CHARLES UNIVERSITY

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Relationship Between Functional Movement And Lower Extremity Strength: A New Approach To Athletic Performance Determination

Dissertation

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Prague, 2024

Declaration

I declare that I have created this dissertation on my own and that I have cited all used information sources and literature. This work, or its substantial part, has not been previously used to obtain any academic degree.

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Prague, June 2024

Acknowledgements

About four years ago, my Erasmus journey became the story of my life. When I look back, it wasn't just a study the pursuit of a doctoral degree. It was a journey full of lessons, challenges, growth, and self-discovery. I have learned so much throughout this experience and gained invaluable insights, both professionally and personally. As I close this chapter, I know that my learning and self-improvement will continue. And I consider myself lucky because I wasn't alone and I won't be alone in the next chapter, I was also not alone in writing this final project. For that reason, I owe many thanks and deep gratitude to all those who have been a part of this journey.

The story began with my fascination with the Laboratory of Sport Research Centre (A.K.A. LSM) and its founder my supervisor, Prof. Dr. Ing. František Zahálka, After becoming a member of the laboratory team, I learned something new every single day. Thank you sincerely for everything you've taught me and for your continuous support.

My consultant, Doc. Dr. Tomáš Malý has been an incredible role model despite our different interests in sports, his encouragement in research, teaching, and life in general has been inspiring. Thank you for being not only a supportive colleague but also a constant presence throughout this journey.

Special thanks to Roman Malíř, Maroš Kalata, Dr. David Bujovský, and Ferdia Falloon Verbruggen for their role in the project and for their support in organizing and executing various parts of the research.

A special acknowledgment goes to Dr. Jakub Kokštejn and the entire Department of Sport Games. Being a part of the department and having the chance to work as a lecturer was an extraordinary experience. I also extend many thanks to all the members of the LSM and to everyone working at FTVS and Slavia football club for helping make this project possible.

Last but certainly not least, family is above everything, and I am lucky to have two wonderful families, and I am thankful to the entire ***Svetlik family*** *for everything… Also, my little brother* ***Kadir İmal*** *the best brother ever thank you for showing up every single time...*

Finally, I want to dedicate this doctoral work to three very special people who gave me the strength and motivation to complete this project and to move forward with confidence; my beautiful wife, ***Daniela İmal****, my dear mother,* ***Saime İmal****, and my dear father,* ***Hakan İmal,***

I am deeply grateful to each of you, with respect and love…

Osman İmal

Abstract

Purpose: This longitudinal study examined the associations between biological maturation (as estimated by peak height velocity PHV), functional movement (FM), and lower-body strength (LBS) in elite youth soccer players (U13–U16). The goal was to understand how maturation status influences strength and explosive performance over time, with implications for individualized training and long-term player development. **Methods:** A total of 45 elite male soccer players from a professional Czech academy were evaluated across two consecutive competitive seasons (2022–2023). Participants were classified both by chronological age (U13–U16) and biological maturity status (pre-, circa-, post-PHV). Assessment protocols included the Functional Movement Screen (FMS), isokinetic strength testing of the knee extensors (KE) and flexors (KF) peak torque (PT) at 60°, 180°, and 300°/s, and vertical jump (VJ) performance tests (CMJ, CMJFAF, CMJJH). Longitudinal changes were analyzed using linear mixed-effects models, and relationships among PHV, strength, and jump performance were assessed via Pearson's correlations and multiple regression analyses. **Results**: Significant improvements were observed in strength and VJ performance over the one-year period ($p < 0.001$), particularly among athletes transitioning through PHV. PHV showed strong correlations with both isokinetic strength ($r = 0.58$–0.76) and VJ performance ($r = 0.63$–0.81). FMS scores improved over time ($p < 0.01$) but had limited predictive value for explosive strength ($r < 0.30$). Post-PHV players consistently outperformed pre- and circa-PHV peers across most neuromuscular outcomes ($p < 0.001$; Cohen's $d = 0.75$–1.35). PTKF and PTKE increased with age and PHV, suggesting improved muscle balance and injury resilience. **Conclusion:** Biological maturation is a critical determinant of strength and power development in elite adolescent soccer players. Chronological age alone is insufficient for guiding training; PHV status should inform individualized programming. While FM improves with maturation, it is not a strong standalone predictor of power output. These findings support the integration of biologically informed assessments into long-term athlete development models.

Keywords: biological maturation, peak height velocity, functional movement, youth soccer, isokinetic strength, vertical jump, longitudinal study, athlete development

Abstrakt

Účel: Tato longitudinální studie zkoumala souvislosti mezi biologickou maturací (odhadovanou pomocí maximální rychlosti růstu výšky PHV), funkčním pohybem (FM) a silou dolních končetin (LBS) u elitních mládežnických fotbalistů (kategorie U13–U16). Cílem bylo pochopit, jak stav biologického dozrávání ovlivňuje sílu a výbušný výkon v čase, s důsledky pro individualizovaný trénink a dlouhodobý rozvoj hráčů. **Metody:** Celkem 45 elitních fotbalistů z profesionální české akademie bylo hodnoceno během dvou po sobě jdoucích soutěžních sezón (2022–2023). Účastníci byli rozděleni podle chronologického věku (U13–U16) a podle biologického stavu zralosti (před PHV, okolo PHV, po PHV). Použité protokoly zahrnovaly Functional Movement Screen (FMS), izokinetické testování síly extenzorů (KE) a flexorů kolene (KF) při maximálním točivém momentu (PT) při 60°, 180° a 300°/s a testy vertikálního výskoku (VJ) – CMJ, CMJFAF, CMJJH. Longitudinální změny byly analyzovány pomocí lineárních smíšených modelů a vztahy mezi PHV, silou a výskokem byly hodnoceny pomocí Pearsonovy korelace a vícenásobné regresní analýzy. **Výsledky**: Významné zlepšení bylo zaznamenáno v síle a výkonu ve vertikálním výskoku během jednoho roku ($p < 0{,}001$), zejména u sportovců procházejících PHV. PHV silně korelovalo s izokinetickou silou ($r = 0{,}58–0{,}76$) i s výkonem ve vertikálním výskoku ($r = 0{,}63–0{,}81$). Skóre FMS se v čase zlepšovala ($p < 0{,}01$), ale mělo omezenou prediktivní hodnotu pro výbušnou sílu ($r < 0{,}30$). Hráči po PHV konzistentně překonávali své vrstevníky před PHV a kolem PHV téměř ve všech neuromuskulárních ukazatelích ($p < 0{,}001$; Cohenovo $d = 0{,}75–1{,}35$). PTKF a PTKE se zvyšovaly s věkem a PHV, což naznačuje zlepšení svalové rovnováhy a odolnosti vůči zranění. **Závěr:** Biologická maturace je klíčovým faktorem rozvoje síly a výbušnosti u elitních dorostových fotbalistů. Chronologický věk sám o sobě není dostatečný pro vedení tréninku; při tvorbě individuálních tréninkových plánů by měl být zohledněn stav PHV. Ačkoliv se funkční pohyb zlepšuje s dozráváním, není silným prediktorem výkonu. Výsledky podporují začlenění hodnocení biologického dozrávání do dlouhodobých rozvojových modelů sportovců.

Klíčová slova: biologická maturace, maximální rychlost růstu výšky, funkční pohyb, mládežnický fotbal, izokinetická síla, vertikální výskok, longitudinální studie, rozvoj sportovce.

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List of Abbreviations

ACL – Anterior Cruciate Ligament

AIC – Akaike Information Criterion

APHV – Age at Peak Height Velocity

BA – Biological Age

BMC – Bone Mineral Content

BMD – Bone Mineral Density

BMI – Body Mass Index

BM – Biological Maturation

CA – Chronological Age

CMJ – Countermovement Jump

CMJ-FA – Countermovement Jump-Free Arm

CMJF – Countermovement Jump Force

CMJFAF – Countermovement Jump Free Arm Force

CMJFAJH – Countermovement Jump Free Arm Jump Height

CVM – Cervical Vertebrae Maturation

DEXA – Dual-Energy X-ray Absorptiometry

FFM – Fat-Free Mass

FM – Functional Movement

FMS – Functional Movement Screen

GLMMs – Generalized Linear Mixed Models

H – Hamstring

ICC – Intra-class correlation coefficients

JH – Jump Height

KE – Knee Extensors

KF – Knee Flexors

LBS – Lower Body Strength

LESS – Landing Error Scoring System

LTAD – Long-Term Athletic Development

PAH – Predicted Adult Height

PHV – Peak Height Velocity

PPHA – Predicted Adult Height Attained

PT – Peak Muscle Torque

PTKE – Peak Muscle Torque of Knee Extensors

PTKF – Peak Muscle Torque of Knee Flexors

Q – Quadriceps

RAE – Relative Age Effect

RFD – Rate of Force Development

SD – Standard Deviation

SJ – Squat Jump

SQJF – Squat Jump Force

SQJJH – Squat Jump Jump Height

VGRF – Vertical Ground Reaction Force

VIF – Variance Inflation Factor

VJ – Vertical Jump

1 Introduction

Understanding how physical and physiological changes during adolescence impact functional movement (FM), lower body strength (LBS), and injury risk is essential for optimizing performance and preventing injuries in young athletes. In adolescent soccer players, common lower-extremity injuries such as ligament sprains, muscle strains, and tendon injuries can significantly hinder athletic development (Robles-Palazón et al., 2022). Research over the past two decades has shown that targeted neuromuscular and strength training programs can substantially reduce the incidence of these injuries (Emery et al., 2015). For instance, strength training interventions have been shown to reduce overall sports injuries by nearly two-thirds and overuse injuries by almost half (Lauersen et al., 2014). Enhancing neuromuscular control and movement mechanics improves joint stability, and research (randomized controlled trial design) demonstrated a 64% reduction in Anterior cruciate Ligament (ACL) injuries among adolescent female players who engaged in a neuromuscular warm-up routine (Waldén et al., 2012). Additionally, proprioceptive and balance-focused drills improve functional joint stability and significantly reduce ankle sprain risk, particularly in youth soccer (McGuine & Keene, 2006). Addressing muscular imbalances is also critical; incorporating eccentric hamstring exercises like Nordic hamstring curls can reduce hamstring strain incidence by up to 50% (van Dyk et al., 2019), while higher hamstring and quadriceps strength is associated with lower rates of overuse knee injuries (O'Kane et al., 2017). Collectively, exercise programs that improve neuromuscular control, muscle strength, proprioception, and FM proficiency build joint stability and enhance injury resilience in adolescent soccer players (Hüpbscher et al., 2010; Emery et al., 2015; Robles-Palazón et al., 2022). Although previous studies have explored FM and physical performance, the relationship between biological maturation (BM) and these factors in adolescent athletes remains underexplored (Beardsley & Contreras, 2014; Davies et al., 2022; Girard et al., 2016). FM is the efficient performance of movements involving multiple joints and muscles, essential for daily life and sports (Boyle, 2016; Cook et al., 2010).

This doctoral work aims to fill the gap by examining how FM proficiency and LBS vary with BM in young soccer players. While FM proficiency may not directly affect strength performance, it can enhance movement quality and reduce injury risk (Bazanov et al., 2019; Faigenbaum et al., 2013; Lloyd et al., 2015). Some functional movements may not correlate with specific athletic performance tests due to the poor internal consistency and low correlation between them (Li et al., 2015). However, other studies have found relationships between FM proficiency and physical performance in adolescents (Castelli & Valley, 2007; Erwin & Castelli, 2008). Proprioceptive perception and neural control are crucial for motor skills and FM proficiency. These abilities rely on neuromuscular activities to coordinate body segments effectively. Adolescent athletes often face a "proficiency barrier" in motor performance (Pfeifer et al., 2019), where physical performance and FM proficiency may be associated with BM (Lloyd et al., 2015). The Functional Movement Screen (FMS) test serves as a pivotal tool in assessing FM proficiency (Cook et al., 2010). FMS results have a modest relationship with athletic performance and may help identify injury risk, though findings are inconsistent across studies (Kiesel et al., 2007; Parchmann & McBride, 2011; Fitton-Davies et al., 2022). However, FMS is a simple and widely used tool to spot movement deficiencies and guide corrective strategies for practitioners of all backgrounds (Dorrel et al., 2015; Cook et al., 2014; Beardsley & Contreras, 2014). In understanding the intricate dynamics between FM proficiency, physical performance, and peak height velocity (PHV), it becomes evident that BM holds a crucial position in the skill acquisition and physical preparedness of adolescents. By incorporating considerations of BM into developmental strategies, injury risks can be mitigated effectively, ensuring comprehensive growth and performance optimization (Lloyd & Oliver, 2012). Fitton-Davies et al. (2022) suggests that children and youth who score higher on the FMS are also more likely to score highly in tests related to agility, running speed, strength, cardiovascular endurance, and potentially balance also. PHV has been described as a key indicator used to estimate timing of BM, characterizing performance improvements relative to the growth spurt during adolescence (Lloyd et al., 2015; Mirwald et al., 2002; O'Brien et al., 2022; Wrigley et al., 2014). Variability in PHV timing among adolescents underscores the importance of recognizing and monitoring these differences, particularly in team sports, for performance optimization. Research studies in soccer reported high demands of LBS (sprinting, kicking, jumping, acceleration and deceleration events) where knee extensors (KE) and flexors (KF) muscle groups playing significant roles (Maly et al., 2018; Menzel et al., 2013; Turner et al., 2013). Poor neuromuscular control, restricted movement proficiency, or strength imbalances can increase injury risk and hinder LBS development (Alentorn-Geli et al., 2009; Myer et al., 2005). Additionally, non-invasive estimation of BM holds promise for predicting the age of an individual at PHV, leveraging equations incorporating stature, sitting height, body mass, and relative age (Malina et al., 2004; Mirwald et al., 2002). This approach allows for the classification into pre-, circa-, or post-PHV groups, providing valuable insights for tailored interventions and injury prevention (Malina et al., 2004). The importance of such classifications cannot be overstated, particularly in the realm of adolescent sports, where the timing and progression of maturation greatly influence physical performance and injury susceptibility. To address these complex dynamics, this study investigates the interplay between FM proficiency, LBS, and BM in adolescent soccer players. The goal was to clarify the relationships and differences between maturation status, movement capabilities and specific strength (isokinetic and explosive strength).

THEORETICAL PART

2 Foundations of Growth and Maturation

2.1 Biological Maturation and Ontogenetic Development

BM refers to the natural progression of physical, physiological, and biochemical changes that organisms undergo from infancy to adulthood. It is most commonly evaluated during childhood and adolescence, encompassing key developmental domains such as somatic growth (e.g., height, weight), reproductive maturity, and neurobiological changes (Malina, 2002). BM is essential across diverse fields including athletics, healthcare, and education. A central indicator of BM is growth, assessed through skeletal, sexual, and dental maturation. Metrics like height, body composition, and secondary sexual characteristics help determine an individual's biological stage relative to their chronological age (CA). Based on these indicators, individuals are often categorized as biologically advanced, average, or delayed compared to their peers (Jovanović, 2019; Beunen et al., 2006). This classification has important implications in competitive sports, where differences in physical maturity can significantly influence performance outcomes (Takahara & Miyakawa, 2020; Beunen & Malina, 2007). BM involves physical transformations such as increases in height, weight, muscle mass, and changes in body composition (Bagherian et al., 2022; Albaladejo-Saura et al., 2023; Almeida-Neto et al., 2020; Fernández-Galván et al., 2021; Cavallo et al., 2021; Beunen et al., 2006; Albaladejo-Saura et al., 2021). It also includes the maturation of physiological systems, particularly the skeletal, endocrine, and reproductive systems (Almeida-Neto et al., 2020; Cavallo et al., 2021; Beunen et al., 2006; Albaladejo-Saura et al., 2021). Additionally, BM encompasses neurological and cognitive development, such as the maturation of the prefrontal cortex and the advancement of executive functions (Ueda et al., 2015; Gerván et al., 2023). This process unfolds at different tempos among individuals, even within the same CA group (Thurlow et al., 2021; Müller et al., 2017; Leyhr et al., 2023; Rubia, 2023; Rüeger et al., 2022; Beunen et al., 2006) and is shaped by both genetic and environmental factors (Beunen et al., 2006; Albaladejo-Saura et al., 2021). Biological age (BA) assessments typically based on markers such as skeletal and sexual maturity enable a more accurate understanding of developmental progress (Parr et al., 2020; Jovanović, 2019). Bone age, commonly evaluated using radiographic techniques, provides critical insights into growth not captured by CA alone

(Grendstad et al., 2019). Early maturing individuals often exhibit physical advantages, including greater muscle mass and strength, which can enhance athletic performance (Cumming et al., 2017; Rubia et al., 2024; Moeskops et al., 2020). To better conceptualize BA, researchers often divide it into three dimensions: status, timing, and tempo. Status refers to the current level of maturation (e.g., skeletal age), timing to the age at which specific milestones are reached (e.g., onset of puberty), and tempo to the rate at which these changes occur (Parr et al., 2020; Rubia et al., 2023). This framework helps explain variations in performance and development among individuals with the same CA. For instance, early maturers often outperform their peers physically, highlighting the role of maturity status in sports (Rubia et al., 2024; Towlson et al., 2018).

Common measures of BM include skeletal age, sexual maturity indicators, and PHV (Almeida-Neto et al., 2020; Cavallo et al., 2021; Beunen et al., 2006; Albaladejo-Saura et al., 2021). These assessments provide critical insights into an individual's developmental status and are particularly valuable in contexts like medicine, developmental psychology, and sports science (Bagherian et al., 2022; Almeida-Neto et al., 2020; Fernández-Galván et al., 2021; Cavallo et al., 2021; Beunen et al., 2006; Albaladejo-Saura et al., 2021). Recent research has emphasized the importance of neuroanatomical maturation. Certain brain regions, notably the prefrontal cortex, continue developing into the third decade of life, supporting complex cognitive abilities and decision-making processes (Brown et al., 2012; Miller et al., 2012; Ueda et al., 2015). This prolonged maturation trajectory has meaningful implications for the timing of educational and physical interventions, particularly during adolescence. Moreover, BM is affected by a range of factors. Hormonal shifts during growth spurts influence muscle and fat distribution, complicating the alignment between biological and chronological age (Beunen et al., 2006). Broader influences such as nutrition, socioeconomic status, and ethnicity also play a role, highlighting the necessity of a comprehensive understanding of BM that integrates individual and contextual dimensions (Beunen et al., 2006; Figueiredo et al., 2009).

2.1.1 Chronological vs. Biological Age

CA is a fixed measure that simply reflects the time elapsed since birth tracked in years, months, and days. In contrast, BA varies among individuals and captures dimensions of growth such as skeletal, dental, and sexual maturity. BM, influenced by genetic, nutritional, and environmental factors, can be categorized into different stages to better understand individual developmental trajectories (Brown et al., 2012; Fernandes et al., 2021). During adolescence, for instance, the onset of puberty may occur at different times, creating marked differences in BA among peers with the same CA (Wilczyński et al., 2022; Mijalković et al., 2024). This distinction between chronological and biological age is particularly relevant in fields such as sports, healthcare, and education. Research shows that earlier BM is often linked to enhanced athletic performance, underlining the importance of recognizing BM in talent identification and development (Niklasson et al., 2024; Cumming et al., 2017). Moreover, the association between maturity and physical capabilities necessitates individualized approaches in physical education and sports training (Portella et al., 2017; Jovanović, 2019). Recognizing these differences is equally important in healthcare, where many diagnostic tools and treatment guidelines rely on CA despite the variability in biological development (Portella et al., 2017; Bacil et al., 2015). A more nuanced assessment approach, accounting for biological markers, can lead to more accurate evaluations and improved care (Hill et al., 2019; Johnson et al., 2017). The implications of biological maturity extend into psychosocial domains as well. A mismatch between biological and chronological development can affect adolescents' social interactions, peer relationships, and self-image (Cumming et al., 2010). Therefore, awareness of both age constructs is essential for professionals supporting adolescent development across contexts.

2.1.2 Ontogenetic Development

Ontogenetic development thus integrates both chronological and biological maturation, with the latter offering a deeper understanding of individual differences in growth patterns and their influence on health, performance, and social well-being. While CA is easy to measure, its utility is limited, particularly in pediatric populations, where children of the same age may differ significantly in biological development due to varying genetic and environmental inputs (Yapıcı et al., 2022; Gómez-Campos et al., 2018). This variation is especially prominent during puberty, a period marked by substantial physiological transformations that affect both health and performance outcomes (Gómez-Campos et al., 2018; Lloyd et al., 2014). For example, indicators like handgrip strength align more closely with biological rather than CA, illustrating the limitations of using CA alone to gauge physical fitness (Yapıcı et al., 2022; Gómez-Campos et al., 2018).

Additionally, BM interacts with relative age effects in youth sports, where younger athletes within the same age group may be at a disadvantage compared to their older, more biologically mature counterparts (Coelho-e-Silva et al., 2013). This has major implications for talent selection and development, prompting a shift toward evaluating maturity status in addition to CA (Portella et al., 2017).

In conclusion, distinguishing between chronological and biological age is fundamental to understanding human growth. Their interplay shapes physical capabilities, health evaluations, and intervention timing, making it crucial to integrate both dimensions in developmental assessments and practical applications across medicine, sports science, and education.

2.2 Growth Spurt and Sensitive Periods

Growth spurts are well-documented developmental phenomena, particularly prominent during infancy and adolescence. In infancy, significant spurts occur around 2–3 weeks, 3–6 months, and again at approximately 12 months, reflecting the foundational role of intrauterine growth in early postnatal development (Pan et al., 2005; Zhang et al., 2023). During adolescence, a specific phase known as the pubertal growth spurt occurs, typically earlier in females (ages 10–12) and later in males (ages 12–14) (Girshovitz et al., 2023; Wyatt et al., 2024). This phase is driven largely by hormonal changes particularly sex steroids that lead to marked increases in height, muscle mass, and skeletal development (Al-Maadadi & Ikhlef, 2014). Adolescent growth spurts are characterized by rapid gains in height and weight, underpinned by hormonal shifts that influence skeletal growth and body composition (Riederer, 2023). While these transformations can improve athletic performance, they may also introduce temporary challenges such as reduced coordination, a phenomenon often referred to as "adolescent awkwardness" (Patel et al., 2020). This disruption results from the nervous system struggling to adapt to sudden physical changes, leading to short-term declines in motor skill proficiency (Quatman-Yates et al., 2011). The broader developmental context includes concepts such as sensitive periods and developmental milestones. Growth spurts signify rapid changes in physical and physiological attributes at distinct life stages both prenatal and postnatal contributing significantly to overall developmental outcomes. Sensitive periods are defined as critical windows during which the body or brain is particularly responsive to environmental influences, enhancing the effectiveness of interventions during these times (North et al., 2013; Gilman & McCormick, 2010). For example, early childhood is a sensitive period for language development, where rich linguistic exposure can lead to superior outcomes (Zhang et al., 2023). Similarly, prenatal exposure to harmful substances like methylmercury during sensitive windows can have lasting impacts on brain development (Pan et al., 2005; Chu et al., 2020). Parental understanding of developmental milestones is also vital. Effective parent-child interactions during sensitive periods promote emotional security and cognitive development, while gaps in parental knowledge may hinder the timely recognition of delays (Sheldrick & Perrin, 2013; Malina, 2004; Habbash et al., 2022; Alkhazrajy & Aldeen, 2017; Al-Maadadi & Ikhlef, 2014; Rikhy et al., 2010). From a motor development perspective, sensitive periods also play a crucial role. Early childhood is particularly conducive to motor skill acquisition due to the heightened plasticity of the nervous system (Guimarães et al., 2024; Rikhy et al., 2010). Varied motor experiences during this time have been shown to significantly influence long-term skill retention and performance (Furuya et al., 2022). Adolescence, while often associated with temporary disruptions in coordination, also represents a key phase for refining complex movements, as motor proficiency evolves alongside neuromuscular development (Quatman-Yates et al., 2011). Training strategies that align with these sensitive periods such as targeted regimes for young athletes can enhance foundational motor skills essential for future athletic success (Hooren & Croix, 2020; Fuentes-Barría et al., 2021; Ciubotaru & Grosu, 2024). Beyond skill acquisition, these periods influence broader aspects of physical development. Foundational motor skills, when developed during optimal windows, create the basis for more complex athletic abilities. Investment in motor training during these formative years has been linked to higher proficiency and performance in later stages (Chen & Su, 2021; Pavlović et al., 2020). Growth spurts and sensitive periods represent pivotal elements of human development. While growth spurts denote rapid physical change, sensitive periods underscore optimal windows for acquiring critical physical and cognitive skills.

Overall, the adolescent growth spurt significantly influences strength and motor skills development. Effective training must consider the dynamic interplay of physiological changes to support adolescents through this transformative period while mitigating injury risks and maximizing athletic potential.

2.3 Key Influences on Maturation

Growth and maturation during adolescence are influenced by a combination of factors, including body composition, genetic predispositions, hormonal changes, nutrition, and training

Genetic and Hormonal Influences: Genetics plays a critical role in determining the timing and rate of maturation. Variants in genes related to growth hormone production and insulin-like growth factor signaling can dictate individual differences in height and overall maturation rates (Mansukoski & Johnson, 2020; Albin et al., 2012). Hormonal changes during puberty, particularly increases in testosterone for boys and estradiol for girls, drive muscle growth, fat distribution, and skeletal maturity (Granados et al., 2015; Cole et al., 2013).

Somatic Changes and Body Composition: During BM, individuals experience a series of somatic changes that include increases in height, muscle mass, and changes in body composition. Hormonal changes during puberty stimulate the growth plates in long bones, resulting in rapid height increases (Sin et al., 2015; Vale et al., 2014). Additionally, there are notable shifts in muscle mass and fat distribution, with boys experiencing greater muscle development and girls seeing increased fat deposition (Polo et al., 2012; Sharifi et al., 2012). PHV, which typically occurs around puberty, individuals undergo significant changes in body composition. This period is marked by rapid increases in height, muscle mass, and changes in fat distribution, influenced largely by hormonal fluctuations. The timing of PHV is pivotal in determining overall body composition during adolescence, impacting both body fat distribution and muscle mass development (Cole, 2020; Nyati et al., 2023). Boys often experience greater muscle hypertrophy due to elevated testosterone levels, while girls see an increase in body fat percentage influenced by estrogen (Moura et al., 2014; Hobold et al., 2017).

