39. Lloyd, R. S.; Oliver, J. L.; Hughes, M. G.; Williams, C. A. Specificity of Test Selection for the Appropriate Assessment of Different Measures of Stretch-Shortening Cycle Function in Children. *J. Sports Med. Phys. Fitness* **2011**, *51* (4), 595–602.

40. Markovic, G.; Dizdar, D.; Jukic, I.; Cardinale, M. Reliability and Factorial Validity of Squat and Countermovement Jump Tests. *J. Strength Cond. Res.* **2004**, *18* (3), 551. https://doi.org/10.1519/1533-4287(2004)18<551:RAFVOS>2.0.CO;2.

41. Lloyd, R. S.; Oliver, J. L.; Hughes, M. G.; Williams, C. A. Reliability and Validity of Field-Based Measures of Leg Stiffness and Reactive Strength Index in Youths. *J. Sports Sci.* **2009**, *27* (14), 1565–1573. https://doi.org/10.1080/02640410903311572.

42. De Blas, X.; Padullés, J. M.; Del Amo, J. L. L.; Guerra-Balic, M. Creation and Validation of Chronojump-Boscosystem: A Free Tool to Measure Vertical Jumps. *Int. J. Sport. Sci* **2007**, No. 30, 334–356. https://doi.org/10.5232/ricyde2012.03004.

43. Beckham, G. K.; Sato, K.; Santana, H. A. P.; Mizuguchi, S.; Haff, G. G.; Stone, M. H. Effect of Body Position on Force Production During the Isometric Midthigh Pull. *J. Strength Cond. Res.* **2018**, *32* (1), 48–56. https://doi.org/10.1519/JSC.0000000000001968.

44. Dos'Santos, T.; Thomas, C.; Jones, P. A.; Comfort, P. Assessing Muscle-Strength Asymmetry via a Unilateral-Stance Isometric Midthigh Pull. *Int. J. Sports Physiol. Perform.* **2017**, *12* (4), 505–511. https://doi.org/10.1123/ijspp.2016-0179.

45. Comfort, P.; Dos'Santos, T.; Beckham, G. K.; Stone, M. H.; Guppy, S. N.; Haff, G. G. Standardization and Methodological Considerations for the Isometric Midthigh Pull. *Strength Cond. J.* **2019**, *41* (2), 57–79. https://doi.org/10.1519/SSC.0000000000000433.

46. Haff, G. G.; Ruben, R. P.; Lider, J.; Twine, C.; Cormie, P. A Comparison of Methods for Determining the Rate of Force Development During Isometric Midthigh Clean Pulls. *J. Strength Cond. Res.* **2015**, *29* (2), 386–395. https://doi.org/10.1519/JSC.0000000000000705.

47. Webb, P., & Lander, J. An Economical Fitness Testing Battery for High School and College Rugby Teams. *Sport. Coach* **1983**, No. 7, 44–46.

48. Gabbett, T. J.; Kelly, J. N.; Sheppard, J. M. Speed, Change of Direction Speed, and Reactive Agility of Rugby League Players. *J. Strength Cond. Res.* **2008**, *22* (1), 174–181. https://doi.org/10.1519/JSC.0b013e31815ef700.

49. Meir, R.; Newton, R.; Curtis, E.; Fardell, M.; Butler, B. Physical Fitness Qualities of Professional Rugby League Football Players: Determination of Positional Differences. *J. Strength Cond. Res.* **2001**, *15* (4), 450. https://doi.org/10.1519/1533-4287(2001)015<0450:PFQOPR>2.0.CO;2.

50. Lloyd, R. S.; Radnor, J. M.; De Ste Croix, M. B. A.; Cronin, J. B.; Oliver, J. L. Changes in Sprint and Jump Performances After Traditional, Plyometric, and Combined

Resistance Training in Male Youth Pre- and Post-Peak Height Velocity. *J. Strength Cond. Res.* **2016**, *30* (5), 1239–1247. https://doi.org/10.1519/JSC.0000000000001216.

51. Kelly, V. G.; Jackson, E.; Wood, A. Typical Scores from the 1.2km Shuttle Run Test to Determine Maximal Aerobic Speed. *J. Aust. Strength Cond.* **2014**, *22* (5), 183–185.

52. Kelly, V.; Wood, A. The Correlation between the 30-15 Intermittent Fitness Test and a Novel Test of Running Performance. *J. Aust. Strength Cond.* **2013**, *21* (Supp. 1), 91–94.

53. Baker, D. Barker - Recent-Trends-in-High-Intensity-Aerobic_training.Pdf. *UK Strength Cond. Assoc.* **2011**, *Summer 201* (22), 3–8.

54. Baker, D.; Heaney, N. Review of the Literature-Normative Data for Maximal Aerobic Speed for Field Sport Athletes. *J. Aust. Strength Cond.* **2015**, *23* (7), 60–67.

55. Perroni, F.; Vetrano, M.; Rainoldi, A.; Guidetti, L.; Baldari, C. Relationship among Explosive Power, Body Fat, Fat Free Mass and Pubertal Development in Youth Soccer Players: A Preliminary Study. *Sport Sci. Health* **2014**, *10* (2), 67–73. https://doi.org/10.1007/s11332-014-0175-z.

56. Hermassi, S.; Konukman, F.; Al-Marri, S. S.; Hayes, L. D.; Bartels, T.; Schwesig, R. Associations between Biological Maturation, Physical Performance, Postural Control, and Mathematical Achievement in Youth Soccer Players. *PLoS One* **2024**, *19* (3), e0298301. https://doi.org/10.1371/journal.pone.0298301.

57. Amatori, S.; Pintus, A.; Corsi, L.; Bensi, R.; Zanini, L.; Rocco, V.; Guidetti, L.; Baldari, C.; Rocchi, M. B. L.; Sisti, D.; Perroni, F. Chronological Age, Relative Age, Pubertal Development, and Their Impact on Countermovement Jump Performance in Adolescent Football Players: An Integrative Analysis. *Heliyon* **2024**, *10* (17), e36879. https://doi.org/10.1016/j.heliyon.2024.e36879.

58. Moore, S. A.; McKay, H. A.; Macdonald, H.; Nettlefold, L.; Baxter-Jones, A. D. G.; Cameron, N.; Brasher, P. M. A. Enhancing a Somatic Maturity Prediction Model. *Med. Sci. Sports Exerc.* **2015**, *47* (8), 1755–1764. https://doi.org/10.1249/MSS.0000000000000588.

59. Petersen, A. C.; Crockett, L.; Richards, M.; Boxer, A. A Self-Report Measure of Pubertal Status: Reliability, Validity, and Initial Norms. *J. Youth Adolesc.* **1988**, *17* (2), 117–133. https://doi.org/10.1007/BF01537962.

60. Ford, P.; De Ste Croix, M.; Lloyd, R.; Meyers, R.; Moosavi, M.; Oliver, J.; Till, K.; Williams, C. The Long-Term Athlete Development Model: Physiological Evidence and Application. *J. Sports Sci.* **2011**, *29* (4), 389–402. https://doi.org/10.1080/02640414.2010.536849.

61. Malina, R. M.; Dompier, T. P.; Powell, J. W.; Barron, M. J.; Moore, M. T. Validation of a Noninvasive Maturity Estimate Relative to Skeletal Age in Youth Football Players. *Clin. J. Sport Med.* **2007**, *17* (5), 362–368. https://doi.org/10.1097/JSM.0b013e31815400f4.

62. Philippaerts, R. M.; Vaeyens, R.; Janssens, M.; Van Renterghem, B.; Matthys, D.; Craen, R.; Bourgois, J.; Vrijens, J.; Beunen, G.; Malina, R. M. The Relationship between Peak Height Velocity and Physical Performance in Youth Soccer Players. *J. Sports Sci.* **2006**, *24* (3), 221–230. https://doi.org/10.1080/02640410500189371.

63. Brownlee, T. E.; Murtagh, C. F.; Naughton, R. J.; Whitworth-Turner, C. M.; O’Boyle, A.; Morgans, R.; Morton, J. P.; Erskine, R. M.; Drust, B. Isometric Maximal Voluntary Force Evaluated Using an Isometric Mid-Thigh Pull Differentiates English Premier League Youth Soccer Players from a Maturity-Matched Control Group. *Sci. Med. Footb.* **2018**, *2* (3), 209–215. https://doi.org/10.1080/24733938.2018.1432886.

64. Morris, R. O.; Jones, B.; Myers, T.; Lake, J.; Emmonds, S.; Clarke, N. D.; Singleton, D.; Ellis, M.; Till, K. Isometric Midthigh Pull Characteristics in Elite Youth Male Soccer Players: Comparisons by Age and Maturity Offset. *J. Strength Cond. Res.* **2020**, *34* (10), 2947–2955. https://doi.org/10.1519/JSC.0000000000002673.

65. Negra, Y.; Sammoud, S.; Nevill, A. M.; Chaabene, H. Change of Direction Speed in Youth Male Soccer Players: The Predictive Value of Anthropometrics and Biological Maturity. *Pediatr. Exerc. Sci.* **2022**, 1–7. https://doi.org/10.1123/pes.2021-0178.

66. Bloomfield, J.; Polman, R.; O’Donoghue, P. Physical Demands of Different Positions in FA Premier League Soccer. *J. Sport. Sci. Med.* **2007**, *6* (1), 63–70.

67. Negra, Y.; Chaabene, H.; Hammami, M.; Amara, S.; Sammoud, S.; Mkaouer, B.; Hachana, Y. Agility in Young Athletes: Is It a Different Ability From Speed and Power? *J. Strength Cond. Res.* **2017**, *31* (3), 727–735. https://doi.org/10.1519/JSC.0000000000001543.

68. Vänttinen, T.; Blomqvist, M.; Nyman, K.; Häkkinen, K. Changes in Body Composition, Hormonal Status, and Physical Fitness in 11-, 13-, and 15-Year-Old Finnish Regional Youth Soccer Players During a Two-Year Follow-Up. *J. Strength Cond. Res.* **2011**, *25* (12), 3342–3351. https://doi.org/10.1519/JSC.0b013e318236d0c2.

69. Lloyd, R. S.; Read, P.; Oliver, J. L.; Meyers, R. W.; Nimphius, S.; Jeffreys, I. Considerations for the Development of Agility During Childhood and Adolescence. *Strength Cond. J.* **2013**, *35* (3), 2–11. https://doi.org/10.1519/SSC.0b013e31827ab08c.

70. Viru, A.; Loko, J.; Harro, M.; Volver, A.; Laaneots, L.; Viru, M. *Critical Periods in the Development of Performance Capacity During Childhood and Adolescence*; 1999; Vol. 4. https://doi.org/10.1080/1740898990040106.

71. Tonson, A.; Ratel, S.; Fur, Y. Le; Cozzone, P.; Bendahan, D. Effect of Maturation on the Relationship between Muscle Size and Force Production. *Med. Sci. Sport. Exerc.* **2008**, *40* (5), 918–925. https://doi.org/10.1249/MSS.0b013e3181641bed.

72. Gunnar Mathisen; Pettersen, S. A. Anthropometric Factors Related to Sprint and Agility Performance in Young Male Soccer Players. *Open Access J. Sport. Med.* **2015**, 337. https://doi.org/10.2147/OAJSM.S91689.

73. Yang, S.; Chen, H. Physical Characteristics of Elite Youth Male Football Players Aged 13–15 Are Based upon Biological Maturity. *PeerJ* **2022**, *10*, e13282. https://doi.org/10.7717/peerj.13282.

74. Lehnert, M.; Holík, R.; Prycl, D.; Sigmund, M.; Sigmundová, D.; Malý, T. Talent Identification in Football: Different Effects of Maturation on Sprinting, Change of Direction and Jumping in 13-Year-Old Players. *Appl. Sci.* **2024**, *14* (13), 5571. https://doi.org/10.3390/app14135571.

75. Meyers, R. W.; Oliver, J. L.; Hughes, M. G.; Cronin, J. B.; Lloyd, R. S. Maximal Sprint Speed in Boys of Increasing Maturity. *Pediatr. Exerc. Sci.* **2015**, *27* (1), 85–94.

https://doi.org/10.1123/pes.2013-0096.

76. Meyers, R. W.; Oliver, J. L.; Hughes, M. G.; Lloyd, R. S.; Cronin, J. B. Influence of Age, Maturity, and Body Size on the Spatiotemporal Determinants of Maximal Sprint Speed in Boys. *J. Strength Cond. Res.* **2017**, *31* (4), 1009–1016. https://doi.org/10.1519/JSC.0000000000001310.

77. Radnor, J. M.; Oliver, J. L.; Waugh, C. M.; Myer, G. D.; Lloyd, R. S. Muscle Architecture and Maturation Influence Sprint and Jump Ability in Young Boys: A Multistudy Approach. *J. Strength Cond. Res.* **2022**, *36* (10), 2741–2751. https://doi.org/10.1519/JSC.0000000000003941.

78. Armstrong, N.; Fawkner, S.; G. Exercise Metabolism. In *Paediatric Exercise Science and Medicine*; Oxford University PressOxford, 2008; pp 213–226. https://doi.org/10.1093/med/9780199232482.003.0016.

79. Harrison, C. B.; Gill, N. D.; Kinugasa, T.; Kilding, A. E. Development of Aerobic Fitness in Young Team Sport Athletes. *Sport. Med.* **2015**, *45* (7), 969–983. https://doi.org/10.1007/s40279-015-0330-y.

80. Deprez, D.; Buchheit, M.; Fransen, J.; Pion, J.; Lenoir, M.; Philippaerts, R. M.; Vaeyens, R. A Longitudinal Study Investigating the Stability of Anthropometry and Soccerspecific Endurance in Pubertal High-Level Youth Soccer Players. *J. Sport. Sci. Med.* **2015**, *14* (2), 418–426.

Chapter 3

STUDY III

Impact of Biological Maturation on Match Workload in Portuguese Elite Male Academy Soccer Players

Biology of Sport

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Impact of Biological Maturation on Match Workload in Portuguese Elite Male Academy Soccer Players

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1. Abstract

Aims: Youth soccer academies are vital for identifying and nurturing talented players, crucial for professional success. This study investigated the impact of biological maturation on match performance in highly skilled male soccer players aged U-14 to U-17.

Methods: Sixty male Portuguese professional academy soccer players were assessed for match workload and biological maturation at six points across the 2021-22 and 2022-23 seasons, with evaluations conducted every three months. Participants were clas-sified into pre- and circa-peak height velocity (PHV) and post-PHV groups based on their predicted percentage of adult height.

Results: Mixed-effects models revealed age significantly impacted TD/min (β = -2.371, p = 0.001). The best-fitting model (AIC = 14481.497) included maturity status and its interaction with age, showing significant effects for all parameters (p = 0.001). HSR/min was mainly influenced by age (β = 0.527, p = 0.001), with minimal maturity impact, while age positively affected SD/min (β = 0.174, p = 0.001) without significant interaction effects. Total Ac and Dec/min were significantly influenced by age, maturity, and their interaction (Model 3: AIC = 1510.667), with maturity's impact decreasing as age increased.

Conclusions: Chronological age alone may insufficiently account for the substantial impact of biological maturity on athletic perfor-mance. While age influences high-speed running and sprint distance, the interaction between age and maturation is crucial for total distance covered and dynamic actions, including acceleration and deceleration. The effect of biological maturation diminishes with increasing age, emphasizing the need for age-specific training strategies.

Keywords: Soccer, somatic maturity, adolescent, performance indicators, external load.

2. Introduction

The purpose of soccer academies is to identify and develop young, talented players who can thrive at higher levels and potentially earn professional contracts [1–3]. Research on youth soccer players in academies shows that 60-80% of U16 and U17 athletes have a bone age exceeding their actual age by at least one year [4,5]. In this regard, variations in biological maturation complicate the identification of players likely to excel at the senior level, affecting selection, physical ability, and performance [6]. These players outperform their peers in speed, strength, power, agility, and endurance tests [8,9]. Despite age-based grouping in academies, significant physical differences exist. Children of the same age can differ in skeletal age by up to five years, indicating maturation levels. Advanced-aged male players exhibit greater height, weight, and mass-for-stature than their peers do [8–10]. These differences include roughly 50% in body mass, 29 cm in height, 10-15% in the percentage of predicted adult height (PPAH), and 3-8.6 kg in fat-free mass [11,12]. Maturation-related factors are likely to influence performance [13]. Thus, significant physical developmental differences among pubertal athletes complicate talent identification [14].

Most research on workload relationships focuses on adult populations, with limited studies targeting younger athletes (i.e., <U-16) [14,16]. Adolescents are particularly vulnerable due to their rapid growth and maturation, and inappropriate workloads may adversely affect their development and injury risk [17,18]. Some studies have consistently demonstrated that biological maturation is positively correlated with superior physical performance in young soccer players. Buchheit, Mendez-Villanueva, Simpson, and Bourdon [19] found that earlier-maturing players, aged 13-18, outperformed later-maturing players in key physical metrics such as maximum speed, high-speed distance covered, and overall intensity during competitive play {Formatting Citation}. This pattern contributes to the overrepresentation of early-maturing players in soccer academies because late-maturing players face athletic disadvantages during competition, which could hinder their progression to higher levels of competition. Buchheit and Mendez-Villanueva [12] confirmed these findings in U15 players, showing that those advanced in maturation reached higher peak speeds and covered more distances at speeds above 16 km/h, mainly in midfielders and wingers. Interestingly, no significant differences in total distance covered were observed between early- and late-maturing players, suggesting that match running metrics may depend more on playing position than on overall physical capacity.

There are several methods for assessing biological maturity [20]. Multiple approaches exist for evaluating an individual's biological maturation, as this process affects various systems (including somatic, skeletal, endocrine, sexual, and dental systems). Researchers have previously utilized multiple indicators to assess biological maturity in young soccer players, including secondary sexual characteristics, bone age, the chronological age at which peak height velocity (PHV) occurs, and the size of the testes [1,2,21–25]. Among these methods, skeletal age is typically considered the most objective or clinical technique for determining biological maturity. Nevertheless, its application in academy soccer is often restricted due to the procedure's invasive nature, the requirement for radiation exposure, and related ethical issues [26,27]. Previous studies investigating the relationship between biological maturation and match-running metrics have used methods such as Mirwald maturity offset [28] or maturity ratio [30]. However, these methods have limitations as they may not fully capture the intricacies of biological development. Studies on the relationship between biological maturation and match-running metrics have used the Mirwald maturity offset [29] or maturity ratio [30]. Concerns persist regarding inconsistencies between estimated and actual chronological ages at the APVH, especially for males not close to the PHV [28,31]. The Khamis-Roche method uses the Fels Longitudinal Study to estimate adult height, classifying young individuals into groups based on predicted adult stature percentages (≥ 85.0% and < 90.0%, or ≥ 90.0% and < 95.0%) [6,31–33]. These groupings, which cover the adolescent growth spurt, can be adjusted as needed with benchmarks for adult height at 18 years [6,32,33]. Therefore, the Khamis-Roche method is effective for assessing somatic maturation, with an error margin of approximately 2% in anthropometric measurements, which is consistent with previous research [34,35] and should be used to monitor maturity consistently.

Despite the significance of comprehending how the match workload evolves concerning the maturity status of each player, there is a lack of information in the scientific literature. The primary goal was to determine the effects of biological maturation on game performance. Additional objectives include evaluating differences in match workloads across maturation groups and field positions and identifying the most significant physical performance indicators. Furthermore, this study aimed to establish benchmark values for match workload metrics and conduct a longitudinal analysis of each player's development throughout the long-term athlete development (LTAD) process.

3. Materials and Methods

3.1. Experimental Approach to the Problem

This study utilized a longitudinal approach involving repeated measurements of the same entities. Sixty male soccer players were recruited from a professional soccer academy in Portugal and various aspects of growth, maturation, and external workload were investigated. The biological maturity and workload assessment occurred during the initial evaluation of the 2021-22 season, starting in the first week of July 2021 and concluding in the first week of May 2023 (Table 1). The research plan involved six assessment points spanning the 2021-22 and 2022-23 sports seasons, with three evaluations carried out per season, each three months apart (Table 1). Players were divided into two categories according to their biological maturation level as determined by the Khamis-Roche method [34]. The first category, Group 1, included participants in the pre-and circa-PHV stages (<95.00% PAH), while the second category, Group 2, consisted of those in the post-PHV stage (≥95.00% PAH). Owing to the small number of athletes in the pre-PHV stage (n=4), the analysis combined the pre-PHV and PHV classification groups.

Table 1 - Assessment during the two sports seasons.

Season	**2021-22**			**2022-23**		
Year	**2021**	**2022**	**2022**	**2022**	**2023**	**2023**
Month	August	January	May	August	January	May
Week	1st	1st	1st	1st	1st	1st
Assessment Number	1st	2nd	3rd	4th	5th	6th

3.2. Subjects

Sixty male soccer players aged 12.0 to 18.1 years (mean 15.1 ± 1.1 years), had an average height of 174.9 cm (±8.0 cm) and body mass of 64.1 kg (±8.5 kg). Players belonged to the U14, U15, U16, and U17 age groups underwent their initial assessment for the 2020-21 season. All players completed the study without any dropouts or missing data. The inclusion criteria required participants to have at least three years of soccer experience, two seasons with the current academy/club, and no use of supplements affecting growth and maturation. Players injured during the off-season and those who did not participate in the medical study were excluded. Players averaged 5.5 ± 1.1 years of training/match experience at national and international levels. This study was approved by the Faculty of Physical Education and Sports Ethics Committee of the University of Lusófona. All participants were briefed on the procedures, and their parents or legal guardians signed an open-ended consent form allowing withdrawal at any time. The study adhered to the ethical standards of the Declaration of Helsinki for human subject studies.

Table 2. Anthropometric, Body Composition, Maturity characteristics, and Match running metrics from under-14 to under-17.

Maturity Group	**Pre/Circa-PHV**	**Post-PHV**
	(n = 28)	(n = 32)
Anthropometric and maturity characteristics		
Chronological Age (years)	13.8 ± 0.6	15.4 ± 0.8
Height (cm)	166.8 ± 5.3	175.6 ± 6.5
Mass (kg)	53.4 ± 5.5	65.4 ± 6.3
PAH (%)	92.3 ± 1.9	97.8 ± 1.5
Match running metrics		
Total distance (m/min)	137.1 ± 16.5	141.7 ± 16.6
High-speed running (m/min)	1.5 ± 0.7	1.33 ± 0.7
Sprint distance (m/min)	0.01 ± 0.0	0.01 ± 0.0
Total Accelerations/Decelerations (cnt/min)	0.02 ± 0.0	0.02 ± 0.0

3.3. Procedures

Anthropometry and Body Composition. The anthropometric profile was used to perform the assessments according to the International Society for the Advancement of Kinanthropometry [35]. A certified and experienced Level I technician conducted the evaluations, following the guidelines of the International Society for the Advancement of Kinanthropometry [37]. The technician performed anthropometric measurements of young soccer players, including body mass, standing height, and sitting height. An anthropometer (SECA 206) was used to measure height with an accuracy of 0.1 cm, while an electronic scale (TANITA BC-601) measured weight with an accuracy of 0.1 kg. The inter- and intra-observer technical error of measurement for standing and seated height was 5%, whereas for weight, it was less than 5%. The BMI (kg/m2) was calculated using BM/HT2, and eight skinfolds (triceps, subscapular, biceps, suprailiac, abdominal, supraspinal, thigh, and calf) were measured twice (at 0.1 mm) using a Harpenden skinfold caliper (British Indicators, Ltd., London, UK). Double anthropometric measurements were obtained for each athlete, and the mean of the two measurements was used to compute eight skinfolds (8SKF). A 5% intra-observer measurement error was considered acceptable for SKF; otherwise, a third measurement was performed.

Microcycle Contextualization. The weekly training regimen during the competition season included a match day (MD), followed by a rest day (MD+1/-6), and a recovery session (MD+2/-5). The pre-match training was organized as follows: MD+3/-4 focused on position-specific drills and small group games. MD+4/-3 emphasized tactical preparation for the upcoming match, featuring moderate-intensity positional exercise. MD+5/-2 involved activation drills that simulated certain technical and tactical aspects, ending with set-piece practice. MD+6/-1 was designated as the rest of the day for all the teams. The weekly schedule can be adjusted based on the match-day developments. Young players engaged in four 90-minute weekly training sessions with matches typically scheduled on weekends. The U14-U15 matches lasted 80 minutes, while the U16-U17 matches ran for 90 minutes, both played on outdoor artificial turf fields with 11-player teams. Academy players averaged 12 hours of combined weekly training, comprising four to five soccer sessions, one to two strength and power workouts, one to two speeds, change of direction drills, and one competitive match per week.

Players Position. Sixty young male soccer players were categorized into seven distinct positions: goalkeepers (n = 7), central center-back players (n = 9), winger-back players (n = 10), central midfielders (n = 15), wingers (n = 12), or forward players (n = 7). While it is acknowledged that young soccer players (i.e., U-12 to U-18) may adopt various positions during training [38], the criterion for determining each player's position was the most significant volume of play in that specific role.

Biological Maturation. Height, body mass, chronological age, and average parent height were used to predict the adult height of each player and determine biological maturity [34]. The heights of the biological parents of each player were self-reported and adjusted for over-estimation using the equations in Epstein, Valenki, Kalarchian, and McCurley (1995) [39]. Using the Khamis-Roche method, it is possible to predict the final adult height of men between 4.0 and 17.5 years old, considering a median error associated with the use of the 2.2 cm method, which is an average error that can vary between 0.8 and 2.8 cm [34]. As previously mentioned, players were classified into three groups based on their predicted adult height percentage (PAH). Circa-PHVs accounted for 88-95% of the expected adult stature. Pre-PHVs were less than 88%, whereas post-PHVs exceeded 95% [33,40,41]. Two groups were established for data analysis based on biological maturation (maturity status). Group 1 was comprised of young soccer players with a predicted adult height percentage of < 95%. Group 2 included players with a predicted adult height percentage ≥ 95%. The composition of each group was adjusted during the study period. Group 1 had 28 players at the initial evaluation, whereas group 2 had 32. The distribution of samples between the two groups (pre-PHV/PHV and post-PHV) was also assessed.