Nutritional Impact: Proper nutrition is essential for supporting growth and optimizing the effects of training during adolescence. Adequate intake of macro- and micronutrients is crucial for hormonal responses that facilitate growth (Cole et al., 2013; Gabel et al., 2016). A balanced diet rich in protein, calcium, and vitamins can enhance growth velocity and improve physical performance outcomes. In contrast, caloric deficits or poor nutritional choices can lead to compromised growth and delayed maturity, highlighting the importance of proper nutrition for young athletes (Kile et al., 2010; Rudavsky et al., 2018).

Impact of Training: Adolescence is a formative phase marked by critical physiological transformations, including rapid increases in muscle mass, bone density, and motor coordination. Structured physical training, particularly a combination of aerobic and resistance exercises, supports these developments by enhancing strength, cardiovascular capacity, and neuromuscular function. Studies such as Chun et al. (2024) highlight the value of these regimens in improving skeletal health and physical performance. However, the trend of early sports specialization introduces significant risks, including overuse injuries, delayed hormonal maturation, and mental strain (Feeley et al., 2015; Naughton et al., 2000). These outcomes often result from repetitive training loads, limited recovery, and psychological pressure associated with competitive performance. To mitigate these risks and maximize the benefits of training, evidence supports age-appropriate, individualized training approaches that align with biological maturity (Myer et al., 2011). These should incorporate variability, adequate recovery, and nutritional strategies to support metabolic demands and recovery processes. Proper intake of protein, calcium, and essential vitamins is crucial to optimize growth outcomes and safeguard long-term health. Ultimately, a balanced model that integrates physical, nutritional, and psychological considerations is essential for fostering sustainable development in adolescent athletes while preventing adverse outcomes associated with excessive or inappropriate training.

2.4 Early Specialization vs. Long-Term Development

The practice of early specialization in youth sport defined as intensive, year-round training in a single discipline from an early age has become increasingly prevalent, often driven by aspirations of achieving elite-level performance during adolescence. This trend is particularly evident in sports where peak performance occurs early, such as gymnastics and figure skating (Moseid et al., 2018; Black et al., 2018). While early specialization may provide short-term advantages, including rapid skill acquisition and enhanced competitive opportunities, a growing body of literature indicates that these benefits are frequently outweighed by substantial long-term risks to physical health, psychological well-being, and motor development. Physiologically, early specialization is closely linked to a higher incidence of overuse injuries, as repetitive loading of developing musculoskeletal structures can lead to chronic damage with lasting consequences (Matzkin & Garvey, 2018; Wilhelm et al., 2017). Psychologically, young athletes engaged in specialized training are more vulnerable to increased stress, anxiety, and burnout, often due to heightened performance expectations and reduced enjoyment of sport (Feeley et al., 2015; Hall et al., 2015). Furthermore, early exclusive focus on a single sport can impede the acquisition of a broad range of motor skills, thereby limiting physical literacy and overall athletic versatility. In contrast, the practice of sport sampling engaging in multiple sports during early developmental stages has been shown to enhance motor coordination, increase adaptability, and support sustained athletic engagement (Black et al., 2018; Carder et al., 2020; Post et al., 2021).

In response to these concerns, long-term athletic development (LTAD) models have been proposed as comprehensive frameworks for guiding youth athlete training. LTAD emphasizes developmentally appropriate, multi-sport participation and recognizes the critical role of BM, psychosocial development, and structured physical conditioning in optimizing performance over time. Through the integration of diverse sporting experiences and a focus on holistic growth, LTAD frameworks aim to mitigate the risks associated with early specialization while promoting lifelong engagement in sport.

2.5 Assessing Maturation

Assessing BM is a multifaceted process involving various methods to evaluate an individual's developmental stage. The most frequently used indicators include skeletal, sexual, morphological, and dental maturity. Each provides unique insights into biological development and collectively contributes to a holistic understanding (Valente-dos-Santos et al., 2015; Beunen et al., 2006; Malina et al., 2015). The choice of assessment method may depend on various factors, including the age of the individual, the context of the assessment (e.g., clinical, athletic), and the resources available (Perroni, 2024). Assessing skeletal maturity involves both invasive and non-invasive methods, each with its own advantages and limitations. Understanding these methods is crucial for evaluating biological maturation in children and adolescents, particularly in clinical and athletic contexts.

2.5.1 Assessment methods

2.5.1.1 Skeletal Maturity Assessment

Radiographic Assessment: One of the most common invasive methods for assessing skeletal maturity is through radiographic imaging, particularly X-rays of the left hand and wrist. This method allows for the evaluation of skeletal age by comparing the ossification patterns of bones against established standards, such as the Greulich and Pyle method or the Fels method (Rüeger et al., 2022; Phogat et al., 2015). These methods provide a detailed view of skeletal development, allowing for precise age estimation based on the maturation of specific bones.

Dual-Energy X-ray Absorptiometry (DEXA) Maturity Assessment: *DEXA* is the gold standard for evaluating bone mineral density (BMD) and bone mineral content (BMC) in adolescent athletes. It provides precise insights into skeletal health during peak growth phases, which is crucial given the high incidence of growth-related bone stress injuries during adolescence (Armento et al., 2023; Vlachopoulos et al., 2017). High-impact sports such as soccer and gymnastics are associated with greater BMD than low-impact activities like swimming, emphasizing the role of mechanical loading in bone strength (Stenqvist et al., 2023; Ubago-Guisado et al., 2019). Nutrition is a key factor in bone health. Low energy availability, commonly observed in weight-sensitive sports, increases the risk of low BMD, osteopenia, and stress fractures particularly among female athletes experiencing menstrual dysfunction (Nose-Ogura et al., 2019). Nutritional monitoring and intervention are essential to support both bone integrity and athletic performance (Lee & Lim, 2019). Iron status, as indicated by serum ferritin levels, also correlates with BMC, especially in male athletes, underscoring the importance of sufficient micronutrient intake (Gümüş et al., 2019). Combining DEXA assessments with training load management and nutritional evaluation offers a comprehensive strategy for enhancing adolescent sports performance and preventing injuries.

Cervical Vertebrae Maturation (CVM) Method: This technique involves lateral cephalometric radiographs to assess the maturation of cervical vertebrae. The CVM method has been shown to be valid, reliable, and reproducible for determining skeletal maturity (Yang et al., 2022; Souza et al., 2021; Zhao et al., 2012). It provides an alternative to hand-wrist radiographs, especially in orthodontic contexts.

2.5.1.2 Sexual Maturity Assessment

Sexual maturity is most commonly assessed using the Tanner staging system, which classifies pubertal development based on the appearance of secondary sexual characteristics such as breast development in females and genital development in males. These stages are strongly correlated with underlying hormonal changes and provide critical insight into the timing and progression of puberty (Hill et al., 2019; Malina et al., 2015; Beunen et al., 2006). While Tanner staging is typically performed through physical examination, non-invasive alternatives have been developed for use in large-scale studies. One such tool is the Pubertal Development Scale, a validated self-report instrument that enables adolescents to assess their own stage of development with reasonable accuracy (Hibberd et al., 2014).

2.5.1.3 Dental Maturity Assessment

Morphological indicators such as height, weight, body mass index (BMI), and body composition serve as indirect yet informative measures of BM. When tracked longitudinally, these metrics can provide valuable insight into growth patterns and developmental progress. Among more specific indicators, dental age estimation has proven particularly effective, especially in younger children. One widely accepted method is the Demirjian method, which assesses the developmental stages of selected teeth using panoramic radiographs (Demirjian et al., 1973). This approach has been validated across various populations and offers a relatively reliable estimate of biological maturity (Bäckström et al., 2000; Nikolic et al., 2005; Yadav et al., 2017).

2.5.1.4 Assessing Somatic & Morphological Maturation Using Predictive Anthropometric Models

Several anthropometric prediction models have been developed to estimate BM and the timing of PHV in youth. The most widely cited is the Mirwald et al. (2002) model, which calculates a maturity offset the number of years before or after PHV using sex-specific regression equations based on chronological age, body mass, standing height, sitting height, and leg length. Although extensively validated in athletic populations, its accuracy diminishes for early or late maturers (Fransen et al., 2018; Malina et al., 2020). To address this limitation, Moore et al. (2015) introduced a revised model with updated coefficients to better predict age at PHV (APHV), particularly in longitudinal studies. Another method, the Khamis-Roche (1994) approach, estimates adult height based on age, stature, weight, and mid-parental height. From this, the percentage of predicted adult height attained (PPHA) can be calculated, offering a non-invasive proxy for biological age frequently used in both sports and clinical contexts (Meyer et al., 2013). Population-specific adaptations have also emerged. Kozieł and Malina (2017) modified the Mirwald model for Polish youth, yielding improved accuracy for that demographic. While practical and field-friendly, all these models demonstrate reduced precision at the individual level, especially for those outside average growth trajectories (Fransen et al., 2018; Kozieł & Malina, 2017).

Table 1. Summary of Key Anthropometric Models

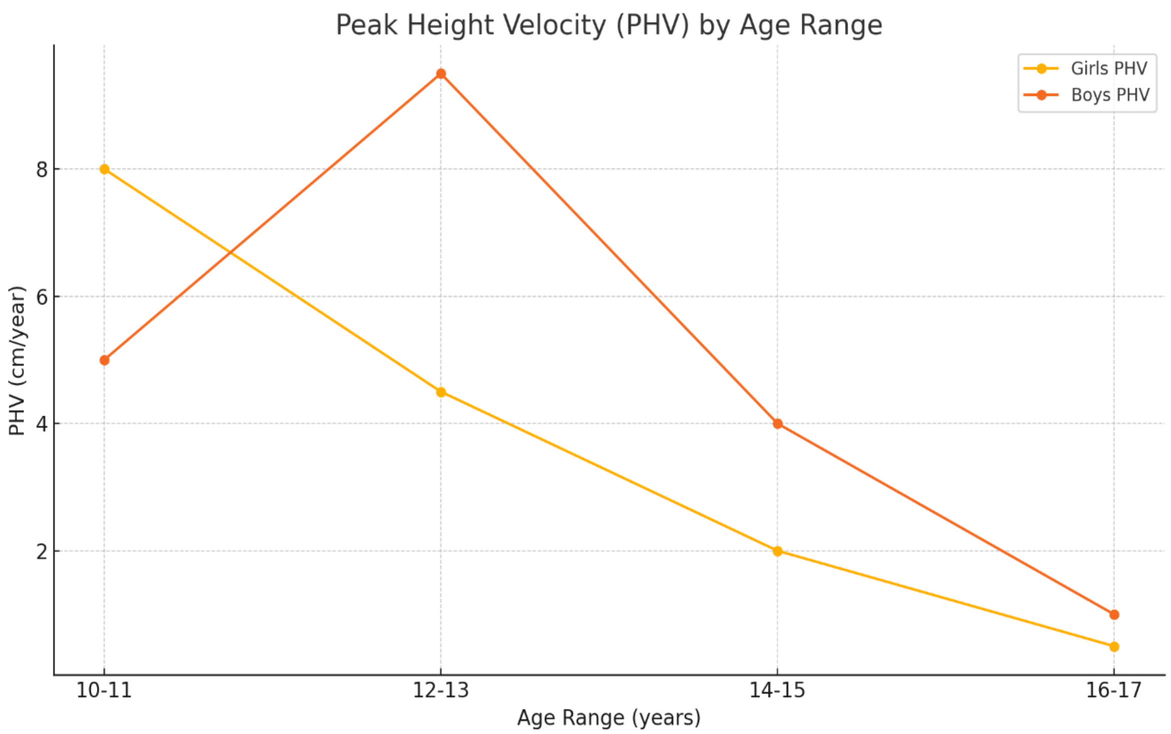
Model	Year	Output	Key Variables	Target Population
Mirwald et al.	2002	Maturity Offset	Age, height, weight, SH, LL	General youth population
Moore et al.	2015	Age at PHV (APHV)	Age, height	Improved accuracy for broader maturity range
Kozieł & Malina	2017	Maturity Offset	Same as Mirwald	Polish youth sample
Fransen et al. (Validation)	2018	Validation	Validation	Evaluation of Mirwald accuracy
Khamis-Roche / PPHA	1994	%Adult Attained	Age, height, weight, mid-parental height	Long-term growth estimation

Leg length (LL), Sitting Height (SH).

2.5.1.4.1 Peak Height Velocity Assessment

PHV represents a pivotal biological milestone during adolescence, marking the period of maximum linear growth in stature. Typically, PHV occurs around ages 10–11 in girls and 12–14 in boys, though timing can vary considerably due to genetic, environmental, and lifestyle influences (Malina 2002; Tsutsui et al., 2022; Werneck et al., 2017). PHV is widely recognized across clinical, athletic, and developmental contexts as a robust indicator of biological maturity, physical development, and training readiness (Sluis et al., 2015; Hagen et al., 2022). The most direct and widely used method for assessing PHV involves longitudinal height measurements using calibrated stadiometers. By tracking stature at regular intervals (e.g., every 3–6 months), the peak rate of growth can be identified, typically expressed in cm/year (Nyati et al., 2023; Lüdin et al., 2021). While highly accurate, this method requires years of consistent data collection, making it less practical in certain contexts such as short-term research studies or sports programs.

Figure 1. Growth Trends During PHV



Malina, R. M., Bouchard, C., & Bar-Or, O. (2004) &Mirwald, R. L., Baxter-Jones, A. D. G., Bailey, D. A., & Beunen, G. P. (2002).

Maturity Offset Calculations

Predictive equations such as the Mirwald et al. (2002) model estimate an individual's maturity offset the number of years before or after PHV based on CA, height, sitting height, and weight. This allows for estimation of the APHV without prolonged longitudinal tracking (Oliveira et al., 2020; Leite, 2024; Müller et al., 2016). Other refined models incorporate additional variables like leg length or age × height interactions to improve predictive accuracy across diverse populations (Lüdin et al., 2021; Cumming et al., 2010).

Table 2 Representative Equations

Boys: MO = -9.236 + (0.0002708 × leg length × sitting height) - (0.001663 × age × leg length) + (0.007216 × age × sitting height) + (0.02292 × weight/height × 100)
Girls: MO = -9.376 + (0.0001882 × leg length × sitting height) + (0.0022 × age × leg length) + (0.005841 × age × sitting height) - (0.002658 × age × weight) + (0.07693 × weight/height × 100)
Boys: APHV = -7.999994 + (0.0036124 × age × height)
Girls: APHV = -7.709133 + (0.0042232 × age × height)

Mirwald et al. (2002), Moore et al. (2015), Kozieł & Malina (2017)

PHV serves not only as a developmental benchmark but also informs clinical diagnosis, training adaptation, and injury prevention. For instance, early or delayed PHV timing may assist in identifying conditions like idiopathic scoliosis, growth hormone disorders, or delayed puberty (Mao et al., 2018; Don et al., 2018). In athletic populations, PHV-based assessments guide training in segmentation and performance monitoring. Adolescents undergoing rapid growth may experience temporary declines in coordination or increased injury risk. PHV is closely associated with changes in body composition, strength, and motor control. Early maturers often exhibit superior speed and power, influencing short-term performance and potentially biasing talent selection (Gastin & Bennett, 2013; Jakovljević, S., et al., 2016). Conversely, late maturers may require adjusted developmental pathways to reach peak potential. Functional performance assessments such as sprint tests, vertical jumps, and agility drills often correlate with proximity to PHV (Malina et al., 2004; Guimarães, E., et al., 2019).

In addition, International studies consistently show that PHV occurs on average around ages 10–11 for girls and 12–14 for boys, with annual height increases of 8–12 cm during the peak (Komlos, 2006; Baxter-Jones et al., 2008). Boys generally experience a later, but more pronounced growth spurt compared to girls, averaging around 9.5 cm per year (Ulbrichová et al., 2015; Malina et al., 2004). Cultural and regional variations in PHV timing and magnitude are influenced by genetics, nutrition, and socioeconomic factors. Adolescents in developed nations tend to reach PHV earlier and at greater magnitudes due to better healthcare and nutrition (Costa-Font & Kossarova, 2015; Krejzek et al., 2015). In the Czech Republic, studies indicate PHV typically occurs around age 13 in boys and 11.5 in girls, aligning with global averages (Krejzek et al., 2015; Ulbrichová et al., 2015). Historical data show a trend toward earlier maturation over recent decades, reflecting improved living conditions and nutritional status (Komlos, 2006). Post-communist socioeconomic shifts in Central Europe have significantly influenced children's growth metrics. Research indicates that Czech youth today are taller and mature earlier than in the past, likely due to improved public health and diet (Costa-Font & Kossarova, 2019; Bakaľár et al., 2020).

Table 3. *Czech adolescent populations age specific PHV timing*

Age Range (Years)	**Girls PHV (cm/year)**	**Boys PHV (cm/year)**
10–11	8.0	5.0
12–13	4.5	9.5
14–15	2.0	4.0
16–17	0.5	1.0

J. Vignerova´ et al. / Economics and Human Biology 4 (2006).

In summary, PHV should not be evaluated in isolation. Combining measurement tools enhances maturity assessment precision (Sousa-e-Silva, P. R., et al., 2023; Santos, D. A., et al., 2020; Gülü, M., et al., 2023). Thess multi-methods approaches accommodate inter-individual variation and supports evidence-based decision-making in both clinical and performance settings. PHV remains a cornerstone indicator of somatic growth and BM. While direct longitudinal tracking offers gold-standard accuracy, validated prediction models and skeletal indicators provide practical alternatives in various applied settings. Integrating PHV data with complementary assessments supports safer training progression, more accurate diagnosis, and optimized long-term development strategies.

2.6 Application in Youth Sports

The application of BM understanding in youth sports is essential to optimize performance, ensure athlete well-being, and develop long-term athletic potential. Several strategies grounded in research can help mitigate risks associated with early specialization and support equitable talent identification and development. These approaches aim to foster more sustainable athletic careers, especially in sports like soccer where selection and performance are often influenced by developmental disparities. The multi-sport development model encourages young athletes to participate in varied sports to build a broad foundation of physical, cognitive, and psychosocial skills. This approach is increasingly supported by research as a safeguard against the drawbacks of early specialization, such as overuse injuries, psychological stress, and premature dropout (Bell et al., 2018; Côté & Fraser-Thomas, 2007). Sampling multiple sports enhances motor coordination, agility, and adaptability (Komínková & Perič, 2020), while providing young athletes with transferable physical literacy. Effective implementation of this model requires educating parents and coaches. Structured workshops and continuous education programs can increase awareness of the risks tied to early specialization and the benefits of diverse sports exposure (Bean et al., 2014; Anderson-Butcher et al., 2014). Balanced training programs featuring appropriate loading, rest, and cross-training can also prevent overuse injuries and psychological burnout (Rottensteiner et al., 2013; Super et al., 2016).

Talent identification and selection play a pivotal role in high-performance pathways, yet the processes are often complicated by variability in growth and maturation. Talent is multidimensional comprising physical ability, sport-specific skills, and psychosocial traits (Chester et al., 2021). As such, effective identification requires a holistic assessment strategy that evaluates technical, tactical, physical, and psychological components. Timing remains a significant challenge. Early selection can disadvantage late-maturing athletes and skew development programs toward short-term gains (Malina et al., 2010). LTAD frameworks advocate for developmentally sensitive selection models, where early adolescence is seen as a period for skill development rather than filtering for elite performance (Balyi & Hamilton, 2004; Ford et al., 2011). To avoid common pitfalls such as selection biases and psychological burden programs should adopt longitudinal tracking and standardized assessment protocols, enabling fairer evaluation of long-term potential (Vaeyens et al., 2008). Educating stakeholders about relative age effects (RAE) and maturational differences can reduce systemic biases and foster inclusive development (Finnegan et al., 2024).

One innovative solution to mitigate maturity-related imbalances is bio-banding the practice of grouping youth athletes by biological maturity rather than CA (Malina et al., 2019; Sullivan et al., 2024). This approach addresses developmental variance by ensuring athletes compete and train in environments that match their physical capabilities rather than their age. Research has shown that bio-banding enhances skill development, particularly among late-maturing players, who can take on leadership roles and develop confidence in a more equitable setting (Salter et al., 2022; Kelly et al., 2021). It can also reduce injury risk, as training loads are more appropriately matched to physiological readiness (Kozieł & Malina, 2017). Despite its promise, bio-banding faces practical challenges, including variability in maturity assessment techniques, logistical complexity in reorganizing teams, and resistance due to misunderstandings among stakeholders (Bradley et al., 2019; MacMaster et al., 2021). Therefore, stakeholder education and institutional support are crucial to scale its implementation effectively, particularly in organized academies and federated sport systems. Notably, major organizations such as the English Premier League have incorporated bio-banding into their development systems to promote equitable competition and long-term player tracking (Cumming et al., 2017; Romann et al., 2020). Continued research is needed to evaluate bio-banding's long-term effects on injury prevalence, psychosocial outcomes, and talent retention (Towlson et al., 2023).

2.7 Soccer Performance and Biological Maturation

In soccer where speed, power, and rapid decision-making are essential to performance, BM plays a pivotal role in shaping both athletic outcomes and talent identification processes. Players who are at or beyond their PHV typically exhibit superior physical performance metrics, such as sprint speed, strength, and agility, when compared to their less mature peers, regardless of technical proficiency (Perroni et al., 2024; Aquino et al., 2017). This maturation-driven performance advantage can lead to maturity-biased selection, wherein early maturers are disproportionately favored for advancement, while late developers, despite their long-term potential, are often overlooked or deselected. The Relative Age Effect (RAE) further exacerbates this imbalance. Athletes born earlier in the selection year are more likely to be biologically advanced, benefiting from both physical maturity and accumulated experience relative to their younger peers (Finnegan et al., 2024). Together, biological maturity and RAE can distort talent identification by privileging short-term performance indicators over developmental potential. Incorporating maturity status into selection frameworks is therefore essential. Evaluation should extend beyond physical metrics to include technical ability, cognitive development, psychological resilience, and coachability. Biological maturity also influences skill acquisition, with more mature players often demonstrating enhanced motor coordination, postural control, and confidence in executing complex movements (Cumming et al., 2017; Sierra-Díaz et al., 2017). However, an overemphasis on maturity-linked advantages may obscure the potential of biologically younger players who excel in cognitive or technical domains. One emerging solution is the implementation of bio-banding, which involves grouping players based on biological rather than chronological age. This approach mitigates the confounding effects of maturation, offering a more equitable platform for assessing performance and potential (Malina et al., 2019; Towlson et al., 2023). Evidence suggests that bio-banding can reduce selection bias, promote more balanced competition, and enhance the developmental experiences of late-maturing athletes. Ultimately, refining talent identification systems to account for biological variability is critical to fostering a more inclusive and developmentally appropriate sporting environment. Such practices not only support fairer assessment but also reduce the risk of prematurely excluding athletes who may emerge as high performers with continued physical and psychological maturation.

3 Functional Movement Proficiency

3.1 Concept and Relevance to Youth Athletes

FM is a foundational component of physical development, referring to the capacity to perform basic yet complex movement patterns that involve the coordinated integration of multiple body systems. These patterns, typically multi-planar and multi-joint are critical not only for daily activities but also for athletic performance, neuromuscular health, and injury prevention. The significance of FM in the context of youth athletes lies in its intersection with physical growth, motor development, and long-term health outcomes. Emerging literature emphasizes that FM proficiency enables efficient, controlled, and purposeful motion by integrating strength, stability, mobility, balance, and motor coordination (Cook et al., 2014; Myer et al., 2011). These abilities underpin athletic skill acquisition and serve as predictors of both performance potential and susceptibility to injury. During adolescence a period marked by rapid somatic and neurological changes movement patterns often become disrupted due to transient imbalances in strength and flexibility, increasing the need for early assessment and targeted intervention (Lloyd et al., 2015; Malina et al., 2004). Deficits in FM are increasingly recognized as early indicators of musculoskeletal dysfunction and chronic pain in later life. Poor movement competency during youth is associated with impaired neuromuscular control, postural abnormalities, and increased injury incidence (McKeown et al., 2014; Kiesel et al., 2005). This has significant implications for adolescent athletes, who are exposed to high training loads and often specialize in sport prematurely, placing additional stress on developing tissues (Jayanthi et al., 2013; DiFiori et al., 2014). Beyond performance and injury, FM is deeply interwoven with broader health indicators. Cross-sectional and longitudinal studies have demonstrated strong associations between low FM scores and higher body fat percentage, reduced physical activity levels, and metabolic risk profiles in children and adolescents (Hardy et al., 2012; Duncan et al., 2013). In particular, overweight and obese youth often display compromised movement quality due to mechanical inefficiencies and reduced relative strength, which may reinforce sedentary behavior and health disparities (Lubans et al., 2010; Bremer & Cairney, 2016). Furthermore, movement skill competence is a determinant of physical literacy defined as the motivation, confidence, and ability to be physically active for life (Whitehead, 2010). Evidence suggests that youth who demonstrate higher motor competence are more likely to engage in moderate-to-vigorous physical activity, thereby establishing positive behavioral trajectories with long-term health benefits (Robinson et al., 2015; Barnett et al., 2016). Functional movement screening, such as the FMS, has been used effectively to identify deficiencies in mobility, stability, and coordination, providing a basis for corrective exercise prescription and motor learning interventions (Cook et al., 2014; Schneiders et al., 2011). Importantly, the development of FM should be considered both a means and an outcome within youth athletic programs. Integrating movement competency training into sport participation enhances biomechanical efficiency, reduces asymmetries, and prepares athletes for more advanced physical demands. Additionally, by cultivating quality movement patterns early, practitioners may mitigate the onset of overuse injuries, optimize performance, and support athlete retention (Faigenbaum et al., 2009; Lloyd & Oliver, 2012). FM represents a multidimensional construct that is essential for physical development, health promotion, and athletic excellence. For youth athletes, its relevance spans across developmental, performance, and clinical domains. The growing body of literature supports the incorporation of movement assessments and interventions into early physical education and training programs. Addressing functional movement deficits proactively can enhance motor skill acquisition, facilitate injury prevention, and foster a lifelong engagement with physical activity.