External Workload. During each match, every player was equipped with a personal GPS unit (10-Hz, APEX, StatsSports, UK). These devices were operated at a 10-Hz frequency and incorporated accelerometer sampling at 100-Hz. The devices were positioned on the upper back of each participant using a flexible neoprene strap that could be adjusted for fit. Post-match, the collected information was transferred to a computer and examined using the STATSports software package (Sonra 3.0, 2020). This study focuses on five specific match-running metrics, as listed in Table 3. The analysis included only data from participants who played for at least 60 min in a match. To ensure consistent comparisons across all data points, the metrics were standardized by dividing them by each player's total playing time (60 min or more) per match. These values were then multiplied by 60 to express the metrics on a per-60-minute basis.

Table 3. Definition of GPS metrics used for monitoring match external workload from under-14 to under-17.

GPS Metric	**Definition**
Total distance (m/min)	The total distance covered at all speeds per minute
High speed running distance (m/min)	The distance covered at ≥5.5 $m.s^{-1}$ per minute
Sprint running distance (m/min)	The distance covered ≥7.0 $m.s^{-1}$ per minute
Accelerations (n/min)	The number of accelerations above 3.0 $m.s^{-2}$
Decelerations (n/min)	The number of decelerations above 3.0 $m.s^{-2}$
Total of Accelerations and Decelerations (n/min)	The sum of total number of accelerations and of decelerations above 3.0 $m.s^{-2}$

3.4. Statistical Analysis

Zero-order Pearson correlations were first performed to check for potential overlap among the performance metrics, with correlations ranging from 0.02 to 0.61, indicating moderate relationships. This suggests that each parameter retains the independent properties that are relevant to short-term performance. Descriptive statistics for all performance measures are reported as mean ± standard deviation. To investigate changes in external workload parameters (total distance per minute, high-speed running per minute, sprint distance per minute, and total accelerations and decelerations per minute) as a function of chronological age and maturity status (pre- and circa-PHV players were coded as 0 and post-PHV players were coded as 1), was employed a two-level growth model. At Level 1, successive measurements over time for each player were modeled to capture individual changes and account for random errors. These changes were expressed as centered values to improve interpretability and reduce multicollinearity. At Level 2, differences in growth trajectories between groups defined by maturity status were examined. The 95% confidence intervals (CI) for each effect were calculated to make inferences regarding the effects' actual (population) values. Multilevel linear mixed models were employed to assess the impact of chronological age and maturity status on performance. Three models were created for each dependent variable: (1) age as the sole fixed effect; (2) age and maturity status as fixed effects; and (3) age, maturity status, and their interaction as fixed effects. The different models included playing position as a control variable to mitigate its influence as a confounding factor. Player ID was included as a random effect in all models to account for repeated measures and nested data structure. The normality of the residuals was evaluated using histograms and QQ plots, while homoscedasticity was checked using residual plots. Variance Inflation Factors (VIFs) were calculated to check for multicollinearity among predictors. Model fit was compared using log-likelihood values and the Akaike Information Criterion (AIC). The statistical analyses were performed using the Statistical Package for the Social Science, version 28.0 (SPSS Inc., Chicago, IL, USA).

4. Results

For total distance per minute (TD/min), Model 1, which included only age as a fixed effect, showed significant adverse effects of age ($\beta = -2.371$, $p = 0.001$), indicating that older athletes tended to cover less distance per minute. Model 3, which incorporated maturity status and its interaction with age, provided the best fit (AIC = 14481.497). This model provided significant effects for all parameters: intercept (β = -207.282, p = 0.001), age (β = 14.828, p = 0.001), maturity status (β = 133.276, p = 0.001), and their interaction (β = -9.378, p = 0.001).

In the context of high-speed running per minute (HSR/min), Model 1 showed significant positive effects of age (β = 0.527, p = 0.001), indicating that older athletes engaged more in high-speed running (HSR). Although Model 3, which included interaction terms, had the lowest AIC (7534.281), it did not yield significant effects for any of the parameters.

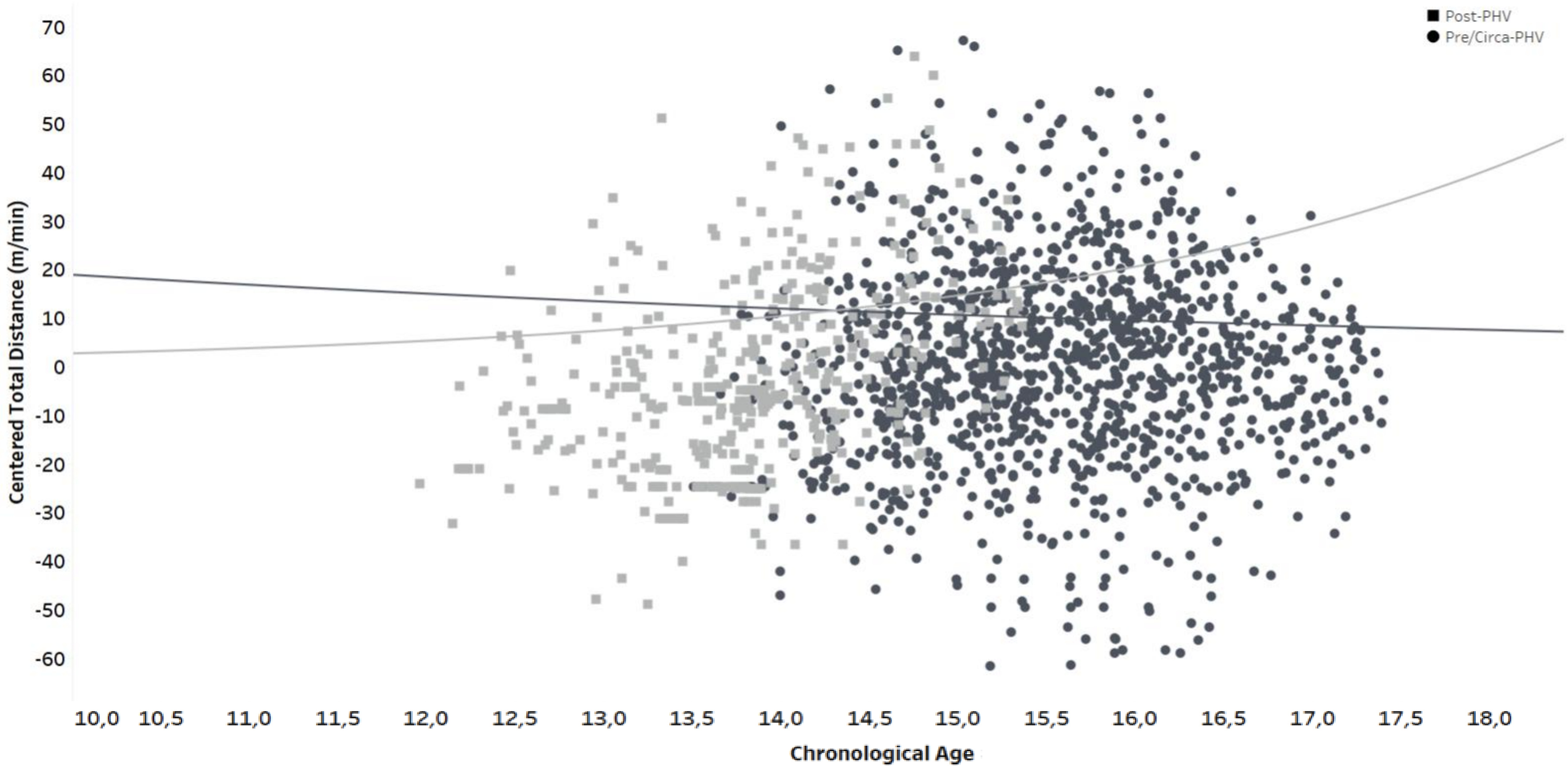
For sprint distance per minute (SD/min), Model 1 revealed a significant positive effect of age (β = 0.174, p = 0.001), indicating that older athletes sprinted more frequently. Model 2, which included maturity status, also showed significance (β = -0.020, p = 0.001); however, Model 3 did not yield significant results ($p > 0.05$) when the interaction terms were added. This suggests that while age significantly influences sprint distance (SD), the effect of maturity status and its interaction with age are not substantial.

Regarding total Ac and Dec per minute (Total Ac & Dec/ min), Model 3 provided the best fit with the lowest AIC (1510.667) and showed significant effects for all parameters: intercept (β = -4.746, p = 0.001), age (β = 0.349, p = 0.001), maturity status (β = 1.761, p = 0.002), and their interaction (β = -0.134, p = 0.001).

Table 4 - Mixed-Effects Model Results for All Metrics.

Metric	Model	Intercept (p-value)	Age (p-value)	Maturity (p-value)	Interaction (p-value)	AIC	Random Effect Variance
Total distance/min	1	34.838 (0.002)	-2.371 (0.001)	-	-	14513.913	145.546
	2	34.497 (0.003)	-2.331 (0.007)	-0.145 (0.929)	-	14511.076	145.648
	3	-207.282 (0.001)	14.828 (0.001)	133.276 (0.001)	-9.378 (0.001)	14481.497	133.987
High-speed running/min	1	4.414 (0.001)	0.527 (0.001)	-	-	7536.351	5.250
	2	-8.628 (0.001)	0.614 (0.001)	-0.323 (0.001)	-	7535.250	5.228
	3	-0.032 (0.996)	0.005 (0.991)	-5.073 (0.128)	0.333 (0.153)	7534.281	5.194
Sprint distance/min	1	-2.627 (0.001)	0.174 (0.001)	-	-	3982.742	0.516
	2	-2.675 (0.001)	0.179 (0.001)	-0.020 (0.001)	-	3986.050	0.516
	3	-0.638 (0.769)	0.035 (0.820)	-1.146 (0.326)	0.079 (0.334)	3988.291	0.513
Total accelerations and decelerations/min	1	-0.905 (0.001)	0.060 (0.001)	-	-	1532.902	0.099

	2	-1.276 (0.001)	0.103 (0.001)	-0.158 (0.001)	-	1517.752	0.097
	3	-4.746 (0.001)	0.349 (0.001)	1.761 (0.002)	-0.134 (0.001)	1510.667	0.097



Key: Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 1. Representation of the Total Distance (m/min) in terms of chronological age evolution according to maturity status.

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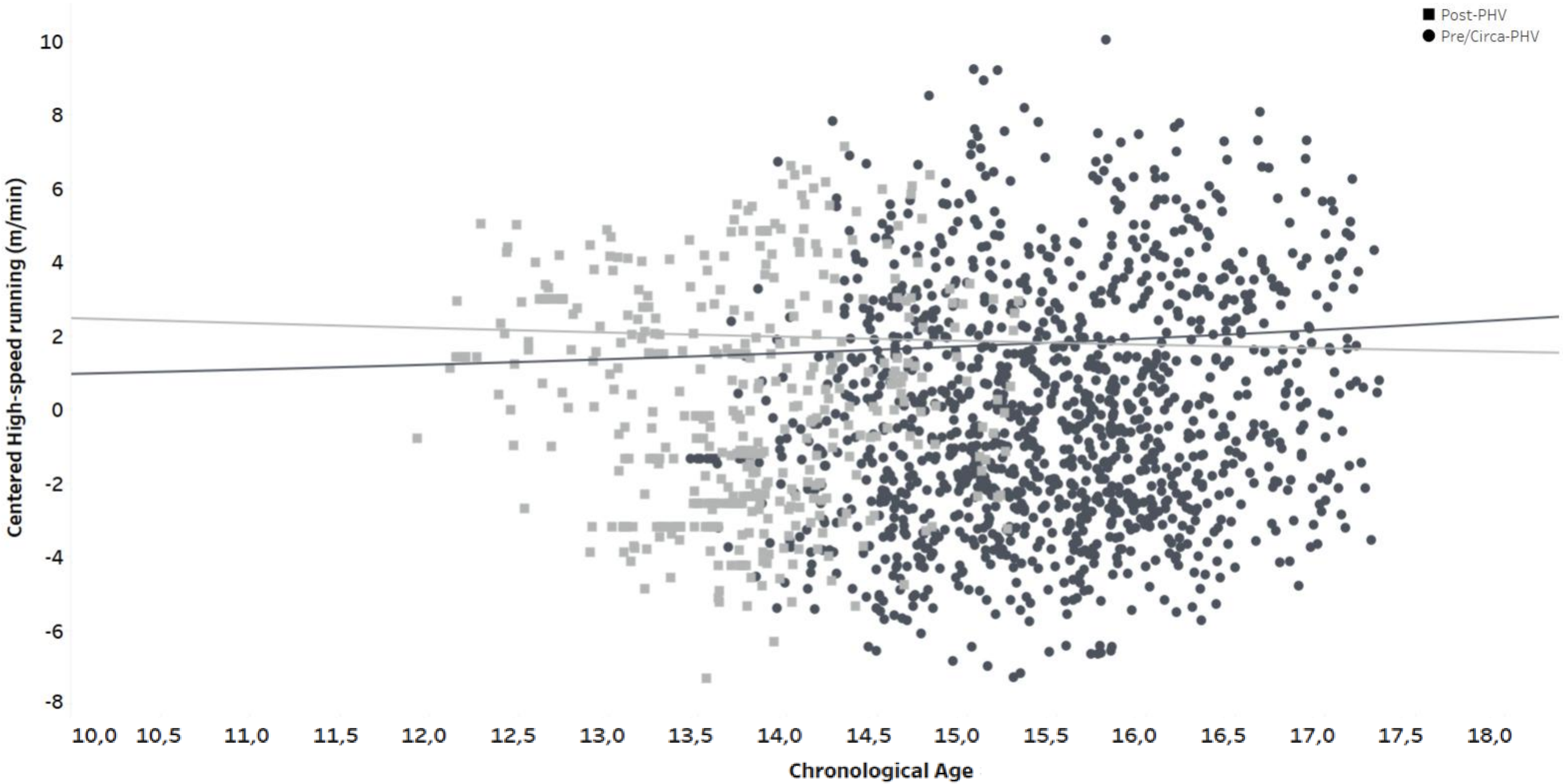
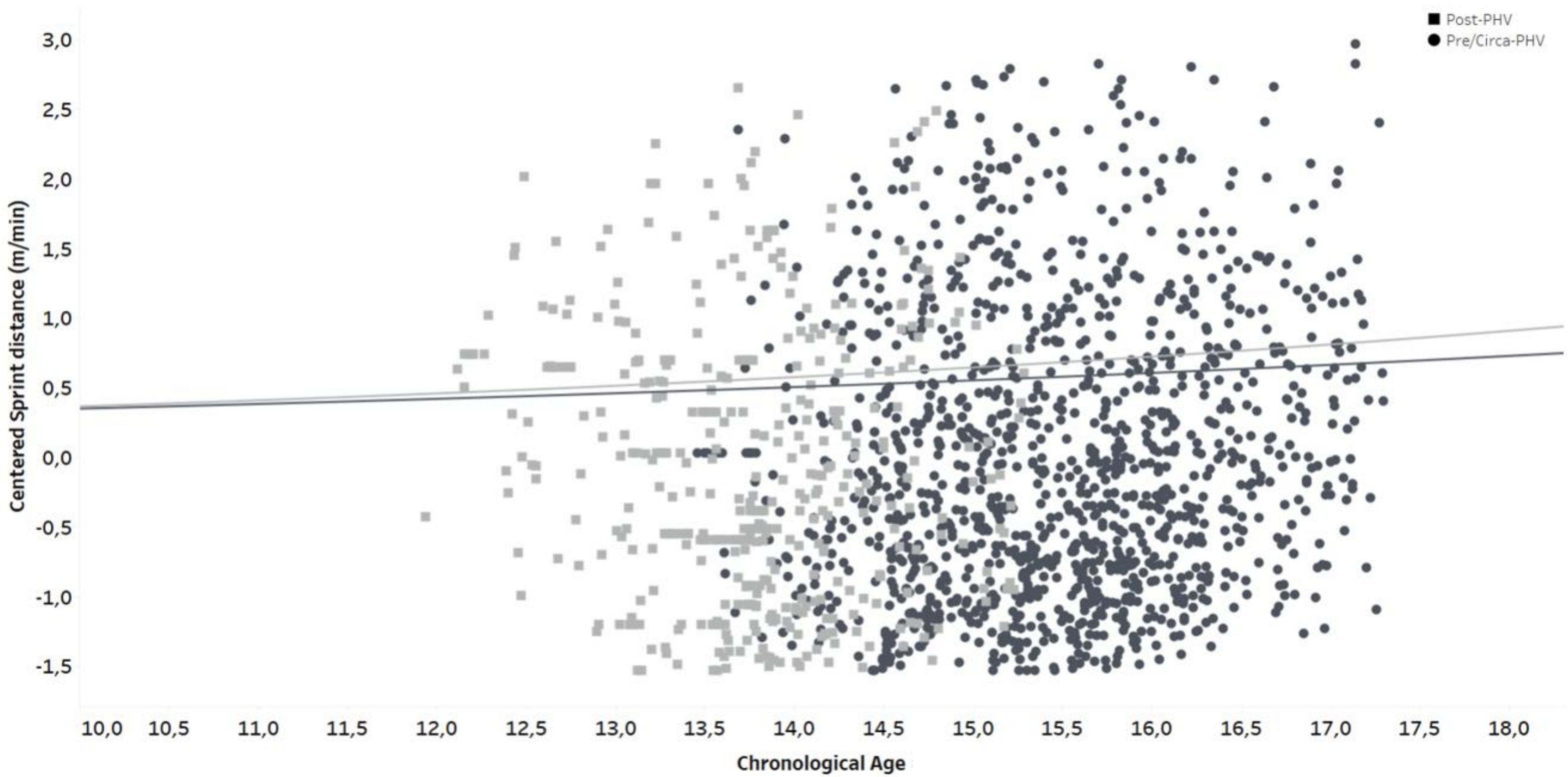


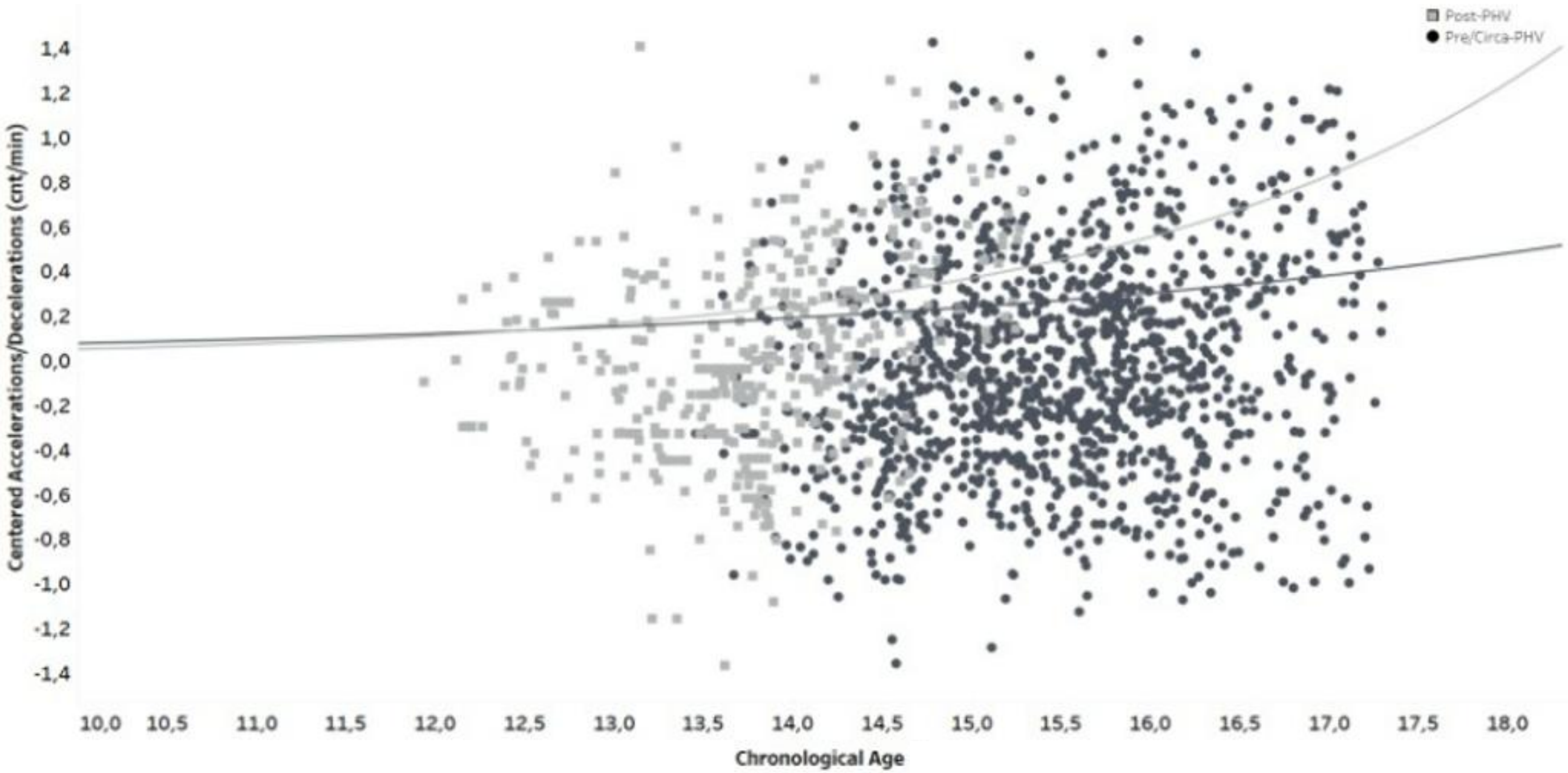
Key: Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 2. Representation of the High-Speed Running (m/min) in terms of chronological age evolution according to maturity status.



Key: Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 3. Representation of the Sprint Distance (m/min) in terms of chronological age evolution according to maturity status.



Key: Pre-Peak height velocity; Circa-PHV = Circa-Peak height velocity; Post-PHV = Post-Peak height velocity;

Figure 4. Representation of the Accelerations/ Decelerations (cnt/min) in terms of chronological age evolution according to maturity status.

5. Discussion

The primary objective was to assess how maturity status influences performance parameters over two consecutive seasons, with a focus on understanding how these factors interact with match workload. The findings underscore that age and maturity status independently influence various performance metrics such as TD/min, HSR/min, SD/min, and total Acc and Dec/min. The main findings were as follows: 1) as players age, the effect of maturity on TD tends to decrease; 2) although age significantly contributes to HSR and SD, the impact of maturity on these parameters is less pronounced; and 3) for Acc and Dec, age and maturity have significant effects, although the influence of maturity diminishes with age. This study explored the influence of biological maturation on the match workload of young soccer players and found significant associations between maturity, age, and critical physical performance metrics.

Our research showed that age played a significant role in determining TD/min, with older athletes generally covering less distance per minute but participating more in HSR/min and SD/min. The outcomes of our study (Table 2) align with those of previous research on young soccer players, which demonstrated that older players tend to perform better in high-intensity activities such as sprinting and HSR, but cover less of the overall distance [19,20]. These results demonstrate that older age groups traversed greater overall distances, achieved higher distances in HSR and very high-speed running distance (VHSR), and displayed faster velocities than younger groups [42,43]. It suggests that older participants have enhanced physical and athletic abilities, while also facing greater physical demands associated with competing in higher age brackets. It is imperative to express a caveat regarding previous studies and their comparison with our findings, particularly concerning the definitions of speed bands for the analysis of external loads in HSR and VHSR analyses, as numerous studies employ diverse bands, which has implications for comparative analysis. The reduction in TD/min as players age may also indicate that more experienced athletes exhibit enhanced performance owing to their accumulated expertise. This includes a profound understanding of physical capabilities, technical skills, and tactical knowledge [44]. Such expertise allows them to apply these abilities more efficiently, supported by a more comprehensive grasp of the game's intricacies and requirements [44]. Model 3, which incorporated both maturity and age interactions, showed that biological maturation plays a more substantial role in younger soccer players, supporting the study by Figueiredo et al. [10] in highlighting that physical development has a stronger impact on performance in early adolescence. Biological maturation also significantly influenced performance, particularly in the younger age groups (U14). The influence of maturation on TD/min decreased with age, suggesting that maturity exerts a more pronounced effect on younger athletes, a finding that is in line with that of Parr et al. [43]. This is further supported by Figueiredo et al. [10], who highlighted the importance of maturation in physical performance in early adolescence. As maturation progresses and physical and athletic attributes such as muscle mass and height become more uniform across players, the advantage of early maturity in TD/min diminishes, indicating that older players rely less on covering large distances and more on tactical movements.

Chronological age was the main factor affecting HSR/min performance. Model 1, which included only age, found a positive correlation between age and HSR ($\beta = 0.527$, $p = 0.001$), indicating that older players engage more frequently in high-speed movements. This pattern can be explained by the development of physical abilities such as strength and muscular power, which progress throughout adolescence, allowing more mature players to perform more sprints during matches. Although the inclusion of maturation and interaction terms in Model 3 resulted in a slightly better statistical fit (lower AIC), the parameters for maturation were not significant, suggesting that age alone was the main factor for HSR. For high HSR/min, age emerged as the primary determinant, with older players engaging more in high-speed activities. This result reinforces the findings of Buchheit and Mendez-Villanueva [12], who indicated that early maturing players tend to excel in high-speed tasks. The lack of significant interaction effects in Model 3 suggests that, while maturation may initially benefit younger players in high-speed activities, its influence becomes less pronounced as they reach mid-adolescence. This may be due to the increasing role of tactical understanding and technical skills, which become progressively more important than biological maturity in the older age groups. Lovell et al. [44] further highlighted this phenomenon, noting that while early maturation offers an advantage in younger athletes, its impact diminishes with age, consistent with our findings in the U15 and U16 groups. Thus, while HSR is positively associated with age, the effect of maturation diminishes, implying a shift from purely physical to skill-based factors that influence high-speed running performance.