3.2 Functional Movement Assessments

FM refers to the capacity to perform essential movement patterns that are biomechanically sound, neuromuscularly coordinated, and adaptable across various physical demands. These patterns serve as the foundation for higher-order motor skills and athletic performance, while also playing a crucial role in injury prevention and long-term musculoskeletal health. As such, FM assessment has emerged as a central component of both performance optimization and clinical evaluation in youth, adult, and aging populations. FM encompasses qualities such as mobility, stability, proprioception, balance, and intersegmental coordination, all of which contribute to efficient task execution. Deficiencies in these domains often stemming from muscle imbalances, asymmetries, or poor motor control can lead to suboptimal performance and increased injury susceptibility (Cook et al., 2014; Myer et al., 2011). This recognition has spurred the development of standardized tools to evaluate movement quality, with the FMS being the most prominent. The FMS, introduced by Cook et al. (2006), is a screening tool comprising seven movement tasks (e.g., deep squat, inline lunge, rotary stability) designed to assess fundamental patterns that underpin complex athletic skills. Each movement is scored on a scale of 0 to 3, with a maximum composite score of 21. A score below 14 has been widely associated with an increased risk of injury, although recent research urges caution in over-relying on this threshold (Bushman et al., 2015; Knapik et al., 2015).

Table 4. FMS Test Scoring Criteria

TEST	3 POINTS	2 POINTS	1 POINT	0 POINTS
DS	The upper body is in a parallel position to the tibia. The femur is under the horizontal plane. The knees are at foot line. Stick at foot level on the head.	The upper body is parallel to the tibia. The femur is under the horizontal plane. Knees at foot line; stick over shoulder, 2x6 inch board under heels.	Tibia and the upper body are not parallel. The femur is not under the horizontal plane. Knees misaligned. Lumbar flexion occurs. 2x6 inch board used.	Intense pain during movement and an unsuccessful attempt.
ST	Hips, knees, and wrists aligned on sagittal plane. Minimal or no lumbar movement. Stick and foot are parallel.	Sequencing between hips, knees, and wrists disappears. Lumbar movement observed. Stick and foot not parallel.	Loss of balance is recorded. Foot and step contact occurs.	Intense pain during movement and an unsuccessful attempt.
ILL	Contact with stick is maintained with lumbar extension. No body movement. Sticks and feet stable on sagittal plane. Back knee touches floor.	Stick does not stay in contact with lumbar extension. Body movement occurs. Knee behind front foot does not touch the floor.	Loss of balance is noted.	Intense pain during movement and an unsuccessful attempt.
SM	Fists are within the length of 1 hand.	Fists are within 1.5 hand length.	Fists are more than 1.5 hand length apart.	Intense pain during movement and an unsuccessful attempt.
ASLR	Ankle is positioned between middle thigh and ASIS using a stick.	Ankle is in line with middle patella using stick.	Ankle is below middle patella/joint line using stick.	Intense pain during movement and an unsuccessful attempt.
TSPU	Men: thumbs at forehead. Women: hands at jaw level.	Men: hands at chin level. Women: hands at shoulder level.	Men cannot perform movement at chin level. Women cannot perform movement at shoulder level.	Intense pain during movement and an unsuccessful attempt.
RS	Unilateral correct movement while keeping spine parallel to the ground. Knee and elbow touch.	Correct diagonal repetition; spine parallel to ground. Knee and elbow touch.	Cannot perform diagonal movement.	Intense pain during movement and an unsuccessful attempt.

Cook et.al. (2010). Deep squat (DS), hurdle step (HS), in line lunge (ILL), shoulder mobility (SM), active straight leg raise (ASLR), trunk stability push-up (TSPU), rotary stability (RS).

Systematic reviews have confirmed the utility of the FMS in identifying asymmetries and dysfunctional movement, particularly in athletic populations (Moran et al., 2017; Dyer et al., 2019). However, critiques of its predictive validity emphasize that the FMS should be used as one component within a broader functional assessment strategy, rather than a stand-alone predictor of injury (Bonazza et al., 2017). Furthermore, the screen lacks sensitivity to sport-specific or developmental differences unless combined with tailored interventions. While the FMS remains a cornerstone tool, additional instruments contribute important dimensions to functional assessment. The Bruininks-Oseretsky Test of Motor Proficiency (BOT-2), for instance, provides detailed insights into fine and gross motor skills, making it particularly valuable in pediatric developmental evaluations (Mancini et al., 2020). The Y-Balance Test, a dynamic balance assessment, and Landing Error Scoring System (LESS), used for evaluating jump-landing mechanics, are also commonly employed to detect performance-related movement deficiencies (Plisky et al., 2006; Padua et al., 2009). These tools collectively capture a more nuanced picture of motor control, functional asymmetry, and neuromechanical readiness, especially when used in concert with strength, flexibility, and proprioceptive testing.

Table 5. Key Anatomical Landmarks for Test Alignment

Landmark	**Purpose During Movement Analysis**
Tibial tuberosity	Reference for lower leg alignment
Anterior superior iliac spine (ASIS)	Hip positioning and alignment
Lateral and medial malleolus	Ankle joint tracking
Most distal wrist crease	Arm and hand positioning
Knee joint line	Assessing alignment and depth in lower body
Bar grip line	Reference point in overhead patterns
Wall	Stability check (e.g., shoulder mobility)
Middle of femur	Lower limb segment assessment
Thumbs and upper body	Rotation and symmetry in upper body movements

Cook et.al. (2010).

FM assessments not only identify deficits but inform the design of individualized corrective programs. Multiple studies have shown that targeted interventions, focusing on core stability, joint mobility, and neuromuscular coordination, can significantly improve FMS scores and reduce injury incidence (Clark et al., 2022; Peterson & Verscheure, 2011). These improvements are not merely cosmetic; they reflect underlying adaptations in motor control strategies that enhance biomechanical efficiency and performance resilience.

In youth populations, particularly those engaged in early sport specialization, FM assessments have important implications for injury prevention and motor development.

Research suggests that children and adolescents with poor movement proficiency are at greater risk for both overuse injuries and long-term musculoskeletal issues (Faigenbaum et al., 2009; Lloyd et al., 2015). Moreover, movement screening can highlight developmental disparities exacerbated by maturation, timing or excess body mass. The implications of FM extend beyond sport. Numerous studies have demonstrated a robust association between movement quality and health-related outcomes, including obesity, metabolic syndrome, and physical inactivity (Duncan et al., 2013; Bremer & Cairney, 2016). Children with lower movement competency are more likely to exhibit sedentary behavior and reduced cardiorespiratory fitness, reinforcing the role of FM as a modifiable determinant of health.

Moreover, FM proficiency contributes to physical literacy a multidimensional construct encompassing motor competence, confidence, motivation, and lifelong participation in physical activity (Whitehead, 2010; Robinson et al., 2015). By improving fundamental movement patterns during early life stages, practitioners can positively influence behavioral trajectories that extend well into adulthood.

3.3 Functional Movement in Soccer

FM proficiency is a foundational component of athletic performance in soccer, particularly among developing athletes in elite youth settings. It encapsulates the capacity to execute coordinated, efficient, and biomechanically sound movement patterns necessary for high-level performance. These patterns encompassing sprinting, cutting, jumping, kicking, and dynamic stabilization are integral to the game's demands, which are characterized by unpredictability, frequent accelerations/decelerations, and rapid directional shifts. As such, the study of FM is critical not only for optimizing performance but also for minimizing injury risk, particularly during periods of accelerated growth such as PHV a key developmental inflection point examined in this thesis. FMS is a widely adopted assessment protocol designed to evaluate mobility, stability, and symmetry across seven fundamental movement tasks. It provides a standardized method of identifying functional deficits and compensatory patterns that may predispose athletes to injury or limit performance potential. In soccer-specific contexts, FMS has emerged as both a diagnostic and prescriptive tool, allowing practitioners to compensate interventions that address movement inefficiencies before they manifest as clinical symptoms. The empirical justification for FMS use in youth soccer has been growing. Sannicandro et al. (2023) demonstrated significant differences in FMS composite scores across competitive levels in youth soccer players, suggesting a correlation between FM quality and the ability to meet the physical demands of elite performance. Similarly, Lorenzo and Bertollo (2019) showed that an 8-week intervention targeting mobility and neuromuscular control significantly enhanced FMS scores among adolescent athletes. These findings support the utility of FMS not only as an injury screening tool but as a developmental benchmark aligned with the physiological transitions that occur during PHV.

Moreover, Akpınar (2022) found that structured soccer training improves bilateral motor coordination and reduces lateralization, which is crucial in a sport where symmetrical function underpins technical execution (e.g., passing, shooting, dribbling) under pressure. The capacity to maintain symmetrical load distribution is especially pertinent during the adolescent growth spurt, a phase typified by transient neuromuscular imbalance. From a methodological perspective, critiques of the FMS often focus on its scoring granularity and predictive power. While early research (e.g., Kiesel et al., 2007) suggested cutoff scores could predict injury risk, subsequent studies have called for caution in interpreting these thresholds as definitive. Bushman et al. (2015) and Butcher-Mokha et al. (2016) argue for a more nuanced approach that views FMS scores as part of a broader injury risk profile, particularly when considering adolescent athletes whose neuromuscular systems are in flux due to maturational changes. Nonetheless, the screen remains valuable for its capacity to identify asymmetries and compensatory strategies that may intersect with musculoskeletal vulnerability during growth spurts. In developmental soccer, the interaction between FM and athletic performance must be understood within a systems-based framework. Kokštejn et al. (2019) conceptualized fundamental motor skills as mediators between physical fitness and soccer-specific motor competencies. This model aligns with dynamic systems theory, which posits that movement outcomes arise from the interaction of organismic, environmental, and task constraints a particularly relevant approach during adolescence, when biological maturation alters these constraints in real time.

This study's focus on LBS and PHV situates functional movement as a moderating variable. As peak growth velocity often precedes neuromuscular adaptation, adolescents may experience a transient decrease in coordination and stability (i.e., "adolescent awkwardness"). By tracking changes in FMS scores longitudinally across U13–U16 categories, we can investigate how FM proficiency evolves alongside, and potentially buffers against, strength imbalances and movement inefficiencies emerging during PHV.

Furthermore, studies such as Carling (2010) have detailed the heightened physiological loads associated with in-game actions like sprinting with the ball or initiating direction changes. Dugdale et al. (2020) emphasize the high frequency of these actions in elite youth matches, highlighting the importance of agility, change-of-direction speed, and proprioceptive acuity all underpinned by foundational movement skills. Therefore, developing a robust functional movement foundation is not merely preparatory but integral to sustained performance in high-load match contexts. The neuromechanical basis of FM is deeply entwined with proprioception and motor control. Proprioceptive inputs arising from joint mechanoreceptors and muscle spindles are essential for calibrating movement strategies in response to dynamic match scenarios. Aman et al. (2015) found that proprioceptive training enhanced balance and coordination, particularly in populations with developing or impaired neuromuscular control. Given that the maturation of these systems varies inter-individually during adolescence, proprioceptive training may serve as a compensatory strategy during periods of rapid growth. Neural control of movement, as outlined by Ramayya et al. (2020), involves coordinated activity across cortical and subcortical networks during movement initiation and correction. In this context, proprioceptive acuity becomes critical for pre-movement planning and mid-action adjustments a requirement in soccer where external stimuli are continuously changing. Tulimieri and Semrau (2024) reinforce this in rehabilitation settings, where proprioceptive deficits significantly impede motor recovery. While their work is clinical, the theoretical implications for injury prevention in sport are compelling. Innovations in neurorehabilitation, such as those introduced by Tzorakoleftherakis et al. (2015), offer new frontiers for athlete support through sensory feedback enhancement. Although still emerging in performance contexts, such technologies could inform future development of training paradigms that augment proprioceptive feedback during high-speed, multi-directional actions in soccer.

In light of these conceptual, methodological, and applied insights, the inclusion of FMS and related functional assessments in longitudinal soccer research is both empirically and practically justified. For this thesis, monitoring FMS scores in tandem with LBS and maturity status across age categories (U13 to U16) offers a multifaceted view of motor development during adolescence. This enables identification of movement vulnerabilities coinciding with PHV and informs control intervention strategies. Practically, coaches and practitioners are advised to incorporate FM assessments regularly into their monitoring protocols, particularly during windows of accelerated growth. Doing so allows for individualized adjustments in training load, skill development, and injury mitigation strategies, ultimately enhancing player retention and LTAD.

FM in soccer is not a peripheral concern but a central pillar of athletic performance and injury prevention. Its interrelationship with physical strength, maturation timing, and neuromotor control demands rigorous and nuanced exploration, especially within elite youth environments where developmental trajectories are dynamic and nonlinear. By embedding FMS and proprioceptive frameworks within longitudinal player profiling, this thesis contributes a systems-informed lens to talent development in soccer.

4 Strength Development in Adolescents

The development of muscular strength during adolescence requires a multifactorial perspective that integrates physiological maturation, nutritional adequacy, psychological readiness, and training methodology. This developmental phase is marked by rapid biological changes that interact dynamically with external training stimuli, and as such, strength progression in youth athletes cannot be meaningfully interpreted without accounting for these individual differences. Within the context of elite youth soccer where the interplay between movement quality, physical capacity, and maturity timing is central tracking strength development across maturation stages is essential for optimizing performance outcomes and mitigating injury risk. Adolescence is characterized by hormonal fluctuations that significantly influence musculoskeletal growth and neuromuscular function. Notably, increases in anabolic hormones particularly testosterone, growth hormone, and insulin-like growth factor-1 (IGF-1) stimulate muscle hypertrophy, protein synthesis, and enhanced motor unit recruitment (Hayta et al., 2023). These physiological shifts underpin the observed non-linear gains in muscular strength, which often accelerate during and after PHV.

Crucially, BM does not occur uniformly across individuals. Early maturers tend to exhibit greater absolute strength due to advanced development of lean body mass and musculoskeletal architecture. However, longitudinal studies (e.g., Jones et al., 2018) suggest that this early advantage may attenuate over time as late maturers “catch up” in terms of relative strength-to-body mass ratios and functional capacity. This highlights the importance of contextualizing strength gains in relation to maturation status rather than CA especially in longitudinal designs such as the current study. Ignoring inter-individual differences in maturation can obscure meaningful interpretations of training outcomes and lead to misguided comparisons in talent development settings.

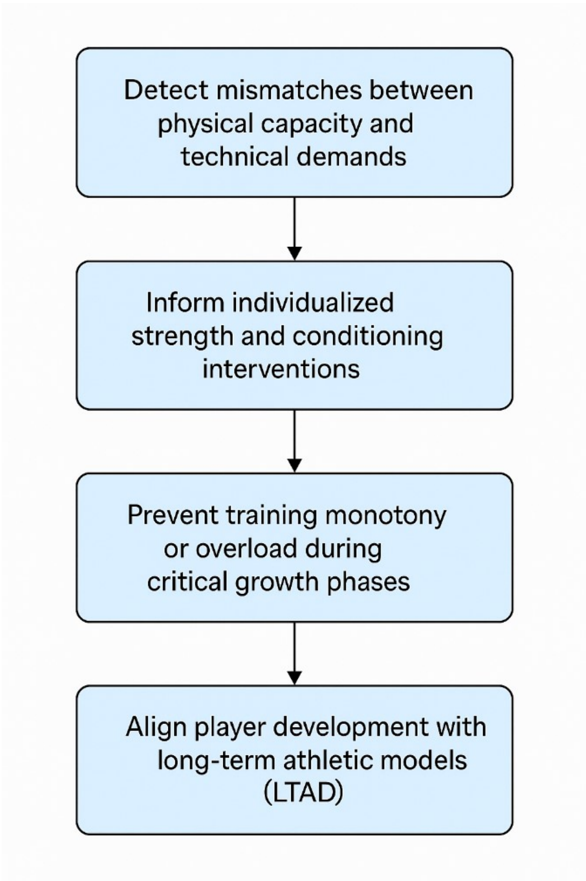
Neuromuscular maturation plays a pivotal role in strength gains independent of muscle hypertrophy. Enhanced motor unit synchronization, firing frequency, and intermuscular coordination contribute significantly to early strength improvements, especially in prepubescent and peri-pubertal athletes. This reinforces the principle that strength adaptations during early adolescence are not solely reliant on muscle size but are also attributable to neural factors underscoring the need for strength assessments that capture both absolute and relative performance markers.

Adequate nutritional intake is indispensable for supporting the anabolic demands of strength training during adolescence. Macronutrient sufficiency, particularly protein and carbohydrate intake, is essential for muscle repair, glycogen replenishment, and sustained energy availability. Adolescent athletes exhibit higher protein requirements than their sedentary peers due to increased protein turnover associated with training and growth. Brink et al. (2016) and Gong et al. (2024) both confirm the elevated protein demands in youth athletes, noting that suboptimal intake can compromise recovery, impair performance, and potentially increase injury susceptibility. Micronutrients also play a non-trivial role in the development of strength and structural integrity. Calcium and vitamin D are particularly critical for optimizing bone mineralization during peak bone accrual phases (Petrulytė & Guogienė, 2018), which often coincide with PHV. Inadequate intake of these nutrients can exacerbate injury risk especially stress-related skeletal injuries during a period of rapid musculoskeletal change. Thus, nutritional screening should be integrated alongside physical profiling in adolescent athletic development programs to ensure a holistic approach to performance enhancement.

The efficacy and safety of resistance training in adolescents have been extensively documented in the literature, debunking earlier concerns about its potential harm when appropriately supervised and periodized. Contemporary evidence (e.g., Muehlbauer et al., 2012) affirms that resistance training contributes to significant gains in muscular strength, power, and neuromuscular efficiency, provided that programming is aligned with the individual's maturity status, technical competence, and training age. A key consideration is the principle of training age specificity, which advocates for progressive overload based on prior training exposure rather than arbitrary increases in intensity or volume. Adolescents with limited resistance training experience may initially benefit most from neuromuscular coordination drills, bodyweight resistance exercises, and basic movement competency training an approach that complements FM development as emphasized earlier in this thesis. As technical proficiency and musculoskeletal robustness increase, the program can progressively incorporate higher-load strength exercises with emphasis on multi-joint movements, eccentric control, and velocity-based resistance protocols.

In elite youth soccer, muscular strength is not an end in itself but a facilitator of performance components such as sprinting speed, jump height, deceleration capacity, and injury resilience. When integrated with movement quality assessments such as FMS and maturity-based profiling, strength metrics offer valuable insight into each player's developmental trajectory.

Figure 2. Adaptive Training Strategy Based on Growth and Development Monitoring



Given in figure 2 the non-linear and individualized nature of adolescent growth, longitudinal monitoring across the U13 to U16 age categories is essential to follow flowchart in the figure:

By anchoring strength development in a maturation-sensitive and evidence-based framework, this thesis aims to bridge the gap between normative data, practical application, and individualized athletic development.

Adolescent strength development is a complex, non-linear process shaped by hormonal, nutritional, neuromuscular, and psychological variables. Its trajectory is intimately linked with BM and, when appropriately trained and monitored, serves as a cornerstone of performance enhancement in elite youth soccer. The incorporation of normative data that accounts for PHV and FM status can support more precise, individualized interventions that align with both performance goals and athlete wellbeing.

4.1 Strength in the Context of Soccer

Strength development during adolescence is a foundational pillar of athletic development and a key determinant of soccer performance. This developmental window is marked by complex physiological, hormonal, and psychosocial transformations that shape an athlete's ability to generate, control, and apply force. In elite youth soccer, where the demands of the sport extend beyond raw strength to include agility, speed, power, and resilience, a nuanced understanding of strength typologies and their developmental trajectories is essential. Pubertal maturation introduces a surge of anabolic hormones most notably testosterone and growth hormone which catalyze neuromuscular and musculoskeletal development (Brink et al., 2016; Yapıcı et al., 2022; Zhang et al., 2023). These hormonal changes underpin strength gains through hypertrophic and neural adaptations, with adolescent males typically demonstrating accelerated development due to greater androgen exposure. However, individual differences in maturation timing, as indexed by PHV create substantial variability in strength expression and responsiveness to training (Beunen & Thomis, 2000). Accordingly, maturation-sensitive programming becomes imperative to ensure developmental appropriateness and training efficacy. Different types of strength contribute uniquely to soccer performance, depending on the positional and tactical demands placed on the athlete. Resistance training during adolescence must be both developmentally appropriate and individualized based on the athlete's biological age and neuromuscular readiness. Research supports the application of periodized training that aligns with the athlete's maturation trajectory, optimizing strength gains while minimizing injury risk (Fourchet et al., 2015; Melekoğlu et al., 2018).

Table 6. Typology of Strength Methods

Type of Strength	Definition	Soccer Relevance	Age Focus & PHV Consideration
Absolute Strength	Total force a muscle group can exert, regardless of body mass	Crucial for shielding, tackles, duels	Develops post-PHV with increased muscle mass
Relative Strength	Force generated relative to body weight	Key in sprinting, jumping, and deceleration	Monitored pre-/post-PHV; can peak earlier than absolute strength
Explosive Strength	Ability to generate maximal force in minimal time	Essential for shooting, vertical jumping	Best targeted post-PHV with neural emphasis pre-PHV
Speed Strength	Force applied rapidly during high-velocity actions	Sprint acceleration, quick cuts, ball striking	Developments throughout adolescence; sensitive to neural maturation
Endurance Strength	Sustained force production over time	Repeated efforts, second-half performance	Builds progressively across adolescence with aerobic base
Maximal Strength	Greatest force in a single maximal contraction	Foundational for all force-based movements	Prioritized post-PHV with adequate technique base
Isometric Strength	Force production without joint movement	Core stabilization, body control during static contact	Safely trainable across all ages with low injury risk
Dynamic Strength	Force production during active muscle shortening/lengthening	Running mechanics, ball control, directional changes	Focused post-PHV; technique is essential pre-PHV
Reactive Strength	Efficient use of stretch-shortening cycle (eccentric to concentric transition)	Plyometric actions bounding, counter-movements, rapid changes in direction	Highly trainable post-PHV; plyometrics introduced carefully earlier
Isokinetic Strength	Force exerted at constant limb velocity across joint range	Laboratory assessment; rehabilitation context	Advanced testing; limited field application in youth
Functional Strength	Coordinated, sport-specific force application with stability and control	Integrated in movement tasks defending, dribbling, cutting	Emphasized pre- and post-PHV for sport transfer

This typology provides a functional framework for tailoring strength development programs to each player's maturity status and game role, emphasizing an integrated model of performance development.

Functional strength training, which bridges traditional resistance training with sport-specific movement, is particularly relevant in soccer due to its requirement for multi-planar movement under unpredictable conditions. Mersmann et al. (2016) argue that functional strength training improves not only force production but also movement efficiency, proprioception, and injury resilience particularly important during adolescent growth spurts when coordination may temporarily regress.

Strength development is not purely physiological; it is shaped by motivation, self-perception, social support, and environmental context. Xia et al. (2023) found that psychosocial factors including parental encouragement, peer comparison, and coach-athlete relationships significantly impact adolescents' engagement with resistance training. These influences can mediate the athlete's consistency, self-efficacy, and long-term athletic identity formation. Accordingly, strength programs in elite settings should be athlete-centered, incorporating goal setting, positive feedback, and autonomy to foster intrinsic motivation.

Table 7. Practical Applications of Tracking Strength Across U13–U16 Using PHV-Adjusted Benchmarks

1.	*Identify lagging physical qualities relative to biological development*
2.	*Detect disproportionate gains in absolute vs. relative strength*
3.	*Inform return-to-play criteria post-injury*
4.	*Align strength development with technical-tactical training loads*

Note: Strength monitoring that accounts for maturation status supports individualized programming and injury prevention within the LTAD framework.

In conclusion, strength development in adolescent soccer players is a multifaceted process driven by physiological maturation, psychological readiness, and contextualized training design. A typology-based understanding of strength linked with PHV-sensitive programming and psychosocial scaffolding can optimize LTAD and enhance performance in a sport defined by rapid, forceful, and coordinated movement. By integrating these concepts into longitudinal monitoring frameworks, practitioners can foster resilient, well-rounded athletes prepared for the demands of elite competition.

4.2 Lower Body Strength Frame of the Study

Lower body strength is a critical determinant of physical performance in soccer, underpinning fundamental actions such as sprinting, jumping, kicking, decelerating, and rapidly changing direction. These capabilities are essential not only for performance efficacy but also for injury prevention and movement control particularly in high-speed, high-force scenarios typical of elite-level play. During adolescence, the importance of lower body strength is accentuated by the non-linear interaction between neuromuscular development, hormonal maturation, and training responsiveness. Consequently, a nuanced approach to evaluating and developing LBS across the adolescent growth curve is essential for evidence-based athlete management.

Lower extremity strength directly correlates with critical soccer-specific performance metrics. As Mota et al. (2010) and Oliver et al. (2023) have demonstrated, increases in leg strength contribute to enhanced sprint acceleration, greater kicking velocity, and improved balance and control during rapid directional changes. These outcomes are rooted in the biomechanical advantages conferred by greater ground reaction force production and improved rate of force development (RFD) both of which are largely influenced by muscular strength in the hip, knee, and ankle joint complexes. Strong lower limbs contribute to injury resilience by improving joint stabilization, correcting neuromuscular imbalances, and increasing load tolerance in musculoskeletal tissues. This is particularly relevant during PHV, a period when adolescents are vulnerable to coordination deficits and overuse injuries due to rapid musculoskeletal growth and asynchronous neuromotor development. A growing body of literature supports the efficacy of diverse strength training modalities in enhancing lower limb performance among youth athletes. Traditional resistance training, targeting major muscle groups through progressive overload, is a well-established method for developing isokinetic and isometric strength. Mota et al. (2010) found that structured resistance training led to substantial gains in both absolute leg strength and sprint capacity in adolescent soccer players. These effects are compounded by neural adaptations, particularly in earlier phases of maturation, where increased motor unit recruitment, firing frequency, and synchronization precede visible hypertrophy. Complementary to traditional strength training is plyometric training, which focuses on the enhancement of explosive strength through repeated stretch-shortening cycle (SSC) movements. Franco-Márquez et al. (2015) reported significant improvements in vertical jump (VJ) height, reactive strength index (RSI), and acceleration after an 8-week plyometric intervention in youth soccer athletes. These findings underscore the value of dynamic and ballistic training elements in fostering neuromuscular efficiency and RFD capacities essential to explosive in-game actions such as jumping for aerial duels or initiating first-step acceleration. Combined strength and power training protocols which integrate resistance, plyometric, and functional components are shown to yield synergistic benefits. Peña-González et al. (2019) demonstrated that such interventions improved bilateral symmetry and reduced inter-limb strength imbalances, a known risk factor for lower limb injuries and suboptimal movement mechanics. Importantly, these programs also produced higher gains among athletes at advanced maturity stages, reinforcing the concept that training adaptation is influenced by biological age.

A central variable in strength development during adolescence is the athlete's maturational status. Those at more advanced stages of puberty (i.e., post-PHV) typically exhibit greater responsiveness to strength training due to elevated levels of testosterone and growth hormone, which facilitate hypertrophy and recovery (Peña-González et al., 2019). Conversely, pre- and circa-PHV athletes often show more prominent neural rather than structural adaptations. This developmental distinction necessitates the use of maturity-based training frameworks, in which load, intensity, and exercise type are calibrated according to each athlete's biological age rather than chronological age. For instance, younger athletes with lower skeletal maturity may benefit more from low-load, high-velocity movements and proprioceptive drills that enhance inter- and intramuscular coordination. Older, post-PHV athletes, in contrast, can safely tolerate higher external loads and benefit from hypertrophy-oriented protocols with more advanced resistance and plyometric integration. The inclusion of PHV monitoring in this study, therefore, enables a biologically informed interpretation of lower body strength data, increasing both the internal validity and translational utility of the findings.

In this longitudinal investigation, lower body strength assessments were selected to align with key soccer performance demands and to reflect developmental trajectories relative to PHV. By anchoring strength data within a maturational framework, the study aims to enhance the precision of talent development systems and reduce the risk of both overtraining and underdevelopment during critical stages of growth. LBS is not merely a performance variable but a multidimensional construct shaped by BM, training stimulus, and neuromuscular coordination. Effective assessment and development of LBS during adolescence require maturity-sensitive methods and sport-specific integration. Through longitudinal strength profiling aligned with PHV status, this study contributes to the refinement of developmental models in elite youth soccer, offering applied value to coaches, sports scientists, and practitioners tasked with guiding athletes through their formative years.

4.2.1 Explosive Strength Performance in Soccer

Explosive strength defined as the capacity to exert maximal force in minimal time is a cornerstone of athletic performance in soccer. It supports high-intensity actions such as sprint acceleration, vertical jumping, rapid deceleration, and agile directional changes. These explosive efforts are integral to game-defining events including aerial duels, breakaway sprints, and defensive recoveries. For adolescent athletes, explosive strength not only predicts performance potential but also contributes to injury mitigation through enhanced neuromuscular control and joint stability. The development of explosive strength during adolescence is mediated by a complex interplay of neuromuscular and endocrine factors, particularly in relation to biological maturation. Early-maturing athletes often demonstrate advanced performance in power-based tasks due to increased anabolic hormone concentrations especially testosterone and growth hormone which facilitate muscle hypertrophy and motor unit recruitment (Keiner et al., 2022; Cossio-Bolaños et al., 2021). These hormonal shifts enhance the RFD, a physiological hallmark of explosive strength. However, maturation-dependent advantages must be interpreted cautiously. While early maturers may show elevated jump or sprint metrics, these differences may reflect temporary anthropometric or hormonal advantages rather than superior neuromuscular efficiency. Therefore, training interventions and performance evaluations must be contextualized within biological, rather than merely chronological, age. Incorporating PHV-based maturity tracking as done in this study ensures more valid assessments and appropriate training expectations across developmental stages.

Two primary training modalities have shown consistent efficacy in improving explosive strength in youth soccer populations: plyometric training and resistance training. Plyometric training, involving rapid eccentric–concentric movements (e.g., depth jumps, bounding, hop-to-box), enhances the stretch-shortening cycle and improves muscle-tendon unit stiffness, ground contact efficiency, and neuromuscular coordination (Campo et al., 2009). These adaptations translate directly into improved VJ performance, acceleration, and agility. Resistance training contributes to increased force output and muscular coordination under load. Studies have shown that lower-limb strength protocols significantly improve sprint times and power output in adolescent soccer players (Oliver et al., 2023; Giminiani & Visca, 2017). While neural adaptations dominate early training phases, post-PHV athletes may also experience hypertrophic gains that further elevate explosive output.

Combined strength power training has shown superior results due to synergistic effects on both neuromuscular and morphological adaptations. Καρατράντου et al. (2019) highlight that integrated programs lead to greater improvements in RFD and VJ height compared to isolated training modalities. Additionally, gender-specific considerations must be acknowledged. Female athletes typically exhibit lower baseline explosive strength due to differences in lean mass and neuromuscular recruitment. As Myer et al. (2009) emphasize, targeted neuromuscular training including jump-landing mechanics and proprioceptive drills is essential to enhance explosive strength and reduce the incidence of ACL and other lower-extremity injuries in female athletes. Inclusive programming tailored to both maturation and sex is essential for equitable athletic development.

VJ performance is a widely recognized and ecologically valid indicator of explosive strength, particularly in youth soccer. The ability to generate vertical displacement correlates strongly with sprint acceleration, quickness, and aerial proficiency traits that are critical in both offensive and defensive contexts. As such, the VJ test provides a reliable, low-cost, and field-applicable measure of lower-body power, making it a valuable tool in longitudinal athlete monitoring systems. Jlid et al. (2019) found a strong correlation between VJ height and isokinetic knee extensor strength in adolescent soccer players, confirming the physiological linkage between strength capacity and jump output. This correlation underscores the importance of comprehensive strength development including both concentric and eccentric force training for optimizing VJ performance. Multiple studies affirm the efficacy of plyometric and resistance training in improving VJ height in youth athletes: Manouras et al. (2016) and Akbari et al. (2018) demonstrated that structured lower-body resistance training led to significant increases in VJ performance, especially when combined with neuromuscular skill training. Özmen & Aydoğmuş (2017) reported that programs combining plyometric and strength components produced superior improvements in jump height, suggesting a synergistic mechanism involving both neural and mechanical adaptations. These gains are further amplified when training programs are periodized according to the athlete's maturity status and integrated with assessments of neuromuscular symmetry. BM substantially affects jump performance, with post-PHV adolescents often exhibiting increased VJ height due to enhanced lean body mass, motor control, and anabolic hormone activity (Moreira et al., 2017; Leão et al., 2022). However, this relationship is also moderated by anthropometric and biomechanical variables. Athletes with higher BMI or unfavorable strength-to-weight ratios may underperform despite advanced maturation. Loturco et al. (2019) and Yanci & Cámara (2016) emphasize the importance of relative strength and inter-limb symmetry in jump efficiency. Asymmetries between limbs if uncorrected can impair jump mechanics, reduce performance, and increase injury risk. Therefore, monitoring VJ height alongside force platform data or asymmetry indices provides a more comprehensive view of athletic readiness and developmental needs.

Explosive strength and its primary field indicator, VJ performance represents a critical element of athletic development in adolescent soccer. Its maturation-sensitive trajectory necessitates tailored interventions that combine resistance, plyometric, and neuromuscular training elements. By situating explosive strength development within a biological age framework and tracking it longitudinally, this study contributes to the refinement of talent identification and individualized training practices in elite youth soccer.

4.2.2 Isokinetic Strength and Assessments in Youth Soccer

Isokinetic strength assessment represents a gold-standard method in sports science and clinical rehabilitation for quantifying muscular performance under controlled conditions. Its application in youth soccer provides critical insights into lower limb function, muscular imbalances, and injury risk factors that are essential to both performance optimization and athlete longevity. By measuring muscular torque at fixed angular velocities through isokinetic dynamometry (e.g., using Biodex or Cybex systems), this method captures high-resolution data on the force-generating capacity of key muscle groups, particularly the quadriceps and hamstrings. Isokinetic strength refers to the ability of muscles to produce force at a constant speed throughout a joint's range of motion. This is distinct from isometric (static) and isotonic (variable-speed) contractions, offering unique advantages in assessing both concentric and eccentric muscle actions. Angular velocities commonly used in testing include 60°/s (for maximal strength), 120°/s, and 180°/s, 300°/s (for strength-speed and endurance assessments), enabling a comprehensive profile of muscular performance (Cerrah & Bayram, 2022).

Common Assessing Variables

- Peak Torque (Nm): Maximum force generated.
- Torque-to-Body Weight Ratio (Nm/kg): Relative strength indicator.
- Fatigue Index (%): Endurance capacity over repeated efforts.
- Hamstring-to-Quadriceps (H:Q) Ratio: A key indicator of muscle balance.

In soccer, the quadriceps and hamstrings are foundational for actions such as kicking, sprinting, stopping, and changing direction. Isokinetic testing is particularly useful for evaluating the functional status of these muscle groups, as imbalances between agonist (quadriceps) and antagonist (hamstrings) muscles are strongly linked to injury risk especially to the ACL and hamstring strains. A hamstring-to-quadriceps strength ratio in the range of 0.6–0.7 is widely considered optimal for minimizing ACL injury risk (Östenberg et al., 2000).

Furthermore, asymmetry between limbs exceeding 15% is generally viewed as a red flag in return-to-play decisions. Soyal et al. (2023) emphasize that objective thresholds derived from isokinetic testing can serve as both pre-rehabilitation indicators and return-to-play benchmarks following lower limb injuries. Peak torque and RFD from isokinetic outputs have been positively correlated with key performance metrics, including sprint acceleration, jump height, and kicking velocity (Śliwowski et al., 2017; Gouveia et al., 2023).

Adolescence is characterized by dramatic increases in muscle mass, neuromuscular efficiency, and hormonal activity, all of which influence isokinetic strength outcomes. Research by Çelenk et al. (2019) indicates that older and more biologically mature adolescents exhibit significantly higher peak torque outputs and improved muscular endurance at all angular velocities. These findings highlight the importance of contextualizing isokinetic data within biological rather than chronological age categories a principle central to this thesis. Despite the value of isokinetic testing, there remains a paucity of normative data stratified by PHV status, particularly in elite youth soccer. The present study contributes to addressing this gap by integrating isokinetic strength assessments within a longitudinal design that tracks strength development alongside BM and movement functionality.

EXPERIMENTAL PART

5 Methodology

5.1 Scientific Problem

The scientific problem addressed in this study is the investigation of the associations between movement functionality, LBS, and BM (as indicated by PHV) in elite youth soccer players aged U13 to U16 across two competitive seasons. This problem is significant because understanding these associations can help in developing optimised training programs and injury prevention strategies for young athletes.

5.2 Research Questions

1. What are the associations between movement functionality, LBS, and BM (as indicated by PHV) in elite youth soccer players aged U13 to U16 across two competitive seasons?
2. How does BM (PHV) influence the development of LBS and jump performance in youth soccer players?
3. Does FM proficiency (FMS) improve over time, and how is it related to strength and power performance?
4. What are the differences in performance outcomes between pre-, circa-, and post-PHV athletes? How do performance metrics vary by age group (U13–U16) and across the two seasons (2022 vs 2023)?
5. Can movement screening and strength testing help predict athletic development and potential injury risk during periods of rapid growth?

5.3 Hypotheses of the Study

H1: It is hypothesized that there is a significant association between BM (measured via PHV) and the development of LBS and VJ performance in elite youth soccer players (anticipated $p < 0.001$), with a moderate to strong correlation expected ($r = 0.52–0.76$), suggesting that maturation is a central factor in neuromuscular development.

H2: It is expected that FMS scores will improve significantly from 2022 to 2023 ($p < 0.01$), particularly in older and post-PHV athletes. However, FMS is hypothesized to exhibit only weak correlations with explosive strength and jump performance ($r = 0.19–0.33$), indicating limited predictive value despite maturation-related improvements.

H3: It is hypothesized that players in the post-PHV group will demonstrate significantly higher isokinetic strength and jump performance compared to those in the pre- and circa-PHV groups ($p < 0.001$), with large effect sizes anticipated (Cohen's $d = 0.75–1.35$), supporting the performance advantages of biological maturity.

H4: It is expected that peak torque of knee flexors (PTKF) and extensors (PTKE) will improve with biological age and PHV transition status ($p < 0.01$), with moderate correlations projected ($r = 0.44–0.59$), reflecting maturation-related strength development and improved muscular balance.

H5: It is hypothesized that significant improvements in strength (e.g., H180, Q180), power (CMJ, CMJFAF), and FMS scores will occur from 2022 to 2023 ($p < 0.001$), especially among athletes transitioning from pre- to circa- or post-PHV status. These changes are expected to show moderate to strong associations with biological maturation ($r = 0.51–0.71$).

H6: Isokinetic knee strength at 60°/s is hypothesized to correlate strongly with PHV status ($p < 0.001$), with predicted correlation coefficients in the range of $r = 0.58–0.72$, reflecting developmental progression in slow-velocity strength capacity.

H7: It is hypothesized that isokinetic strength at 180°/s and 300°/s will be strongly correlated with VJ performance ($p < 0.001$), with correlations expected between $r = 0.63–0.81$, indicating that high-velocity strength is a key determinant of explosive power in youth soccer players.

5.4 Objectives of the Study

The objectives of the study are to: **a)** examine the relationships between movement functionality, LBS, and BM specifically PHV in elite youth soccer players aged U13 to U16 across two consecutive competitive seasons. This objective aims to understand how these variables interact, **b)** evaluate how these variables develop over time, how they interact during key stages of maturation, and how this information can inform individualized training strategies and injury prevention protocols in youth football. This objective focuses on the practical applications of the study's findings.

6. Materials and Methods

6.1 Study Design and Timeline

This study was conducted over two competitive seasons, 2022 and 2023, involving elite youth soccer players aged U13 to U16. The study design included longitudinal tracking of participants to assess changes in movement functionality, LBS, and BM. The timeline for data collection was structured around key competitive periods and training cycles to ensure comprehensive coverage of the athletes' development. The research design was mixed-longitudinal and was conducted during the Pre-season 2022-2023 and 2023-2024. All measurements were performed under consistent conditions during the morning hours (8.30 – 11.30 a.m.). The participants were familiarized with the experimental protocol and did not perform any strenuous physical activity with high intensity of any significant duration at least for 48 hours prior to testing. All athletes were fully informed about the aim of the study and employed testing procedures. Written informed consent to the testing procedures and data use for further research was obtained from the athletes' parents and assent from the children. The study was approved by the Institution's ethics committee (hidden for review Number) and confirmed to the Declaration of Helsinki regarding the use of human subjects.

6.2 Participant Selection and Grouping (U13–U16, PHV categories)

The participant cohort consisted of youth elite male soccer players recruited from professional soccer academies in the Czech Republic. Players were categorized into four chronological age groups: Under-13 (U13), Under-14 (U14), Under-15 (U15), and Under-16

(U16). Additionally, biological maturity was assessed using predicted peak height velocity (PHV), allowing for secondary grouping based on maturation status.

The study aimed to enroll approximately 18 players per age category from two professional clubs, targeting a total sample size of around 160 participants over a two-year period. Recruitment was conducted in coordination with academy staff during the competitive season and aligned with training cycles to minimize disruptions and ensure ecological validity.

In the first year of data collection, 86 players initially participated. After thorough data processing and the exclusion of incomplete or invalid records, 79 players were retained for statistical analysis and subsequent publication (Appendix A). These players were distributed as follows: U13 (n = 19), U14 (n = 20), U15 (n = 19), and U16 (n = 21).

In the second year, 45 players from the original groups met the inclusion criteria and were included in the final analysis. Thus, the final cumulative sample for the project comprised 45 male youth soccer players, categorized under the same age groups as in the first year. These participants completed all measurement protocols and met eligibility requirements for the second round of data collection. The second-year/final chronological age group distribution was as follows: U13 (n = 13), U14 (n = 10), U15 (n = 10), and U16 (n = 12).

These players were drawn from a single elite-level academy in the Czech Republic. All participants were classified as highly trained or elite youth athletes according to the criteria proposed by McKay et al. (2022). Each player had between 4 and 9 years of formal soccer training experience and participated in structured training four times per week (75–90 minutes per session), along with one competitive match per week. Match durations varied by age group: U13–U15 played 2 × 40-minute halves, while U16 players competed in 2 × 45-minute halves. Notably, the older age groups (U15 and U16) included players who were members of their respective national youth teams: U15 (n = 6) and U16 (n = 8), underscoring the high-performance level of the sample.

In addition to chronological age (CA) groupings, players were also categorized based on their estimated biological maturity using PHV calculations. This dual categorization enabled more nuanced analyses of developmental factors and performance metrics, helping to minimize the confounding effects of maturation timing. The data demonstrate a clear longitudinal structure in strength, power, and movement quality, validating the utility of PHV categorization for monitoring and programming in elite youth soccer within the studied age groups (see Table 8).

Table 8. Descriptive data of the participants including performance metrics for 2022 and 2023

Age group		**U13 (n=13)**	**U14 (n=10)**	**U15 (n=10)**	**U16 (n=12)**
		Mean ± SD	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
Chronological age (years)	**2022**	12.27 ± 0.27	13.23 ± 0.32	14.43 ± 0.17	15.24 ± 0.29
	2023	13.30 ± 0.27	14.26 ±0.32	15.46 ± 0.17	16.27 ± 0.29
Body height (cm)	**2022**	155.52 ± 5.25	161.28 ± 4.30	171.47 ± 7.71	174.90 ± 6.52
	2023	162.98 ± 7.02	166.50 ± 11.60	176.12 ± 6.80	178.02 ± 5.43
Body weight (kg)	**2022**	42.95 ± 4.78	46.46 ± 3.22	56.50 ± 7.18	61.25 ± 7.33
	2023	45.03 ± 11.76	54.09 ± 4.64	62.99 ± 6.36	65.81 ± 7.01
Body fat (%)	**2022**	17.04 ± 3.15	15.91 ± 1.33	13.98 ± 2.23	15.48 ± 1.97
	2023	16.62 ± 3.46	14.97 ± 1.43	13.99 ± 2.42	15.28 ± 2.13
PHV	**2022**	-1.70 ± 0.35	-0.98 ± 0.25	0.68 ± 0.54	1.23 ± 0.57
	2023	-0.61 ± 0.49	0.37 ± 0.30	1.96 ± 0.49	2.29 ± 0.67
FMS	**2022**	16.54 ± 2.34	17.40 ± 1.36	17.10 ± 2.55	18.83 ± 1.91
	2023	18.00 ± 1.66	18.90 ± 1.70	18.80 ± 1.83	19.00 ± 1.91
Maturity status (n)	**2022**	Pre (13), Circa (N) Post (N)	Pre (4), Circa (6) Post (N)	Pre (N), Circa (8) Post (2)	Pre (N), Circa (4) Post (8)
	2023	Pre (2), Circa (11) Post (N)	Pre (N), Circa (9) Post (1)	Pre (N), Circa (8) Post (2)	Pre (N), Circa (4) Post (8)
Maturity timing (n)	**2022**	Early (N) Average (8) Late (5)	Early (N) Average (3) Late (7)	Early (N) Average (5) Late (5)	Early (N) Average (5) Late (7)
	2023	Early (N) Average (8) Late (5)	Early (N) Average (6) Late (4)	Early (N) Average (9) Late (1)	Early (N) Average (7) Late (5)
Training age (years)	**2022**	>4	>5	>6	>7
	2023	>5	>6	>7	>8
Training load (hours)	**2022**	>8	>8	>10	>10
	2023	>8	>10	>10	>10

n, number of the players; cm, centimetres; kg, kilogram; N, none

6.3 Assessments

The following assessments were conducted to gather data on the participants…

6.3.1 Anthropometrics and Maturation Estimation (Mirwald's Equation, PHV)

Anthropometric Data Collection

Anthropometric measurements were conducted by an ISAK-certified technician with over eight years of experience. Body weight was measured using a Tanita® MC-980MA bioelectrical impedance scale (Tanita®, Japan; accuracy ±0.1 kg), and standing height was recorded with a SECA® stadiometer (SECA®, Germany; accuracy ±1 mm). Additional measurements included seated height and leg length, the latter calculated as standing height minus seated height. CA, height, weight, seated height, and leg length were collected for all participants to estimate biological maturity using the maturity offset method.

Maturity Offset and PHV Estimation

BA in this study was estimated non-invasively using the maturity offset equation developed by Mirwald et al. (2002), which calculates the number of years an individual is from reaching their predicted PHV. This widely accepted method has been validated for both boys and girls, with standard errors of ±0.57 and ±0.59 years, respectively (Malina et al., 2004; 2012). The equation incorporates key anthropometric variables, including CA (recorded in decimal years), standing height, seated height, leg length (subischial length), and body weight, with all measurements recorded in centimeters or kilograms as appropriate. Additionally, five ratio variables were calculated to support the model: weight divided by height, BMI, sitting height divided by height, leg length divided by height, and leg length divided by sitting height.

Based on the maturity offset values, participants were categorized into three biological BM groups: Pre-PHV (more than 1 year before PHV; offset < -1.0), Circa-PHV (within ±1 year of PHV; $-1.0 \leq$ offset $\leq +1.0$), and Post-PHV (more than 1 year after PHV; offset $> +1.0$), as summarized in Table 8. Maturity timing was also evaluated by comparing each participant's estimated PHV age to national reference data for Czech youth, where the average age at PHV is 12.9 years (Vignerová et al., 2006). Participants were further classified as early maturing if their estimated PHV age was below 11.9 years, average maturing if between 11.9 and 13.9 years, and late maturing if above 13.9 years. This dual classification—based on both maturity offset and maturity timing—allowed for a more detailed and accurate assessment of biological development relative to CA. Descriptive anthropometric data for participants, grouped by CA, are presented in Table 8.

The equation for male participants is as follows: *Maturity Offset (years) = –9.236 + (0.0002708 × Leg Length × Sitting Height) – (0.001663 × Age × Leg Length) + (0.007216 × Age × Sitting Height) + (0.02292 × Weight/Height ratio).*

6.3.2 Functional Movement Screening Protocol

FMS was conducted using a standardized protocol to assess participants' movement proficiency. The FMS protocol includes evaluations of flexibility, stability, and fundamental movement patterns, offering a comprehensive overview of physical function. The FMS test comprises seven movement patterns: Deep Squat, Hurdle Step, In-line Lunge, Shoulder Mobility, Active Straight Leg Raise, Trunk Stability Push-Up, and Rotary Stability (Cook et al., 2020). Each movement is scored on a scale from 0 to 3, and participants complete three attempts per movement. The total FMS score is calculated by summing the highest score from each movement pattern, with a maximum possible score of 21. A score of at least 2 on each movement, or a total score of 21, is considered optimal. Scores below 14 are associated with a higher risk of movement dysfunction, and professional evaluation is recommended, particularly if the participant experiences pain during any movement (Cook et al., 2020). To ensure high validity and reliability, the assessment followed the recommendations of Moran et al. (2016), including independent administration, standardized verbal instructions, equipment setup, pain inquiries, and thorough documentation of results. The FMS assessments were conducted by a certified physiotherapist with 7 years of experience and a sport scientist with 6 years of experience. The participants were introduced to each movement pattern without specific criteria. Additionally, the test protocol was conducted without a warm-up routine to observe the natural form of the participants (Cook et al., 2020).

6.3.3 Lower Limb Isokinetic Knee Extensors & Flexors Strength

Peak muscle torque (PT) of the knee extensors (PTKE) and knee flexors (PTKF) during concentric muscle contraction, at three angular velocities (60, 180 and 300°s−1) was measured by an isokinetic dynamometer (Cybex NORM® and Humac NORM® CA, USA). All participants were tested after a warm-up protocol with 5 minutes of indoor cycling at 120 watts and between 90 - 110 revolutions per minute. Also, players performed two sets with 10 repetitions of front squats, front lunges, and glute bridges. The diagnostics protocol was set for two concentric test repetitions with maximal effort per velocity. During the test, all participants were motivated verbally. Isokinetic strength testing for KE and KF was conducted individually for each limb in random order (dominant, non-dominant). The values for PTKE and PTKF were presented as the sum of the best values for both lower limbs. Results were normalized to players' body mass.

6.3.4 Lower Limb Vertical Jump Peak Power

Each participant performed three types of vertical jumps to evaluate lower limb peak power: countermovement jump (CMJ), countermovement jump-free arm (CMJ-FA), and squat jump (SJ). The highest attempt was used for data processing. Vertical ground reaction force (VGRF) was recorded using two force platforms (Kistler B8611A Kistler®, Switzerland) at 1000 Hz. Evaluated parameters included jump height and relative peak VGRF during take-off phase. Data was recorded with Bio-Ware 5.4.3.0, and additional processing was done using MATLAB R2020b. The force plates allowed for isolated limb observation, with the data later combined for statistical analysis.

6.4 Data Collection and Standardization Procedures

The independent variables in this study included BM status classified as pre-PHV, circa-PHV, and post-PHV and CA groups (U13, U14, U15, U16). These groupings allowed for the examination of both developmental and maturational influences on performance. The dependent variables were FM proficiency measured by FMS and LBS, evaluated through isokinetic testing PTKE and PTKF and various VJ tests, including CMJ, CMJFAF, and SJ. All measurements were collected using standardized protocols. Anthropometrics were assessed using stadiometers, bioelectrical impedance devices (Tanita), and seated height tools. FM assessments followed FMS protocols administered by trained evaluators. Strength testing was conducted on Cybex isokinetic dynamometers at angular velocities of 60°/s, 180°/s, and 300°/s for both flexors and extensors. Jump performance was recorded using Kistler force plates, providing reliable kinetic and kinematic data. Testing environments were controlled, and players were instructed to refrain from strenuous activity 24 hours prior to testing to minimize fatigue-related variability.