Similar to HSR, SD/min was influenced predominantly by age, with older players engaging more in sprinting. The positive relationship observed in Model 1 between age and sprint frequency ($\beta = 0.174$, $p = 0.001$) suggests that sprinting ability develops with age, potentially because of greater muscle strength and neuromuscular efficiency. Maturation also contributed to SD/min, albeit modestly, with younger, more mature players engaging in slightly less sprinting than their less mature peers. This finding aligns with Lovell et al. [44], who observed that maturation benefits performance but that the effect weakens with age, especially as factors such as technical skill and game awareness become increasingly critical. The lack of significant interaction effects in Model 3 further supports the notion that age, rather than biological maturity, has a primary influence on sprinting activity, particularly in the older age groups. Consequently, while early maturing players may demonstrate superior sprinting in younger age brackets, these advantages are overshadowed by other performance factors as players progress in age.

Acc and Dec/min results showed that age, biological maturation, and their interaction significantly influenced these dynamic movements. Model 3 provided the best fit, highlighting the significant effects of age ($\beta = 0.349$, $p = 0.001$), maturation ($\beta = 1.761$, $p = 0.002$), and their interaction ($\beta = -0.134$, $p = 0.001$) on the frequency of acceleration and deceleration. A negative interaction term indicates that the combined effect of age and maturation on these movements is less than the sum of their individual effects. Specifically, younger players with advanced biological maturation demonstrated higher frequencies of acceleration and deceleration, suggesting a performance advantage associated with early physical development. However, as players age, the influence of biological maturation diminishes. This change may be attributed to age-related improvements in neuromuscular control and coordination, which reduces reliance on frequent dynamic movements. Figueiredo et al. [7] similarly found that early maturers excel in strength- and power-dependent activities during youth. However, these physical advantages are progressively offset by the development of technical skills and neuromuscular efficiency as the players mature [6].

These findings suggest an evolution in movement patterns with age. Younger players tend to rely heavily on frequent accelerations and decelerations owing to their physical maturity, whereas older players employ these movements more selectively, reflecting advanced tactical and technical gameplay. This shift underscores the importance of age specific training. For younger players, programs should focus on enhancing neuromuscular control along with physical strength. For older players, the emphasis should shift toward refining tactical and technical skills. The interplay between age, maturation, and their interaction offers critical insights into optimizing player development and improving matchplay efficiency.

6. Limitations and future directions

The restricted sample size potentially constrains the generalizability of the findings to wider populations or varying competitive levels. Subsequent research should encompass more diverse cohorts to bolster external validity. Although this study concentrated on external load parameters, a more holistic approach incorporating internal workload measures could yield additional insights. Precise delineation of the methodologies employed for assessing biological maturation, along with the metrics and speed ranges utilized to quantify the external load, is crucial for facilitating more accurate comparisons. The cross-sectional design of this study precludes the determination of the long-term effects of biological maturation on player development. Future investigations should encompass a sample representing players across various stages of biological maturation, including the pre-, PHV, and post-PHV phases, to provide a more comprehensive analysis. The exclusive focus on male soccer players limits the applicability of the findings to female athletes; thus, subsequent studies should include female soccer players to examine potential similarities in maturation-related trends across the sexes.

7. Conclusions

This study demonstrated that CA and biological maturation significantly influenced key external load parameters in young male soccer players. CA was a primary determinant of metrics such as HSR and SD. However, the interaction between age and biological maturation significantly influenced the TD/min, Acc/min, and Dec/min. As the players matured, the isolated impact of biological maturation on physical performance metrics decreased. These findings emphasize the importance of incorporating biological maturation into player assessments to enhance the precision of performance evaluations and inform age-specific training strategies for youth soccer.

8. Practical Applications

The findings of this study have several implications for coaches and practitioners of young soccer players. First, the significant influence of age on performance metrics suggests that training programs should be tailored to the developmental stages of athletes. Younger players may benefit from focusing on developing fundamental skills and physical attributes, whereas older players can incorporate more advanced training techniques and tactics. Second, this study highlights the importance of biological maturation in player selection and development. Early maturing players may possess physical advantages; however, ensuring that their development is balanced and sustainable is crucial. Coaches should monitor the progress of all players regardless of their maturation status and provide appropriate support and guidance. Finally, the findings emphasize the need for individualized training programs that account for the unique needs of each player. While age and maturity status can provide valuable insights, it is essential to consider other factors, such as playing position, injury history, and individual preferences. By tailoring training programs according to the specific characteristics of each athlete, coaches can optimize their development and maximize their potential.

9. References

1. le Gall, F.; Carling, C.; Williams, M.; Reilly, T. Anthropometric and Fitness Characteristics of International, Professional and Amateur Male Graduate Soccer Players from an Elite Youth Academy. *J. Sci. Med. Sport* **2010**, *13* (1), 90–95. https://doi.org/10.1016/j.jsams.2008.07.004.

2. Carling, C.; Le Gall, F.; Reilly, T.; Williams, A. M. Do Anthropometric and Fitness Characteristics Vary According to Birth Date Distribution in Elite Youth Academy Soccer Players? *Scand. J. Med. Sci. Sports* **2009**, *19* (1), 3–9. https://doi.org/10.1111/j.1600-0838.2008.00867.x.

3. Reilly, T.; Williams, A. M.; Nevill, A.; Franks, A. A Multidisciplinary Approach to Talent Identification in Soccer. *J. Sports Sci.* **2000**, *18* (9), 695–702. https://doi.org/10.1080/02640410050120078.

4. Johnson, A. Monitoring the Immature Athlete. *Aspetar Sport. Med. J.* **2015**, *4* (1), 114–118.

5. Johnson, A.; Doherty, P. J.; Freemont, A. Investigation of Growth, Development, and Factors Associated with Injury in Elite Schoolboy Footballers: Prospective Study. *BMJ* **2009**, *338* (feb26 1), b490–b490. https://doi.org/10.1136/bmj.b490.

6. Cumming, S. P.; Searle, C.; Hemsley, J. K.; Haswell, F.; Edwards, H.; Scott, S.; Gross, A.; Ryan, D.; Lewis, J.; White, P.; Cain, A.; Mitchell, S. B.; Malina, R. M. Biological Maturation, Relative Age and Self-Regulation in Male Professional Academy Soccer Players: A Test of the Underdog Hypothesis. *Psychol. Sport Exerc.* **2018**, *39*, 147–153. https://doi.org/10.1016/j.psychsport.2018.08.007.

7. Figueiredo, A. J.; Gonçalves, C. E.; Coelho e Silva, M. J.; Malina, R. M. Characteristics of Youth Soccer Players Who Drop out, Persist or Move Up. *J. Sports Sci.* **2009**, *27* (9), 883–891. https://doi.org/10.1080/02640410902946469.

8. Malina, R. M.; Rogol, A. D.; Cumming, S. P.; Coelho e Silva, M. J.; Figueiredo, A. J. Biological Maturation of Youth Athletes: Assessment and Implications. *Br. J. Sports Med.* **2015**, *49* (13), 852–859. https://doi.org/10.1136/bjsports-2015-094623.

9. van der Sluis, A.; Elferink-Gemser, M.; Brink, M.; Visscher, C. Importance of Peak Height Velocity Timing in Terms of Injuries in Talented Soccer Players. *Int. J. Sports Med.* **2015**, *36* (04), 327–332. https://doi.org/10.1055/s-0034-1385879.

10. Figueiredo, A. J.; e Silva, M. J. C.; Cumming, S. P.; Malina, R. M. Size and Maturity Mismatch in Youth Soccer Players 11- to 14-Years-Old. *Pediatr. Exerc. Sci.* **2010**, *22* (4), 596–612. https://doi.org/10.1123/pes.22.4.596.

11. Hannon, M. P.; Carney, D. J.; Floyd, S.; Parker, L. J. F.; McKeown, J.; Drust, B.; Unnithan, V. B.; Close, G. L.; Morton, J. P. Cross-Sectional Comparison of Body Composition and Resting Metabolic Rate in Premier League Academy Soccer Players: Implications for Growth and Maturation. *J. Sports Sci.* **2020**, *38* (11–12), 1326–1334. https://doi.org/10.1080/02640414.2020.1717286.

12. Buchheit, M.; Mendez-Villanueva, A. Effects of Age, Maturity and Body Dimensions on Match Running Performance in Highly Trained under-15 Soccer Players. *J. Sports Sci.* **2014**, *32* (13), 1271–1278. https://doi.org/10.1080/02640414.2014.884721.

13. Abbott, W.; Williams, S.; Brickley, G.; Smeeton, N. Effects of Bio-Banding upon Physical and Technical Performance during Soccer Competition: A Preliminary Analysis. *Sports* **2019**, *7* (8), 193. https://doi.org/10.3390/sports7080193.

14. Brink, M. S.; Nederhof, E.; Visscher, C.; Schmikli, S. L.; Lemmink, K. A. P. M. Monitoring Load, Recovery, and Performance in Young Elite Soccer Players. *J. Strength Cond. Res.* **2010**, *24* (3), 597–603. https://doi.org/10.1519/JSC.0b013e3181c4d38b.

15. Hannon, M. P.; Coleman, N. M.; Parker, L. J. F.; McKeown, J.; Unnithan, V. B.; Close, G. L.; Drust, B.; Morton, J. P. Seasonal Training and Match Load and Micro-Cycle Periodization in Male Premier League Academy Soccer Players. *J. Sports Sci.* **2021**, *39* (16), 1838–1849. https://doi.org/10.1080/02640414.2021.1899610.

16. Nobari, H.; Fani, M.; Clemente, F. M.; Carlos-Vivas, J.; Pérez-Gómez, J.; Ardigò, L. P. Intra- and Inter-Week Variations of Well-Being Across a Season: A Cohort Study in Elite Youth Male Soccer Players. *Front. Psychol.* **2021**, *12*. https://doi.org/10.3389/fpsyg.2021.671072.

17. Ribeiro, N.; Martinho, D. V.; Pereira, J. R.; Rebelo, A.; Monasterio, X.; Gonzalo-

Skok, O.; Valente-dos-Santos, J.; Tavares, F. Injury Risk in Elite Young Male Soccer Players: A Review on the Impact of Growth, Maturation, and Workload. *J. Strength Cond. Res.* **2024**. https://doi.org/10.1519/JSC.0000000000004889.

18. Parry, G. N.; Williams, S.; McKay, C. D.; Johnson, D. J.; Bergeron, M. F.; Cumming, S. P. Associations between Growth, Maturation and Injury in Youth Athletes Engaged in Elite Pathways: A Scoping Review. *Br. J. Sports Med.* **2024**, *58* (17), 1001–1010. https://doi.org/10.1136/bjsports-2024-108233.

19. Buchheit, M.; Mendez-Villanueva, A.; Simpson, B. M.; Bourdon, P. C. Match Running Performance and Fitness in Youth Soccer. *Int. J. Sports Med.* **2010**, *31* (11), 818–825. https://doi.org/10.1055/s-0030-1262838.

20. Goto, H.; Morris, J. G.; Nevill, M. E. Influence of Biological Maturity on the Match Performance of 8- to 16-Year-Old, Elite, Male, Youth Soccer Players. *J. Strength Cond. Res.* **2019**, *33* (11), 3078–3084. https://doi.org/10.1519/JSC.0000000000002510.

21. Figueiredo, A. J.; Gonçalves, C. E.; Coelho E Silva, M. J.; Malina, R. M. Youth Soccer Players, 11–14 Years: Maturity, Size, Function, Skill and Goal Orientation. *Ann. Hum. Biol.* **2009**, *36* (1), 60–73. https://doi.org/10.1080/03014460802570584.

22. Hansen, L.; Klausen, K.; Bangsbo, J.; Müller, J. Short Longitudinal Study of Boys Playing Soccer: Parental Height, Birth Weight and Length, Anthropometry, and Pubertal Maturation in Elite and Non-Elite Players. *Pediatr. Exerc. Sci.* **1999**, *11* (3), 199–207. https://doi.org/10.1123/pes.11.3.199.

23. le Gall, F.; Carling, C.; Williams, M.; Reilly, T. Anthropometric and Fitness Characteristics of International, Professional and Amateur Male Graduate Soccer Players from an Elite Youth Academy. *J. Sci. Med. Sport* **2010**, *13* (1), 90–95. https://doi.org/10.1016/j.jsams.2008.07.004.

24. Malina, R. M.; Eisenmann, J. C.; Cumming, S. P.; Ribeiro, B.; Aroso, J. Maturity-Associated Variation in the Growth and Functional Capacities of Youth Football (Soccer) Players 13-15 Years. *Eur. J. Appl. Physiol.* **2004**, *91* (5–6), 555–562. https://doi.org/10.1007/s00421-003-0995-z.

25. Philippaerts, R. M.; Vaeyens, R.; Janssens, M.; Van Renterghem, B.; Matthys, D.;

Craen, R.; Bourgois, J.; Vrijens, J.; Beunen, G.; Malina, R. M. The Relationship between Peak Height Velocity and Physical Performance in Youth Soccer Players. *J. Sports Sci.* **2006**, *24* (3), 221–230. https://doi.org/10.1080/02640410500189371.

26. Malina, R. M.; Reyes, M. E. P.; Eisenmann, J. C.; Horta, L.; Rodrigues, J.; Miller, R. Height, Mass and Skeletal Maturity of Elite Portuguese Soccer Players Aged 11–16 Years. *J. Sports Sci.* **2000**, *18* (9), 685–693. https://doi.org/10.1080/02640410050120069.

27. Fransen, J.; Bush, S.; Woodcock, S.; Novak, A.; Deprez, D.; Baxter-Jones, A. D. G.; Vaeyens, R.; Lenoir, M. Improving the Prediction of Maturity From Anthropometric Variables Using a Maturity Ratio. *Pediatr. Exerc. Sci.* **2018**, *30* (2), 296–307. https://doi.org/10.1123/pes.2017-0009.

28. Kozieł, S. M.; Malina, R. M. Modified Maturity Offset Prediction Equations: Validation in Independent Longitudinal Samples of Boys and Girls. *Sport. Med.* **2018**, *48* (1), 221–236. https://doi.org/10.1007/s40279-017-0750-y.

29. Mirwald, R. L.; G. Baxter-Jones, A. D.; Bailey, D. A.; Beunen, G. P. An Assessment of Maturity from Anthropometric Measurements. *Med. Sci. Sport. Exerc.* **2002**, *34* (4), 689–694. https://doi.org/10.1097/00005768-200204000-00020.

30. Robert M Malina; Claude Bouchard; Oded Bar-Or. *Growth, Maturation, and Physical Activity*; 2004.

31. Nevill, A.; Burton, R. F. Commentary on the Article “Improving the Prediction of Maturity From Anthropometric Variables Using a Maturity Ratio.” *Pediatr. Exerc. Sci.* **2018**, *30* (2), 308–310. https://doi.org/10.1123/pes.2017-0201.

32. Cumming, S. P.; Brown, D. J.; Mitchell, S.; Bunce, J.; Hunt, D.; Hedges, C.; Crane, G.; Gross, A.; Scott, S.; Franklin, E.; Breakspear, D.; Dennison, L.; White, P.; Cain, A.; Eisenmann, J. C.; Malina, R. M. Premier League Academy Soccer Players’ Experiences of Competing in a Tournament Bio-Banded for Biological Maturation. *J. Sports Sci.* **2018**, *36* (7), 757–765. https://doi.org/10.1080/02640414.2017.1340656.

33. Malina, R. M.; Cumming, S. P.; Rogol, A. D.; Coelho-e-Silva, M. J.; Figueiredo, A. J.; Konarski, J. M.; Kozieł, S. M. Bio-Banding in Youth Sports: Background, Concept, and Application. *Sport. Med.* **2019**, *49* (11), 1671–1685. https://doi.org/10.1007/s40279-

019-01166-x.

34. Khamis, H. J.; Roche, A. F. Predicting Adult Stature without Using Skeletal Age: The Khamis-Roche Method. *Pediatrics* **1994**, *94* (4 Pt 1), 504–507.

35. Parr, J.; Winwood, K.; Hodson-Tole, E.; Deconinck, F. J. A.; Hill, J. P.; Teunissen, J. W.; Cumming, S. P. The Main and Interactive Effects of Biological Maturity and Relative Age on Physical Performance in Elite Youth Soccer Players. *J. Sports Med.* **2020**, *2020*, 1–11. https://doi.org/10.1155/2020/1957636.

36. Marfell-Jones, M. J., Stewart, A. D., & de Ridder, J. H. *International Standards for Anthropometric Assessment*; International Society for the Advancement of Kinanthropometry, Ed.; 2012.

37. Sweeney, L.; Cummin, S.; MacNamara, Á.; Horan, D. The Selection Advantages Associated with Advanced Biological Maturation Vary According to Playing Position in National-Level Youth Soccer. *Biol. Sport* **2023**, *40* (3), 715–722. https://doi.org/10.5114/biolsport.2023.119983.

38. Epstein, L. H.; Valoski, A. M.; Kalarchian, M. A.; McCurley, J. Do Children Lose and Maintain Weight Easier Than Adults: A Comparison of Child and Parent Weight Changes From Six Months to Ten Years. *Obes. Res.* **1995**, *3* (5), 411–417. https://doi.org/10.1002/j.1550-8528.1995.tb00170.x.

39. Cumming, S. P.; Lloyd, R. S.; Oliver, J. L.; Eisenmann, J. C.; Malina, R. M. Bio-Banding in Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of Youth Athletes. *Strength Cond. J.* **2017**, *39* (2), 34–47. https://doi.org/10.1519/SSC.0000000000000281.

40. Johnson, D. M.; Cumming, S. P.; Bradley, B.; Williams, S. The Influence of Exposure, Growth and Maturation on Injury Risk in Male Academy Football Players. *J. Sports Sci.* **2022**, *40* (10), 1127–1136. https://doi.org/10.1080/02640414.2022.2051380.

41. Harley, J. A.; Barnes, C. A.; Portas, M.; Lovell, R.; Barrett, S.; Paul, D.; Weston, M. Motion Analysis of Match-Play in Elite U12 to U16 Age-Group Soccer Players. *J. Sports Sci.* **2010**, *28* (13), 1391–1397. https://doi.org/10.1080/02640414.2010.510142.

42. Parr, J.; Winwood, K.; Hodson-Tole, E.; Deconinck, F. J. A.; Hill, J. P.; Cumming, S. P. Maturity-Associated Differences in Match Running Performance in Elite Male Youth Soccer Players. *Int. J. Sports Physiol. Perform.* **2022**, *17* (9), 1352–1360. https://doi.org/10.1123/ijspp.2020-0950.

43. Sal de Rellán-Guerra, A.; Rey, E.; Kalén, A.; Lago-Peñas, C. Age-related Physical and Technical Match Performance Changes in Elite Soccer Players. *Scand. J. Med. Sci. Sports* **2019**, *29* (9), 1421–1427. https://doi.org/10.1111/sms.13463.

44. Lovell, R.; Fransen, J.; Ryan, R.; Massard, T.; Cross, R.; Eggers, T.; Duffield, R. Biological Maturation and Match Running Performance: A National Football (Soccer) Federation Perspective. *J. Sci. Med. Sport* **2019**, *22* (10), 1139–1145. https://doi.org/10.1016/j.jsams.2019.04.007.

Chapter 4

STUDY IV

From Theory to Practice: The Role of Growth, Maturation, and Workload in Injury Risk Mitigation for Young Soccer Players

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From Theory to Practice: The Role of Growth, Maturation, and Workload in Injury Risk Mitigation for Young Soccer Players

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1. Abstract

The development of young male soccer players entails intricate interactions among growth, maturation, and workload, which significantly impact injury risk. Peak height velocity (PHV) constitutes a critical phase during which players undergo rapid physical changes, potentially increasing their susceptibility to injury. Given the variability in biological maturation, practitioners must implement individualized strategies to manage workloads and mitigate the risk of injury. This review synthesizes the current evidence on growth and maturation monitoring, offering a framework for integrating these insights into practical training interventions. It emphasizes the importance of longitudinal assessments, tailored workload management, and communication strategies among coaches, medical staff, and players. Practical applications include systematic tracking of growth metrics, bio-banding, modifying workloads based on maturity status, and implementing recovery protocols for high-risk individuals. These strategies enable practitioners to identify players undergoing accelerated growth and adjust training accordingly to reduce injury risk while optimizing long-term development. By bridging the gap between theoretical knowledge and applied practice, this review provides

actionable recommendations to support young athletes throughout their developmental journey, ensuring a balance between performance enhancement and injury mitigation.

Keywords: long-term athletic development; intrinsic factors; extrinsic factors; assessment; monitoring

2. Introduction

Youth soccer academies invest considerable resources in developing players who can either progress to the first team or generate transfer revenue [1–3]. To protect this investment, it is essential to manage injury risks during key developmental periods, especially the adolescent growth spurt [1,4–6]. Strength and conditioning coaches play a pivotal role in youth development by applying evidence-based strategies that enhance physical performance while reducing injury risk [1,7–13]. A comprehensive and integrated plan is essential to support long-term athletic progression and overall player wellbeing [2,4].

For strength and conditioning coaches working with young soccer players, understanding growth and biological maturation is fundamental to tailoring training and reducing injury risk [1,4,14]. Because players of the same chronological age often differ significantly in biological maturity, coaches must assess and account for these individual differences when planning workloads [7,15–18]. Regular monitoring of biological maturity can help determine a player's readiness for increased training intensity and match demands [4,14]. The adolescent growth spurt represents a critical phase, as rapid changes in body size and neuromuscular function can elevate the risk of injury, particularly in elite youth players exposed to high training volumes [1,4,6]. To support player development safely and effectively, strength and conditioning professionals must understand how growth and maturation interact with workload, and apply this knowledge to daily practice [4].

Growth refers to measurable changes in body size and composition, including height, weight, and proportions of fat and muscle mass [7,17,19,20]. During adolescence, boys typically undergo a rapid acceleration in height, known as peak height velocity (PHV), between ages 13 and 14, followed by peak weight velocity (PWV) around 14 to 15 years of age [20–25]. These changes follow a proximal-distal growth pattern, where distal segments like feet and hands mature earlier than central structures (63,83,97). As such, training and performance may be affected by temporary disruptions in coordination, often called "adolescent awkwardness" [26–28]. These motor control challenges are further influenced by delayed muscular development relative to skeletal growth [29,30], which potentially reduces proprioceptive ability and increases the risk of injury. For strength and conditioning coaches, it is essential to monitor PHV and PWV to adjust training loads and manage expectations around performance [6,24,29,31]. Inadequate workload control during this phase can contribute to overuse injuries, making it critical to individualize exposure to training and match demands in line with biological development [32,33].

Maturation refers to the biological process of progressing from childhood to adulthood and can be assessed through various systems, such as somatic, skeletal, sexual, and dental development [19,20,34]. It is typically described by three key dimensions: maturity status (current level of maturation), timing (age at which milestones such as peak height velocity [PHV] occur), and tempo (rate of progression through maturation) [24]. These differences are primarily driven by variations in the timing (onset) and tempo (rate) of maturation, resulting in status differences among players of the same chronological age [17,24,35]. In practical terms, strength and conditioning coaches should be aware that biological maturity does not uniformly align with chronological age. For instance, two 13-year-old players may differ substantially in physical qualities owing to differences in their biological maturation.

In academy environments, somatic maturation, which focuses on changes in height, weight, and body proportion, is most commonly assessed using non-invasive anthropometric techniques [24,36]. Predictive models based on standing height, sitting height, leg length, and body mass allow practitioners to estimate the age at PHV (APHV) and predict adult height, offering a practical, low-cost alternative to radiographic methods [14,37]. These tools help coaches adjust to workloads, manage injury risks, and set realistic performance expectations. However, caution is advised when using these predictions at the individual level because they may be affected by population-specific assumptions and measurement errors. Therefore, whenever possible, somatic indicators should be complemented by longitudinal monitoring and a comprehensive understanding of how growth and maturation affect performance to support accurate interpretation and individualized decision-making [14,24,36,37].

Recent studies have highlighted a link between somatic maturation (which describes the biological process associated with the body's physical development, particularly in terms of height, weight, and body proportions) and injury risk in male youth soccer players [10,13,38–40], although further research is needed to establish definitive evidence-based strategies. Some studies have suggested that players in the circa-PHV phase, typically defined as 88–96% of predicted adult height (PAH), may be more susceptible to injury due to rapid increases in body size, biomechanical instability, and neuromuscular control challenges [41,42]. This period is also commonly associated with growth-related conditions, such as apophyseal injuries [43]. However, other findings report comparable injury rates between circa- and post-PHV players [38] or even a higher injury burden in post-PHV athletes, although differences may not always reach statistical significance [44]. These discrepancies underscore the importance of avoiding generalizations and instead considering individual variability and methodological differences across studies. Three key growth- and maturation-related risk factors have been reported in the literature. First, the circa-PHV period appears to represent a vulnerable stage in which athletes are adapting to rapid somatic changes that may compromise motor coordination and increase injury susceptibility [41,42]. Second, a rapid growth rate, particularly rates exceeding 7.2 cm/year, has been associated with a higher incidence of musculoskeletal injuries, especially in the lower limbs, which are the most frequently affected regions in youth soccer. This threshold has been reported in specific studies examining growth-related injury risk [41,45,46], while other studies support the broader association between accelerated growth and increased injury risk, without defining a precise cutoff point [11,47–49]. Third, accelerated growth of the lower limbs has also been associated with an elevated risk of overuse injuries in the bone and growth plate structures [49].

Despite recognizing these risk factors, few studies have offered practical solutions to reduce the risk of injury during periods of rapid growth [6,50]. Coaches and practitioners should implement proactive strategies such as early identification of at-risk players and adjusting training content and load based on maturity status [6]. Differentiating between modifiable factors such as workload and non-modifiable factors such as growth and maturation is crucial for developing individualized risk profiles and guiding decision-making [4]. Ultimately, integrating a maturity-informed framework into training practices can help reduce injury impact and promote safer long-term development [1,4,51].

Effective injury mitigation in youth soccer requires coordinated efforts across performance, coaching, and medical teams [1,4,6,51]. Bridging the gap between research and practice is essential to protecting young players while supporting their athletic development. Strength and conditioning professionals play a pivotal role in this process, not only by enhancing performance, but also by reducing injury risk and promoting long-term athlete health. Key strategies such as regular monitoring of growth, individualized workload management, and training adjustments based on maturity status can significantly reduce injury risk when properly applied [1,4,6]. Despite advances in research, many academies struggle to apply scientific insights that align with the practical demands of youth development. While circa-PHV and fast-growing players are often highlighted as being at elevated injury risk, post-PHV athletes may also be vulnerable, whether due to accumulated fatigue, previous injuries, increased training and match exposure, or simply because they are more prone to sustaining more burdensome injuries, such as those involving muscle or joint structures, or lumbar bone stress injuries [13].

This narrative review aims to translate scientific evidence into practical applications by offering a flexible framework that accounts for the variability among players, teams, and academy settings. It promotes actionable strategies such as longitudinal growth monitoring, individualized workload control, and maturity-based training adjustments to support informed decision-making. The ultimate goal is to help coaches and practitioners create development environments that balance performance, health, and individual needs, allowing young soccer players to grow, perform, and thrive on and off the field.

3. Practical Applications of Injury Risk in Elite Young Male Soccer Players – Growth and Maturation

From an applied perspective, strength and conditioning coaches must adopt a multifaceted approach that integrates monitoring of growth and maturation with evidence-based training interventions. The implementation of regular anthropometric assessments and maturity estimations can provide valuable insights into an athlete’s developmental trajectory, allowing for tailored training prescriptions [36]. Furthermore, fostering collaboration within multidisciplinary teams, including physiotherapists, sports scientists, and technical coaches, ensures a holistic approach to injury mitigation and long-term athletic development [23]. An integrative model can facilitate optimal workload management and mitigate the likelihood of training-induced injuries, while promoting sustainable performance gains.

The interaction between rapid physical development and increased workload presents a multifactorial challenge for practitioners who aim to optimize performance while reducing injury risk. Given that periods of accelerated growth have been linked to heightened susceptibility to musculoskeletal injuries [1], it is imperative to establish individualized monitoring and training strategies that account for biological rather than chronological age [18]. The findings reinforce the growing body of evidence indicating that maturation plays a significant role in injury susceptibility, circa-PHV being a particularly vulnerable period for young athletes [10,13,36,42,47,49]. This discussion contextualizes the current findings within the existing body of literature, emphasizes practical implications for practitioners, and offers evidence-based recommendations for mitigating injury risk in young athletes. The disproportionate growth of bones compared to the adaptive capacity of muscles and tendons creates an imbalance that may predispose athletes to conditions such as Sever's Disease or Osgood-Schlatter syndrome [52]. These findings emphasize the necessity of structured workload management during PHV to prevent excessive mechanical stress on the immature musculoskeletal structures.

A key aspect of injury risk management in adolescent soccer players is the regular assessment of growth and maturation indicators [1,4,36]. The use of anthropometric measurements, such as standing stature, sitting height, and body mass, coupled with parental stature data, allows for the calculation of predicted adult height using the Khamis-Roche method [53,54]. This approach has been widely supported in the literature as a non-invasive and practical means of estimating biological maturity [14,24,36]. Tracking these parameters longitudinally enables practitioners to identify PHV during which players are at heightened risk of musculoskeletal injuries [54]. Furthermore, Monasterio et al. [55] presented important insights into the assessment of growth and maturation in the context of soccer academies; namely, an accurate assessment of maturity status concerning PHV can be achieved through visual evaluation of individual growth trajectories by a skilled observer. Although equations designed to predict maturity offset tend to misclassify most athletes, PAH% has emerged as a comparatively valid alternative approach [55]. Visual evaluation of the growth curves by an experienced assessor showed the highest agreement with maturity status (circa- or post-PHV) classifications based on longitudinal data [55].

Conversely, workload monitoring remains a crucial strategy for reducing injury risk. Research linking workload to injury risk primarily centers on mature athletes and may not apply to younger players [56,57]. Moreover, it is essential to recognize that training elicits distinct biological and psychological adaptations in young soccer players compared to adults, which is vital for comprehending how fatigue correlates with heightened risk of injury [56,58]. Effective workload management has emerged as a critical factor for reducing injury risk among young soccer players. Previous research has demonstrated that excessive spikes in acute workloads relative to chronic workloads significantly increase the likelihood of injury [59]. Furthermore, competition-to-training ratios should be carefully balanced to avoid excessive game exposure, as competition inherently carries a higher risk of injury than training [60]. Young players should maintain a training-dominant workload distribution to optimize physical development and mitigate injury risk [9]. However, a recent investigation revealed a notable connection between exposure to training, growth rate, and the occurrence of injuries among young soccer players [41]. The study found that a 2 SD change in weekly training duration corresponded to a 168% increase in the likelihood of injury [41]. Furthermore, the study identified a direct linear correlation between growth rate and injury frequency, as well as a nonlinear association between injury risk and the percentage of predicted adult stature (PPAH), with the peak occurring at 92% of the predicted adult height [41]. These observations are consistent with previous research, indicating that periods of rapid growth create biomechanical and neuromuscular challenges that may increase the susceptibility of young athletes to injuries [14,36]. These findings reinforce this relationship and highlight the importance of progressive exposure to high-intensity activities, particularly in athletes undergoing rapid growth [1,4]. According to these findings, it is fundamental to manage workloads during microcycles based on growth and maturation indicators, incorporating strategies in the field and gym sessions. The study by Johnson et al. [6] aimed to use interdisciplinary collaboration between technical coaches, sports scientists, and medical staff to mitigate this risk and presented crucial content for mitigating injury risk by an iterative sequence of prevention in male academy soccer players [6]. Johnson et al. [6] found that a modified training program for adolescent soccer players led to a notable decrease in injuries. This approach involves slightly reducing team-based exercises and introducing personalized elements with small reductions in team-based training, substituted with low-intensity individual skills, balance and coordination, impact attenuation, and strength training, including eccentric hamstring strengthening and single-leg stability drills, which may serve as protective mechanisms [1,6,61]. These results underscore the necessity for personalized training modifications that address the distinct developmental paths of adolescent athletes [1,6,62].

To enhance injury risk management, practitioners can establish a "red flag list" to systematically identify players who exhibit multiple risk factors [1,4]. This list should include athletes experiencing rapid growth spurts (higher growth rates, e.g., annual growth rates ≥ 7.2 cm) and maturity status (circa-PHV) framing with the following factors: workloads or prior injury history enabling targeted interventions [1,6]. Players flagged for heightened risk can undergo tailored modifications to training volume and intensity, integrating preventive strategies, such as neuromuscular training, recovery protocols, and close monitoring of weekly workload fluctuations [1,4]. By regularly updating this list, coaching and medical staff can proactively mitigate injury risks and promote long-term player development [36,54].

Practitioners working in soccer academies must consistently monitor growth and maturation indicators to help reduce the injury risk in elite youth players (Table 1). Developing individualized workload strategies based on maturity status (e.g., somatic maturity status) [1,4]. However, growth and maturation affect more than just workload tolerance and can influence neuromuscular coordination and control, contributing to temporary declines in movement efficiency and increasing susceptibility to injury [63]. Energy demands also increase significantly during rapid growth periods, and inadequate nutritional intake can result in relative energy deficiency, further compromising performance and recovery [64]. Moreover, growth and maturation may influence selection and deselection processes within academies, with newly integrated players, regardless of maturity status, potentially requiring additional support to adapt to unfamiliar training loads and social environments [15]. For example, a late-maturing player recruited into an older age group may experience cumulative fatigue and under-recovery when exposed to the same external loads as their more physically mature peers. This scenario may necessitate reduced training volume, technical support, and psychosocial guidance to facilitate adaptation and prevent overload. Similarly, a player experiencing rapid growth (e.g., >7.2 cm/year) may show compromised neuromuscular control and movement patterns, increasing the risk of overuse injuries, particularly in the lower limbs. In such cases, close monitoring, neuromuscular-focused interventions, and workload adjustments are essential during this high-risk window. Given this complexity, a holistic and individualized approach is required. This includes routine maturity assessments, targeted neuromuscular training, nutritional guidance, and psychosocial support, all integrated within a flexible workload management framework [1,4,6,9,41].

Table 1- Key Highlights: Growth, Maturation, Workload Injury Risk in Elite Young Male Soccer Players.

Risk Factors & Strategies	Key Findings	Practical Applications	Supporting Studies
Growth and Maturation-Related Injury Risk Factors	- During accelerated skeletal growth, the growth plates thicken and become more vulnerable to injuries. As athletes grow, their cartilage and joint surfaces undergo mechanical change. - Tissues and structures are vulnerable points in muscle, tendon, and skeletal connection chains. The skeletal attachment site (apophysis) in younger players is weaker, whereas in mature players, the muscles, ligaments, and tendons are more prone to failure. - Adolescent athletes with less-developed growth plates are more susceptible to traction and shear stress. Athletes experience significant changes in limb mass, moments of inertia, and length during adolescence's rapid somatic growth phase. - Apophyseal injuries often occur due to tensile forces and mechanical stress, potentially causing inflammation and pain. Adolescent athletes during growth spurts are particularly susceptible, as these anatomical regions may lack sufficient structural integrity to withstand high physical exertion. <u>- Pre-PHV</u> Higher incidence of growth-related injuries (e.g., Osgood-Schlatter disease) due to rapid growth. Fast-growing players (> 7.2 cm/year) show 2.5-5.4 times higher overall injury incidence compared to moderately growing players. <u>- Circa-PHV</u> Injury incidence and burden are higher in circa-PHV compared to pre-PHV period. Growth-related injuries were more frequent around PHV. <u>- Post-PHV</u> Increased incidence of joint and ligament injuries, especially in hips and lower back. Higher risk for chronic overuse injuries due to increased training demands. Vulnerability to spondylolysis and lower back injuries.	- Monitoring stature, body mass, and somatic maturity estimates every 2–3 months can help identify injury-prone periods. - Use growth data and somatic maturity to inform training modifications, and integrate growth monitoring into academy screening protocols to guide injury mitigation strategies.	[47] [36] [42] [49] [10] [5] [4] [1] [65] [55] [13] [66] [67] [2]

Bio-Banding: Training and Games/ Gym Training	- Bio-banding is the process of grouping athletes based on biological maturity (e.g., pre-, circa and post-PHV). rather than chronological age. - Bio-banding can be applied for: ▪ Injury Risk Reduction: By aligning athletes based on maturity, bio-banding aims to reduce the risks associated with mismatches in size and strength that can lead to injuries. ▪ Fairer Physical Matchups: Helps balance physical matchups during training and competition, ensuring a more level playing field. ▪ Enhanced Physical Literacy: Gym training under bio-banding promotes physical literacy, allowing athletes to develop agility, balance, coordination, and strength in line with their maturation levels. ▪ Psychosocial Benefits: Bio-banding fosters a sense of belonging and reduces feelings of inadequacy among younger or less physically developed athletes. Training and competing with peers of similar biological maturity can boost confidence and motivation.	- Group athletes by biological maturity rather than chronological age for training and competition; adjust tactical approaches based on maturity profiles. - It allows practitioners to tailor training loads to athletes' physical development, which can be particularly crucial during periods of rapid growth. - Bio-banding allows for prescribing developmentally appropriate training workloads and content that align with an athlete's maturity status. This targeted approach can optimize physical qualities while improving overall performance. - Adjust competitive demands based on individual growth trajectories. - Ensure progressive physical challenges for all maturity levels. - Balance, coordination, and landing Mechanics drills: These specific exercises were incorporated to improve motor control and mitigate the risk of injuries associated with growth spurts. - Designing training programs that adapt dynamically to changes in an athlete's growth and maturity status ensures that practices remain safe and effective. - Design drills that emphasize movement control, especially during Pre-PHV and Circa-PHV. - Ensure diverse movement patterns in training to prevent repetitive strain injuries, especially during Pre-PHV and Circa-PHV. - Training can be tailored using the maturity status: ▪ Pre-PHV: Focus on fundamental movement, mobility, and strength	[42] [10] [1] [5] [63] [9] [15] [47] [36] [42] [49] [10] [5] [4] [1] [65] [41] [68] [38] [23] [69] [70] [6] [2]

		training. ▪ Circa-PHV: Technical proficiency, controlled strength training, and movement pattern consistency. ▪ Post-PHV: Gradually increases the training volume and intensity while prioritizing recovery. - Use the visual assessment of longitudinal growth curves by an experienced assessor remains the most reliable method for classifying players as pre-, circa-, or post-PHV.	
Workload Monitoring	- Periodization and modified workload training volumes can mitigate the injury risk by preventing excessive fatigue and overuse injuries. - Monitoring the internal and external workload. - Monitoring the cumulative workload (including both physical (training/competition) and non-physical (school, life stressors) demands, contributes to injury risk.	- Prioritize recovery strategies for post-PHV athletes facing higher workloads. - Apply workload management strategies to align with biological development. - Utilize GPS and heart rate monitors to gather data on training intensity and volumes, adjusting plans as necessary. - Consider holistic approaches that account for total workload, integrating academic and social factors into planning training regimens.	[4] [1] [58] [6] [53] [68] [69] [37] [70] [2]
Communication regarding fatigue and well-being	- Athletes may underestimate fatigue, potentially leading to injuries if they do not report it.	- Foster an environment where players feel comfortable reporting fatigue; integrate regular check-ins.	[71]
Recovery strategies and focused sessions	- Effective recovery can mitigate the impact of high workloads and reduce injury risk.	- Implement recovery-centric training sessions and encourage rest days; educate on recovery techniques and dietary habits. - Schedule regular recovery periods, incorporating active recovery sessions and monitoring fatigue levels to prevent overtraining.	[72] [60] [38] [4] [1]

4. Developing a Framework for Growth, Maturation, and Workload in Injury Risk Mitigation for Young Soccer Players – An Academy Case Study Example

To create practical guidelines for coaching and managing young soccer players effectively, it is crucial to understand the theoretical concepts and scientific findings outlined in this narrative review. Integrating these tangible applications into coaching strategies and athlete supervision methods promotes a proactive strategy to reduce injury risk and enhance the performance of young soccer players [4].

The assessment and monitoring of growth in young elite soccer players are essential for effectively managing their training and mitigating injury risk. As highlighted in previous research, the physical development of adolescent athletes is marked by significant changes that can predispose them to injuries, if not adequately monitored [1,4,6,36,41]. A structured approach is essential for evaluating growth, identifying individual risk factors, and implementing tailored intervention strategies for at-risk players ("red flags"). Understanding these factors is crucial for developing appropriate monitoring strategies and interventions to mitigate injury risk, especially considering the increased vulnerability during periods of rapid growth and maturation [6]. The framework for monitoring and intervention was structured in three key steps. “Step 1: How, Who, and When to Measure” (Figure 1) – This involves systematically assessing players’ growth, maturation, and workload using objective and subjective measures such as GPS data, sRPE scores, and periodic anthropometric assessments. Strength and conditioning staff, sports scientists, and medical professionals should collaborate at regular intervals to ensure accurate data collection. “Step 2: How to Report to Coaches and Medical Staff” (Figure 1) – The collected data should be translated into actionable insights using clear visual reports, threshold-based risk categories, and direct communication with coaching and medical teams and academy directors (for instance, they can propose a player to be lifted). Ensuring that all stakeholders are aligned in their understanding of the data is crucial for decision making. “Step 3: What to Change in the Practice Environment When Warning Signs Are Detected?” – If an athlete exhibits high injury risk factors, training modifications should be implemented, such as reducing load, altering movement patterns, emphasizing recovery, or incorporating specific corrective exercises tailored to the player’s needs.

Step 1: How, Who, and When to Measure", a multidisciplinary team (MDT), including sports scientists, strength and conditioning coaches, and medical staff, oversees the measurements and data interpretation [1,4]. Growth should be assessed using anthropometric measurements, including standing height, sitting height, limb length, and body mass, to track changes over time by staff qualified according to the anthropometric assessment guidelines set by the International Society for the Advancement of Kinanthropometry (ISAK) [1,4,41]. These anthropometric variables allow for the detection of players who may have potential health or performance issues [16,24,41,55]. By monitoring changes in limb length, practitioners can identify takeoff PHV and assess the growth rate of the lower body [24,37,76]. Specifically, growth rates for leg length that exceed 3.6 cm/year are associated with an increased risk of injury, allowing for timely intervention and individualized training adjustments [4,6,41]. Additionally, tracking body mass along height measurements provides a clearer picture of an athlete's body composition and permits the identification of PWV [23,24], which is important for tailoring training programs and ensuring that athletes maintain healthy growth trajectories [4]. Systematic and longitudinal assessments of growth and biological maturation are essential to guide training, inform load management, and support injury risk-mitigation strategies in young soccer players [77]. Maturity-specific approaches to player development and talent identification have been increasingly adopted by soccer academies [55]. An effective approach for growth monitoring is the use of curve-fitting techniques based on serial anthropometric data, which allow for the estimation of individual growth velocity (cm/year) and peak height velocity timing [78]. The growth rate can be categorized into high (>7.2 cm/year), moderate (3.5–7.2 cm/year), and low (<3.5 cm/year) (Figure 2) [41,48], which may help identify periods of increased injury risk or altered neuromuscular control. The percentage of predicted adult height (PPAH) remains a widely used indicator of somatic maturation, with players commonly classified as pre-PHV (<88%), circa-PHV (88–95%), and post-PHV (>95%) [19,41]. However, caution must be exercised when interpreting these classifications, as threshold band selection affects accuracy. Wider bands may increase Type 1 errors (overestimating the number of players in each maturity group), whereas narrower bands may miss players at risk, leading to Type 2 errors. Therefore, the choice of banding should be aligned with the monitoring objective and contextual needs of the soccer academy. To balance feasibility with biological accuracy, assessments are recommended every 3–4 months (3–4 assessments/year) between the U10 and U17 age groups [1,4,36,37,61]. For players identified as having increased risk, commonly referred to as "Red Flags" (e.g., rapid growth, recent injuries, or significant asymmetries), monthly assessments may be warranted, particularly between U12 and U15. Nevertheless, shorter intervals between measurements can amplify biological variability and technical error, potentially leading to the misclassification of growth status. To mitigate these issues, practitioners should calculate and monitor absolute and relative typical errors of measurement (TEM), particularly intra-rater reliability, to enhance the robustness of individual tracking over time. For practical applications, a tailored assessment frequency is proposed: three assessments per season for U10–U12, four assessments for U12–U15, three for U16, two for U17, and one per season from U18 onwards. This schedule aims to balance scientific rigor, resource availability, and the varying growth rates and injury risks across age groups.

Interventions need to prioritize the identification of three primary risk factors associated with increased injury risk in young soccer players: somatic maturity status, stature growth rate, and lower-limb growth rate [6]. It is crucial to intervene during the circa-PHV phase, as athletes experience rapid physical changes that can substantially affect their performance, coordination, and susceptibility to injuries [6]. Nevertheless, it is imperative to adopt a longitudinal perspective and acknowledge that players at various maturity stages require continuous monitoring and tailored support. Growth and maturation strategies should not be confined to individuals undergoing PHV or to those experiencing accelerated growth. Individualized interventions must encompass all developmental stages, ensuring that each athlete receives appropriate training and load management based on their unique maturation trajectory. Players showing signs of rapid growth circa-PHV are marked as "Red Flags." Using these risk factors, coaching and medical staff can effectively stratify players based on their injury risk profiles, thereby facilitating targeted intervention strategies. To build a list of “Red Flag” players was following the critical growth threshold for increased injury risk has been established at growth rates exceeding 7.2 cm/year for stature and 3.6 cm/year for lower limb length [41,48]. These thresholds correspond to phases of rapid skeletal elongation, which can temporarily disrupt neuromuscular coordination, alter movement biomechanics, and increase susceptibility to soft tissue and overuse injuries [5,6,27]. Circa-PHV (typically defined as 88–96% of predicted adult height) has been associated with increased injury risk in young soccer players due to rapid changes in body dimensions and reduced neuromuscular control [27,41,44,79–81]. Furthermore, especially attention to–88-92% of predicted adult height, the peak rate of adolescent growth occurs [6,76,82]. Recent literature indicates that wider PAH% ranges tend to classify pre- and post-PHV players as circa-PHV players, while narrower ranges (e.g., 90%-93%) fail to detect some circa-PHV players but effectively identify most pre- and post-PHV players [55]. Those utilizing PAH% should select ranges that align with their classification purpose. Ranges of 85%-96% and 88%-93% demonstrated the highest agreement with the circa-PHV classification when compared to full growth curves using ±1.0 and ±0.5-year thresholds, respectively [55]. Implementing these ranges would result in a more balanced distribution of classification errors across pre-, circa-, and post-PHV phases. Modifications should be considered when identifying players within a particular range. To reduce the risk of injury and effectively manage workloads during the circa-PHV stage, a wider range of 85%-96% encompasses most circa-PHV players. However, when prescribing strength-training interventions, particularly those requiring greater coordination and stability, narrower circa-PHV ranges (e.g., 88–93% or 90–93%) may be more appropriate to better align with the specific neuromuscular challenges observed during this phase [55]. This abrupt physiological change can lead to a mismatch between musculoskeletal development and neuromuscular control, increasing the risk of movement inefficiencies and injury [23,27,83]. However, it is important to recognize that neuromuscular efficiency and motor control are not solely dependent on the maturity status. Players with good or poor motor strategies were found across all the maturity groups. Therefore, athletes should be systematically challenged with developmentally appropriate stimuli regardless of their maturation level [63]. For instance, a pre-PHV player demonstrating good motor control may benefit from complex coordination drills with added visual or cognitive demands rather than load-based strength training because their hormonal profile may not support anabolic adaptation [63]. Conversely, a post-PHV player with limited coordination may have the capacity to improve strength through external loading but may not be ready for such training if foundational motor skills are underdeveloped [84]. Tailoring motor control and strength development strategies in this way helps ensure that training is both safe and effective, and aligned with each athlete’s biological and functional profile.

According to the three risk factors identified previously, if the young player presents two of the three risk factors, he is included in the "Red Flags" list. Based on the number of identified risk factors (Figure 3), players were categorized into three injury risk levels: High Risk (≥2 risk factors), Moderate Risk (1 risk factor), and Low Risk (no identified risk factors) [6].

The second step, “Step 2: How to Report to Coaches and Medical Staff” – collected data should be translated into actionable insights using clear visual reports, threshold-based risk categories, and direct communication with coaching and medical teams [1,4]. Data visualization techniques, such as growth curves, load distribution charts, and injury risk indicators, should be employed to present the monitoring findings in a concise and interpretable format (Figure 4). These standardized reports consolidate key developmental and performance metrics, including growth velocity, workload progression, and injury risk classification, into clearly defined categories (e.g., low, moderate, and high). By establishing threshold-based indicators, information becomes more actionable, enabling medical and coaching staff to rapidly identify at-risk players and implement timely interventions. Figure 4 illustrates a standardized player monitoring report that integrates key biological and anthropometric variables, such as biological age, growth rate, percentage of predicted adult stature, and limb-specific development, into a color-coded format. This visual summary enhances clarity and allows staff to quickly identify players at elevated risk, thereby supporting timely and coordinated decision making. Regular interdisciplinary meetings should be held to discuss findings and align staff to make necessary adjustments to workloads, recovery protocols, and specific athletic interventions. Ensuring that all stakeholders are aligned in their understanding of the data is crucial for effective decision making and improved athletic outcomes [4].

The third and last step, “Step 3: What to Change in the Practice Environment When Warning Signs Are Detected”, if an athlete exhibits high injury risk factors, training/game modifications should be implemented to mitigate potential adverse effects. Adjustments may include reducing the overall workload, modifying session intensity, and altering movement patterns to reduce mechanical stress [1,4,6]. Recovery should be emphasized through structured rest days, optimized sleep, and nutrition strategies. Additionally, specific corrective exercises, including proprioceptive drills, balance training, and strength training, should be integrated into daily routines to address musculoskeletal imbalances and improve movement efficiency. Coaches and medical staff should collaborate closely to ensure that these interventions are tailored to individual needs, while maintaining the athlete’s development pathway. Regular reassessment of flagged players is essential for tracking progress and refining intervention strategies accordingly [4]. This last step is highly important because it aims to implement the action plan after the evaluation and reporting steps with all the stakeholders involved in the process. For players identified as "Red Flags," it is important to implement a multifaceted intervention strategy designed to mitigate injury risk while promoting physical development. This strategy comprises of several key components. A critical aspect of athlete development is the education of the coaches, staff, directors, players, and families regarding growth and maturation. It is essential that all parties involved comprehend the rationale behind specific interventions and the necessity for differentiated strategies among athletes [1,4,85]. By providing a comprehensive understanding of the changes that athletes undergo at various stages of biological maturation, we can ensure that interventions are not only efficacious, but also safe. Tailoring training and support to an individual's maturity level, rather than solely their chronological age, facilitates performance optimization while minimizing injury risk [1,4,85]. When all stakeholders align with these principles, athletes receive the care and guidance necessary for their development, thereby fostering a positive and supportive developmental environment.