Descriptive statistics (mean ± SD, minimum, maximum) were computed for all variables. Mixed-effects linear models were employed to assess within-subject changes over time (2022 vs. 2023), particularly useful for analyzing repeated measures with missing values and nested data structures. Between-group comparisons across PHV categories and CA were evaluated using fixed-effects models, and Cohen's d and partial eta squared (η^2) were used to quantify effect sizes. Pearson correlation coefficients (r) assessed associations between BM, FM, LBS, and jump performance. Further, linear regression models were used to predict explosive strength outcomes (e.g., jump height and isokinetic strength) based on PHV status, age, and FMS scores.

Graphical visualizations included:

- Scatter plots with regression lines to explore key relationships (e.g., PHV vs. Jump Height; PHV vs. Strength; FMS vs. Jump),
- Heatmaps to present correlation matrices between variables,
- Grouped bar and line charts to visualize changes in strength, FMS, and jump performance over time,

- Plots of PTKF and KE and muscle group trends across angular velocities (60°, 180°, 300°/s), years, and maturity levels,
- Intra-class correlation coefficients (ICC) to report test-retest reliability of strength and movement assessments.

6.5 Statistical Analysis

All statistical analyses were conducted using R version 4.4.3 (R Core Team, 2023) in RStudio version 2023.06.0.421 (RStudio Team, 2022). Data preprocessing and organization were completed in Microsoft Excel, followed by data import and analysis in R. Only participants with complete data relevant to the given analysis were included (complete case analysis), consistent with recommendations by Kwak and Kim (2017). Missing data were excluded only when unrelated to a specific test or model.

Descriptive statistics (mean ± SD) were computed for all demographic, anthropometric, and performance variables, and stratified by age group (U13–U16), BM status (pre-, circa-, and post-PHV), and test year (2022 and 2023). Correlation matrices were created using the corrplot package (Wei & Simko, 2021) to examine relationships among PTKE and PTKF variables (H60°/s, H180°/s, H300°/s, Q60°/s, Q180°/s, Q300°/s angular velocities, jump tests, and FMS scores. ICCs were calculated to assess year-to-year test–retest reliability using a two-way consistency model, via the ICC function from the IRR package (Gamer et al., 2019).

To investigate the effects of BM and CA on performance outcomes, a series of multiple linear regression models were constructed separately for 2022 and 2023. Each model included either PHV category (pre-, circa-, post-) or BA (AG) as predictors. The dependent variables included isokinetic strength (e.g., H180, Q180), jump performance (e.g., CMJJH, CMJF, CMJFAF, SQJJH, SQJF), and FMS scores. To assess within-subject changes across years, mixed-effects models were used. These models incorporated testing year and BA as fixed effects and participant ID as a random effect to account for repeated measures. This allowed for evaluation of longitudinal changes while controlling for individual differences. The model structure was as follows:

Multiple regression models were used to examine the effects of PHV category (pre/circa/post) and BA (AG) on each motor test outcome. Models were conducted separately for 2022 and 2023. An overview of the models is presented in the result tables.

Table 9. Statistical analysis formulas for Inferential Analysis

• formula: 'strength_H_180 ~ PRE_POST + AG' • formula: 'strength_Q_180 ~ PRE_POST + AG' • formula: 'CMJJH_1 ~ PHV_1_cat + AG' • formula: 'CMJF_1 ~ PHV_1_cat + AG' • formula: 'CMJFAF_1 ~ PHV_1_cat + AG' • formula: 'SQJJH_1 ~ PHV_1_cat + AG' • formula: 'SQJF_1 ~ PHV_1_cat + AG'
• formula: 'CMJJH_2 ~ PHV_2_cat + AG' - data 2023 • formula: 'CMJF_2 ~ PHV_2_cat + AG' - data 2023 • formula: 'CMJFAF_2 ~ PHV_2_cat + AG' - data 2023 • formula: 'SQJJH_2 ~ PHV_2_cat + AG' - data 2023 • formula: 'SQJF_2 ~ PHV_2_cat + AG' - data 2023

Table 10 Assessing differences between 2022 and 2023, mixed-effects models were used with testing year and biological age (AG) as fixed effects, and participant ID as a random effect.

• formula: 'strength_H_180 ~ PRE_POST + AG + (1|ID)' • formula: 'strength_Q_180 ~ PRE_POST + AG + (1|ID)' • formula: 'CMJJH ~ PRE_POST + AG + (1|ID)' • formula: 'CMJF ~ PRE_POST + AG + (1|ID)' • formula: 'CMJFAJH ~ PRE_POST + AG + (1|ID)' • formula: 'CMJFAF ~ PRE_POST + AG + (1|ID)' • formula: 'SQJJH ~ PRE_POST + AG + (1|ID)' • formula: 'SQJF ~ PRE_POST + AG + (1|ID)' • formula: 'FMS.Score ~ PRE_POST + AG + (1|ID)'

All models were evaluated for compliance with key statistical assumptions. Normality of residuals was tested using the Shapiro-Wilk test ($\alpha \leq 0.05$). When normality was violated, appropriate generalized linear models (GLMMs) were fitted using alternative distributions (log-normal, gamma, or Weibull), following best practices outlined by Delignette-Muller et al. (2024). Distribution fitting was performed using the fitdistrplus package, utilizing the descdist, fitdist, and cdfcomp functions. Cullen and Frey skewness–kurtosis plots guided distribution selection, and final model selection was based on Akaike Information Criterion (AIC) values.

Multicollinearity among predictors was assessed using Variance Inflation Factors (VIF) via the check collinearity function from the performance package (Lüdecke et al., 2022). A VIF value below 5 was considered acceptable (Akinwande et al., 2015), while VIF > 10 indicated problematic multicollinearity warranting variable exclusion or model adjustment. Homoscedasticity and residual patterns were visually assessed through quantile–quantile plots and residual diagnostics using the simulate Residuals function from the DHARMa package (Hartig & Lohse, 2022). These checks ensured model validity and reliable estimation of effect sizes. All statistical tests were two-tailed, and significance was set at $p < 0.05$, with effect sizes and 95% confidence intervals reported where applicable. For correlation strength, the following interpretation was applied: weak ($r = 0.10–0.29$), moderate ($r = 0.30–0.49$), and strong ($r \geq 0.50$).

7 Results

7.1 Descriptive Statistics

Descriptive statistics for anthropometric and maturational variables are presented in Table 8. CA distributions were similar across years, while BA (PHV) varied by group. The test–retest reliability analysis using intra-class correlation coefficients (ICCs) indicated excellent reliability for stature (ICC = 0.92), body fat (ICC = 0.93), and PHV (ICC = 0.99), and moderate reliability for FMS scores (ICC = 0.59), suggesting these metrics were stable across seasons except for functional screening, which showed more fluctuation.

Table 11. ICC Results – Test–Retest Reliability 2022 vs. 2023

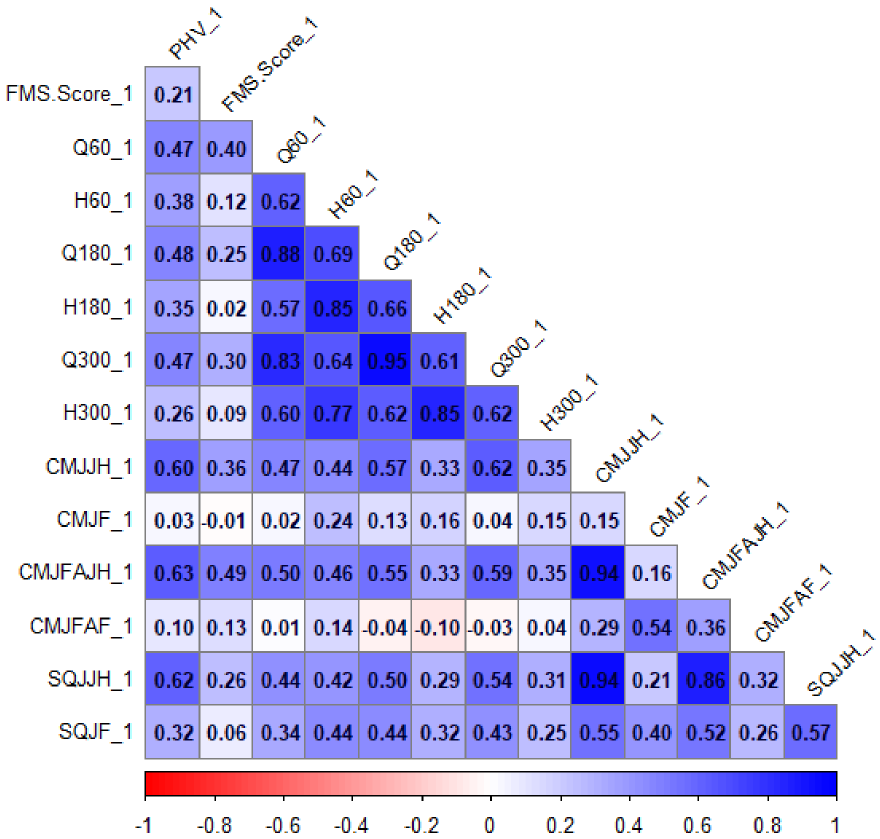
Variable	**ICC**	**95% CI (Lower–Upper)**	***p*-value**	**Interpretation**
Stature	0.920	[0.855, 0.956]	< .001	Excellent Reliability
Weight	0.808	[0.650, 0.894]	< .001	Good Reliability
Fat (%)	0.934	[0.880, 0.964]	< .001	Excellent Reliability
PHV	0.986	[0.975, 0.992]	< .001	Excellent Reliability
FMS Score	0.591	[0.256, 0.775]	0.0018	Moderate Reliability

Test–retest reliability analyses using two-way consistency ICCs revealed that anthropometric measures (e.g., stature, fat %, PHV) demonstrated excellent reliability across years (ICC ≥ 0.92). This supports the robustness of these BM indicators for longitudinal tracking. Weight showed good reliability (ICC = 0.81), reflecting moderate growth dynamics between seasons.

FMS scores, while statistically significant (p = .0018), yielded only moderate reliability (ICC = 0.59), likely due to the influence of tester subjectivity, neuromuscular fluctuations, and motivational factors. This underscores that FMS is more sensitive to short-term variability than structural metrics.

Considering the intricate interplay between BM and physical performance, this study adopts a meticulous approach, offering a comprehensive two-stage results table to dissect the nuanced differences across age groups. The analysis rigorously evaluates various parameters revealing disparities in FMS scores, LBS, and PHV timing among distinct age cohorts in different years (Figure 3 and 4).

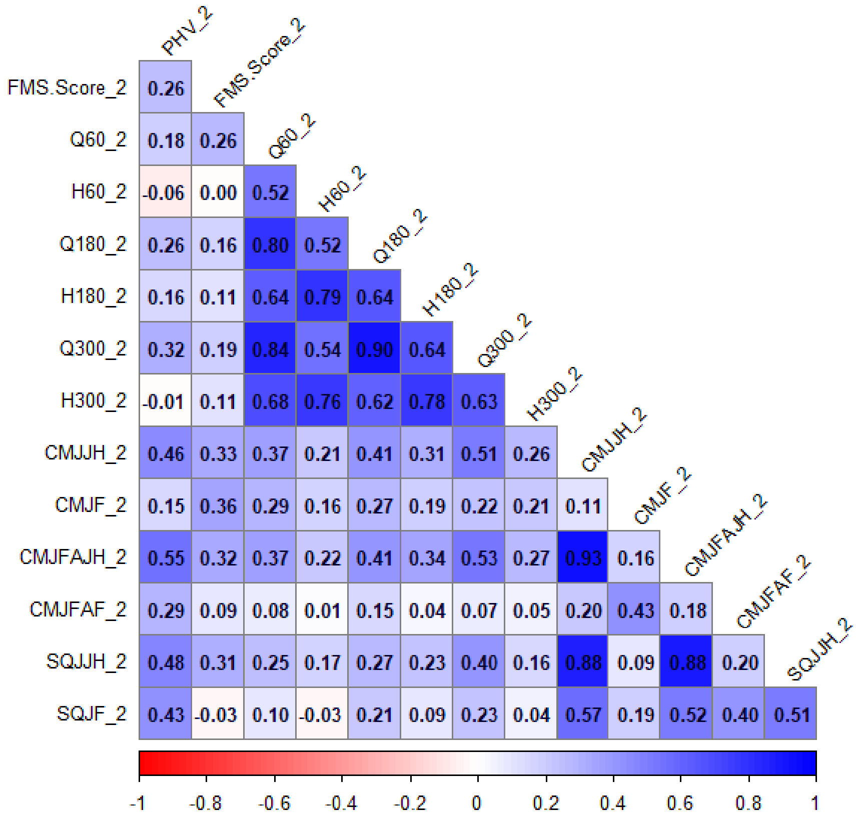
Figure 3. Correlation Matrices PHV, FMS, Strength, and Jump Performance



This matrix shows correlations between PHV, FMS, strength (PT of H and Q at 60°, 180°, 300°) and jump metrics (CMJ, CMJFAH/F, SQJ) in the 2022 season.

PHV shows moderate correlations with strength: Q180_1 (r = 0.48), H180_1 (r = 0.35), CMJFAJH_1 (r = 0.63), SQJJH_1 (r = 0.62), supporting H1, H3, H6, H7 – maturation influences strength/jump performance. FMS.Score_1 has weak correlations overall, highest with Q60_1 (r = 0.47), low with jump tests (r = 0.10–0.21), supporting H2 – limited predictive value. Jump metrics strongly intercorrelated: CMJJH_1 & CMJFAJH_1 (r = 0.94), CMJJH_1 & SQJJH_1 (r = 0.94).

Figure 4. Correlation Matrices PHV, FMS, Strength, and Jump Performance



This matrix shows correlations between PHV, FMS, strength (PT of H and Q at 60°, 180°, 300°) and jump metrics (CMJ, CMJFAH/F, SQJ) in the 2023 season.

Correlations stay strong: PHV_2 & Q180_2 (r = 0.64), PHV_2 & CMJFAJH_2 (r = 0.55), CMJJH_2 & SQJJH_2 (r = 0.88), supporting H1, H5, H7 – maturation/strength linked to jump ability. FMS.Score_2 still weak: CMJFAJH_2 (r = 0.32), CMJJH_2 (r = 0.46); slightly improved from 2022, but supports H2 – limited value. Quadriceps strength remains a better predictor of jump performance than hamstrings.

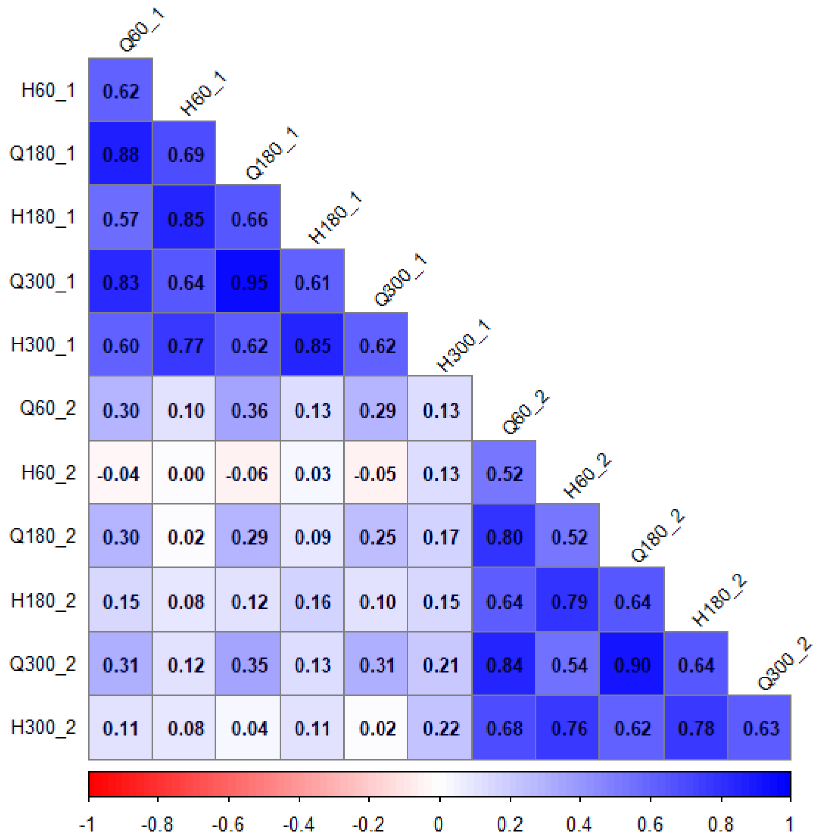
7.3 Lower Body Strength Performance Across the Maturation

Multivariate relationships between PHV, strength, and jump performance correlation matrices from 2022 and 2023 (Figures 3–6) demonstrate consistent multivariate relationships. Strong correlations were observed between PHV and jump height metrics, including CMJFAJH_1 (r = 0.63), CMJJH_1 (r = 0.60), CMJFAJH_2 (r = 0.55), CMJJH_2 (r = 0.46), SQJJH_1 (r = 0.62), and SQJJH_2 (r = 0.48), supporting hypotheses H1 and H5 indicating that maturation is a key driver of jump performance. Moderate correlations were found between PHV and strength variables, such as Q180_1 (r = 0.48), Q180_2 (r = 0.26), Q300_1 (r = 0.47), and Q300_2 (r = 0.32), suggesting a consistent, albeit reduced, relationship between maturation and strength across years. In contrast, FMS scores showed weak associations with most variables. FMS.Score_1 had minimal correlations with PHV_1 (r = 0.21) and jump metrics (r = 0.10–0.26), while FMS.Score_2 showed slightly stronger but still limited relationships, such as with CMJFAJH_2 (r = 0.32) and SQJJH_2 (r = 0.48), reinforcing H2 and its claim of limited predictive validity.

Notably, there was strong internal consistency among jump metrics, with very high correlations between CMJJH_1 and both CMJFAJH_1 and SQJJH_1 (r = 0.94), as well as between CMJFAJH_2 and both CMJJH_2 (r = 0.93) and SQJJH_2 (r = 0.88), suggesting that different jump tests measure similar explosive power qualities.

Group comparisons revealed significant differences across FMS scores, PTKE/PTKF, jump height (JH), and vertical ground reaction force (VGRF). Older age groups (U15–U16) consistently outperformed younger cohorts (U13–U14), especially in vertical jump height and isokinetic strength, highlighting maturation-related gains in physical performance. Knee extensor strength showed significant differences across most age groups, whereas knee flexor strength differences were primarily observed between U13/U14 and U16. No significant differences were detected in normalized PTKE or PTKF between pre-, circa-, and post-PHV groups. However, jump height performance was significantly better in older groups, with VGRF differences during squat jumps reaching significance only between U14 and U16.

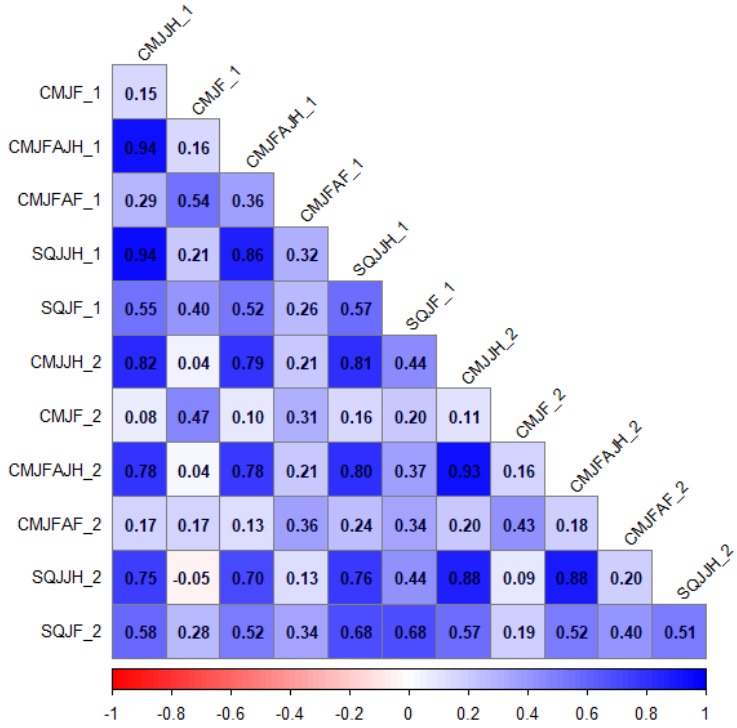
Figure 5. Strength Correlation Matrix (Hamstrings & Quadriceps)



The correlation matrix figure showing the relationships between hamstring and quadriceps peak force outputs across different angular velocities and years (2022 & 2023):

Strong within-year correlations in 2022: Q180_1–Q300_1 (r = 0.95), H180_1–H300_1 (r = 0.85), Q60_1–Q180_1 (r = 0.88), confirming high internal consistency in strength testing. Cross-year correlations were lower: Q180_1–Q180_2 (r = 0.29), H180_1–H180_2 (r = 0.16), suggesting developmental and technical variability over time. Quadriceps measures were more stable than hamstrings, supporting H6 and H7 lower/moderate velocity strength is interrelated, but year-to-year tracking in youth remains inconsistent.

Figure 6. Correlation Matrix Jump Performance.



The correlation matrix showing relationships between jump performance variables across testing years 2022 and 2023.

Figure 6 presents Pearson correlation coefficients among various jump test outcomes for 2022 (_1) and 2023 (_2), including jump height and force measures from both countermovement (CMJ) and squat jumps (SJ). Variables include CMJJH (CMJ – Jump Height), CMJFAJH (CMJ – Flight-derived Jump Height), CMJF (CMJ – Force), CMJFAF (CMJ – Flight-derived Force), SQJJH (SJ – Jump Height), and SQJF (SJ – Force). Very high within-year correlations were observed between height-based metrics: CMJJH_1 & CMJFAJH_1 (r = 0.94), CMJJH_1 & SQJJH_1 (r = 0.94), CMJJH_2 & CMJFAJH_2 (r = 0.78), and SQJJH_2 & SQJF_2 (r = 0.88). These findings demonstrate strong internal consistency between height and flight-derived measures within each season, confirming that these jump variables are reliably capturing related physical qualities such as explosive leg power. Cross-year correlations were moderate: CMJJH_1 & CMJJH_2 (r = 0.82), CMJFAJH_1 & CMJFAJH_2 (r = 0.78), and SQJJH_1 & SQJJH_2 (r = 0.70). These indicate that jump height performance traits show relatively stable tracking over time, despite expected individual variability due to maturation, training adaptation, or physical development across youth athletes.

By contrast, force-based metrics showed weaker correlations both within and across years. For example, CMJF_1 & CMJF_2 correlated poorly ($r = 0.10$), suggesting greater sensitivity to short-term factors such as fatigue, movement technique, or day-to-day variability in neuromuscular output. This pattern implies that while force output is important, it may be less stable across repeated testing, particularly in adolescent populations. Overall, these results support hypotheses H1, H3, H5, and H7 by confirming that vertical jump performance especially height-based variables is highly interrelated within a session and moderately stable between years. Force variables, although relevant, may require more careful interpretation due to their higher variability and lower reliability across time points.

7.3.1 Jump Performance Across Maturation

Significant improvements were observed across all jump metrics: CMJF, CMJFAF, CMJFAJH, CMJJH, SQJF, and SQJJH. Pre–post-test plots (Figures 3-6) show consistent upward trends for all age groups, especially U13–U15. Notably, CMJJH and SQJJH (vertical height) increased most steeply, while force-based measures (CMJF, SQJF) showed more moderate changes. These trends confirm H3, H5, and H7, indicating maturation as a key driver of explosive lower-limb performance. Correlation matrices (Figures 5-6) further confirmed strong associations between jump height and high-velocity strength (Q180–Q300; r = 0.78–0.95), affirming that power-oriented muscle function develops in tandem with maturity and strength gains.

Table12. SQJF EMMs by Age and PHV 2022 vs. 2023

Age	PHV Status	2022 EMM ± SE [CI]	2023 EMM ± SE [CI]	Δ Change
13	Circa	2.01 ± 0.12 [1.77–2.25]	2.02 ± 0.05 [1.91–2.13]	≈ 0.00
14	Circa	2.04 ± 0.07 [1.90–2.18]	2.09 ± 0.06 [1.98–2.21]	↑ +0.05
15	Circa	2.04 ± 0.06 [1.92–2.15]	2.19 ± 0.06 [2.07–2.31]	↑ +0.15
16	Circa	2.00 ± 0.07 [1.85–2.15]	2.23 ± 0.08 [2.07–2.39]	↑ +0.23
13	Post	2.25 ± 0.15 [1.96–2.55]	2.08 ± 0.10 [1.87–2.29]	↓ –0.17

Estimated Marginal Means (EMM) of SQJF (Height in m) by Age and PHV Category.

Table 13. Overall SQJF by Age

Age Group	SQJF (EMM ± SE)	95% CI (m)	*p*-value
13	2.02 ± 0.05	[1.92–2.11]	< .001
14	2.07 ± 0.05	[1.96–2.17]	< .001
15	2.14 ± 0.05	[2.04–2.25]	< .001
16	2.22 ± 0.05	[2.12–2.31]	< .001

**No PHV Split.*

Table 12 shows modest but consistent improvements in SQJF performance across age and maturation status. Notably, circa-PHV players at U15 and U16 improved by +0.15 to +0.23 meters from 2022 to 2023, while U13 post-PHV players showed a slight decrease (–0.17 m), possibly reflecting variability in early maturers. The overall trend, confirmed in the age-only table, suggests age-related neuromuscular gains consistent with RQ2, RQ4, and Hypotheses H1, H3, and H5.