<u>1. Modified/adjusted Workload:</u> Managing workload is fundamental for preventing overuse injuries, particularly during periods of rapid growth in youth players. This process involves not only monitoring external workload (e.g., total distance, sprinting, and accelerations), but also interpreting internal responses, such as fatigue or recovery status [1,4]. While technologies such as GPS systems and HRV monitoring offer valuable insights, they may not be feasible in all contexts owing to cost or technical limitations. Therefore, practical alternatives, such as the Rating of Perceived Exertion (RPE), can be used to assess internal load and training intensity on a session-by-session basis [72,86]. Another accessible and effective strategy involves monitoring pain or discomfort in typical growth-sensitive regions, such as the knees, heels, or hips, especially around the PHV. Self-reported complaints in these areas can serve as early warning signs of overuse (e.g., Osgood-Schlatter and Sever’s disease), prompting timely adjustment of workloads and training content [6,87]. When symptoms or excessive fatigue are identified, it is essential to adjust the weekly microcycle, either by reducing the total volume, limiting exposure to high-impact actions (e.g., decelerations, sharp changes of direction), or modifying the player's involvement in more intense sessions [1,4]. A critical aspect of the intervention involves adjusting workloads to suit an individual athlete's growth and recovery needs. Implementing a periodized training program that balances workload across the week can help mitigate overuse injuries [88]. Coaches can assess players' external workloads using GPS tracking devices and sports monitoring software [89]. Through careful analysis of data measuring distance and speed, coaches can identify

trends and patterns that suggest an increased risk of athletic injury. For young soccer players, coaches and medical personnel should employ external workload metrics, including total distance covered and high-speed running, to monitor the training and game demands. Tracking these parameters aids in recognizing injury risks and modifying training regimens as needed [89]. To comprehend fatigue levels, it is crucial to measure the internal workload by assessing heart rate variability. In both resource-rich and resource-limited environments, integrating simple screening tools (e.g., RPE, wellness questionnaires, growth-related pain checklists) with contextual awareness enables coaches to implement a multimodal workload management strategy tailored to the needs of the squad, maturity profile, and resource availability.

2. Soccer-Specific Skills: Incorporating soccer-specific drills, including rondos, positional games with numerical superiority, passing circuits, and ball control under pressure, can be strategically employed to enhance technical proficiency while minimizing excessive mechanical load, particularly for players undergoing periods of accelerated growth [1,6,90,91]. These drills should not replace regular training, but should be selectively integrated or adapted to maintain technical development during periods when young players report discomfort or symptoms commonly associated with the growth spurt, allowing continued skill acquisition while reducing mechanical stress [79]. Furthermore, the inclusion of coordinative movement patterns such as multidirectional dribbling, turning, and quick changes in direction enhances neuromuscular control and supports the acquisition of broader physical literacy, which is a key foundation for injury prevention and long-term athletic development [63,92]. Physical literacy includes competence in fundamental movement skills as well as confidence and motivation to apply these skills in sport-specific contexts [93]. By combining soccer-specific skill work with structured exposure to motor variability, practitioners can cultivate adaptable movement strategies, enhance perceptual-motor integration, and mitigate injury risk while aligning training content with a player's maturation process [18]. This hybrid approach is particularly advantageous during the circa-PHV window, when athletes may experience temporary declines in coordination, balance, and strength.

3. Neuromuscular Development and Individualized Strength Training: Neuromuscular development is a critical component of injury prevention and long-term athletic

progression in youth soccer. This includes the integration of balance, coordination, landing mechanics, mobility, and strength training, each tailored to an athlete's biological maturation and movement competency. Exercises that enhance proprioception, joint stability, and motor control are particularly important for preparing athletes to safely execute high-risk actions such as jumping, cutting, or changing direction, which are frequent mechanisms of injury in soccer [6,94–96]. Structured neuromuscular training, including single-leg landings, reactive jumps, and unstable surface drills, can significantly reduce lower-limb injuries like ACL and ankle sprains [94–96]. These routines should be embedded in warm-ups and progress systematically in line with the player's technical ability and maturity status [97]. Mobility training serves as a foundational element in all stages. During prepubescence, it helps establish a joint range of motion and tissue extensibility [23]. As athletes approach PHV, they may develop musculoskeletal imbalances and flexibility deficits due to limb length changes, requiring structured and individualized mobility training [23,62,98]. Post-PHV mobility should be integrated into strength programs and warm-ups, with emphasis on dynamic movement in key regions, such as the hips, ankles, and thoracic spine [63,99]. Sport-specific mobility drills (e.g., lunge variations, hip openers, and dynamic stretches) can enhance movement efficiency and help athletes tolerate the physical demands of training and competition [63,99]. Thus, mobility training complements strength training by ensuring that the developing tissues remain adaptable, resilient, and capable of supporting proper techniques throughout physical development.

Strength training is a crucial element in the mitigation of injuries and the promotion of long-term athletic development in youth soccer. Empirical evidence indicates that well-designed and supervised strength programs substantially mitigate the risk of lower-limb injuries, particularly during adolescence, a phase characterized by rapid physical transformations and temporary challenges in motor coordination [97,99,100]. In young soccer players, strength training should be guided by both biological maturation and movement competency to ensure appropriate progression and long-term athletic development [15,16]. While the maturity stage provides a valuable context, exercise prescription must primarily reflect the athlete's technical ability and neuromuscular control. Pre-PHV athletes typically benefit from focusing on fundamental body weight movements (e.g., push-ups and squats) and exploratory motor tasks, such as games and free play, to build coordination and movement quality [7,23,69,98]. However, if a pre-PHV player demonstrates high technical proficiency and psychosocial maturity, more complex stimuli, such as unstable surfaces, decision-making drills, dual tasks, external perturbations, or light external resistance, may be appropriate. Circa-PHV athletes can begin progressive strength training with close supervision, emphasizing proper technique, gradual load increases, and targeted neuromuscular development [7,23,69,98]. Post-PHV players may tolerate more advanced strength training protocols and higher loads, but only if they demonstrate solid movement patterns. If motor control is lacking, as is often the case in early maturing or previously uncoached players, training should prioritize re-establishing movement efficiency before progressing the load. In all cases, the integration of technical quality, maturity status, and individual responsiveness is essential for safe and effective programming [7,23,69,98]. Regardless of stage, individualized progression, monitoring, and continuous technical reinforcement are essential. Complementary programs, such as FIFA 11+ Kids, offer accessible and evidence-based frameworks that support neuromuscular control, coordination, and strength development in young players [101,102]. Such interventions serve as valuable tools across different academy contexts, particularly when resources are limited or gym access is restricted. However, it is crucial to implement these tailored strategies to create a safe and effective training environment that supports healthy development and optimizes performance. Monitoring and assessment are imperative to evaluate the effectiveness of these interventions, allowing for necessary adjustments based on the athlete's ongoing growth and response to training [1,4]. When it comes to training in a gym context, it is essential to conduct individual planning that meets the development requirements of each player. In this sense, there is individual planning based on the biological maturity of each player. The objective is to establish appropriate movement patterns and build confidence in physical activity [7,23,69]. During circa-PHV, focus was placed on introducing low-load strength training, prioritizing the improvement of movement techniques, and ensuring that exercises were performed with control. This phase is ideal for players to understand the technical aspects related to fundamental movement patterns. During the circa-PHV period, athletes need to develop motor skills and learn and consolidate essential movement patterns such as fundamental strength exercises, balance, and coordination. These fundamentals are crucial for long-term performance and should be tailored to an individual's capacity. By focusing on technical development during this phase, players build a solid foundation that will help them excel at more advanced stages of their athletic development [7,23,69]. Throughout puberty, boys may undergo a swift growth spurt, often leading to what is commonly referred to as "adolescent awkwardness." This phase is marked by rapid changes in size and proportion, potentially causing alterations in motor control, particularly in certain athletes. [26–28]. During this stage of development, some players need to be reperfected with previously acquired movement patterns [23]. Finally, during post-PHV, athletes can begin implementing more traditional hypertrophy-focused strength-training protocols, utilizing greater workload and lower repetitions. Emphasis should be placed on progressive overload and diversified training practices, including compound lifts, to effectively stimulate muscle adaptation [7,23,69].

5. Limitations

The interpretation and application of growth and maturation data in youth soccer must be approached with an understanding of the several inherent limitations. First, growth and biological maturation are highly individualized processes influenced by genetic, environmental, nutritional, and psychosocial factors, many of which are beyond the control of practitioners. Although predictive models, such as the percentage of predicted adult height, offer useful estimations, they do not account for intra-individual variability in maturity status, timing, or tempo, limiting their precision when applied to real-world decision making.

Second, this article focuses exclusively on young male soccer players, reflecting the professional scope and practical experience of the authors, which is centered on boys' academic soccer. However, we acknowledge that young female athletes also experience growth- and maturation-related challenges, which warrant further research. Future studies should investigate sex-specific developmental trajectories, workload responses, and injury risk profiles to inform the best practices for female players.

Third, although the recommendations provided in this review are grounded in scientific evidence and practical experience, their implementation may vary, depending on the resources available in each context. Elite academies are often equipped with the infrastructure and staffing necessary for systematic monitoring and individualized programming. However, in grassroots or lower-resource settings, clubs may encounter difficulties in applying the same strategies with the same level of precision or frequency. This variability does not reflect a limitation of the framework itself but rather highlights the importance of developing scalable, flexible approaches that can be adapted to the realities of each environment. Promoting educational initiatives and low-cost monitoring tools can help bridge this gap and support the broader adoption of effective practices across different levels of football development.

6. Future Directions for Research

Despite increasing interest in the management of growth, maturation, and workload in youth soccer, further research is necessary to refine and expand the existing evidence. Future studies should investigate sex-specific responses to growth, maturation, and workload as the current literature predominantly focuses on male athletes. Additionally, longitudinal multicenter studies are required to better understand the cumulative effects of biological maturation, workload exposure, and training interventions across various academy contexts and competitive levels. Research should also assess the effectiveness of low-resource strategies for growth and injury monitoring, to support evidence-based practices in environments with limited access to technology and staff. Furthermore, the development and validation of decision-support tools that integrate biological, physical, and psychological variables could assist practitioners in tailoring training more precisely. Finally, evaluating the long-term outcomes of individualized training and injury mitigation frameworks, including return-to-play success, injury recurrence, and progression to senior levels, could contribute to optimizing youth developmental pathways in soccer.

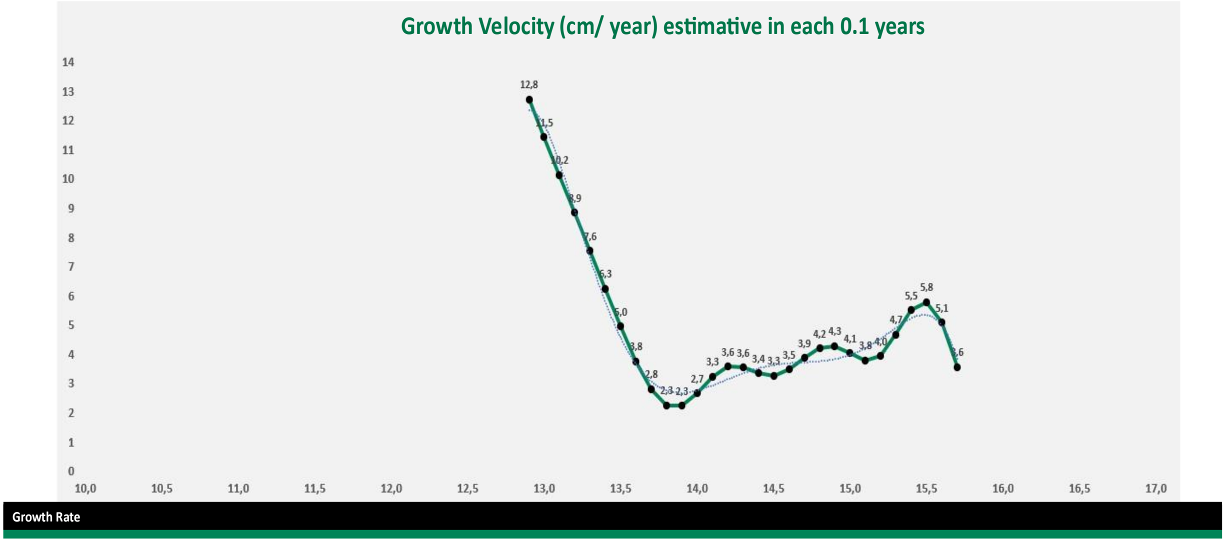
7. Conclusion

Effective management of growth, maturation, and workload is essential to reduce injury risk and support the long-term development of young soccer players. Adolescence is characterized by rapid and individualized physical changes that can affect both performance and vulnerability to injuries. Recognizing this complexity, practitioners must move beyond generalized training prescriptions and adopt individualized strategies based on biological maturity and physical readiness.

Regular monitoring of both external and internal training loads enables an informed adjustment to training demands, allowing coaches and sports science staff to balance stress and recovery more effectively. Equally important is fostering open communication between players and staff to identify early signs of fatigue or maladaptation and to create a responsive and supportive training environment.

Ultimately, implementing an evidence-based, maturity-informed framework grounded in systematic monitoring, education, and individualized training can help practitioners optimize performance, safeguard athlete health, and guide young players through a safe and productive developmental journey in soccer.

Figure 1 - Framework for Monitoring Growth, Maturation, and Workload in Youth Soccer Players.



12,9	13,0	13,1	13,2	13,3	13,4	13,5	13,6	13,7	13,8	13,8	13,9	14,0	14,1	14,2	14,2	14,3
12,8	11,5	10,2	8,9	7,6	6,3	5,0	3,8	2,8	2,3	2,3	2,7	3,3	3,6	3,6	3,6	3,6

14,4	14,5	14,6	14,7	14,8	14,9	15,0	15,1	15,2	15,3	15,4	15,5	15,6	15,7	15,8	15,9	16,0
3,4	3,3	3,3	3,5	3,9	4,2	4,3	4,1	3,8	4,0	4,7	5,5	5,8	5,1	3,6	1,6	-0,6

Figure 2 - Report about Growth Velocity (cm/ year) estimative in each 0.1 years.

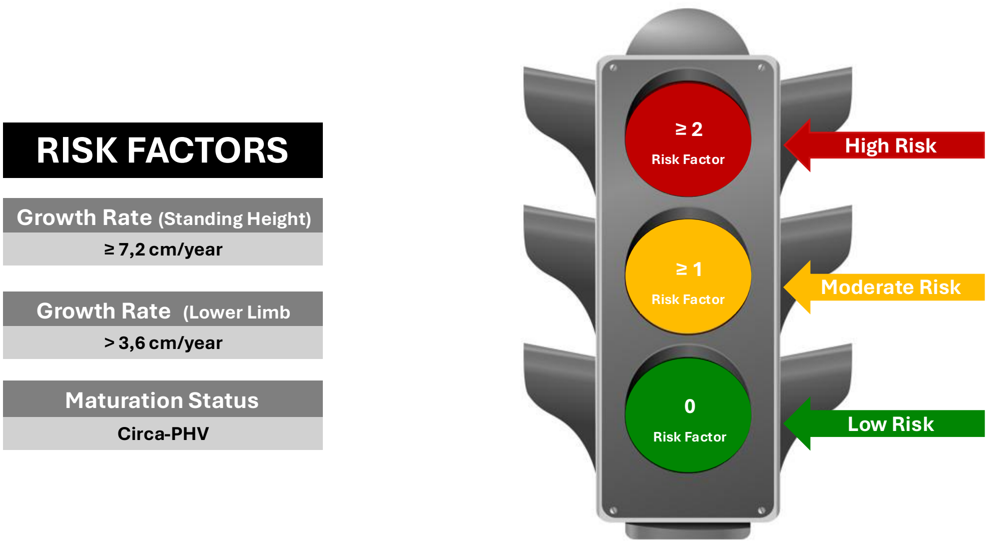


Figure 3 - The traffic light system for injury risk factors (growth and maturation).

Name Player	Birth Quarter	Decimal Age	Biological Age	Timing of Maturity	Stature (cm)	Predicted Adult Stature (cm)	Predicted Adult Stature 90% Confidence Interval		% Predicted Adult Stature	Growt Rate (cm/year)	Lower Limb Growth Rate (cm/year)	Risk Factor
							Minimum	Maximal				
Player 1	1	12,9	14,2	Early	178,6	**192,6**	191,2	193,9	90,6%	**9,9**	**5,0**	**High Risk**
Player 2	2	12,8	12,3	Late	152,4	**174,4**	173,1	175,8	86,1%	4,8	1,5	**Low Risk**
Player 3	1	13,0	14,2	Early	168,1	**181,1**	179,8	182,4	90,8%	**9,5**	0,8	**High Risk**
Player 4	1	13,1	13,7	Early	169,9	**185,9**	184,6	187,2	91,4%	6,6	2,8	**Moderate Risk**

Figure 4 - Report of Assessments of Growth and Maturity (Under 13).

8. References

1. Baxter-Jones ADG, Eisenmann JC, Sherar LB. Controlling for Maturation in Pediatric Exercise Science. Pediatr Exerc Sci. 2005;17:18–30. Available from: https://journals.humankinetics.com/view/journals/pes/17/1/article-p18.xml

2. Bergeron MF, Mountjoy M, Armstrong N, Chia M, Côté J, Emery CA, et al. International Olympic Committee consensus statement on youth athletic development. Br J Sports Med. 2015;49:843–851. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2015-094962

3. Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. Exerc Sport Sci Rev. 1988;16:503–540.

4. Beunen G, Malina RM. Growth and Biologic Maturation: Relevance to Athletic Performance. In: The Young Athlete. Wiley; 2007:3–17. Available from: https://onlinelibrary.wiley.com/doi/10.1002/9780470696255.ch1

5. Beunen GP, Rogol AD, Malina RM. Indicators of biological maturation and secular changes in biological maturation. Food Nutr Bull. 2006;27:244–256.

6. Bisi MC, Stagni R. Development of gait motor control: What happens after a sudden increase in height during adolescence? Biomed Eng Online. 2016;15:1–12.

7. Bizzini M, Dvorak J. FIFA 11+: an effective programme to prevent football injuries in various player groups worldwide—a narrative review. Br J Sports Med. 2015;49:577–579. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2015-094765

8. Boeyer ME, Middleton KM, Duren DL, Leary EV. Estimating peak height velocity in individuals: a comparison of statistical methods. Ann Hum Biol. 2020;47:434–445. Available from: https://www.tandfonline.com/doi/full/10.1080/03014460.2020.1763458

9. Bradley B, Johnson D, Hill M, McGee D, Kana-ah A, Sharpin C, et al. Bio-banding in academy football: player’s perceptions of a maturity matched tournament. Ann Hum Biol. 2019;46:400–408. Available from: https://www.tandfonline.com/doi/full/10.1080/03014460.2019.1640284

10. Brownlee TE, O'Boyle A, Morgans R, Morton JP, Erskine RM, Drust B. Training duration may not be a predisposing factor in potential maladaptations in talent development programmes that promote early specialisation in elite youth soccer. Int J Sports Sci Coach. 2018;13:674–678. Available from: https://journals.sagepub.com/doi/10.1177/1747954117752127

11. Bult HJ, Barendrecht M, Tak IJR. Injury Risk and Injury Burden Are Related to Age Group and Peak Height Velocity Among Talented Male Youth Soccer Players. Orthop J Sports Med. 2018;6:1–7. Available from: http://www.ncbi.nlm.nih.gov/pubmed/30560140

12. Caine D. Physeal injuries in children's and youth sports: reasons for concern? Br J Sports Med. 2006;40:749–760. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsm.2005.017822

13. Corso M. Developmental changes in the youth athlete: Implications for movement, skills acquisition, performance and injuries. J Can Chiropr Assoc. 2018;62:150–160.

14. Cumming SP, Lloyd RS, Oliver JL, Eisenmann JC, Malina RM. Bio-banding in Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of Youth Athletes. Strength Cond J. 2017;39:34–47. Available from: http://dx.doi.org/10.1038/s41598-017-16996-w

15. DiFiori JP, Benjamin HJ, Brenner JS, Gregory A, Jayanthi N, Landry GL, et al. Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. Br J Sports Med. 2014;48:287–288. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2013-093299

16. Donaldson A, Lloyd DG, Gabbe BJ, Cook J, Finch CF. We have the programme, what next? Planning the implementation of an injury prevention programme. Inj Prev. 2017;23:273–280. Available from: https://injuryprevention.bmj.com/lookup/doi/10.1136/injuryprev-2015-041737

17. Edwards LC, Bryant AS, Keegan RJ, Morgan K, Jones AM. Definitions, Foundations and Associations of Physical Literacy: A Systematic Review. Sports Med. 2017;47:113–126. Available from: http://link.springer.com/10.1007/s40279-016-0560-7

18. Emery CA, Roy T-O, Whittaker JL, Nettel-Aguirre A, van Mechelen W. Neuromuscular training injury prevention strategies in youth sport: a systematic review and meta-analysis. Br J Sports Med. 2015;49:865–870. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2015-094639

19. Faigenbaum AD, Lloyd RS, MacDonald J, Myer GD. Citius, Altius, Fortius: beneficial effects of resistance training for young athletes: Narrative review. Br J Sports Med. 2016;50:3–7. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2015-094621

20. Faigenbaum AD, Lloyd RS, Myer GD. Youth Resistance Training: Past Practices, New Perspectives, and Future Directions. Pediatr Exerc Sci. 2013;25:591–604. Available from: https://journals.humankinetics.com/view/journals/pes/25/4/article-p591.xml

21. Ford PR, Carling C, Garces M, Marques M, Miguel C, Farrant A, et al. The developmental activities of elite soccer players aged under-16 years from Brazil, England, France, Ghana, Mexico, Portugal and Sweden. J Sports Sci. 2012;30:1653–1663. Available from: http://www.tandfonline.com/doi/abs/10.1080/02640414.2012.701762

22. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, et al. A new approach to monitoring exercise training. J Strength Cond Res. 2001;15:109–115. Available from: http://journals.lww.com/00124278-200102000-00019

23. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? Br J Sports Med. 2016;50:273–280. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2015-095788

24. Gabbett TJ, Ullah S. Relationship between running loads and soft-tissue injury in elite team sport athletes. J Strength Cond Res. 2012;26:953–960. Available from: https://journals.lww.com/00124278-201204000-00010

25. Gabbett TJ, Whyte DG, Hartwig TB, Wescombe H, Naughton GA. The relationship between workloads, physical performance, injury and illness in adolescent male football players. Sports Med. 2014;44:989–1003.

26. Le Gall F, Carling C, Reilly T, Vandewalle H, Church J, Rochcongar P. Incidence of injuries in elite French youth soccer players: a 10-season study. Am J Sports Med. 2006;34:928–938.

27. Hartwig TB, Gabbett TJ, Naughton G, Duncan C, Harries S, Perry N. Training and match volume and injury in adolescents playing multiple contact team sports: a prospective cohort study. Scand J Med Sci Sports. 2019;29:469–475. Available from: https://onlinelibrary.wiley.com/doi/10.1111/sms.13343

28. Hawkins D, Metheny J. Overuse injuries in youth sports: biomechanical considerations. Med Sci Sports Exerc. 2001;33:1701–1707. Available from: http://journals.lww.com/00005768-200110000-00014

29. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes. Am J Sports Med. 2006;34:490–498. Available from: https://journals.sagepub.com/doi/10.1177/0363546505282619

30. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. Int J Sports Physiol Perform. 2019;14:270–273.

31. Jayanthi N, Schley S, Cumming SP, Myer GD, Saffel H, Hartwig T, et al. Developmental training model for the sport specialized youth athlete: a dynamic strategy for individualizing load-response during maturation. Sports Health. 2022;14:142–153. Available from: https://journals.sagepub.com/doi/10.1177/19417381211056088

32. Jayanthi NA, LaBella CR, Fischer D, Pasulka J, Dugas LR. Sports-specialized intensive training and the risk of injury in young athletes. Am J Sports Med. 2015;43:794–801. Available from: https://journals.sagepub.com/doi/10.1177/0363546514567298

33. Johnson A. Monitoring the immature athlete. Aspetar Sports Med J. 2015;1:114–118.

34. Johnson A, Doherty PJ, Freemont A. Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: prospective study. BMJ. 2009;338:1–4. Available from: https://www.bmj.com/lookup/doi/10.1136/bmj.b490

35. Johnson D, Williams S, Bekker S, Bradley B, Cumming S. English academy football practitioners' perceptions of training load, maturation and injury risk: a club case study.

Int J Sports Sci Coach. 2024;19:417–428. Available from: https://journals.sagepub.com/doi/10.1177/17479541231188071

36. Johnson D, Williams S, Bekker S, Bradley B, Cumming S. English academy football practitioners' perceptions of training load, maturation and injury risk: a club case study. Int J Sports Sci Coach. 2024;19:417–428. Available from: http://journals.sagepub.com/doi/10.1177/17479541231188071

37. Johnson D, Williams S, Bradley B, Cumming SP. Can we reduce injury risk during the adolescent growth spurt? An iterative sequence of prevention in male academy footballers. Ann Hum Biol. 2023;50:452–460. Available from: https://www.tandfonline.com/doi/full/10.1080/03014460.2023.2261854

38. Johnson DM, Cumming SP, Bradley B, Williams S. The influence of exposure, growth and maturation on injury risk in male academy football players. J Sports Sci. 2022;40:1127–1136. Available from: https://www.tandfonline.com/doi/full/10.1080/02640414.2022.2051380

39. Johnson DM, Williams S, Bradley B, Sayer S, Murray Fisher J, Cumming S. Growing pains: maturity associated variation in injury risk in academy football. Eur J Sport Sci. 2020;20:544–552. Available from: https://doi.org/10.1080/17461391.2019.1633416

40. Jones S, Almousa S, Gibb A, Allamby N, Mullen R, Andersen TE, et al. Injury incidence, prevalence and severity in high-level male youth football: a systematic review. Sports Med. 2019;49:1879–1899. Available from: https://doi.org/10.1007/s40279-019-01169-8

41. Kemper GLJ, Van Der Sluis A, Brink MS, Visscher C, Frencken WGP, Elferink-Gemser MT. Anthropometric injury risk factors in elite-standard youth soccer. Int J Sports Med. 2015;36:1112–1117.

42. Khamis HJ, Roche AF. Predicting adult stature without using skeletal age: the Khamis-Roche method. Pediatrics. 1994;94:504–507. Available from: https://pubmed.ncbi.nlm.nih.gov/7936860/

43. Lehnert M, De Ste Croix M, Šťastný P, Maixnerová E, Zaatar A, Botek M, et al. The influence of fatigue on injury risk in male youth soccer. 2019.

44. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, et al. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. J Strength Cond Res. 2016;30:1491–1509. Available from: https://journals.lww.com/00124278-201606000-00001

45. Lloyd RS, Faigenbaum AD, Stone MH, Oliver JL, Jeffreys I, Moody JA, et al. Position statement on youth resistance training: the 2014 International Consensus. Br J Sports Med. 2014;48:498–505. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2013-092952

46. Lloyd RS, Oliver JL. The Youth Physical Development Model. Strength Cond J. 2012;34:61–72. Available from: https://journals.lww.com/00126548-201206000-00008

47. Lloyd RS, Oliver JL, Faigenbaum AD, Howard R, De Ste Croix MBA, Williams CA, et al. Long-term athletic development – Part 1. J Strength Cond Res. 2015;29:1439–1450. Available from: https://journals.lww.com/00124278-201505000-00036

48. Lloyd RS, Oliver JL, Faigenbaum AD, Myer GD, De Ste Croix MBA. Chronological age vs. biological maturation. J Strength Cond Res. 2014;28:1454–1464. Available from: https://journals.lww.com/00124278-201405000-00035

49. MacMaster C, Portas M, Parkin G, Cumming S, Wilcox C, Towlson C. The effect of bio-banding on the anthropometric, physical fitness and functional movement characteristics of academy soccer players. PLoS One. 2021;16:1–16. Available from: http://dx.doi.org/10.1371/journal.pone.0260136

50. Malina R, Martinho D, Oliveira T, Celis-Moreno JM, Figueiredo AJ, Seabra A, et al. Estimated annual increments in stature and weight among soccer players 11–18 years. Biol Sport. 2025. Available from: https://www.termedia.pl/doi/10.5114/biolsport.2025.144294

51. Malina RM. Top 10 research questions related to growth and maturation of relevance to physical activity, performance, and fitness. Res Q Exerc Sport. 2014;85:157–173. Available from: http://www.tandfonline.com/doi/abs/10.1080/02701367.2014.897592

52. Malina RM, Cumming SP, Rogol AD, Coelho-e-Silva MJ, Figueiredo AJ, Konarski JM, et al. Bio-banding in youth sports: background, concept, and application. Sports Med. 2019;49:1671–1685. Available from: https://doi.org/10.1007/s40279-019-01166-x

53. Malina RM, Rogol AD, Cumming SP, Coelho e Silva MJ, Figueiredo AJ. Biological maturation of youth athletes: assessment and implications. Br J Sports Med. 2015;49:852–859. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2015-094623

54. Malina RM, Rogol AD, Cumming SP, Coelho e Silva MJ, Figueiredo AJ. Biological maturation of youth athletes: assessment and implications. Br J Sports Med. 2015;49:852–859.

55. Mandorino M, Figueiredo AJ, Condello G, Tessitore A. The influence of maturity on recovery and perceived exertion, and its relationship with illnesses and non-contact injuries in young soccer players. Biol Sport. 2022;39:839–848. Available from: https://www.termedia.pl/doi/10.5114/biolsport.2022.109953

56. Mandorino M, Figueiredo AJ, Gjaka M, Tessitore A. Injury incidence and risk factors in youth soccer players: a systematic literature review. Part II: intrinsic and extrinsic risk factors. Biol Sport. 2023;40:27–49. Available from: https://www.termedia.pl/doi/10.5114/biolsport.2023.109962

57. Materne O, Chamari K, Farooq A, Tabben M, Weir A, Holmich P, et al. Shedding light on incidence and burden of physeal injuries in a youth elite football academy: a 4-season prospective study. Scand J Med Sci Sports. 2022;32:165–176. Available from: https://onlinelibrary.wiley.com/doi/10.1111/sms.14059

58. Materne O, Chamari K, Farooq A, Weir A, Hölmich P, Bahr R, et al. Association of skeletal maturity and injury risk in elite youth soccer players: a 4-season prospective study with survival analysis. Orthop J Sports Med. 2021;9:1–11. Available from: http://journals.sagepub.com/doi/10.1177/2325967121999113

59. McBurnie AJ, Dos'Santos T, Johnson D, Leng E. Training management of the elite adolescent soccer player throughout maturation. Sports. 2021;9:1–21.

60. McCall A, Pruna R, Van der Horst N, Dupont G, Buchheit M, Coutts AJ, et al. Exercise-based strategies to prevent muscle injury in male elite footballers: an expert-led Delphi survey of 21 practitioners belonging to 18 teams from the Big-5 European Leagues. Sports Med. 2020;50:1667–1681. Available from: https://link.springer.com/10.1007/s40279-020-01315-7

61. McKay, CD, Cumming, SP, and Blake, T. Youth sport: Friend or Foe? Best Practice & Research Clinical Rheumatology, 33:141–157, 2019. Available from: https://linkinghub.elsevier.com/retrieve/pii/S152169421930018X

62. Molinari, L, Gasser, T, and Largo, R. A comparison of skeletal maturity and growth. Annals of Human Biology, 40:333–340, 2013. Available from: http://www.tandfonline.com/doi/full/10.3109/03014460.2012.756122

63. Monasterio, X. Relative skeletal maturity status affects injury burden in U14 elite academy football players: a 9-season prospective study. Scand J Med Sci Sports, 2022. Available from: https://onlinelibrary.wiley.com/doi/10.1111/sms.14204

64. Monasterio, X, Cumming, S, Larruskain, J, Johnson, DM, Gil, SM, Bidaurrazaga-Letona, I, et al. The combined effects of growth and maturity status on injury risk in an elite football academy. Biol Sport, 41:235–244, 2024. Available from: https://www.termedia.pl/doi/10.5114/biolsport.2024.129472

65. Monasterio, X, Gil, S, Bidaurrazaga-Letona, I, Lekue, JA, Diaz-Beitia, G, Santisteban, JM, et al. Peak height velocity affects injury burden in circa-PHV soccer players. Int J Sports Med, 44:292–297, 2023. Available from: http://www.thieme-connect.de/DOI/DOI?10.1055/a-1983-6762

66. Monasterio, X, Gil, SM, Bidaurrazaga-Letona, I, Cumming, SP, Malina, RM, Williams, S, et al. Estimating maturity status in elite youth soccer players: Evaluation of methods. 2024.

67. Monasterio, X, Gil, SM, Bidaurrazaga-Letona, I, Lekue, JA, Santisteban, JM, Diaz-Beitia, G, et al. The burden of injuries according to maturity status and timing: A two-decade study with 110 growth curves in an elite football academy. Eur J Sport Sci, 0:1–11, 2021. Available from: https://doi.org/10.1080/17461391.2021.2006316

68. Monasterio, X, Gil, SM, Bidaurrazaga-Letona, I, Lekue, JA, Santisteban, JM, Diaz-Beitia, G, et al. Injuries according to the percentage of adult height in an elite soccer academy. J Sci Med Sport, 24:218–223, 2021. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1440244020307362

69. Mountjoy, M, Sundgot-Borgen, JK, Burke, LM, Ackerman, KE, Blauwet, C, Constantini, N, et al. IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. Br J Sports Med, 52:687–697, 2018. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2018-099193

70. Murray, A. Managing the training load in adolescent athletes. Int J Sports Physiol Perform, 12:S2-42–S2-49, 2017. Available from: https://journals.humankinetics.com/view/journals/ijspp/12/s2/article-pS2-42.xml

71. Myer, GD, Faigenbaum, AD, Edwards, NM, Clark, JF, Best, TM, and Sallis, RE. Sixty minutes of what? A developing brain perspective for activating children with an integrative exercise approach. Br J Sports Med, 49:1510–1516, 2015. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2014-093661

72. Myer, GD, Faigenbaum, AD, Ford, KR, Best, TM, Bergeron, MF, and Hewett, TE. When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth? Curr Sports Med Rep, 10:155–166, 2011. Available from: http://journals.lww.com/00149619-201105000-00012

73. Myer, GD, Sugimoto, D, Thomas, S, and Hewett, TE. The influence of age on the effectiveness of neuromuscular training to reduce ACL injury in female athletes. Am J Sports Med, 41:203–215, 2013. Available from: https://journals.sagepub.com/doi/10.1177/0363546512460637

74. Owoeye, OBA, VanderWey, MJ, and Pike, I. Reducing injuries in soccer (football): An umbrella review of best evidence across the epidemiological framework for prevention. Sports Med Open, 6:46, 2020. Available from: https://sportsmedicine-open.springeropen.com/articles/10.1186/s40798-020-00274-7

75. Parr, J, Winwood, K, Hodson-Tole, E, Deconinck, FJA, Parry, L, Hill, JP, et al. Predicting the timing of the peak of the pubertal growth spurt in elite male youth soccer

players: Evaluation of methods. Ann Hum Biol, 47:400–408, 2020. Available from: http://dx.doi.org/10.1080/03014460.2020.1782989

76. Parry, GN, Williams, S, McKay, CD, Johnson, DJ, Bergeron, MF, and Cumming, SP. Associations between growth, maturation and injury in youth athletes engaged in elite pathways: A scoping review. Br J Sports Med, 58:1001–1010, 2024. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2024-108233

77. Philippaerts, RM, Vaeyens, R, Janssens, M, Van Renterghem, B, Matthys, D, Craen, R, et al. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci, 24:221–230, 2006. Available from: http://www.tandfonline.com/doi/abs/10.1080/02640410500189371

78. Quatman-Yates, CC, Quatman, CE, Meszaros, AJ, Paterno, MV, and Hewett, TE. A systematic review of sensorimotor function during adolescence: A developmental stage of increased motor awkwardness? Br J Sports Med, 46:649–655, 2012.

79. Radnor, JM, Moeskops, S, Morris, SJ, Mathews, TA, Kumar, NTA, Pullen, BJ, et al. Developing athletic motor skill competencies in youth. Strength Cond J, 42:54–70, 2020. Available from: https://journals.lww.com/10.1519/SSC.0000000000000602

80. Rathleff, MS, Winiarski, L, Krommes, K, Graven-Nielsen, T, Hölmich, P, Olesen, JL, et al. Pain, sports participation, and physical function in adolescents with patellofemoral pain and Osgood-Schlatter disease: A matched cross-sectional study. J Orthop Sports Phys Ther, 50:149–157, 2020. Available from: https://www.jospt.org/doi/10.2519/jospt.2020.8770

81. Read, PJ, Oliver, JL, Myer, GD, De Ste Croix, MBA, Lloyd, RS. Altered landing mechanics are shown by male youth soccer players at different stages of maturation. Phys Ther Sport, 32:48–53, 2018.

82. Read, PJ, Oliver, JL, De Ste Croix, MBA, Myer, GD, Lloyd, RS. Assessment of injury risk factors in male youth soccer players. Strength Cond J, 38:12–21, 2016.

83. Read, PJ, Oliver, JL, De Ste Croix, MBA, Myer, GD, Lloyd, RS. An audit of injuries in six English professional soccer academies. J Sports Sci, 36:1542–1548, 2018. Available from: https://www.tandfonline.com/doi/full/10.1080/02640414.2017.1402535

84. Renshaw, I, Chow, JY, Davids, K, Hammond, J. A constraints-led perspective to understanding skill acquisition and game play. Phys Educ Sport Pedagogy, 15:117–137, 2010. Available from: http://www.tandfonline.com/doi/abs/10.1080/17408980902791586

85. Ribeiro, N, Martinho, DV, Pereira, JR, Rebelo, A, Monasterio, X, Gonzalo-Skok, O, et al. Injury risk in elite young male soccer players: A review on the impact of growth, maturation, and workload. J Strength Cond Res, 38:1834–1848, 2024. Available from: https://journals.lww.com/10.1519/JSC.0000000000004889

86. Malina, RM, Bouchard, C, Bar-Or, O. Growth, Maturation, and Physical Activity, 2nd ed. Champaign, IL: Human Kinetics; 2004.

87. Rommers, N, Rössler, R, Goossens, L, Vaeyens, R, Lenoir, M, Witvrouw, E, et al. Risk of acute and overuse injuries in youth elite soccer players: Body size and growth matter. J Sci Med Sport, 23:246–251, 2020. Available from: https://doi.org/10.1016/j.jsams.2019.10.001

88. Rössler, R, Donath, L, Verhagen, E, Junge, A, Schweizer, T, Faude, O. Exercise-based injury prevention in child and adolescent sport: A systematic review and meta-analysis. Sports Med, 44:1733–1748, 2014. Available from: http://link.springer.com/10.1007/s40279-014-0234-2

89. Ryan, D, Lewin, C, Forsythe, S, McCall, A. Developing world-class soccer players: An example of the academy physical development program from an English Premier League team. Strength Cond J, 40:2–11, 2018. Available from: https://journals.lww.com/00126548-201806000-00002

90. Salter, J, De Ste Croix, MBA, Hughes, JD, Weston, M, Towlson, C. Monitoring practices of training load and biological maturity in UK soccer academies. Int J Sports Physiol Perform, 16:395–406, 2021.

91. Sanders, JO, Qiu, X, Lu, X, Duren, DL, Liu, RW, Dang, D, et al. The uniform pattern of growth and skeletal maturation during the human adolescent growth spurt. Sci Rep, 7:1–9, 2017. Available from: https://www.nature.com/articles/s41598-017-16996-w

92. Van Der Sluis, A, Elferink-Gemser, MT, Brink, MS, Visscher, C. Importance of peak height velocity timing in terms of injuries in talented soccer players. Int J Sports Med, 36:327–332, 2015.

93. Van Der Sluis, A, Elferink-Gemser, MT, Coelho-e-Silva, MJ, Nijboer, JA, Brink, MS, Visscher, C. Sport injuries aligned to peak height velocity in talented pubertal soccer players. Int J Sports Med, 35:351–355, 2014.

94. Steffen, K, Andersen, TE, Bahr, R. Risk of injury on artificial turf and natural grass in young female football players. Br J Sports Med, 41:i33–i37, 2007. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsm.2007.036665

95. Torres-Ronda, L, Beanland, E, Whitehead, S, Sweeting, A, Clubb, J. Tracking systems in team sports: A narrative review of applications of the data and sport-specific analysis. Sports Med Open, 8:1–22, 2022. Available from: https://doi.org/10.1186/s40798-022-00408-z

96. Towlson, C, Salter, J, Ade, JD, Enright, K, Harper, LD, Page, RM, et al. Maturity-associated considerations for training load, injury risk, and physical performance in youth soccer: One size does not fit all. J Sport Health Sci, 10:403–412, 2021. Available from: https://doi.org/10.1016/j.jshs.2020.09.003

97. Unnithan, V, White, J, Georgiou, A, Iga, J, Drust, B. Talent identification in youth soccer. J Sports Sci, 30:1719–1726, 2012. Available from: http://www.tandfonline.com/doi/abs/10.1080/02640414.2012.731515

98. Viel, S, Vaugoyeau, M, Assaiante, C. Adolescence: A transient period of proprioceptive neglect in sensory integration of postural control. Motor Control, 13:25–42, 2009. Available from: https://journals.humankinetics.com/view/journals/mcj/13/1/article-p25.xml

99. Wachholz, F, Tiribello, F, Mohr, M, van Andel, S, Federolf, P. Adolescent awkwardness: Alterations in temporal control characteristics of posture with maturation and the relation to movement exploration. Brain Sci, 10:1–15, 2020. Available from: https://www.mdpi.com/2076-3425/10/4/216

100. Wik, EH. Growth, maturation and injuries in high-level youth football (soccer): A mini review. Front Sports Act Living, 4:1–9, 2022. Available from: https://www.frontiersin.org/articles/10.3389/fspor.2022.975900/full

101. Wik, EH, Martínez-Silván, D, Farooq, A, Cardinale, M, Johnson, A, Bahr, R. Skeletal maturation and growth rates are related to bone and growth plate injuries in adolescent athletics. Scand J Med Sci Sports, 30:894–903, 2020. Available from: https://onlinelibrary.wiley.com/doi/10.1111/sms.13635

102. Wormhoudt, R, Savelsbergh, GJP, Teunissen, JW, Davids, K. The Athletic Skills Model. Routledge; 2017. Available from: https://www.taylorfrancis.com/books/9781351782111

PART 3

General Discussion

General Discussion

This doctoral research offers important insights into the interplay between growth, BM, and workload in elite male youth soccer players. The four studies conducted revealed several key findings: (i) a distinct correlation between PHV and an elevated risk of injury, particularly during phases of rapid growth; (ii) significant longitudinal effects of BM on physical performance over two competitive seasons, with more mature players exhibiting temporary advantages in strength, speed, and match-related physical metrics; (iii) the influence of maturity status on external match workload, with post-PHV players experiencing greater demands in HSR and SD; and (iv) the development of a practical framework for monitoring growth, maturation, and workload, which provides actionable strategies for injury risk mitigation and individualized training within academy settings. Collectively, these findings highlight the necessity of integrating BM monitoring into long-term athlete development and workload management.

The current doctoral research investigates the complex relationship between growth, BM, and match workload to enhance player development and reduce injury risk in young soccer players. Growth is defined as quantitative changes in body size, such as increases in stature and body mass, whereas BM pertains to the tempo and timing of biological development during adolescence. By addressing the previously fragmented and inconsistent understanding of how maturation and growth influence physical performance, injury susceptibility, and workload patterns, this study offers valuable insights and practical recommendations for optimizing youth athlete development. The findings of this thesis have significant implications for coaches, sports scientists, and medical professionals who work with young soccer players. By incorporating maturation-specific training approaches and individualized workload management strategies, practitioners can better support the long-term development and well-being of young athletes. Furthermore, this study establishes a foundation for future investigations into the nuanced relationships between growth, maturation, and performance in youth sports, potentially leading to more refined and effective player development models.

A significant methodological strength of this thesis is its longitudinal repeated-measures design, which facilitated the monitoring of young elite soccer players over two complete competitive seasons. This approach allowed for the examination of developmental trajectories rather than relying solely on single time-point comparisons, thereby offering a more comprehensive understanding of how growth, BM, and workload interact to influence physical performance and match demands. Longitudinal monitoring is particularly valuable in youth sports, where rapid developmental changes occur, enabling researchers and practitioners to capture the dynamic nature of athlete development during adolescence more effectively.

Prior to this study, the field lacked standardized methodologies for data collection and cohesive frameworks for monitoring and implementing BM-specific principles in soccer academy environments. The absence of integration among growth and maturation monitoring, workload management, and injury mitigation strategies has impeded the practical application of existing research. This thesis aims to address these gaps by employing a robust and systematic approach to investigate the relationships between maturation, workload patterns, and injury risk, ultimately providing evidence-based guidelines for practitioners.

This study is distinguished by its comprehensive methodology. The use of linear mixed-effects models allowed the analyses to account for repeated measurements and inter-individual variability, providing a robust statistical framework for examining developmental changes across time in young soccer players. By addressing significant knowledge gaps, this study investigated the influence of various stages of BM on responses to physical performance assessments and match workloads, while also examining maturity-specific injury risks associated with these workloads. By addressing significant knowledge gaps, this study investigated the influence of various stages of BM on responses to physical performance assessments and match workloads, while also examining the maturity-specific injury risks associated with these workloads. These findings indicate that a uniform approach to training and performance monitoring is inadequate to address the complexities inherent in youth soccer development. Instead, this study highlights the importance of biologically tailored workload management strategies that consider maturation variability, thereby facilitating optimal player development and minimizing injury risk.

The experimental investigations presented in this thesis offer critical insights into performance standards and workload characteristics specific to different stages of maturation. The data indicated significant correlations between maturation status and external workload metrics during competitive matches. Moreover, players at different maturation status demonstrated distinct physiological and neuromuscular responses to workloads, highlighting the need for individualized workload prescriptions to reduce injury risk and enhance performance. This discussion synthesizes findings from a series of experimental studies, aligning them with the overarching thesis and research objectives. The chapter addresses each objective sequentially, illustrating how key aims were achieved and how these findings contribute to the broader body of knowledge on youth soccer development. Where relevant, holistic interpretations are critically analyzed alongside the existing literature to contextualize the broader implications of these findings within the field of sports science.

The estimation of BM in the present thesis relied primarily on the Khamis–Roche method and the PPAH, which are widely used non-invasive indicators in applied sport science settings. These methods are particularly suitable for longitudinal monitoring in youth sport environments, as they allow repeated assessments without exposing athletes to invasive procedures. Although alternative indicators, such as skeletal age assessment, may provide greater precision in estimating biological maturity, their implementation in elite academy environments is often limited by logistical, ethical, and radiation-related considerations. Therefore, the approach adopted in this thesis represents a pragmatic compromise between scientific rigor and ecological feasibility, aligning with monitoring practices commonly implemented in professional soccer academies.

In addition, this chapter critically examines the limitations inherent in the methodologies and approaches utilized throughout the thesis, thereby contextualizing the applicability of the findings in both the research and practical domains. It further offers recommendations for future research aimed at addressing existing knowledge gaps and refining maturity-specific strategies to optimize the development of young athletes. The primary objective of this study was to equip practitioners with evidence-based strategies to effectively monitor and manage the growth, maturation, and workload of young athletes. The implementation of these strategies will enable practitioners to mitigate injury risks while maximizing the long-term performance potential of elite young soccer players. The integration of these findings into soccer academy practices represents a significant advancement in the evidence-based evolution of youth soccer training paradigms.

This doctoral dissertation examines four distinct studies that provide deeper insights into the influence of growth, BM, and workload management on the development of young soccer players. Collectively, these studies address significant gaps in the literature by offering theoretical and practical implications for understanding the effects of maturation on physical performance, injury risk, and workload demands.

Study I conducted a narrative review to investigate the influence of BM on injury risk in young soccer players. This review aimed to enhance practitioners' understanding of the primary modifiable and non-modifiable risk factors for injury and offer vital information on practical strategies to aid stakeholders in making informed decisions. It seeks to demystify these complexities and provide insights that can help in crafting and executing effective strategies to mitigate injury risks, particularly during PHV and within the context of long-term athletic development in young soccer players. These findings highlight the increased vulnerability during PHV and emphasize the need for maturity-sensitive injury mitigation strategies. During this period, practitioners must prioritize regular assessments of anthropometric measurements and growth velocity, ideally every 4–6 weeks, to identify rapid changes in stature and body mass that may signal a heightened risk of injury. Training and match workloads should be carefully adjusted using both external metrics, such as GPS-derived TD, HSR, and ACC/DCC, and internal indicators, including session-rated perceived exertion (session-RPE) and HRV, to avoid sudden workload increases. Implementing individualized neuromuscular and strength programs is advisable, with a focus on core stability, eccentric hamstring exercises, and lower limb flexibility to address temporary deficits in coordination and strength. Additionally, incorporating structured recovery strategies, such as designated rest periods, sleep hygiene, and flexibility/mobility sessions, is crucial for ensuring safe adaptation during this critical developmental stage. By synthesizing research on growth spurts and neuromuscular imbalances in heightened injury risk, this study highlights the importance of longitudinal monitoring and targeted interventions. This emphasizes the need for coaches and medical staff to be informed about maturation-related injury risks and appropriate training modifications. Implementing individualized training programs that consider the maturation status and growth rate of each player can significantly reduce the risk of injury. Future research should aim to develop standardized assessment tools to accurately measure BM and its impact on injury risk among young soccer players.

Study II investigated the role of BM in shaping the physical performance outcomes of elite soccer players. The results showed that CA was a strong indicator of COD and sprinting performance, whereas BM significantly influenced power, maximal strength, and endurance. CA primarily affects COD speed and sprinting ability, with older players typically demonstrating superior performance. Maturation status affects explosive strength, maximal strength, and endurance, especially in post-PHV players, who show more substantial improvements over time. Considering an individual's biological maturity status when designing training protocols can ensure that young soccer players are appropriately challenged without an excessive workload, which could increase susceptibility to injury during accelerated growth. Coaches and talent identification specialists must recognize the differences in maturation to prevent premature preference for early maturing athletes or neglect of those who mature later. Employing bio-banding strategies, which involve grouping athletes based on biological rather than CA, can create more equitable competitive environments and development opportunities. However, the method of grouping should be tailored to the specific objectives of training or competition. For instance, bio-banding based on PPAH is particularly effective in minimizing physical mismatches and reducing injury risk during competitions. In contrast, grouping by maturity offset, such as the distance from PHV, may be more suitable for tracking growth trends and adjusting training workloads. Conversely, CA groupings may be more appropriate for technical–tactical sessions focused on age-specific cognitive and social development. Therefore, LTAD models should incorporate this flexibility, ensuring that athletes are grouped in a manner that best supports the intended goals and that all athletes have the opportunity to achieve their full potential, irrespective of their physical characteristics in early adolescence.

Study III explored the relationship between BM and external match workload. The results showed that CA and BM significantly affected crucial external load parameters in young male soccer players. CA was the main factor affecting metrics such as HSR and SD, whereas the combination of age and BM influenced TD/min, Acc/min, and Dec/min. As players mature, the distinct effects of BM on physical performance metrics appear to diminish. These results underscore the importance of considering BM in player evaluation to enhance performance assessments and inform age-appropriate training strategies. Differences in maturation status may influence selection and development opportunities, despite the potential for future success. These findings highlight the necessity for individualized workload management strategies that consider players' unique developmental trajectories based on their maturity status. However, youth athlete development is also influenced by contextual factors, such as playing position, training history, psychosocial environment, and coaching practices. Future research should therefore adopt more integrative models that consider these multidimensional influences on player development. Coaches and talent identification specialists should be aware of these maturation-related differences to avoid prematurely favoring early maturing players or overlooking late-maturing players. Implementing bio-banding strategies and grouping players according to biological rather than CA could facilitate more equitable competitive environments and development opportunities. LTAD models should incorporate flexibility to accommodate varying rates of maturation, ensuring that all players have the opportunity to reach their full potential, regardless of early adolescent physical characteristics.

The final study (Study IV) investigated the combined effects of growth, BM, and workload on strategies for mitigating injury risk. Through an applied case study, a framework was proposed to integrate growth monitoring, workload periodization, and maturity-based training adaptations to reduce injury rates among young soccer players. This study offers actionable recommendations for practitioners to balance workload and recovery based on individual growth and maturation trajectories, emphasizing the importance of individualized approaches to training and injury mitigation in youth soccer. By considering each player's unique developmental timeline, coaches and medical staff can make informed decisions regarding training intensity, volume, and recovery periods. This personalized approach may lead to improved long-term athletic development and mitigate injury risk, ultimately contributing to the sustainability and success of youth soccer programs.