Table 14. SQJJH 2022 vs. 2023 by Age and PHV

Age	PHV Status	2022 EMM ± SE (CI)	2023 EMM ± SE (CI)	Δ Change
13	Circa	26.51 ± 2.88 [20.69–32.32]	29.80 ± 1.49 [26.79–32.81]	↑ +3.29
14	Circa	26.62 ± 1.67 [23.24–30.00]	28.82 ± 1.56 [25.67–31.97]	↑ +2.20
15	Circa	30.07 ± 1.35 [27.33–32.80]	32.80 ± 1.63 [29.50–36.10]	↑ +2.73
16	Circa	30.64 ± 1.77 [27.06–34.23]	34.52 ± 2.13 [30.21–38.84]	↑ +3.88
13	Post	28.48 ± 3.49 [21.41–35.54]	29.94 ± 2.81 [24.26–35.63]	↑ +1.46

Estimated Marginal Means (EMM) of SQJJH (cm) by Age and PHV Status.

Table 15. Overall Table: SQJJH by Age

Age Group	SQJJH (EMM ± SE)	95% Confidence Interval	*p*-value
13	27.17 ± 1.16	[24.83–29.51]	< .001
14	27.47 ± 1.32	[24.80–30.13]	< .001
15	31.65 ± 1.32	[28.98–34.31]	< .001
16	33.29 ± 1.21	[30.85–35.72]	< .001

**Collapsed PHV.*

SQJJH performance improved consistently from 2022 to 2023 across all circa-PHV age groups, with the largest gains observed at U16 (+3.88 cm) and U15 (+2.73 cm). Post-PHV U13 players also showed a moderate improvement (+1.46 cm), though their confidence intervals suggest more variability. The overall trend by age confirmed this progression, with SQJJH increasing from 27.2 cm (U13) to 33.3 cm (U16). These findings strongly support Hypotheses H1, H3, and H5, showing age- and maturation-related development of VJ capacity.

Table 16. Regression Summary CMJF Models 2022, 2023 and Combined

CMJF 2022 Model

Predictor	Coef.	SE	*t*	*p*	95% CI	Significant
Intercept	2.33	0.21	10.92	<.001	[1.90, 2.77]	✓
AG14	0.004	0.17	0.02	0.983	[–0.35, 0.36]	✕
AG15	0.085	0.24	0.36	0.721	[–0.39, 0.56]	✕
AG16	–0.32	0.25	–1.27	0.211	[–0.83, 0.19]	✕
PHV_post	0.308	0.15	2.09	0.043	[0.01, 0.61]	✓

CMJF 2023 Model

Predictor	Coef.	SE	*t*	*p*	95% CI	Significant
Intercept	2.42	0.07	36.74	<.001	[2.28, 2.55]	✓
AG14	0.125	0.10	1.31	0.197	[–0.07, 0.32]	✕
AG15	0.080	0.10	0.82	0.416	[–0.12, 0.28]	✕
AG16	–0.001	0.12	–0.01	0.995	[–0.23, 0.23]	✕
PHV_post	0.079	0.11	0.75	0.459	[–0.13, 0.29]	✕

CMJF Combined Model

Predictor	Coef.	SE	*t*	*p*	95% CI	Significant
Intercept	2.39	0.06	39.13	<.001	[2.28, 2.51]	✓
AG14	0.105	0.03	3.19	0.003	[0.04, 0.17]	✓
AG15	0.047	0.09	0.50	0.618	[–0.13, 0.22]	✕
AG16	0.102	0.09	1.10	0.276	[–0.07, 0.28]	✕
PHV_post	–0.05	0.09	–0.57	0.574	[–0.22, 0.12]	✕

In table 16 the regression results indicate that in 2022, being post-PHV was a significant predictor of higher CMJF performance ($\beta = 0.31$, $p = .043$), supporting H1 and H3. However, this effect was not replicated in 2023, where no predictor reached significance. In the combined model, AG14 (age group 14) was a significant positive predictor ($\beta = 0.10$, $p = .003$), but PHV status and older ages (AG15, AG16) were not significant. These findings suggest a developmental effect around age 14, but the influence of maturation on CMJF may not be consistent across years or populations, which provides nuanced evidence for H1 and H3, but weakens general support for H5 in this test domain.

Table 17. CMJFAJH Regression Model (Jump Height, Single Model)

Predictor	Coef.	SE	*t*	*p*	95% CI	Sig
Intercept	33.97	1.24	27.48	<.001	[31.61, 36.33]	✓
AG14	3.28	0.39	8.42	<.001	[2.51, 4.05]	✓
AG15	1.38	1.87	0.74	0.466	[–2.20, 4.96]	✕
AG16	5.38	1.87	2.87	0.007	[1.79, 8.96]	✓
PHV_post	8.35	1.78	4.68	<.001	[4.94, 11.76]	✓

The CMJFAJH model, however, showed strong predictive power for PHV_post ($\beta = 8.35$, $p < .001$) and both AG14 ($\beta = 3.28$, $p < .001$) and AG16 ($\beta = 5.38$, $p = .007$), highlighting significant maturation and age-related increases in VJ height. These models collectively support H1, H3, and partially H5, affirming that age and PHV influence jump performance, but their effect size and consistency vary depending on the jump type and year.

Below in CMJFAF models, PHV status was only a significant predictor in 2023 ($\beta = 0.18$, $p = .031$), while age group 14 emerged as a significant factor in the combined model ($\beta = 0.09$, $p = .001$). In contrast, most other predictors showed no statistical significance, suggesting that improvements in CMJFAF may be more subtle and year-dependent.

Table 18. Regression Summary CMJFAF Models 2022, 2023 and Combined

CMJFAF 2022						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	2.19	0.18	12.35	<.001	[1.83, 2.55]	✓
AG14	0.23	0.14	1.58	0.122	[–0.06, 0.52]	✗
AG15	0.24	0.20	1.20	0.236	[–0.16, 0.63]	✗
AG16	0.13	0.21	0.65	0.521	[–0.29, 0.56]	✗
PHV_post	0.13	0.12	1.05	0.299	[–0.12, 0.38]	✗
CMJFAF 2023						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	2.50	0.05	48.95	<.001	[2.39, 2.60]	✓
AG14	0.11	0.07	1.49	0.143	[–0.04, 0.26]	✗
AG15	0.01	0.08	0.12	0.902	[–0.14, 0.16]	✗
AG16	–0.04	0.09	–0.45	0.654	[–0.22, 0.14]	✗
PHV_post	0.18	0.08	2.24	0.031	[0.02, 0.35]	✓
CMJFAF Combined						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	2.43	0.05	50.76	<.001	[2.34, 2.52]	✓
AG14	0.09	0.03	3.45	0.001	[0.04, 0.15]	✓
AG15	0.11	0.07	1.58	0.122	[–0.02, 0.25]	✗
AG16	0.06	0.07	0.89	0.381	[–0.07, 0.20]	✗
PHV_post	0.06	0.07	0.89	0.377	[–0.07, 0.19]	✗

Table 19. Regression Summary CMJJH Models 2022, 2023,and Combined

CMJJH 2022

Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	28.40	2.95	9.63	<.001	[22.44, 34.37]	✓
AG14	–0.15	2.40	–0.06	0.949	[–5.01, 4.70]	✗
AG15	3.05	3.26	0.93	0.356	[–3.54, 9.64]	✗
AG16	5.22	3.46	1.51	0.140	[–1.78, 12.23]	✗
PHV_post	2.10	2.03	1.03	0.308	[–2.01, 6.21]	✗

CMJJH 2023

Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	33.30	1.35	24.59	<.001	[30.56, 36.04]	✓
AG14	–1.08	1.96	–0.55	0.585	[–5.05, 2.89]	✗
AG15	3.20	2.01	1.59	0.119	[–0.86, 7.27]	✗
AG16	5.67	2.37	2.39	0.022	[0.88, 10.47]	✓
PHV_post	–1.66	2.17	–0.76	0.450	[–6.06, 2.74]	✗

CMJJH Combined Model

Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	30.05	1.14	26.27	<.001	[27.86, 32.23]	✓
AG14	2.86	0.30	9.57	<.001	[2.27, 3.45]	✓
AG15	0.04	1.73	0.02	0.982	[–3.28, 3.35]	✗
AG16	3.97	1.73	2.29	0.027	[0.66, 7.29]	✓
PHV_post	6.40	1.65	3.88	<.001	[3.24, 9.56]	✓

Regression models for CMJJH reveal that in 2023, AG16 was a significant predictor of higher jump height ($\beta = 5.67$, $p = .022$), while other factors including PHV were not significant. In the combined model, AG14, AG16, and PHV_post were all statistically significant:

AG14 ($\beta = 2.86$, $p < .001$), AG16 ($\beta = 3.97$, $p = .027$), PHV_post ($\beta = 6.40$, $p < .001$)

These results support H1, H3, and H5, indicating strong maturation-related improvements in CMJJH. While 2022 alone showed no significant predictors, the combined dataset clarifies a robust association with both age and PHV.

Below in the 2022 model, only PHV_post significantly predicted SQJF ($\beta = 0.24$, $p = .006$), while age effects were non-significant. In 2023, AG15 ($p = .042$) and AG16 ($p = .032$) became significant, suggesting strength development among older age groups, while PHV lost significance. The combined model confirmed AG14 ($\beta = 0.05$, $p = .002$) and PHV_post ($\beta = 0.20$, $p = .004$) as robust predictors of performance, with AG16 trending toward significance ($p = .072$).

The findings of Regression Summary SQJF Models strongly support H1, H3, and H5, showing a consistent maturation-linked improvement in squat jump performance with some variation in predictors by year.

Table 20 Regression Summary SQJF Models

SQJF 2022						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	2.01	0.12	16.67	<.001	[1.77, 2.25]	✓
AG14	0.03	0.10	0.31	0.756	[–0.17, 0.23]	✕
AG15	0.03	0.13	0.20	0.846	[–0.24, 0.30]	✕
AG16	–0.01	0.14	–0.08	0.940	[–0.30, 0.28]	✕
PHV_post	0.24	0.08	2.93	0.006	[0.08, 0.41]	✓
SQJF 2023						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	2.02	0.06	36.73	<.001	[1.91, 2.13]	✓
AG14	0.07	0.08	0.92	0.365	[–0.09, 0.23]	✕
AG15	0.17	0.08	2.10	0.042	[0.01, 0.34]	✓
AG16	0.21	0.10	2.22	0.032	[0.02, 0.41]	✓
PHV_post	0.06	0.09	0.70	0.488	[–0.12, 0.24]	✕
SQJF Combined						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	2.02	0.05	43.99	<.001	[1.93, 2.10]	✓
AG14	0.05	0.02	3.34	0.002	[0.02, 0.09]	✓
AG15	0.05	0.07	0.71	0.479	[–0.08, 0.18]	✕
AG16	0.13	0.07	1.85	0.072	[–0.01, 0.26]	○
PHV_post	0.20	0.07	3.06	0.004	[0.08, 0.33]	✓

Table 21. Regression Summary SQJJH Models

SQJJH 2022						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	26.51	2.88	9.21	<.001	[20.69, 32.32]	✓
AG14	0.11	2.34	0.05	0.962	[–4.62, 4.85]	✕
AG15	3.56	3.18	1.12	0.270	[–2.87, 9.99]	✕
AG16	4.14	3.38	1.22	0.228	[–2.70, 10.97]	✕
PHV_post	1.97	1.98	0.99	0.326	[–2.04, 5.98]	✕

SQJJH 2023						
Predictor	**Coef.**	**SE**	**t**	**p**	**95% CI**	**Sig**
Intercept	29.80	1.49	20.05	<.001	[26.79, 32.81]	✓
AG14	–0.98	2.15	–0.46	0.652	[–5.34, 3.38]	✕
AG15	3.00	2.21	1.36	0.181	[–1.46, 7.46]	✕
AG16	4.72	2.60	1.82	0.077	[–0.54, 9.98]	○
PHV_post	0.14	2.39	0.06	0.953	[–4.68, 4.97]	✕

SQJJH Combined						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	27.17	1.16	23.45	<.001	[24.96, 29.39]	✓
AG14	2.09	0.34	6.10	<.001	[1.41, 2.77]	✓
AG15	0.29	1.76	0.17	0.869	[–3.07, 3.65]	✕
AG16	4.47	1.76	2.54	0.015	[1.11, 7.83]	✓
PHV_post	6.11	1.67	3.66	0.001	[2.92, 9.31]	✓

Neither 2022 nor 2023 models showed any statistically significant predictors, although AG16 approached significance in 2023 (p = .077). The combined model, however, identified strong and significant predictors: AG14 (β = 2.09, p < .001), AG16 (β = 4.47, p = .015), PHV_post (β = 6.11, p = .001). These results support H1, H3, and H5, indicating that both chronological and biological maturation contribute meaningfully to improvements in SQJJH.

Table 22 Estimated Marginal Means for CMJF

2022 Results				
Age Group	**PHV Group**	**CMJF (Mean ± SE)**	**95% CI**	***p* Value**
13	Circa	2.33 ± 0.21	[1.90, 2.77]	< .001
14	Circa	2.34 ± 0.12	[2.09, 2.59]	< .001
15	Circa	2.42 ± 0.10	[2.22, 2.62]	< .001
16	Circa	2.01 ± 0.13	[1.75, 2.28]	< .001
13	Post	2.64 ± 0.26	[2.12, 3.17]	< .001
2023 Results				
Age Group	**PHV Group**	**CMJF (Mean ± SE)**	**95% CI**	***p* Value**
13	Circa	2.42 ± 0.07	[2.28, 2.55]	< .001
14	Circa	2.54 ± 0.07	[2.40, 2.68]	< .001
15	Circa	2.50 ± 0.07	[2.35, 2.64]	< .001
16	Circa	2.41 ± 0.09	[2.22, 2.61]	< .001
13	Post	2.49 ± 0.12	[2.24, 2.75]	< .001

CMJF performance showed a general upward trend across age groups, peaking at age 15 in both 2022 and 2023. The post-PHV group (13 years old) consistently demonstrated higher CMJF values compared to their circa-PHV peers, especially in 2022.

Combined Results

Age Group	CMJF (Mean ± SE)	95% CI	*p* Value
13	2.39 ± 0.06	[2.27, 2.52]	< .001
14	2.44 ± 0.07	[2.30, 2.58]	< .001
15	2.50 ± 0.07	[2.36, 2.64]	< .001
16	2.34 ± 0.06	[2.21, 2.47]	< .001

The combined analysis confirmed a significant increase from ages 13 to 15 ($p < .001$), followed by a slight decline at age 16. This plateau or dip may reflect neuromuscular adaptations or training maturity saturation. These trends support H1, H3, and H5, demonstrating how chronological and biological maturation positively influence jump performance, though the effect may plateau in older age groups.

Table 23 CMJFAJH Combined

Age	Jump Height (Mean ± SE)	95% CI	*p* Value
13	33.97 ± 1.24	[31.47, 36.47]	< .001
14	35.35 ± 1.41	[32.50, 38.20]	< .001
15	39.35 ± 1.41	[36.50, 42.19]	< .001
16	42.32 ± 1.29	[39.72, 44.92]	< .001

CMJFAJH demonstrated a robust linear trend in jump height with increasing age. The greatest gains were observed between ages 14 and 16, reinforcing the progressive influence of neuromuscular maturation.

Table 24 Estimated Marginal Means CMJFAF & CMJFAJH

CMJFAF 2022

Age	PHV Group	Mean ± SE	95% CI	*p* Value
13	Circa	2.19 ± 0.18	[1.83, 2.55]	< .001
14	Circa	2.42 ± 0.10	[2.21, 2.62]	< .001
15	Circa	2.42 ± 0.08	[2.26, 2.59]	< .001
16	Circa	2.32 ± 0.11	[2.10, 2.54]	< .001
13	Post	2.32 ± 0.21	[1.88, 2.75]	< .001

CMJFAF 2023

Age	PHV Group	Mean ± SE	95% CI	*p* Value
13	Circa	2.50 ± 0.05	[2.39, 2.60]	< .001
14	Circa	2.61 ± 0.05	[2.50, 2.71]	< .001
15	Circa	2.51 ± 0.06	[2.39, 2.62]	< .001
16	Circa	2.46 ± 0.07	[2.31, 2.60]	< .001
13	Post	2.68 ± 0.10	[2.48, 2.87]	< .001

CMJFAF Combined

Age	Mean ± SE	95% CI	*p* Value
13	2.43 ± 0.05	[2.33, 2.53]	< .001
14	2.55 ± 0.05	[2.44, 2.66]	< .001
15	2.50 ± 0.05	[2.39, 2.61]	< .001
16	2.49 ± 0.05	[2.39, 2.59]	< .001

CMJFAF results revealed consistent improvements across age groups, particularly from age 13 to 15, with a slight stabilization at 16. Notably, post-PHV 13-year-olds consistently outperformed circa-PHV peers at the same age, especially in 2023.

These findings strongly support H1, H3, and H5, showing that biological age and maturation status (PHV) positively affect explosive power as measured through countermovement jump parameters.

Table 25. Estimated Marginal Means CMJJH

2022 Results

Age	**PHV Group**	**CMJJH (cm) ± SE**	**95% CI**	***p* Value**
13	Circa	28.40 ± 2.95	[22.44, 34.37]	< .001
14	Circa	28.25 ± 1.71	[24.78, 31.72]	< .001
15	Circa	31.45 ± 1.39	[28.64, 34.26]	< .001
16	Circa	33.63 ± 1.82	[29.95, 37.30]	< .001
13	Post	30.50 ± 3.58	[23.26, 37.75]	< .001

2023 Results

Age	**PHV Group**	**CMJJH (cm) ± SE**	**95% CI**	***p* Value**
13	Circa	33.30 ± 1.35	[30.56, 36.04]	< .001
14	Circa	32.22 ± 1.42	[29.35, 35.09]	< .001
15	Circa	36.50 ± 1.49	[33.50, 39.51]	< .001
16	Circa	38.97 ± 1.95	[35.04, 42.91]	< .001
13	Post	31.64 ± 2.56	[26.46, 36.82]	< .001

Combined Results

Age	**CMJJH (cm) ± SE**	**95% CI**	***p* Value**
13	30.05 ± 1.14	[27.74, 32.36]	< .001
14	30.09 ± 1.30	[27.45, 32.72]	< .001
15	34.02 ± 1.30	[31.39, 36.65]	< .001
16	36.45 ± 1.19	[34.04, 38.85]	< .001

CMJJH performance improved significantly with age in both 2022 and 2023. The sharpest increases occurred between ages 14 and 16, particularly in 2023. While 13-year-old post-PHV participants outperformed their circa-PHV counterparts in 2022, this gap diminished in 2023, suggesting performance convergence with maturity. The combined model confirmed a strong age-related progression, with peak CMJJH at age 16 ($p < .001$), aligning with expected neuromuscular development stages. These findings support H1, H3, and H5, indicating maturation (both biological and chronological) as a critical factor in lower limb explosive power development.

Figure 7. CMJF (Pre vs. Post, by Age Group)

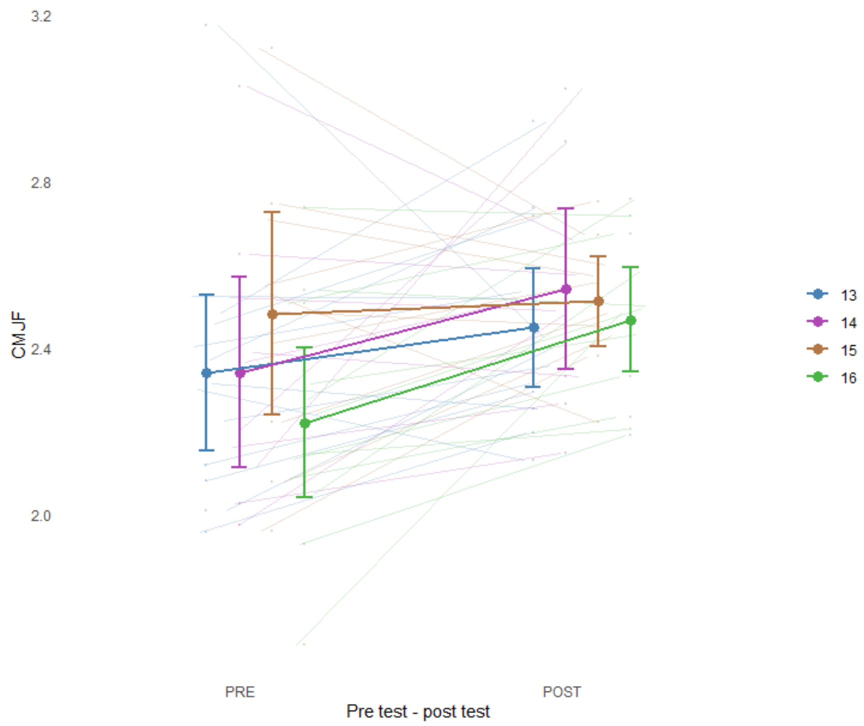


Figure 7 illustrates the mean change in Countermovement Jump Force (CMJF) from PRE to POST season for each age group (U13–U16). The individual participant lines reveal within-subject change, while the colored lines represent group means with standard error bars.

U13 and U14 groups showed a clear increase in CMJF from pre- to post-test, with U14 showing the most consistent improvement across individuals. U15 athletes demonstrated a plateau, with marginal change between time points, suggesting a possible stabilization of neuromuscular development in mid-adolescence. U16 athletes exhibited the largest increase in group mean, but with higher variability (wider error bars), indicating heterogeneity in training response or maturation timing. These trends are consistent with H1, H3, and H5, highlighting the influence of both age and maturation on lower-body strength adaptations across the season.

Figure 8. CMJFAF (Pre vs. Post, by Age Group)

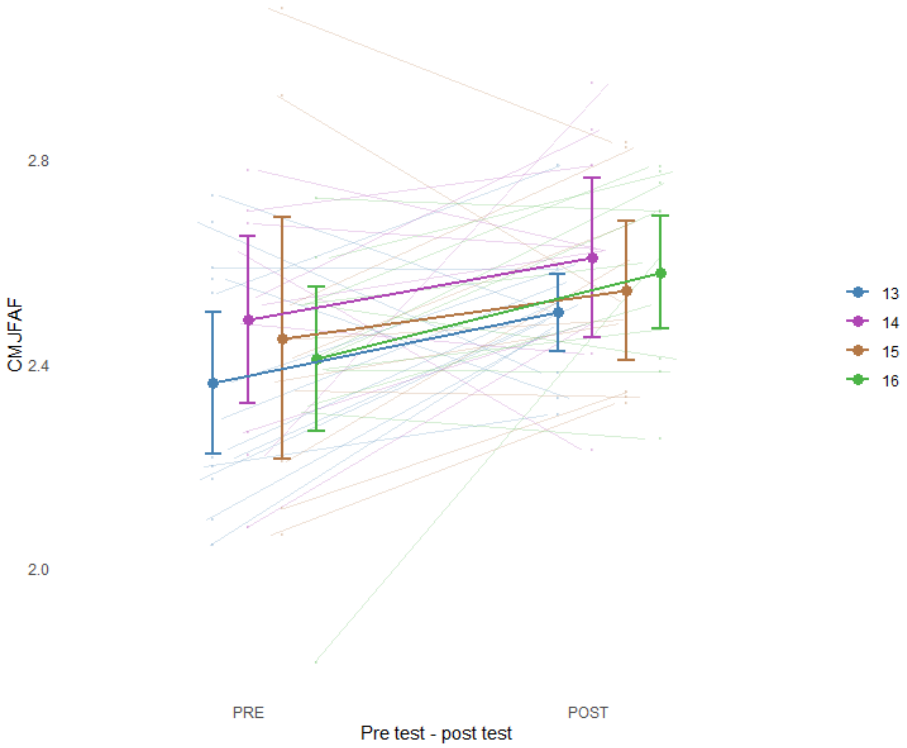


Figure 8 displays the seasonal change in CMJFAF performance across ages 13 to 16. Each line represents an individual athlete's progression, while the group means (colored lines) with standard errors indicate average trends.

All age groups show positive progression from pre- to post-test, with the steepest improvement in U16, suggesting enhanced flight time likely linked to strength and coordination development. U14 and U13 groups demonstrated steady gains with relatively tight error margins, indicating consistent adaptations across individuals. U15 athletes, although improving, showed less group-level change, possibly reflecting a transitional maturation phase or variability in training effect. The general upward trends support H1, H3, and especially H5, reinforcing the idea that during critical maturational windows, flight time and power-based jumping capacity improve with both biological and chronological development.

Figure 9. CMJFAJH (Pre vs. Post, by Age Group)

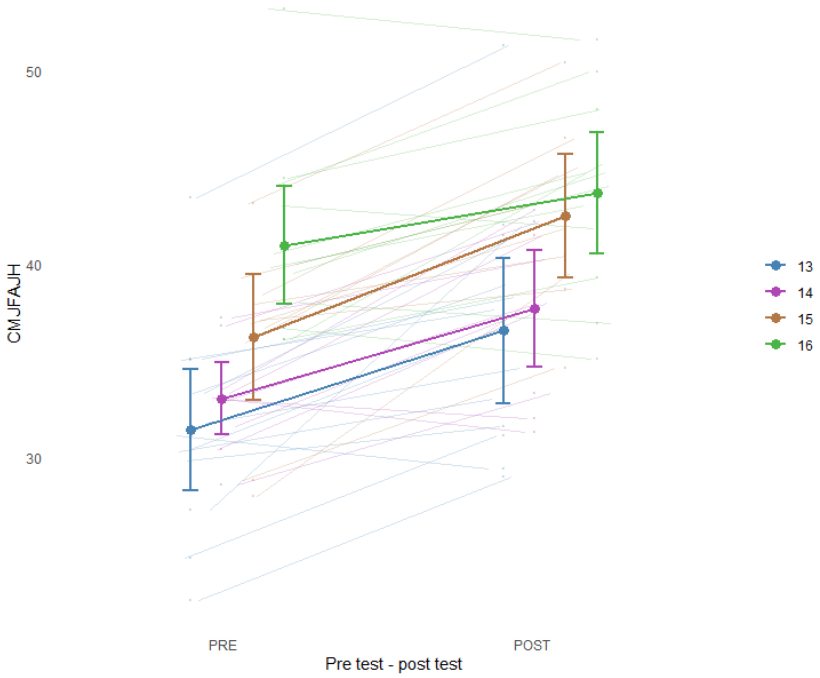


Figure 9 presents the change in CMJFAJH (jump height) performance from pre- to post-test by age group (U13–U16). Each line shows an individual player's progression, and group averages are depicted with error bars.