While the present findings provide valuable insights into the interaction between BM, physical performance, and match workload in elite youth soccer players, the results should be interpreted within the specific context of the study. Data were collected within a single elite academy (Sporting Clube de Portugal), characterized by highly structured training processes, advanced monitoring systems, and a high level of player selection. Consequently, the developmental trajectories and workload benchmarks identified in this study may not be directly generalizable to academies operating under different competitive standards, training methodologies, or resource availability. Future research should aim to replicate these findings across multiple academies, countries, and competitive levels to strengthen the external validity of maturation-sensitive monitoring frameworks.

The present research primarily investigated the relationships between biological maturation, CA, and external workload metrics. However, the development of young athletes is a multifactorial process influenced by several contextual factors that were not directly examined in this thesis. Variables such as playing position, training history, psychosocial environment, and coaching practices may also influence physical performance, match workload, and adaptation processes in young soccer players. Future research integrating these contextual dimensions may provide a more comprehensive understanding of the complex mechanisms underlying youth player development.

One of the main practical contributions of this thesis is the development of an integrated monitoring framework that combines growth velocity, BM indicators, and external workload metrics. This framework can support practitioners in identifying periods of increased developmental vulnerability, particularly around PHV, and in adjusting training loads accordingly. By integrating maturation monitoring with workload management, coaches and performance staff may better individualize training prescriptions, reduce injury risk, and optimize long-term athlete development in elite soccer academies.

Scientific Novelty and Original Contributions

This thesis provides an original and multidimensional contribution to the understanding of growth, BM, workload, and physical development in elite youth soccer players. One of the main strengths of the present work is the integration of different but interconnected dimensions of youth athlete development, including growth, maturation, physical performance, match workload, and injury-related considerations, within the same longitudinal research framework.

A novel aspect of this thesis is the combination of longitudinal physical testing and GPS-derived match workload monitoring across two competitive seasons in elite academy soccer players aged 14–17 years. This approach allowed the examination of developmental trajectories over time while considering the substantial interindividual variability associated with BM during adolescence. In addition, the present research contributes maturity-specific reference values for physical performance and match workload metrics in elite youth soccer, potentially supporting more individualized approaches to athlete monitoring and performance interpretation.

Another important contribution of this thesis is the emphasis placed on the practical integration of maturation monitoring within LTAD frameworks. By combining theoretical foundations, empirical evidence, and applied recommendations, this work contributes to bridging the gap between scientific research and applied practice in elite soccer academies. The proposed framework integrating growth, BM, workload monitoring, and injury-related considerations may assist practitioners in developing more individualized, maturation-sensitive, and developmentally appropriate training strategies.

Furthermore, this thesis reinforces the importance of moving beyond chronological age as the sole criterion for athlete evaluation and training prescription during adolescence. The findings consistently support the need to consider BM status when interpreting physical performance, workload responses, and developmental variability in elite youth soccer players. Collectively, these contributions may provide relevant insights for sports scientists, strength and conditioning coaches, medical staff, and academy practitioners working within long-term athlete development environments.

Key Findings and Their Scientific and Practical Implications

1. <u>How does biological maturation influence the risk of injury among young soccer players?</u>

A narrative review (Study I) revealed that injury incidence peaks during PHV due to rapid skeletal growth and neuromuscular imbalances. These findings advocate continuous anthropometric assessments to monitor growth velocity, enabling medical and performance staff to proactively adjust training loads and recovery protocols to reduce injury risk. The implementation of monitoring strategies has the potential to substantially decrease injury rates and improve overall athlete development during this crucial growth phase. Coaches and trainers must be educated on the significance of these assessments and the effective interpretation of data. Furthermore, the development of individualized training programs that consider each athlete's growth rate and biological maturation could optimize performance while reducing the risk of injury.

2. <u>How does maturation affect the physical performance of young athletes?</u>

Study II demonstrated that post-PHV athletes showed significant gains in physical attributes, which is consistent with the previous literature on adolescent neuromuscular development. These insights guide strength and conditioning coaches in designing periodized training interventions that align with the maturity status, ensuring that strength and power development occur in parallel with biological maturation. These findings highlight the importance of customizing training programs to align with the specific developmental stages of each athlete. Coaches should implement progressive overload and periodization strategies that consider accelerated adaptations observed in post-PHV athletes. Additionally, regular monitoring of physical attributes and maturity status is essential to optimize training outcomes and mitigate the risk of overtraining or injury during this pivotal developmental period.

3. <u>What is the relationship between maturation and workload demand during the matches?</u>

Study III provides evidence that more biologically mature players, particularly those in the post-PHV stages, tend to cover greater distances and exert more high-intensity efforts than their less mature peers. This disparity highlights the need for workload adjustments to prevent excessive physical stress in more mature players while ensuring that less mature players receive adequate opportunities for progressive physical development. Performance analysts and coaching staff can integrate these insights to refine talent identification and training progression models. By customizing training regimens to align with the individual maturation status of athletes, practitioners can facilitate long-term athletic development and mitigate dropout rates. Furthermore, the integration of maturity assessments into routine evaluations can improve the precision of performance benchmarks. These strategies provide a more equitable and effective framework for the management of young athletes.

4. <u>How can training load management strategies be optimized to enhance athletic development?</u>

Study IV proposes a practical framework for integrating growth monitoring with training periodization. By incorporating real-time tracking of anthropometric changes and workload metrics, academies can implement evidence-based adjustments to optimize player readiness and performance while minimizing injury risk, empowering coaches to make informed, data-driven decisions regarding training intensity, volume, and recovery periods tailored to the individual growth trajectories of each player. By meticulously monitoring key indicators such as height velocity, weight fluctuations, and strength-to-mass ratios, academies can more effectively support young athletes through critical developmental stages. Moreover, this integrated approach facilitates early identification of potential overtraining or growth-related issues, enabling timely interventions to safeguard players' health and promote long-term development.

The findings of this dissertation have significant implications for soccer academies, scientists and coaches. Key recommendations include the following.

1. Maturity-Specific Training Programs – Strength and conditioning programs should be tailored according to biological maturation, with emphasis on neuromuscular control in pre-PHV players, balanced strength and power training in circa-PHV players, and structured strength progression in post-PHV players. Coaches must consistently evaluate the maturation status of athletes to ensure that training regimens are appropriately adjusted. Customized training programs are crucial for maximizing performance improvements while mitigating the likelihood of injuries owing to unsuitable workloads. Moreover, incorporating sport-specific skills and movements into strength and conditioning routines can significantly enhance their applicability in on-field performance.

2. Bio-Banding and Growth Monitoring – When combined with regular growth monitoring, bio-banding can ensure fair competition and promote optimal player development by categorizing athletes based on biological maturity rather than CA. This approach reduces the physical advantages of early developers and gives late bloomers the chance to demonstrate their skills in more balanced matchups. Nonetheless, CA groupings can also serve a valuable complementary role in research. Training and competing with physically stronger peers of the same CA can enhance the development of technical and tactical skills, allowing late-maturing players to offset their temporary physical disadvantage. For example, this can lead to improvements in decision-making speed, spatial awareness, anticipation, and ball control under pressure. Therefore, coaches and administrators should adopt a flexible strategy, alternating or combining biological and chronological groupings based on specific developmental goals and competitive contexts, while consistently monitoring growth and maturation to guide their decisions.

3. <u>Individualized Workload Management:</u> In context of training periodization, it is imperative to consider factors such as maturity status, positional demands, and prior injury history to optimize player development and minimize the incidence of overuse injuries. Coaches are advised to conduct regular assessments of players' biological maturity and growth rates, and adjust workloads accordingly, particularly during phases of rapid physical development. Position-specific training programs are instrumental in cultivating the unique skills and physical qualities required for the players' roles in the field. Furthermore, the implementation of individualized injury prevention protocols tailored to each player's history can effectively mitigate the risk of recurrent injuries and foster long-term athletic success.

4. <u>Long-Term Athletic Development (LTAD) frameworks:</u> Implementing comprehensive longitudinal tracking systems will enable soccer academies to enhance their talent identification strategies and optimize developmental pathways for young athletes. The collection of extensive data on players' physical, technical, and psychological attributes can provide valuable insight into their progress over time. By analyzing the trends and patterns within this longitudinal data, academies can identify key developmental milestones and adjust their training programs accordingly. Furthermore, these tracking systems facilitate more personalized approaches to player development, allowing tailored interventions that cater to individual needs and potential.

This doctoral dissertation enhances our understanding of the interplay among growth, maturation, and workload in shaping the developmental trajectories of young soccer players. By addressing critical gaps in the extant literature, this study offers a comprehensive framework for talent development, injury mitigation, and workload management in elite soccer. From a scientific standpoint, these findings contribute to maturation-sensitive training methodologies, and their practical application enables practitioners to design evidence-based interventions tailored to the development of individual athletes.

A distinguishing feature of this study is its holistic approach, which examines the complex relationships between biological maturation, physical performance, and injury risk. By integrating these elements, our findings provide valuable insights for the development of individualized evidence-based training programs. This perspective is crucial for optimizing the long-term growth and performance of young soccer players and for ensuring that training strategies align with each athlete's developmental profile.

Beyond soccer, the implications of this research extend to talent development strategies for other sports and physical activity. By providing a structured framework for understanding the intricate relationships among growth, maturation, and workload, this study offers valuable guidance to coaches, trainers, and sports scientists across various disciplines. The findings underscore the importance of a multifaceted approach to youth athlete development that prioritizes not only physical performance but also injury mitigation and long-term well-being. Although the present findings provide important insights into an elite academy environment, caution should be exercised when generalizing these results to other developmental contexts.

Conclusões

A presente tese teve como objetivo explorar as relações entre o crescimento, a maturação biológica e as qualidades físicas em jovens jogadores de futebol, fornecendo conhecimentos que possam contribuir para a otimização das estratégias de treino e de desempenho em programas de desenvolvimento de jovens atletas. Os resultados deste estudo evidenciam o papel crítico da idade cronológica e da maturação biológica na determinação do desempenho físico em diferentes domínios. À medida que os jogadores de futebol progridem ao longo das diferentes fases de crescimento, a complexidade do seu desenvolvimento fisiológico influencia resultados-chave de desempenho, desde qualidades físicas como a resistência e a capacidade de sprint, assim como em relação às métricas relacionadas com a carga de jogo em contexto competitivo.

Uma das observações mais relevantes deste estudo foi o papel significativo da idade cronológica na previsão do desempenho, particularmente em variáveis como a velocidade de mudança de direção e a capacidade de sprint. Os jogadores mais velhos demonstraram consistentemente um desempenho superior quando comparados com os seus pares mais jovens, sugerindo que a idade cronológica constitui um indicador fiável destas qualidades físicas. Contudo, a maturação biológica revelou-se um fator determinante para componentes mais específicas do desempenho físico, nomeadamente a potência, a força máxima e a resistência. Jogadores no período pós-pico de velocidade de crescimento em estatura (pós-PVCA), que já tinham atingido fases mais avançadas de maturação, evidenciaram melhorias mais acentuadas nestas capacidades ao longo do tempo, reforçando a importância do estado maturacional no desenvolvimento atlético.

Outro resultado relevante foi a influência da idade cronológica e da maturação nos parâmetros de carga externa durante a competição. A interação entre estas duas variáveis demonstrou que, enquanto a idade cronológica determinou principalmente variáveis como a corrida de alta intensidade e a distância em sprint, a maturação modulou outras exigências físicas, tais como a distância total por minuto, acelerações por minuto e desacelerações por minuto. À medida que a maturação progredia, o efeito da maturação biológica sobre o desempenho físico pareceu diminuir, indicando que o processo de adaptação associado à maturação desempenha um papel dinâmico ao longo das diferentes fases de crescimento.

Estes resultados reforçam a necessidade de uma abordagem abrangente na avaliação e gestão de jovens jogadores de futebol. Investigações futuras deverão aprofundar a análise das complexas interações entre carga de treino, recuperação e desempenho, particularmente no que se refere à forma como diferentes componentes do treino, nomeadamente a composição das sessões, interagem com os processos de crescimento e maturação. Adicionalmente, a relação entre crescimento, maturação biológica e carga externa evidencia a importância de integrar o estado maturacional nas avaliações dos jogadores, com o objetivo de melhorar a interpretação do desempenho e orientar o desenvolvimento de estratégias de treino sensíveis à maturação e adequadas à idade.

À medida que os jogadores de futebol progridem ao longo das diferentes fases de desenvolvimento, os profissionais devem manter-se atentos às alterações nas exigências físicas e nas capacidades individuais dos atletas. Uma compreensão mais aprofundada de como a maturação influencia indicadores-chave de desempenho permitirá não apenas melhorar os processos de identificação de talento, mas também apoiar intervenções mais individualizadas que promovam o desenvolvimento atlético a longo prazo. Em última análise, uma abordagem individualizada ao treino de força e condicionamento, à recuperação e à gestão da carga de treino, que considere simultaneamente a idade cronológica e o estado maturacional, é essencial para otimizar o desempenho e reduzir o risco de lesão em jovens atletas.

Em síntese, embora a idade cronológica e a maturação constituam fatores fundamentais para compreender o desempenho e as características físicas dos jogadores, é necessária investigação adicional para clarificar de que forma estes processos afetam diferentemente os atletas em função da sua fase de desenvolvimento. Existe, igualmente, uma oportunidade para os investigadores explorarem de forma mais aprofundada como as variações na composição do treino ao longo da época, particularmente durante períodos específicos de crescimento e maturação, influenciam as respostas à carga, os resultados de desempenho e os padrões de recuperação em jovens jogadores de futebol. Este tipo de investigação será determinante para aprofundar a compreensão das necessidades fisiológicas específicas dos jovens atletas e para otimizar o seu desenvolvimento holístico, tanto dentro como fora do campo.

Conclusions

This thesis aimed to explore the relationships between growth, BM, and physical qualities in young soccer players, providing insights that may contribute to the optimization of training and performance strategies within youth athlete development programs. The findings of this study highlight the critical role of both CA and BM in shaping physical performance across different domains. As soccer players progress through distinct developmental stages, the complexity of their physiological development influences key performance outcomes, ranging from physical qualities such as endurance and sprint capacity to match-related external workload metrics during competitive performance.

One of the most relevant observations of this study was the significant role of CA in predicting performance, particularly in variables such as COD speed and sprint capacity. Older players consistently demonstrated superior performance compared with their younger peers, suggesting that CA represents a reliable indicator of these physical qualities. However, BM emerged as an important factor associated with more specific components of physical performance, namely power, maximal strength, and endurance. Post-PHV players, who had already reached more advanced maturational stages, demonstrated greater improvements in these capacities over time, reinforcing the importance of maturation status in athletic development. Another relevant finding was the influence of CA and maturation on external workload parameters during competitive match-play. The interaction between these two variables demonstrated that, while CA primarily influenced variables such as HSR and SD, maturation appeared to modulate other physical demands, including TD/min, Acc/min, and Dec/min. As maturation progressed, the specific influence of BM on physical performance appeared to diminish, suggesting that maturation-related adaptations may play a dynamic role across different developmental stages.These findings reinforce the need for a comprehensive approach to the evaluation and management of young soccer players. Future research should further investigate the complex interactions among workload, recovery, and performance, particularly regarding how different training components, including session composition and workload distribution, interact with growth and maturation processes. Furthermore, the relationship between growth, BM, and external workload highlights the importance of integrating maturation status into player assessments to improve performance interpretation and support the development of maturation-sensitive and age-appropriate training strategies.

As soccer players progress through different developmental stages, practitioners should remain attentive to changes in physical demands and individual athlete capacities. A deeper understanding of how maturation influences key performance indicators may not only improve talent identification processes but also support more individualized interventions that promote LTAD. Ultimately, an individualized approach to strength and conditioning, recovery, and workload management that considers both CA and maturational status is essential for optimizing performance and supporting safer athlete development in young athletes.

In conclusion, although CA and BM represent fundamental factors for understanding performance and physical characteristics in young soccer players, additional research is required to clarify how these processes may differently affect athletes according to their developmental stage. There is also an opportunity for researchers to further explore how variations in training composition throughout the season, particularly during specific periods of growth and maturation, influence workload responses, performance outcomes, and recovery patterns in young soccer players. Such investigations may contribute to a more comprehensive understanding of the specific physiological needs of youth athletes and support the optimization of their holistic development both on and off the field.

Practical Applications

This doctoral thesis emphasizes the importance of understanding the relationship between growth, BM, and physical quality among young soccer players. These findings have several practical applications for sports scientists, coaches, and practitioners aiming to optimize the training and development of young athletes. By integrating the insights derived from this research, it is possible to refine coaching strategies, enhance player development programs, and minimize the risk of injuries, ultimately contributing to young soccer players' well-being and long-term success.

The influence of BM on physical performance underscores the necessity of adapting training regimens to match an athlete's developmental stage. Coaches should consider both CA and maturation status when devising training plans. For instance, the training intensity and focus of physical preparation should be adjusted depending on whether players are pre-PHV (pubertal peak height velocity), circa-PHV, or post-PHV. Notably, post-PHV players exhibited substantial improvements in power, strength, and endurance compared with their pre- and circa-PHV counterparts, suggesting that more demanding training in these areas could optimize their physical qualities. Focusing on specialized training as players progress through their maturation status ensures that they gain the appropriate benefits while avoiding overtraining or undertraining. Individualized approaches are essential for optimizing physical development, maximizing performance gains, and reducing the likelihood of injury.

Accurate BM assessments are valuable tools for refining the talent identification processes. Traditional approaches to player selection often rely on CA, which can result in biased evaluations, particularly when players are assessed at different maturation status. Early maturing players may appear more physically advanced, potentially leading to an overestimation of their long-term potential, while late-maturing players may be unfairly overlooked. Coaches can mitigate these biases and make informed decisions by integrating maturation assessments into talent identification processes. This approach ensures that players' development is assessed based on their true capabilities rather than their developmental timing, thus enabling scouts and practitioners to assess a player's true potential more accurately.

Furthermore, data obtained from maturation assessments can be integrated into LTDA plans. By aligning training and competition demands with a player's growth stage, practitioners can reduce the injury risks associated with mismatched loadings and offer support that matches each player's individual needs. Tailored development pathways also enable professionals to foster sustainable progress over time and to optimize athletes' long-term performance. A critical conclusion of this thesis is the necessity for individualized training programs. It is apparent that BM, in conjunction with other factors such as playing position, injury history, and individual preferences, should inform training decisions. Young athletes do not develop uniformly and coaches should recognize these variations when designing developmental pathways. While early maturing players may experience an initial advantage in terms of physical qualities, their progress should be carefully monitored to prevent early specialization and potential burnout. Conversely, late-maturing players should be provided with additional support and appropriate developmental opportunities to progress without premature overburden. Moreover, considering the position that each player occupies in the field provides an additional dimension of customization. Specific skills and attributes are often more pronounced in field positions and require tailored physical preparations.

The implementation of a comprehensive system to track the physical performance of young soccer players offers valuable insights for ongoing assessment and program development. Sports academies should implement longitudinal tests to monitor progress in key performance metrics, such as endurance, strength, power, and speed. This data-driven approach allows for a continuous evaluation of players' physical development, ensuring that the training intensity is appropriately calibrated and benchmarks are established for future reference. Access to consistent performance data is invaluable for comparing results across teams and academies. These comparative analyses can improve coaching practices, refine development strategies, and assist in the implementation of more individualized, maturation-specific training interventions. By integrating growth and maturation status into the player development framework, academies can foster enhanced development strategies and ensure the health and safety of players. Ultimately, this research underscores the critical need for sports professionals to adopt a more personalized, evidence-based approach to training and development that acknowledges each player's biological clock while providing the requisite support to develop their full potential as athletes.

Limitations and Future Recommendations

This thesis contributes meaningfully to the understanding of the interrelationships among growth, BM, body composition, workload, and physical attributes in young soccer players. However, several limitations should be acknowledged when interpreting the findings. Recognizing these constraints is essential for contextualizing the results and guiding future research aimed at advancing knowledge in youth athlete development.

A notable limitation of the present research is that all data were collected within a single elite soccer academy. Although this context provided high-quality data and strong ecological validity through structured monitoring systems and a standardized training environment, it may limit the generalizability of the findings to other developmental settings, competitive standards, or talent development models. Youth academies may differ substantially regarding training methodologies, competitive exposure, talent identification strategies, and available multidisciplinary resources. Therefore, future research should incorporate multi-club and multi-country samples to facilitate comparisons across diverse developmental contexts and provide more representative reference values for youth soccer populations.

Another limitation relates to the partial integration of workload-related variables across the studies included in this thesis. Although Study III specifically examined external match workload using GPS-derived metrics, the broader interaction between training load, BM, physical development, and recovery processes was not comprehensively explored across all investigations. Variables such as training volume, intensity, recovery strategies, sleep quality, and periodization models may influence athletes' responses to growth and maturation processes. Consequently, future research should further investigate the combined effects of workload, recovery dynamics, and maturation status, particularly across different developmental stages surrounding the PHV period. Such approaches may assist practitioners in more effectively individualizing training prescriptions and supporting LTAD.

Although injury risk and injury-related vulnerability were discussed throughout this thesis, a comprehensive longitudinal injury surveillance system was not systematically implemented across all empirical studies. Consequently, direct associations between maturation-related variables and injury occurrence should be interpreted cautiously. Future longitudinal investigations integrating systematic injury surveillance, workload monitoring, and maturation assessments may provide a more comprehensive understanding of injury susceptibility throughout adolescence.

While the observational studies included in this thesis employed longitudinal repeated-measures designs across two competitive seasons, thereby allowing the examination of developmental trajectories over time, the observation period remains relatively limited within the broader context of LTAD. Growth and BM are dynamic processes unfolding over several years, and the developmental patterns observed during adolescence may evolve substantially as athletes progress into adulthood. Furthermore, although the longitudinal design enabled the investigation of temporal associations, the observational nature of the studies does not allow causal inferences to be established. Therefore, the findings presented throughout this thesis should be interpreted as associative rather than causal relationships between BM, workload, physical performance, and injury-related outcomes. Future research should therefore incorporate extended longitudinal designs tracking athletes across multiple developmental stages to better understand how maturation influences long-term performance trajectories and developmental pathways.

From a methodological perspective, the present thesis primarily focused on external workload indicators, including TD, sprint activity, and ACC profiles. Although these metrics provide valuable insights into match demands, integrating internal load indicators, such as HR responses, HRV, perceptual measures, and wellness-related variables, may provide a more comprehensive understanding of athletes' physiological and psychophysiological responses to training and competition across different maturation stages. Furthermore, the estimation of BM was based primarily on non-invasive anthropometric methods because of their practicality and feasibility in applied sports settings. However, alternative indicators of BM, such as SA assessment, may provide additional precision in specific research contexts, particularly when combined with longitudinal monitoring approaches. Future studies should continue refining methodological approaches for maturity assessment while balancing scientific accuracy with ecological feasibility in elite sport environments.

Another important limitation concerns the relatively narrow range of contextual variables explored in this thesis. Although the present research primarily focused on CA, BM, workload, and physical performance indicators, athlete development during adolescence is inherently multidimensional. Psychological and psychosocial factors such as motivation, perceived stress, emotional well-being, coping strategies, burnout risk, and social support may also influence training adaptation, injury susceptibility, and long-term performance development. Similarly, contextual variables including playing position, training history, educational demands, sleep behaviors, and environmental influences may contribute to interindividual variability in developmental trajectories. Future multidisciplinary investigations integrating biological, physical, psychological, and environmental dimensions may therefore provide a more holistic understanding of youth soccer development.

Additionally, the scope of the present thesis was restricted to male soccer players, limiting the direct applicability of the findings to female athletes. Given the continued growth and professionalization of women's soccer worldwide, future research should investigate how BM influences physical performance, workload responses, and injury-related outcomes in female players. Such investigations may contribute to the development of more inclusive and evidence-informed athlete development models.

In conclusion, while this thesis contributes meaningful insights into growth, BM, workload, and physical development in young soccer players, future research should continue advancing this field through the inclusion of larger and more diverse samples, longer longitudinal monitoring periods, and more comprehensive multidimensional assessment models. The integration of maturation monitoring, workload management, recovery profiling, and individualized training strategies may provide valuable practical applications for optimizing athlete development pathways. Specifically, future studies should explore whether maturation-sensitive training interventions, including strength-, neuromuscular-, coordination-, and movement-based programs implemented during periods of accelerated growth, may enhance physical development while potentially reducing injury susceptibility during critical developmental phases.

Appendix A

Participation in Congresses and Lectures

1. European Football Congress 2023 (EFC2023)


EUROPEAN FOOTBALL CONGRESS 2 0 2 3

13 • 14 APRIL • LISBON • PORTUGAL

CERTIFICATE OF ATTENDANCE

Nuno Ribeiro

attended the EUROPEAN FOOTBALL CONGRESS 2023 (EFC2023) held in Lisbon, Portugal, from 13 to 14 April.

EFC2023 Chairs

João Valente-dos-Santos	Xurxo Dopico-Calvo	Gert Vande Broek	Pavel Háp
Lusófona University	University of A Coruña	KU Leuven	Palacký University Olomouc
Lisbon, Portugal	Coruña, Spain	Leuven, Belgium	Olomouc, Czech Republic

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EUROPEAN
FOOTBALL
CONGRESS
2 0 2 3
BOOK OF ABSTRACTS
Editors:
João Valente-dos-Santos, Xurxo Dopico-Calvo, Gert Vande Broek, Pavel Háp
“BRIDGE THE GAP BETWEEN SCIENCE AND FOOTBALL PRACTICE”
UNIVERSIDADE LUSÓFONA
UNIVERSIDADE DA CORUÑA
KU LEUVEN
Palacký University Olomouc

EFFECTS OF AMBIENT TEMPERATURE ON PHYSICAL, PHYSIOLOGICAL AND COGNITIVE DEMANDS IN FOOTBALL: WHERE DO WE STAND?

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BACKGROUND/AIM

The 2014 World Cup at Brazil exposed players to high temperatures, drawing attention to the need to study and understand the effect that heat has on physical, physiological and anticipatory performance of players [1]. This systematic review examined the effect of ambient temperature on football players who followed an assessment of the impact of physical and physiological demands and anticipation during a football-specific fatigue protocol.