All age groups demonstrated clear and consistent improvements in jump height across the season. U15 and U16 groups reached the highest post-season values, approaching or exceeding 45 cm, reflecting the performance peak in later adolescence. U13 and U14 groups, while improving significantly, remained slightly behind, indicating the ongoing influence of neuromuscular development and maturity. Notably, inter-individual variability was higher in younger groups (longer error bars), while older groups were more consistent. These results strongly support H1, H3, and H5, showing that both chronological age and biological maturation significantly contribute to VJ height performance over time.

Figure 10. CMJJH (Pre vs. Post, by Age Group)

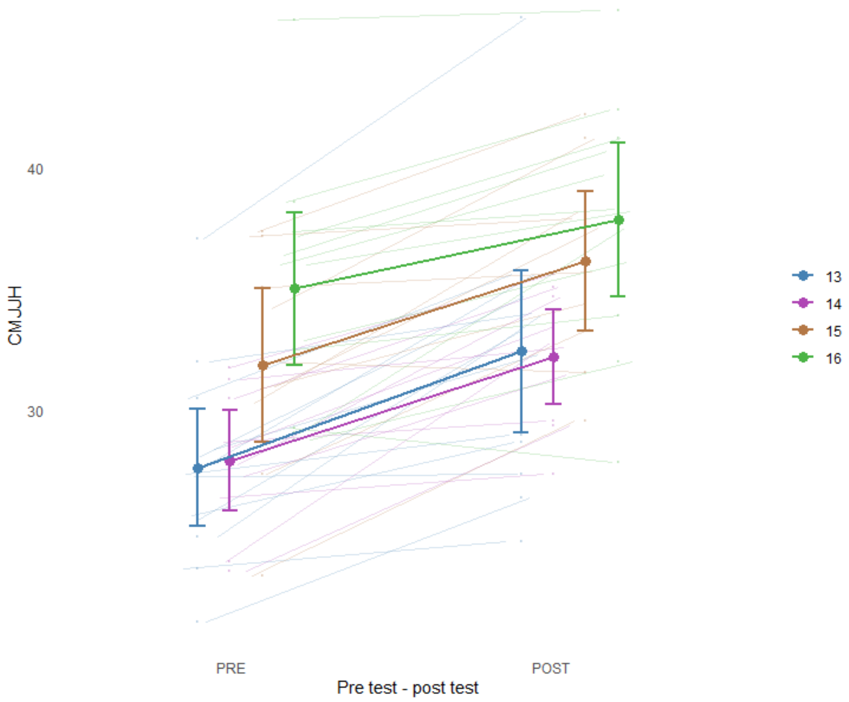


Figure 10 presents the evolution of CMJJH performance from pre- to post-season for U13–U16 players. Each line reflects an individual athlete's change, and colored lines represent group means with standard error.

All age groups showed significant improvements in jump height over the season. U16 players consistently outperformed younger groups and demonstrated the highest pre- and post-values, indicative of advanced neuromuscular maturity. U13 and U14 groups made the largest relative gains, suggesting high responsiveness to training or growth-induced neuromuscular adaptations. Error bars narrowed slightly post-test, particularly in older groups, indicating more consistent performance by season end. These patterns align with H1, H3, and H5, confirming that jump height is strongly influenced by both age and maturity, and reflects effective development during key adolescent phases.

Figure 11. SQJF (Pre vs. Post, by Age Group)

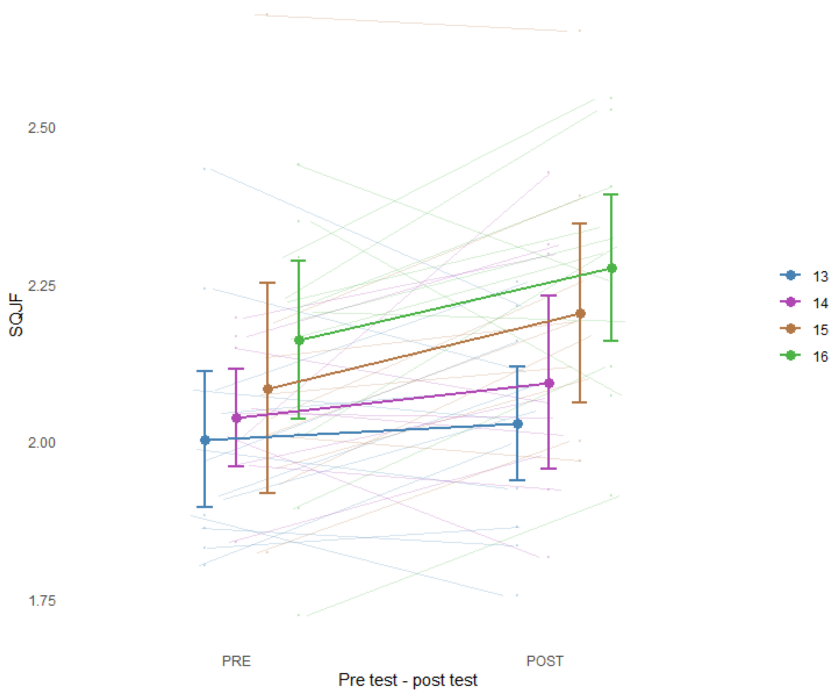


Figure 11 visualizes individual and mean changes in SQJF performance across the competitive season in youth players aged 13 to 16. Colored lines indicate group means with standard errors, while lighter lines represent individual trajectories.

All age groups showed increased jump force post-season, with U16 and U15 athletes displaying the most pronounced gains. U13 and U14 groups exhibited more modest improvements with wider variance, highlighting greater inter-individual variability in neuromuscular adaptation. The U16 group's consistent improvement suggests higher training responsiveness and physical maturity, which aligns with expected strength development patterns during late adolescence. These outcomes reinforce H1, H3, and H5, showing that both age and maturation positively influence improvements in squat-based power, though the magnitude of change differs by developmental stage.

Figure 12. SQJJH (Pre vs. Post, by Age Group)

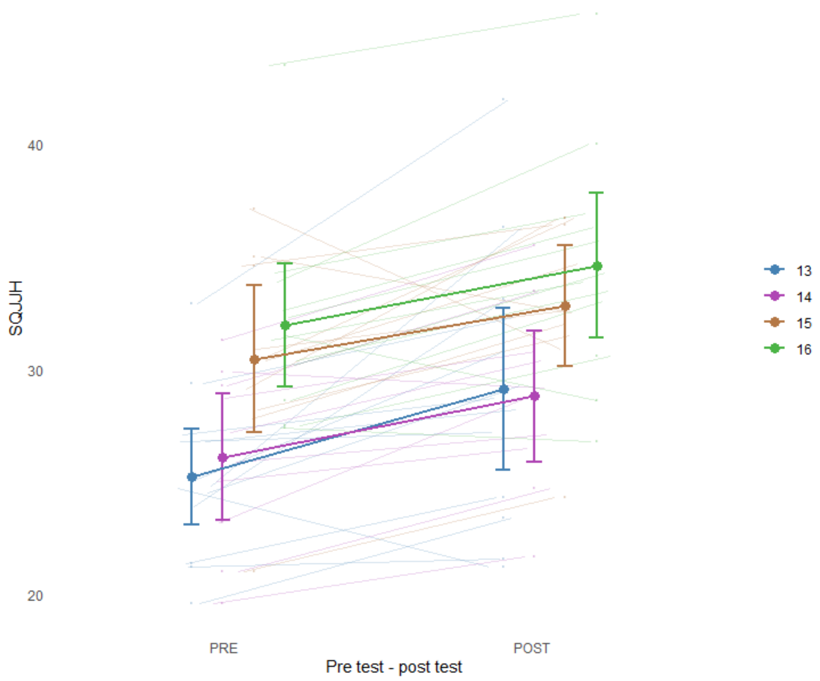


Figure 12 shows the change in Squat Jump Height (SQJJH) across the season for age groups 13–16. Colored lines represent the group means with error bars, while lighter lines reflect individual trajectories.

All age groups displayed clear performance gains from pre- to post-season, with the most substantial increases in U16, indicating greater height achieved during squat jumps. U13 and U14 groups improved moderately, showing more variability possibly due to uneven neuromuscular development or learning effects. U15 and U16 groups demonstrated higher baseline and greater post-test values, consistent with expected maturational strength benefits and improved power efficiency. This figure supports H1, H3, and H5, confirming that biological maturation and chronological age are positively associated with VJ height development especially in squat-dominant tasks.

7.3.2 Isokinetic Strength Performance Across Maturation

Hamstring and quadriceps strength improved significantly over time. Figure 13-17 show clear pre–post increases in H180 and Q180 across all age groups. U15 and U16 players exhibited the highest absolute force values, while U13 and U14 showed the greatest relative improvement. The estimated marginal means confirmed these findings (Table 26-30), supporting H1, H3, and H6. Figure 13 shows distribution plots of peak torque by muscle group and velocity (60°, 180°, 300°/s). Quadriceps consistently outperformed hamstrings across velocities and years, though the gap narrowed slightly in 2023, supporting H4 (improvement in H and Q strength with age). Strength correlations were high within years but weaker across years, as seen in Figures 13-17.

Table 26. Estimated Marginal Means H180 (Nm/kg)

2022 Results				
Age	**PHV Group**	**H180 (Mean ± SE)**	**95% CI**	***p* Value**
13	Circa	0.95 ± 0.15	[0.64, 1.25]	< .001
14	Circa	0.85 ± 0.08	[0.68, 1.01]	< .001
15	Circa	0.94 ± 0.06	[0.82, 1.06]	< .001
16	Circa	1.11 ± 0.07	[0.97, 1.25]	< .001
13	Post	0.84 ± 0.17	[0.50, 1.19]	< .001
2023 Results				
Age	**PHV Group**	**H180 (Mean ± SE)**	**95% CI**	***p* Value**
13	Circa	2.93 ± 0.13	[2.67, 3.18]	< .001
14	Circa	2.86 ± 0.13	[2.60, 3.13]	< .001
15	Circa	3.22 ± 0.14	[2.94, 3.50]	< .001
16	Circa	3.08 ± 0.18	[2.71, 3.44]	< .001
13	Post	2.70 ± 0.24	[2.22, 3.18]	< .001

Combined Results			
Age	**H180 (Mean ± SE)**	**95% CI**	***p* Value**
13	2.59 ± 0.10	[2.39, 2.78]	< .001
14	2.54 ± 0.11	[2.32, 2.77]	< .001
15	2.85 ± 0.11	[2.62, 3.07]	< .001
16	2.88 ± 0.10	[2.68, 3.09]	< .001

H180 strength showed a significant age-related progression across all datasets ($p < .001$).

In 2022, strength values were markedly lower than in 2023, likely reflecting technical limitations or lower absolute force outputs at younger biological stages. In 2023, there was a strong jump in H180 values across all ages, particularly in age 15, aligning with PHV-linked neuromuscular gains. Post-PHV participants at age 13 had slightly lower strength than their circa-PHV peers, suggesting that technical adaptation may temporarily lag behind structural maturation. The combined results confirm a consistent upward trend from ages 13 to 16, strongly supporting H1, H3, H4, and H6. These findings highlight the role of maturation in improving hamstring strength at medium speed (180°/s), contributing to performance enhancement and potential injury risk reduction.

Table 27. Q180 Strength by Age & PHV 2022 vs. 2023

Age	PHV Status	2022 EMM ± SE (CI)	2023 EMM ± SE (CI)	Δ Change
13	Circa	1.32 ± 0.13 [1.07–1.58]	4.26 ± 0.18 [3.89–4.63]	↑ +2.94
14	Circa	1.34 ± 0.07 [1.19–1.48]	4.65 ± 0.19 [4.27–5.04]	↑ +3.31
15	Circa	1.43 ± 0.05 [1.33–1.54]	5.00 ± 0.20 [4.59–5.41]	↑ +3.57
16	Circa	1.59 ± 0.06 [1.47–1.71]	4.88 ± 0.26 [4.35–5.42]	↑ +3.29
13	Post	1.26 ± 0.14 [0.97–1.55]	3.69 ± 0.35 [2.99–4.39]	↑ +2.43

Table ?: Estimated Marginal Means (EMM) of Q180 (Nm/kg) by Age and PHV Category

Table 27 shows dramatic increases in quadriceps strength at 180°/s across all age groups from 2022 to 2023. Circa-PHV athletes improved by +2.9 to +3.6 Nm/kg, depending on age group. Post-PHV U13 players also demonstrated substantial strength gains (+2.43 Nm/kg), although their performance remained slightly below that of their circa peers at older ages. These changes strongly support Hypotheses H1, H3, H5, and H6, highlighting that quadriceps strength at high velocity increases significantly with age, maturation, and training exposure.

Table 28 Bonus: Overall Q180

Age Group	**Q180 (EMM ± SE)**	**95% CI (Nm/kg)**	***p*-value**
13	3.90 ± 0.14	[3.61–4.19]	< .001
14	4.21 ± 0.16	[3.88–4.54]	< .001
15	4.52 ± 0.16	[4.19–4.85]	< .001
16	4.61 ± 0.15	[4.30–4.91]	< .001

**Collapsed by PHV.*

In Table 29. the regression summary of H180 models below shows, No significant predictors were identified in the individual models for 2022 or 2023. However, in the combined model, PHV_post (β = 0.30, p = .040) and AG14 (β = 0.34, p < .001) significantly predicted H180 strength.

Table 29. Regression Summary H180 Models

H180 2022

Predictor	Coef.	SE	*t*	*p*	95% CI	Sig
Intercept	0.946	0.149	6.35	<.001	[0.66, 1.25]	✓
AG14	–0.100	0.125	–0.80	0.429	[–0.37, 0.13]	✕
AG15	–0.003	0.160	–0.02	0.986	[–0.33, 0.31]	✕
AG16	0.168	0.164	1.02	0.313	[–0.17, 0.48]	✕
PHV_post	–0.103	0.082	–1.26	0.214	[–0.27, 0.06]	✕

H180 2023

Predictor	Coef.	SE	*t*	*p*	95% CI	Sig
Intercept	2.927	0.126	23.31	<.001	[2.67, 3.18]	✓
AG14	–0.063	0.182	–0.34	0.732	[–0.43, 0.31]	✕
AG15	0.294	0.186	1.58	0.123	[–0.08, 0.67]	✕
AG16	0.153	0.220	0.70	0.491	[–0.29, 0.60]	✕
PHV_post	–0.230	0.202	–1.14	0.261	[–0.64, 0.18]	✕

H180 Combined

Predictor	Coef.	SE	*t*	*p*	95% CI	Sig
Intercept	2.586	0.097	26.55	<.001	[2.40, 2.77]	✓
AG14	0.344	0.060	5.76	<.001	[0.23, 0.46]	✓
AG15	–0.043	0.148	–0.29	0.774	[–0.33, 0.24]	✕
AG16	0.262	0.148	1.77	0.083	[–0.02, 0.54]	✕
PHV_post	0.298	0.141	2.12	0.040	[0.03, 0.57]	✓

These findings suggest that biological maturation and the developmental stage around age 14 are associated with increased hamstring strength at 180°/s, supporting H1, H4, and partially H5. The lack of consistent significance across years may reflect inter-annual variability in training load, cohort characteristics, or sensitivity of this strength parameter.

Table 30. Regression Summary Q180 Models

Q180 2022						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	1.323	0.126	10.54	<.001	[1.08, 1.58]	✓
AG14	0.015	0.103	0.14	0.888	[–0.20, 0.21]	✕
AG15	0.111	0.136	0.82	0.418	[–0.16, 0.38]	✕
AG16	0.267	0.140	1.91	0.063	[–0.01, 0.54]	○
PHV_post	–0.061	0.071	–0.85	0.399	[–0.20, 0.08]	✕
Q180 2023						
Predictor	**Coef.**	**SE**	***t***	***p***	**95% CI**	**Sig**
Intercept	4.263	0.183	23.26	<.001	[3.89, 4.63]	✓
AG14	0.391	0.266	1.47	0.148	[–0.15, 0.93]	✕
AG15	0.736	0.272	2.71	0.010	[0.19, 1.29]	✓
AG16	0.620	0.321	1.93	0.060	[–0.03, 1.27]	○
PHV_post	–0.572	0.294	–1.94	0.059	[–1.17, 0.02]	○

Q180 Combined

Predictor	Coef.	SE	*t*	*p*	95% CI	Sig
Intercept	3.897	0.144	27.06	<.001	[3.62, 4.17]	✓
AG14	0.321	0.090	3.56	0.001	[0.14, 0.50]	✓
AG15	0.312	0.218	1.43	0.161	[–0.11, 0.73]	✗
AG16	0.621	0.218	2.84	0.007	[0.20, 1.04]	✓
PHV_post	0.709	0.208	3.41	0.001	[0.31, 1.11]	✓

In the combined model, AG14, AG16, and PHV_post were statistically significant predictors of Q180 strength: AG14 (β = 0.32, p = .001), AG16 (β = 0.62, p = .007), PHV_post (β = 0.71, p = .001).

In 2022, none of the predictors were statistically significant, although AG16 approached significance (p = .063).In 2023, AG15 was a significant positive predictor (β = 0.74, p = .010), while PHV_post trended toward significance (p = .059). These results strongly support H1, H3, H4, and H6, showing that both chronological age and biological maturation are robust predictors of quadriceps strength at 180°/s.

Figure 13. Isokinetic Strength Hamstrings vs. Quadriceps 2022 & 2023

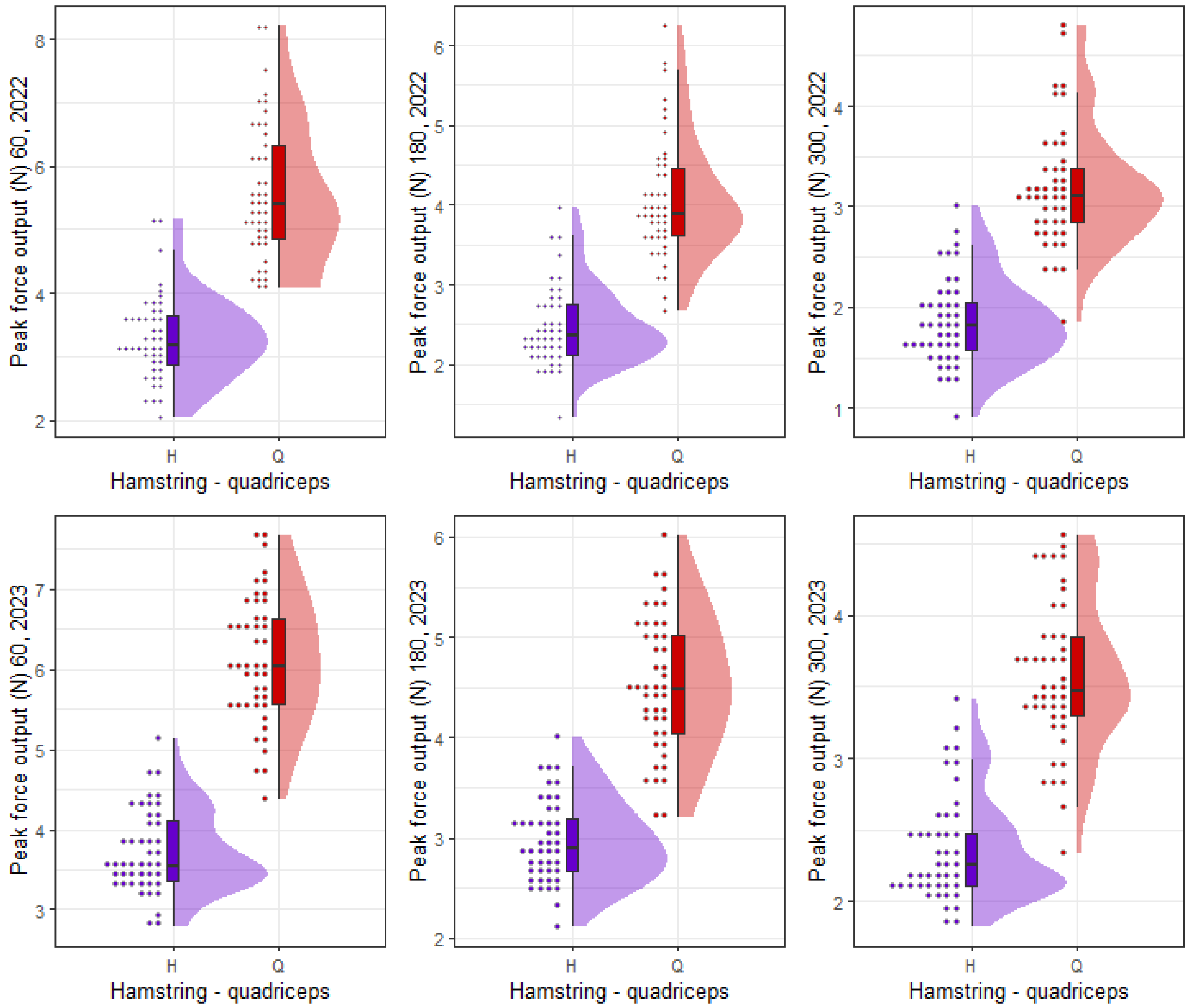
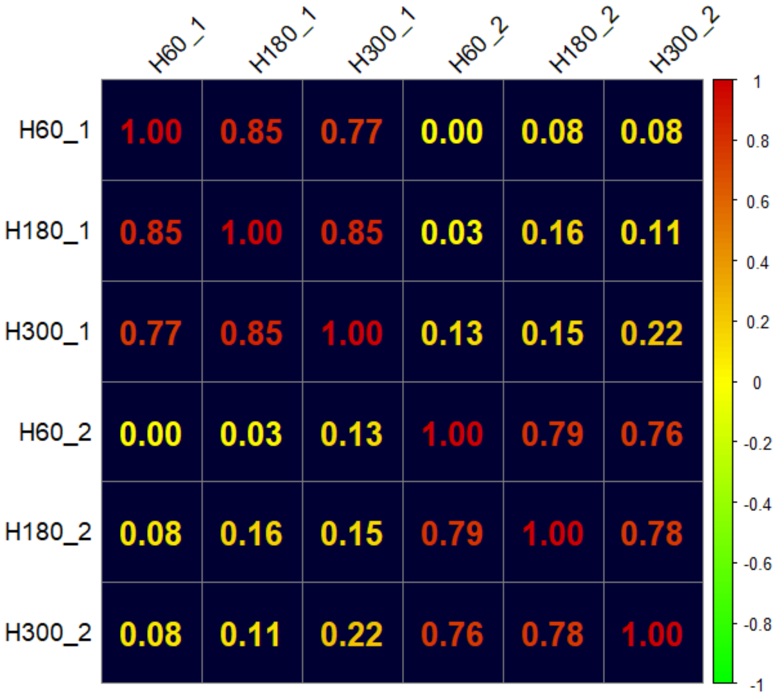


Figure 13 displays peak force outputs for hamstrings (H) and quadriceps (Q) across three angular velocities: 60°/s, 180°/s, and 300°/s for the years 2022 (top row) and 2023 (bottom row). Violin plots show distribution density, boxplots indicate medians and interquartile ranges, and dot overlays show individual data points.

At all three velocities, quadriceps consistently produced higher force output than hamstrings, which is biomechanically expected due to greater muscle mass and leverage advantages. Between 2022 and 2023, there is a noticeable upward shift in both H and Q strength distributions most prominent at 60°/s and 180°/s reflecting overall neuromuscular development. Hamstring force improved more proportionally in 2023 than in 2022, slightly narrowing the H–Q gap, especially at 300°/s, indicating enhanced eccentric strength development, which may aid in injury prevention. The distributions are less skewed and more concentrated in 2023, suggesting improved inter-individual consistency likely due to maturational alignment and progressive training exposure. These results support H4, H5, and

H6, showing that: H and Q strength balance improves with maturation. Low- and mid-speed isokinetic strength capacities increase with age. Training through the adolescent growth phase leads to more uniform and elevated muscular output.

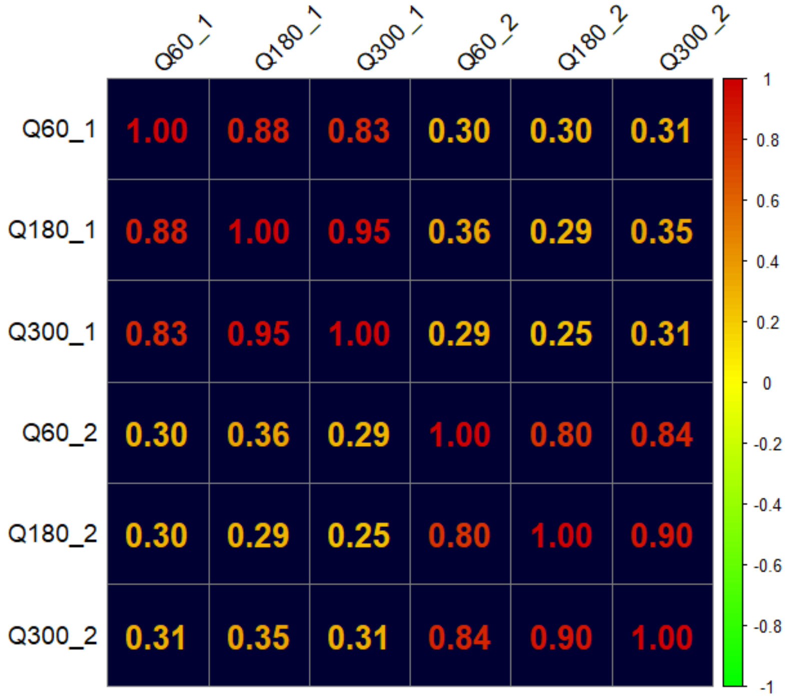
Figure 14. Hamstring Strength Correlations 2022–2023



This matrix depicts correlations between hamstring strength outputs at 60°/s, 180°/s, and 300°/s for 2022 and 2023. Within-year correlations (top-left and bottom-right blocks) are very strong: H60_1 and H180_1: r = 0.85. H180_1 and H300_1: r = 0.85, H60_2 and H180_2: r = 0.79 H180_2 and H300_2: r = 0.78.