METHODS

The data sources used were Cochrane Library, PubMed, Scopus, SPORTDiscus and Web of Science. The P.I.C.O.S. criteria were: (i) Healthy football players with no sex, age, or competitive level restrictions; (ii) Studies using football-specific fatigue-inducing protocol followed by assessment of anticipatory judgments using temporal and/or spatial occlusion, under controlled temperature conditions; (iii) Comparison groups will be the same as the intervention, but using a different temperature during a football-specific fatigue-inducing protocols; (iv) Outcomes will include measures of anticipation, and/or physical or physiological tests; (v) No limitations regarding study design, as long as two groups exposed to different temperatures were present.

RESULTS

The search initially identified 1,289 titles. However, none of the articles met the P.I.C.O.S. adopted, resulting in a total of zero eligible articles. Therefore, it must be concluded that evidence bases of sufficient scientific quality for the understanding the effect of high temperature on physical and physiological demands and anticipatory judgments of football players is lacking.

CONCLUSIONS

The physical and physiological demands and player's judgment ability are fundamental factors in their performance throughout the game, especially when they are exposed to high temperatures. Therefore, the diagnosis we can reach at the end of this review is that there is a gap in the literature.

REFERENCES

[1] Nassis GP, *et al.* (2015). *Br J Sports Med*, 49 (9),609-613.

EFFECTS OF GROWTH, MATURATION, AND WORKLOAD ON INJURY RISK IN YOUNG ELITE MALE FOOTBALL PLAYERS

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BACKGROUND/AIM

The long-term athletic development of young male football players represents a long period of preponderant adaptations for the players development. In this sense, it is essential to evaluate and monitor the different modifiable (i.e., workload) and non-modifiable (i.e., growth and maturation) factors during this period. By doing so, academies could more easily develop the physical, technical and tactical qualities, while minimizing injury risk [1], as they (academies) identify and develop young players, with the aim of competing at senior level and obtaining a professional contract [2]. Therefore, the purpose of the present review is to understand the impact of maturation, growth, and workload on the injury risk of youth male football players.

RESULTS

Faster growth rates (i.e., > 0.6 cm from the previous month) and pre or circa peak height velocity (PHV) periods increase injury likelihood [3]. Furthermore, early mature boys seem to be more prone to injuries. Evidence according to associations between workload and injury in young football players is not yet robust, particularly at pubertal ages.

CONCLUSIONS

According to maturation and growing there are three red flags that practitioners should be monitoring monthly (to ensure greater precision) during the pubertal years, to reduce the risk of injury: (i) PHV year, (ii) Growth rates ≥ 7.2 cm/year (0,6cm/month), and (3) Lower-leg growth rate ≥ 3.6 cm/year (0,3 cm/month). To our knowledge, associations between workload and injury are scarce, specially at pubertal years. Therefore, associations between injury risk and workload (internal or external) should be studied. Moreover, the mediation effect of the workload on the association between growth / maturation and injury is not established. This is a gap in the literature that should be addressed.

REFERENCES

[1] le Gall F, *et al.* (2010). *J Sci Med Sport*, 13 (1), pp. 90-95.
[2] Towlson C, *et al.* (2021). *J Sport Health Sci*, 10 (4), pp. 403-412.
[3] Kemper GLJ, *et al.* (2015). *Int J Sports Med*, 36 (13), pp. 1112-1117.

2. Internal Training Action (Football) - Cristiano Ronaldo Academy - Sporting Clube de Portugal

❖ ***Crescimento e Maturação – Risco de Lesão (40 min)***

- Identificar e avaliar os fatores de risco de lesão em jovens atletas (20 min)
- Apresentar estratégias para a redução do risco de lesão em jovens atletas (20 min)

Formador: Nuno Ribeiro

❖ ***Abordagem Integrada em Contexto de Academia – Crescimento e Maturação (30 min)***

- A importância do Bio-Banding (15 min)
- Como podemos melhorar a nossa abordagem de intervenção? (15 min)

Formador: Nuno Ribeiro

3. Speaker at the course "Strength & Conditioning Course – Dare to know more" at Academia Clínicas Espregueira, on the theme: *"Growth, maturation and performance in sports."*

academia clínicas espregueira

DECLARAÇÃO DE ATIVIDADE FORMATIVA

A Academia Clínicas Espregueira, sita na Estádio do Dragão, Piso -3, Entrada Nascente, 4350-415 Porto, com o número de pessoa coletiva 502420235, declara para os devidos efeitos que **Nuno Ribeiro**, foi formador nesta entidade no(s) curso(s), módulo(s) e ano(s) identificado(s) no quadro:

CURSO(S)	MÓDULO(S)	HORAS	LOCAL(AIS)	ANO(S)
3ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2021
4ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2022
5ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2022
6ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2023
7ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2023
8ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2024
9ª edição - Strength & Conditioning - Dare to know more	Crescimento, maturação e performance no desporto	2h	Plataforma e-learning	2024

Porto, 6 de fevereiro de 2025

(O Responsável pela Entidade Formadora)

Assinado por: **Rogério Barbosa Pereira**
Num. de Identificação: 11347750
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Academia Clínicas Espregueira
Estádio do Dragão, Piso - 3, Entrada Nascente, 4350-415 Porto
Tel. +351 220 100 148

ENTIDADE FORMADORA CERTIFICADA

4. **Speaker at Aspire Academy Sports Medicine Center (Tuesday In-House Education Session) on the topic: *"Growth and Maturity of Young Soccer Players Applying to Elite Academy."***

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15 October 2024

To Whom It May Concern

This is to attest that: **Mr. Nuno Ribeiro** was a guest speaker in our weekly In-House Education session (CPD)at Aspire Academy Sports Medicine Center (AASMC), Doha-Qatar.

Topic: *Growth and Maturation Applying for Young Soccer Players to an Elite Academy*

Date: 15 October 2024, 11:30-12:30pm

Venue: Aspire Academy Football Performance Center

The contribution and sharing of knowledge of **Mr. Nuno** is highly appreciated.

Respectfully yours,

Dr. Alejandro Alvarez Mesa
Medical Director of AASMC

Abdallah Rejeb, PhD
Coordinator In-House Education

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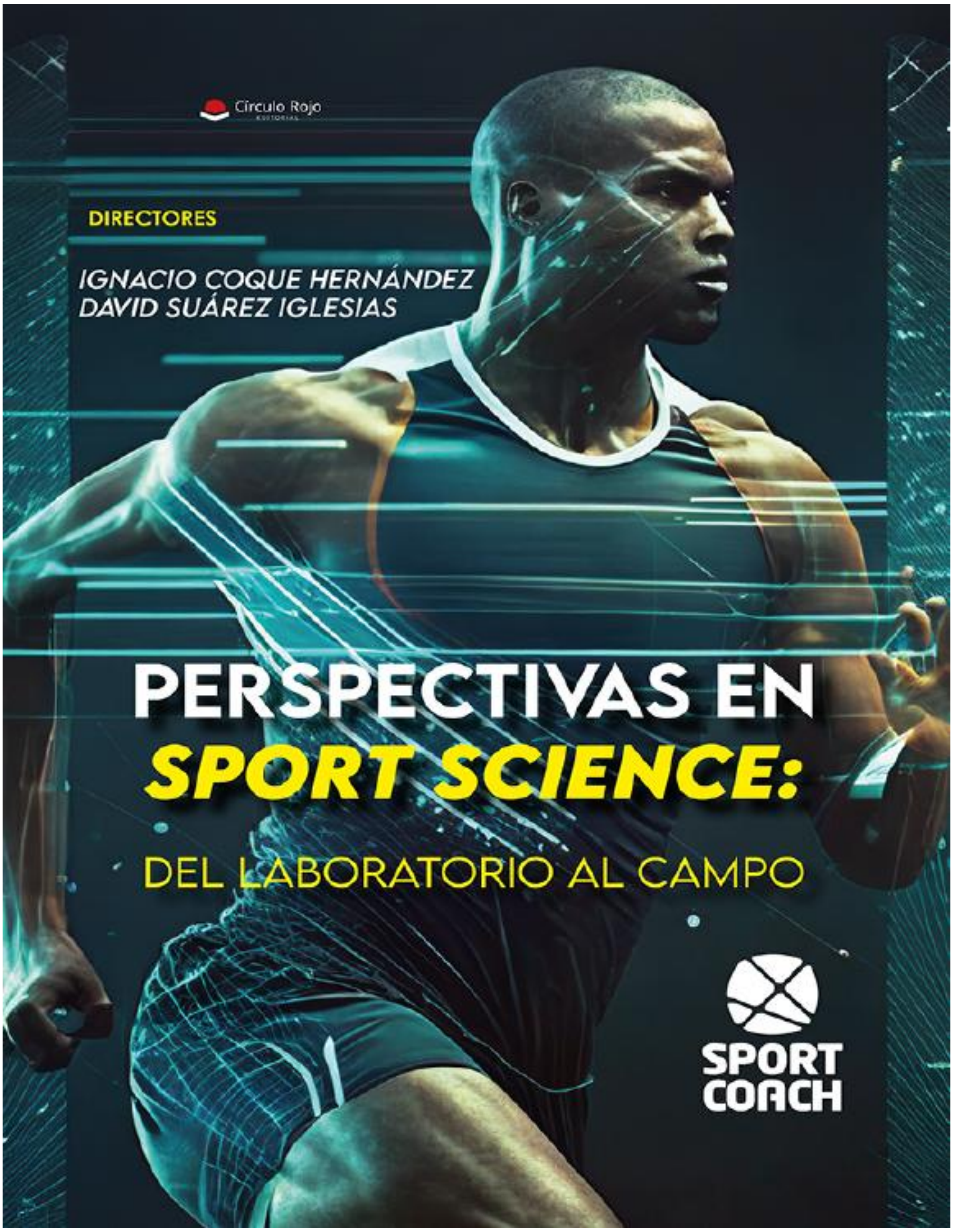
5. Author of the chapter *"Risk of injuries in elite young footballers: effects of growth, maturation and workload"* from the book "Perspectives on Sport Science: From the Laboratory to the Field."



Riesgo de lesiones en futbolistas jóvenes de élite: efectos del crecimiento, la maduración y la carga de trabajo

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Sport Science, SportCoach Academy
Tutor: Dr. David Suárez Iglesias

Nota del autor

Quiero expresar mi más sincero agradecimiento a todos los que hicieron posible este capítulo de libro. En primer lugar, quiero agradecer al Dr. David Suárez Iglesias por su inestimable orientación y guía durante todo el proceso de investigación. Su conocimiento y experiencia fueron fundamentales para el desarrollo de este proyecto. Además, quiero agradecer a mi equipo de colaboradores y colegas, cuyo aporte y apoyo fueron vitales en todas las etapas de este trabajo. Sus contribuciones enriquecieron significativamente el contenido y la calidad de este libro. También quiero agradecer a los revisores y editores que brindaron comentarios constructivos y sugerencias para mejorar este capítulo. Estoy profundamente agradecida con todas las personas mencionadas y aquellas que contribuyeron a este proyecto de una forma u otra. Su apoyo y dedicación fueron fundamentales en el desarrollo de este libro. Este capítulo será útil para los profesionales y académicos interesados en la salud y el rendimiento de los jóvenes futbolistas de élite. Finalmente, quiero resaltar la importancia de este tema en el desarrollo a largo plazo de los jóvenes futbolistas. Comprender el riesgo de lesiones y los factores relacionados con el crecimiento, la maduración y la carga de trabajo es fundamental para promover un entrenamiento seguro y saludable en este grupo de atletas.

Cualquier mensaje con respecto a este capítulo debe ser enviado a Nuno Costa Ribeiro:
nunoribeir@hotmail.com

Appendix B

Acceptance of scientific articles

1. The Journal of Strength and Conditioning Research *"Injury Risk in Elite Young Male Soccer Players: A Review on the Impact of Growth, Maturation, and Workload"*

Brief Review

The Journal of Strength and Conditioning Research™

Injury Risk in Elite Young Male Soccer Players: A Review on the Impact of Growth, Maturation, and Workload

Nuno Ribeiro,[1,7] Diogo V. Martinho,[2] João R. Pereira,[3,4] André Rebelo,[3,4] Xabier Monasterio,[5] Oliver Gonzalo-Skok,[6] João Valente-dos-Santos,[3,4] and Francisco Tavares[7]

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Abstract

Ribeiro, N, Martinho, DV, Pereira, JR, Rebelo, A, Monasterio, X, Gonzalo-Skok, O, Valente-dos-Santos, J, and Tavares, F. Injury risk in elite young male soccer players: a review on the impact of growth, maturation, and workload. *J Strength Cond Res* 38(10): 1834–1848, 2024—The long-term development of young male soccer players involves a prolonged period of significant adjustments, highlighting the importance of studying the complex interaction between dynamic variables, including workload, and inherent elements like growth and maturity. This analysis examines the intricate connections involving the development, maturity, workload, and susceptibility to injuries among adolescent male soccer players. Significantly, these connections become prominent at the peak height velocity (PHV) period, a crucial moment in maturation. Growth rates vary among individuals, and higher rates have been associated with an increased risk of injury in young soccer players, particularly during periods of rapid growth. Identifying possible risk factors and understanding the complex connections between them is crucial to developing specific methods for reducing the risk of injury. Sharing this valuable information with essential stakeholders is crucial for guaranteeing young athletes' comprehensive growth and maturation process. Furthermore, this review emphasizes the immediate need for long-term studies and thorough injury analyses to comprehend better the dynamic interactions that influence injury patterns in young male soccer players. This review will allow practitioners to better understand the main modifiable and nonmodifiable risk factors for injury and provide essential information focusing on practical strategies, facilitating more informed decision making by all stakeholders. The review aims to clarify these complexities and offer crucial insights that can assist in designing and implementing efficient strategies to reduce the risk of injury, specifically for the challenges faced during PHV and within the broader framework of long-term athletic development in young soccer.

Key Words: long-term athletic development, intrinsic factors, extrinsic factors, assessment, monitoring

2. The Biology of Sport *"Impact of Biological Maturation on Physical Tests Performance in Portuguese Elite Male Academy Soccer Players"*

Original Paper DOI:

uncorrected proof

Impact of biological maturation on physical tests performance in Portuguese elite male academy soccer players

AUTHORS: Nuno Ribeiro[1,2,3], Oliver Gonzalo-Skok[4], Joao Valente dos Santos[2,5,6], Joao R. Pereira[2,5,6], Mauro Mandorino[7,8], Jo Clubb[9], Marco Beato[10], Jamie Salter[11], Hadi Nobari[12,13], Nuno Loureiro[3], Ruben Ferreira[3], Joao Pedro Araujo[3], Francisco Tavares[3]

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ABSTRACT: This study examined the influence of biological maturation on the physical performance of highly skilled U-14 – U-17 male soccer players, specifically focusing on sprinting, jumping, and aerobic capacity. Sixty-seven players from a professional academy in Portugal participated in two seasons (2021–2023). Maturation was assessed at six time points, and players were categorized into pre- and circa-peak height velocity (PHV) and post-PHV groups. Owing to the small pre-PHV sample size ($n = 4$), these were combined with the circa-PHV group for the analysis. Key physical attributes were measured, and maturity was assessed using the predicted percentage of adult height. Mixed-effects models indicated that chronological age significantly influenced physical performance, with older players demonstrating a superior change in direction speed ($p < 0.001$) and sprint performance ($p < 0.001$), whereas maturity status had no additional effect. Maturity status interacted with age in the jumping height test ($p = 0.001$), with post-PHV players showing greater improvement. Chronological age and biological maturity significantly influenced endurance ($p = 0.001$) and maximal strength ($p = 0.020$), with post-PHV players exhibiting greater gains. Chronological age and biological maturation significantly affected the physical performance of young soccer players. Relying solely on age may overlook developmental factors and underscore the need for tailored training and assessment strategies.

CITATION: Ribeiro N, Gonzalo-Skok O, dos Santos JV et al. Impact of biological maturation on physical tests performance in Portuguese elite male academy soccer players. Biol Sport. 2026;43:xx–xx.

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Key words:
Maturation
Physical performance tests
Performance indicators
Field testing
Young athletes
Long-term athletic development

3. The Biology of Sport *"Impact of Biological Maturation on Match Workload in Portuguese Elite Male Academy Soccer Players"*

Original Paper

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Impact of biological maturation on match workload in Portuguese elite male academy soccer players

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ABSTRACT: Youth soccer academies are essential for identifying and developing talented players, yet substantial inter-individual variability in biological maturation may influence match workload beyond chronological age. This study investigated the independent and interactive effects of biological maturation and age on match workload in elite male youth soccer players (U14–U17). Sixty Portuguese academy players were assessed at six time points across two competitive seasons (2021–22 and 2022–23). Biological maturation was classified using the percentage of predicted adult height, grouping players as pre-/circa-PHV and post-PHV. Mixed-effects models were used to examine the effects of age, maturity status, and their interaction on match workload metrics. Chronological age significantly influenced high-speed running ($\beta = 0.527$, $p = 0.001$) and sprint distance per minute ($\beta = 0.174$, $p = 0.001$). In contrast, total distance per minute and total accelerations and decelerations per minute were shaped by significant age × maturity interactions ($p \leq .001$), indicating stronger maturity-related effects at younger ages that attenuated across adolescence. Chronological age alone does not adequately account for variability in match workload among elite youth soccer players. Biological maturation plays a significant role, in conjunction with age, in determining the demands of total distance and acceleration/deceleration, with more pronounced effects observed at younger ages and a diminishing influence as players reach post-peak height velocity (PHV) stages. Conversely, high-speed running and sprinting distances are primarily influenced by age. These findings underscore the necessity of incorporating biological maturity into the interpretation of match workload, particularly during early to-mid adolescence.

CITATION: Ribeiro N, Gonzalo-Skok O, Valente-dos-Santos J et al. Impact of biological maturation on match workload in Portuguese elite male academy soccer players. Biol Sport. 2026;43:1329-1340.

Received: 2025-06-17; Reviewed: 2026-02-15; Re-submitted: 2026-02-20; Accepted: 2026-03-14; Published: 2026-04-20

Key words:
Adolescent Performance
External Load
Match Demands
Somatic Maturity
Youth Soccer

4. Strength and Conditioning Journal "*From Theory to Practice: The Role of Growth, Maturation, and Workload in Injury Risk Mitigation for Young Soccer Players*"

From Theory to Practice: The Role of Growth, Maturation, and Workload in Injury Risk Mitigation for Young Male Soccer Players

Nuno Ribeiro,[1,2] Diogo V. Martinho,[3] Xabier Monasterio,[4,5] Oliver Gonzalo-Skok,[6] Nuno Loureiro,[2] Ruben Ferreira,[2] João Pedro Araújo,[2] and Francisco Tavares[2]
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ABSTRACT

The development of young male soccer players entails intricate interactions among growth, maturation, and workload, which significantly impact injury risk. Peak height velocity constitutes a critical phase during which players undergo rapid physical changes, potentially increasing their susceptibility to injury. Given the variability in biological maturation, practitioners must implement individualized strategies to manage workloads and mitigate the risk of injury. This review synthesizes the current evidence on growth and maturation monitoring, offering a framework for integrating these insights into practical training interventions. It emphasizes the importance of longitudinal assessments, tailored workload management, and communication strategies among coaches, medical staff, and players. Practical applications include systematic tracking of growth metrics, bio-banding, modifying workloads based on maturity status, and implementing recovery protocols for high-risk individuals. These strategies enable practitioners to identify players undergoing accelerated growth and adjust training accordingly to reduce injury risk while optimizing long-term development. By bridging the gap between theoretical knowledge and applied practice, this review provides actionable recommendations to support young athletes throughout their developmental journey, ensuring a balance between performance enhancement and injury mitigation.

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INTRODUCTION

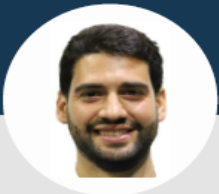
Youth soccer academies invest considerable resources in developing players who can either progress to the first team or generate transfer revenue (58,87,93). To protect this investment, it is essential to manage injury risks during key developmental periods, especially the adolescent growth spurt (35,58,81,84). Strength and conditioning coaches play a pivotal role in youth development by applying evidence-based strategies that enhance physical performance while reducing injury risk (2,11,31,38,47,58,62,63). A comprehensive and integrated plan is essential to support long-term athletic progression and overall player well-being (84,87).

For strength and conditioning coaches working with young soccer players, understanding growth and biological maturation is fundamental to tailoring

KEY WORDS:
long-term athletic development; intrinsic factors; extrinsic factors; assessment; monitoring

Appendix C

Curriculum Vitae



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SKILLS

- Athlete Monitoring (GPS, Heart Rate, RPE)
- Workload Monitoring and Injury Mitigation
- Physical Qualities Development
- Data Analysis (Excel, Power BI, Python, R)
- Scientific Research & Evidence-Based Practice
- Effective Communication and Team Collaboration
- Leadership and Decision-Making

LANGUAGES

- Portuguese (Fluent)
- English (Fluent)
- Spanish (Fluent)

PROFILE

Experienced Strength and Conditioning Coach with a background as a former football player and a proven track record in professional football clubs and elite academies worldwide. I began my career working with Olympic athletes, which shaped a high-performance mindset and commitment to excellence. Specialized in optimizing physical performance through individualized, evidence-based training programs tailored to each player's position, physical profile, and competition demands. Skilled in workload management, injury mitigation, and integrating performance strategies within multidisciplinary teams to support both immediate impact and long-term career sustainability in professional football.

WORK EXPERIENCE

Damac FC (Saudi Pro League) 2024 - 2025

Strength and Conditioning Coach

- Plan and oversee individualized training programs tailored to physical profiles and positional demands.
- Analyze and monitor internal and external training loads to optimize player performance and minimize injury risk.
- Deliver data-driven insights through performance reports to support technical staff decisions.

Al-Shamal SC (Qatar Stars League) 2024 - 2025

Strength and Conditioning Coach

- Implemented evidence-based injury mitigation strategies through individualized interventions.
- Designed and adjusted complementary training loads based on players' readiness and match demands.
- Integrated new technologies for advanced player tracking and workload monitoring.

Pharco FC (Egyptian Premier League) 2022 - 2023

Strength and Conditioning Coach

- Led systematic monitoring of players' workloads to support return-to-play protocols and minimize re-injury rates.
- Developed individualized strength and power programs aligned with athletes' physical profiles.

Sporting CP 2019 - 2022

Strength and Conditioning Coach

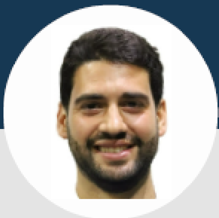
- Led the assessment, longitudinal monitoring, and report on the growth and biological maturation of elite youth players at the academy.
- Coordinated data collection and interpretation to inform age- and maturation-appropriate training strategies across all youth squads.
- In the Women's Main Team, oversaw the analysis of training and match workloads and individualized performance enhancement programs.

Olympic Athletes - Athletics 2014 - 2019

(Rio 2016 & Tokyo 2020)

Strength and Conditioning Coach

- Developed and delivered individualized strength and conditioning programs for Olympic-level track and field athletes.
- Monitored training loads and physical performance to optimize readiness and mitigate injury risk.
- Collaborated with multidisciplinary teams during Olympic preparation camps and competitions.



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UNIVERSITY EDUCATION

PhD in Sports Science 2019 - Present
Lusófona University of Lisbon

Master in Big Data Applied to Physical Conditioning in Football 2023 - 2024
Catholic University San Antonio of Murcia

Master in Physical Conditioning Training in Football 2022 - 2023
Pontifical University of Salamanca

Master in High-Performance Training 2015 - 2016
Pablo Olavide University

Master in Physical Education for Primary School and High School 2016 - 2018
Lusófona University of Lisbon

Bachelor in Sports Science 2010 - 2013
Faculty of Sport at the University of Porto

Specialization in Sports Science 2022 - 2023
Francisco de Vitoria University

Specialization in Rehab in Sports and Exercise Medicine 2013 - 2014
Faculty of Medicine of the University of Porto

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COMPLEMENTARY EDUCATION

COACHING AND PERFORMANCE

A License - Football Coach (CBF Academy)
CONMEBOL

Performance Mentorship Phase 1
EXOS

CSCS Exam Preparation Course (Madrid)
NSCA

Functional Movement Screen Level I and II
FMS

High Performance Training for Sports
Elite Training

Functional Application for Strength and Power (Dan Baker)
Elite Training

Specialist in Programming and Control of Training and Competition Load in Soccer
G-SE

Certificate in Growth & Maturation for Youth Athletes
The Athlete Development Project

HIIT for Soccer (Football)
HIIT Science

COMPLEMENTARY EDUCATION

INJURY MITIGATION AND REHABILITATION

Certificate in Workload and Injury in Team Sports
Barça Innovation Hub - Universitas

The Process of Prevention and Rehabilitation of Football Injuries
Universidad Pontificia de Salamanca (UPSA)

Muscle Injuries in Football: Prevention and Readaptation
INMUV

Readaptation of Injuries in football
Fútbol Revolucionario

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COMPLEMENTARY EDUCATION

RECOVERY

Recovery Strategies in Sports
INMUV

Stretching Global Activo (SGA)
Université De Thèrapie Manuelle

Mobility - An Integral Practical Approach
Master Science Lab

COMPLEMENTARY EDUCATION

BODY COMPOSITION

ISAK - Level 1
The International Society for the Advancement of Kinanthropometry (ISAK)

COMPLEMENTARY EDUCATION

DATA ANALYTICS AND TECHNOLOGY

Physical Performance Certificate - GPS
Catapult

GPS tracker in Sport - Sonra
STATSports

Excel Tricks for S&C Coaches: Beginner to Advanced
Excel Tricks for Sports

Advanced MS Excel Course
QualiCAD

Power Bi for Sport Scientists - Level 1
Sport Horizon UK

Python in Data Science
GADES Solutions

JSCEP Course 4: R for Strength Coaches and Thinking Like a Scientist
Jordan Strength