Cross-year correlations are weak to negligible ($r < 0.22$), suggesting inter-season variability in hamstring performance at the individual level likely reflecting training effects, maturation, or testing sensitivity. These results support H6, highlighting internal consistency within testing sessions, and point to potential developmental shifts that affect between-season continuity.

Figure 15. Quadriceps Strength Correlations 2022–2023



This heat-map shows quadriceps strength interrelationships under the same conditions. Within-year correlations were very strong again: Q180_1 and Q300_1: r = 0.95, Q60_1 and Q180_1: r = 0.88, Q180_2 and Q300_2: r = 0.90.

Cross-year correlations, although slightly stronger than in hamstrings, remained modest (e.g., Q60_1 with Q60_2: $r = 0.30$), again reinforcing potential seasonal variability in output due to growth, adaptation, or technical factors. This further supports H7, confirming that high-velocity strength (Q180/Q300) shows strong internal consistency and predictive power within a single testing session.

In summary, within-session reliability is strong for both hamstrings and quadriceps at all speeds. Between-season consistency is limited, reinforcing the dynamic nature of strength adaptation during youth development. These patterns validate the importance of frequent re-assessment and the need to interpret raw strength measures in the context of maturational timing and training history.

Figure 16. H180 Hamstring Strength at 180°/s

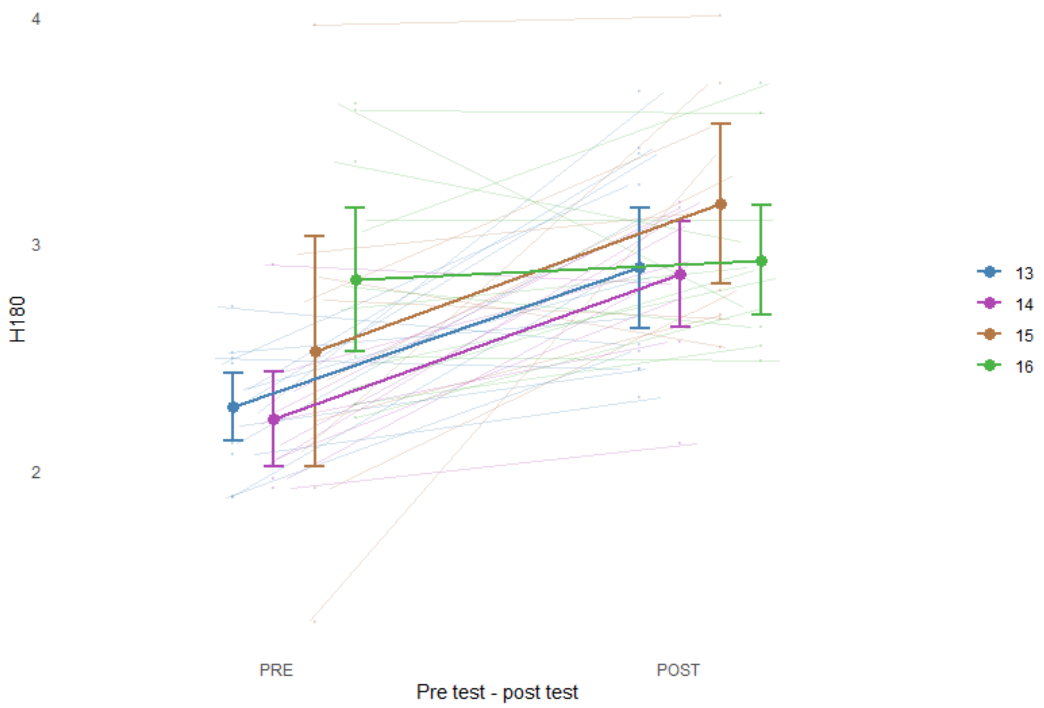


Figure 16 shows improvements in hamstring strength across U13–U16 players from pre- to post-season. Each colored line with error bars represents group means and standard deviations, while the background lines trace individual changes.

All age groups demonstrated clear strength gains, particularly in U13 to U15. U15 athletes showed the largest increase, indicating a key maturational window for strength adaptation. U16 started higher and plateaued, likely due to approaching neuromuscular maturity. These findings align with H4 and H6, suggesting that hamstring strength improves significantly during adolescence, particularly before peak maturity.

Figure 17. Q180 Quadriceps Strength at 180°/s

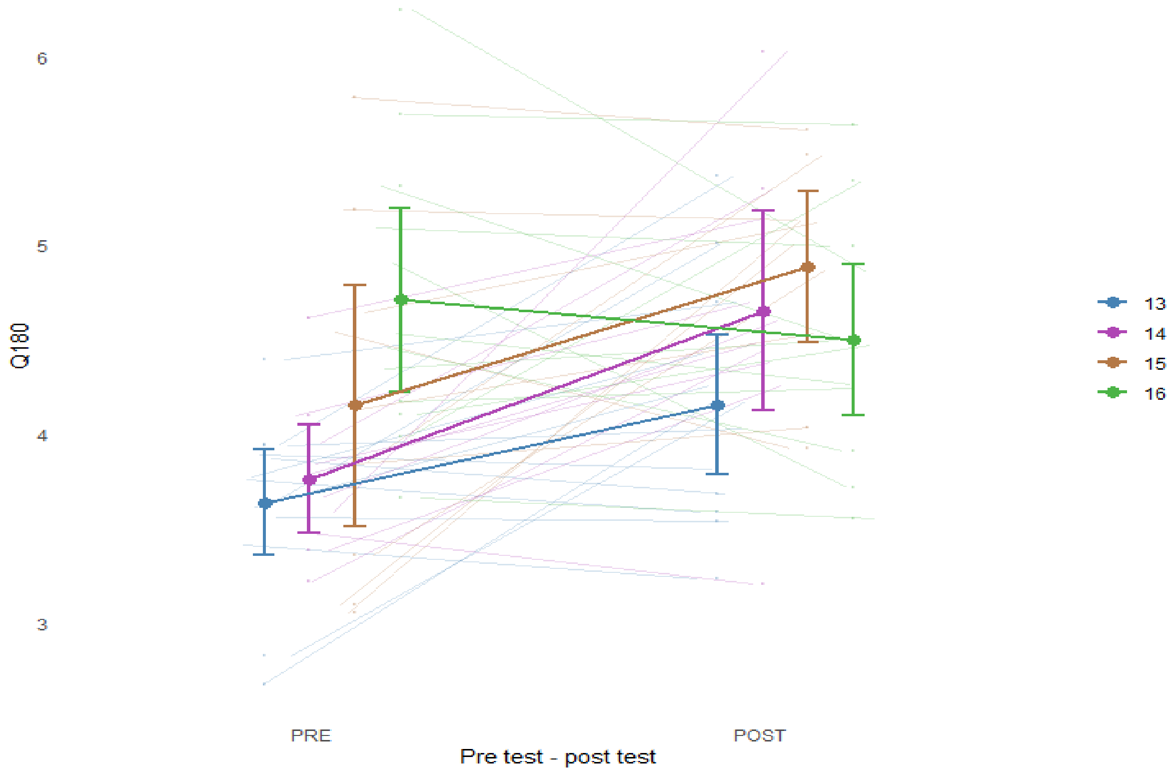


Figure 17 represents quadriceps strength development at the same angular velocity.

All age groups improved, but U15 and U14 displayed the steepest gains. U16 began with the highest values but showed a slight decline or stabilization post-season, potentially due to training saturation or variation in effort/testing conditions. The consistent upward trends in younger groups support H1, H3, and H7, confirming that quadriceps strength increases strongly during maturation, especially at mid-velocity contractions.

Together, these plots suggest that Q180 strength improvements track closely with biological development and can serve as a strong indicator of lower-limb power potential during growth phases.

7.4 Functional movement and Maturation Results

Figure 18 illustrates FMS scores by age group from pre- to post-test. All age groups improved over the season, with the largest gains observed in U13 and U14. However, older athletes (U15–U16) showed less change, suggesting a plateau effect. The statistical model revealed a small but significant effect of biological age (β = 1.65, $p = 0.020$), supporting H2. However, correlations between FMS and performance outcomes were low (r = 0.10–0.32), confirming its limited predictive validity.

Table 31. Estimated Marginal Means FMS Score by Age

Age	FMS Score (Mean ± SE)	95% CI	p Value
13	17.27 ± 0.47	[16.32, 18.22]	< .001
14	18.15 ± 0.54	[17.06, 19.24]	< .001
15	17.95 ± 0.54	[16.86, 19.04]	< .001
16	18.92 ± 0.49	[17.92, 19.91]	< .001

FMS scores showed a modest upward trend with age. The largest and statistically significant improvement occurred from age 13 to 14 (β = 0.83, p = 0.001), with scores plateauing thereafter.

BA (AG) variable had a significant effect on FMS ($\beta = 1.65$, $p = 0.020$), suggesting that more biologically mature players tended to perform better on movement screens. These results support H2 and partially H5: FMS scores improve modestly over time and show limited but statistically relevant association with biological maturity, though not strong enough to serve as a robust predictor of explosive strength or jump performance.

Figure 18. FMS Score (Pre vs. Post, by Age Group)

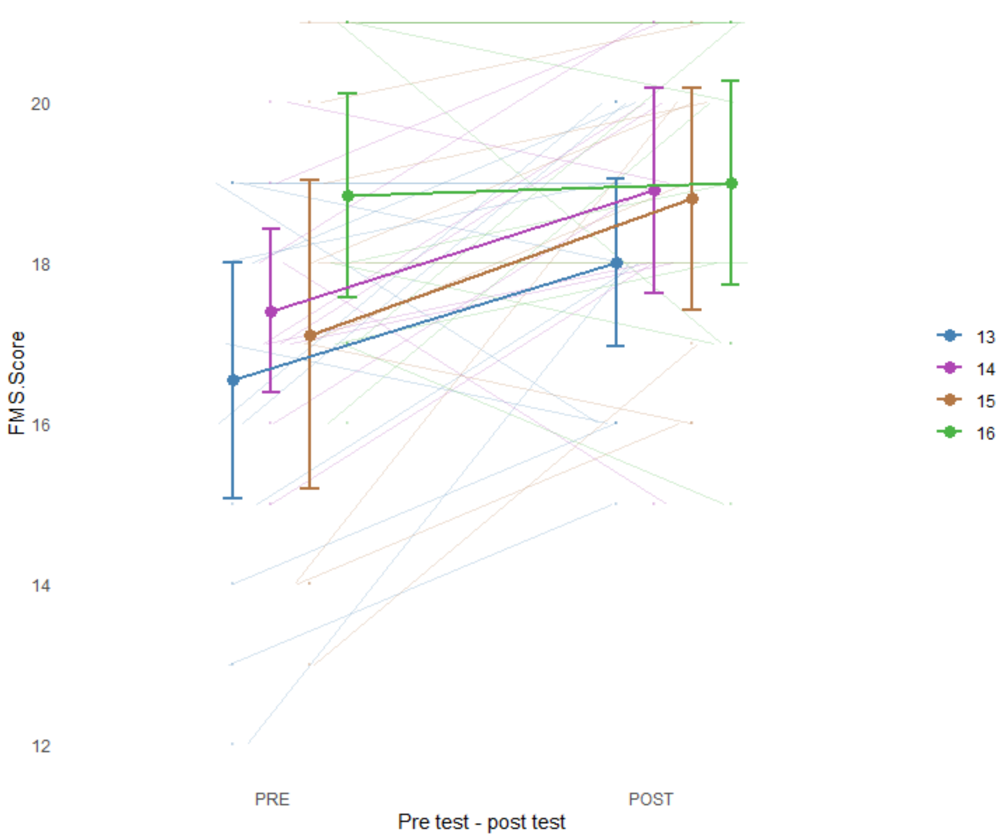


Figure 18 presents the pre- and post-season FMS scores for athletes aged 13–16. The group mean scores are depicted with colored lines and error bars, and individual trajectories are shown with faint background lines.

All age groups exhibited positive changes in FMS scores, indicating improved movement quality and motor control across the season. The most notable gains were seen in U13 and U14 groups, who started with lower scores and showed consistent improvements, suggesting higher trainability in younger athletes. U15 and U16 players maintained relatively higher baseline scores, and while they also improved, the magnitude of change was smaller indicating possible plateauing as athletes' approach maturity. Error bars narrowed at post-test, particularly in older groups, suggesting greater movement consistency and reduced variability following training exposure.

These findings support H2 and partially H5, showing: Functional movement improves with age and training. However, the predictive value of FMS for performance is likely limited, as improvements plateau and vary by age and maturity status.

Overall, table 32 presents a linear model assessing performance across age groups (13–16), using Age 13 as the reference. The intercept shows that 13-year-olds have an average performance score of 17.27, which is highly significant ($p < .001$) with a tight confidence interval [16.37, 18.17], indicating a reliable baseline. Compared to this, Age 14 shows a statistically significant increase of +0.83 ($p = 0.001$), suggesting a meaningful improvement in performance. In contrast, Age 15 (+0.88, $p = 0.226$) and Age 16 (+0.68, $p = 0.348$) show numerical increases, but these are not statistically significant, with confidence intervals that include zero. The overall age group (AG) effect is significant (+1.65, $p = 0.020$), confirming that age contributes meaningfully to performance differences when considered across the full range of groups. Estimated marginal means suggest performance gradually improves with age, peaking slightly at Age 16 (18.92 ± 0.49), though individual variability may mask significant differences in the older groups. These findings highlight a key developmental gain between ages 13 and 14, followed by a plateau in later adolescence.

Table 32. Linear Model Estimating Performance Across Age Groups (13–16 Years)

Term	Coefficient	SE	*t*	*p*	95% CI
Intercept (Age 13)	17.27	0.47	36.55	< .001	[16.37, 18.17]
Age 14 (vs. 13)	+0.83	0.24	3.51	0.001	[0.36, 1.30]
Age 15 (vs. 13)	+0.88	0.72	1.23	0.226	[-0.49, 2.25]
Age 16 (vs. 13)	+0.68	0.72	0.95	0.348	[-0.69, 2.05]
AG effect (overall)	+1.65	0.68	2.42	0.020	[0.34, 2.95]

This table presents the results of a linear regression model evaluating the effect of chronological age on a physical performance outcome (e.g., jump height or strength). Age 13 serves as the reference category. Coefficients represent the estimated difference in performance relative to Age 13. The "AG effect" reflects the overall impact of age group on performance. Statistically significant results ($p < 0.05$) are interpreted as meaningful differences between age groups. The estimated marginal means suggest a consistent performance across age groups, with a slight peak at age 16 (18.92 ± 0.49).

8 Discussion

The findings of this study confirm the significant influence of maturation status operationalized as peak height velocity (PHV) on strength and jump outcomes, while offering nuanced insight into the developmental trajectory of movement competency. One of he most important finding was that PHV emerged as a strong predictor of both JH, PTKF and PTKE values across chronological and biological groups. This aligns with the notion that hormonal changes and muscle development associated with PHV play a crucial role in enhancing physical capabilities (Malina et al., 2004).

The longitudinal data revealed that players experienced significant improvements in LBS and jump performance across the two seasons. These improvements coincided with maturation progress, as indicated by a substantial shift in PHV offset from an average of –0.1 in 2022 to +1.1 in 2023. The positive trends in physical performance metrics suggest that as players transitioned through their growth spurts, they gained greater neuromuscular capacity.

FMS results also improved slightly but plateaued around high average values (~18.7 in 2022 and ~18.6 in 2023), suggesting that movement proficiency was consistently well-maintained. The lack of a strong correlation between FMS and performance metrics such as JH implies that while FMS is crucial for injury prevention and movement quality, it may not directly predict explosive athletic performance. This aligns with prior research which emphasizes the role of strength and neuromuscular coordination in determining jump output, rather than purely movement patterns.

PHV emerged as a significant predictor of strength and jump performance. Regression analyses showed that players closer to or past their PHV demonstrated superior performance, particularly in explosive metrics like countermovement jump (CMJ) and squat jump height. These findings are consistent with established growth and development models, which propose that neuromuscular adaptations accelerate following the adolescent growth spurt. Furthermore, younger players (Pre- and Circa-PHV) exhibited larger year-over-year gains compared to their older (Post-PHV) counterparts, confirming the concept of "sensitive periods" for strength and power development during adolescence.

Importantly, maturation was not a strong predictor of FMS changes, indicating that movement quality can be preserved or enhanced regardless of maturity status, provided that training is targeted and progressive. This suggests that coaches and practitioners should focus on maintaining high-quality movement mechanics throughout all stages of development.

One of the key observations from the study was the consistent improvement in the H AND Q PT results, especially from 2022 to 2023. These results are a known indicator of muscular balance and injury risk, particularly for the ACL. The data showed that younger players (U13–U14) began with lower PT, placing them at higher risk for muscular weakness, but by U15–U16 these results had improved significantly.

This supports the implementation of targeted strength programs emphasizing posterior chain development such as Nordic hamstring curls and eccentric hamstring exercises during early adolescence. As players mature, the balance between muscle groups becomes increasingly critical, not only for performance but also for reducing injury risk. These findings have direct applications in the design of youth soccer training programs. The clear progression in strength and power with maturation supports the use of bio-banding (grouping players by BA) as a tool for tailoring physical development training. Training should prioritize mobility and neuromuscular coordination in the pre-PHV stage, transition into strength and power emphasis during the PHV window and then focus on maximal strength and technical refinement post-PHV.

FMS assessments, while not strongly predictive of jump performance, remain valuable tools for monitoring mobility restrictions and identifying compensatory patterns that could predispose players to injury. Maintaining a high FMS score throughout adolescence should remain a key objective. Moreover, maturation monitoring (using PHV and maturity offset calculations) allows coaches to identify players undergoing rapid growth and adjust their workloads accordingly. During PHV, coordination often temporarily declines due to rapid limb length changes and muscle-tendon imbalances, which necessitates a temporary reduction in load and increased focus on movement control.

The results of this study align with previous literature indicating that BM significantly influences physical performance in youth athletes. Studies by Malina et al. (2004) and Philippaerts et al. (2006) have similarly reported that PHV correlates with increased strength and power output. The lack of direct linkage between FMS and performance also echoes findings by Pichardo et al. (2019), who emphasized that functional screening is more relevant for movement quality and injury risk than performance prediction.

Our study extends this knowledge by providing longitudinal evidence over two seasons and integrating detailed strength metrics (e.g., isokinetic torque at various angular velocities) with growth monitoring. Additionally, the data visualizations generated during this study offer intuitive insights into developmental trends and support practical decision-making for coaching staff.

8.1 Impact of PHV and Maturation on Athletic Performance

BM, as indicated by PHV, had a clear and significant impact on strength and power development in this cohort. Players at or beyond PHV outperformed their pre-PHV peers in all lower-body strength and VJ measures (H3, H6, H7), confirming the hypothesis that maturation accelerates neuromuscular adaptations. This reflects underlying hormonal, morphological, and neuromuscular transformations that peak during adolescence (Malina et al., 2004; Philippaerts et al., 2006). Coaches must consider maturity status, not just age, when assessing performance or assigning training loads.

The findings support using BA (PHV) to guide training intensity and recovery. Movement screens (FMS), while not predictive, can flag mobility/stability deficits. Coaches should expect strength and jump performance spikes near PHV, allowing targeted neuromuscular loading. Additionally, PTKF and PTKE trends suggest reduced injury risk in post-PHV athletes (H4), informing return-to-play or preseason screens. Test–retest ICCs revealed excellent reliability for anthropometrics and PHV (ICC $\geq$ 0.92), and moderate reliability for FMS (ICC = 0.59). However, cross-year correlations in strength outputs were modest (r = 0.20–0.35), highlighting the dynamic, non-linear progression typical of adolescent athletes (Meylan et al., 2014). This supports H5 that substantial changes occur during PHV transitions and cannot be reliably forecasted using previous-year data alone.

The neuroendocrine alterations associated with puberty trigger changes in muscle composition and neuromuscular efficiency. Research shows that the timing of PHV correlates with developmental growth spurts, which directly influence strength and power adaptations. For instance, boys who are pre-PHV often exhibit greater improvements in strength and power output from plyometric training compared to their post-PHV counterparts, as noted by Lloyd et al. (Lloyd et al., 2016). This phenomenon suggests that earlier maturation stages may witness more significant neuromuscular plasticity, likely facilitated by an increase in anabolic hormones such as testosterone during this growth phase (Rumpf et al., 2012). Holmgren et al. support the assertion that the onset of PHV coincides with a period of metabolic and muscular transformation that influences athletic performance (Holmgren et al., 2017). These adaptations facilitate enhanced motor unit recruitment and increased muscle fiber cross-sectional area, which are essential for improving performance metrics in sports that require explosive strength and agility. Therefore, coaching interventions that target neuromuscular training during this critical growth period could capitalize on the heightened plasticity for optimal athletic development. The inter-individual variability in response to training around PHV highlights the necessity for age-specific conditioning strategies. Sluis et al. emphasize that maturity-related differences can influence an athlete's readiness for high-intensity training, leading to variations in injury susceptibility (Sluis et al., 2013). Talented players selected based on chronological age often face challenges as their biological maturity varies, which can affect their overall training responsiveness and injury rates during the growth spurt. Thus, understanding the timing of PHV is vital in tailoring training regimens to align with each athlete's maturity status. Furthermore, both the timing and magnitude of PHV impact how training modalities, like strength training and plyometrics, can be most effectively implemented. Furdock et al. advocate for the evaluation of skeletal maturity and its correlations with training outcomes, suggesting that effective programming should consider an athlete's stage in relation to PHV to enhance responsiveness to interventions (Furdock et al., 2022). This consideration is particularly significant during the competitive season when training loads can substantially increase, stressing the importance of individualized preparations based on maturation levels. Given the crucial role of PHV in shaping an athlete's neuromuscular adaptations, it becomes imperative for coaches to monitor growth patterns alongside physical training. The data emphasize the need for age-appropriate training programs that align with maturation phases, allowing for maximal adaptation during periods of rapid growth (Lloyd et al., 2016; Moran et al., 2017). For instance, monitoring hormonal changes during adolescence can serve as a guide for adjusting training intensity and volume to match their physiological capabilities and optimize performance outcomes.

As it is in the figures, they show tight inter-relationships among jump metrics and between jump and strength variables within seasons, confirming internal consistency. However, between-year correlations dropped, emphasizing that athletic development is influenced not only by BM but also by external factors such as training load, recovery, motivation, and growth variability.

The results further echo longitudinal data by Philippaerts et al. (2006), who demonstrated that performance in anaerobic tasks aligns more closely with BA than CA during adolescence. Our findings reaffirm this, particularly as U15 and U16 athletes, who were predominantly post-PHV, exhibited the highest force and jump values (Figures 3-17).

The data demonstrated that athletes in the post-PHV phase generally outperformed pre- and circa-PHV individuals, indicating that the period immediately following PHV is a critical window for performance development. However, results in peak power during jumping may indicate the influence of technical experience in specific jump patterns, considering the chronological age groups (Bazanov et al., 2019). However, it should be acknowledged that aside from the potential anabolic milieu associated with post-PHV, it is essential for pre-pubertal children to actively engage in youth physical development programs to maximize performance, reduce the likelihood of injury, and maintain general health and well-being (Lloyd & Oliver, 2012). BM refers to the progress towards a mature state, and the literature suggests that there exist significant inter-individual differences in the magnitude, onset, and rate of change of various biological components because of maturational processes when children are grouped according to relative age (Malina et al., 2004). The timing of PHV emerged as a significant determinant for isokinetic strength velocities and several JH outcomes. Specifically, when evaluating BM across different PHV groups, the only notable difference in peak power occurred between the older (post-PHV) and younger (pre and circa-PHV) groups in SJ. The differences in results could partly stem from varying levels of targeted training and conditioning among the age groups. It is essential to consider individual differences within each age group, accounting for player positions, growth rates, and anthropometric characteristics (Mala et al., 2023). Despite these differences in potential stages of BM, all team members undergo the same training (club philosophy and methodology of development across the age groups) and compete in the same categories based on their BM together with chronological age (Deprez et al., 2013; Lloyd & Oliver, 2012; Lloyd et al., 2015; Meylan et al., 2014; Mirwald et al., 2002; Murtagh et al., 2018). By understanding an individual's age-related factors, researchers and clinicians can gain insights into their physical development, enabling more informed decisions regarding health and performance. Consequently, future research should aim for more homogeneous group categorizations to better understand the influence of chronological and biological maturation on soccer performance.

This study highlights that age-related physical performance, when viewed through the lens of BM, can guide safer training periodization and create more balanced competitive groups in soccer. Grouping players by maturation stage increases competition within homogenous groups, encouraging players to improve and match their more advanced peers, similar to match conditions. This approach is particularly effective in controlled settings focused on developing physical attributes like strength, running technique, and motor skills, rather than skill and game development. To effectively apply the study's findings, practitioners should adopt a tiered group training approach aligned with players' BM stages, especially in physical development training. Recognizing the common challenge of limited staff, players could be organized into broad groups (e.g., pre-PHV, circa-PHV, post-PHV) to tailor sessions to their developmental needs. For instance, younger players would focus on foundational strength and technique, while older players would engage in advanced, high-intensity exercises.

8.2 Interpretation of Lower Body Strength

Isokinetic strength (particularly at 180°/s) showed significant gains post-PHV, consistent with H1 and H6. Although all players trained similarly, BM provided a critical underlying driver. This suggests that improvements were not purely due to training but largely influenced by developmental processes like muscle hypertrophy and increased motor unit recruitment. Therefore, when interpreting strength data, practitioners must adjust expectations based on individual maturity timing, not training volume alone (Lloyd et al., 2014).

Athletes reaching or transitioning through PHV showed significant gains in jump height and isokinetic strength, consistent with H1 and H3. Maturation was a strong driver of neuromuscular capability, with PHV correlating positively with CMJ, SQJ, and PTKF and PTKE results ($r = 0.55–0.75$). This reinforces the concept of "maturation-driven windows of opportunity" for performance development (Lloyd & Oliver, 2012). The observed associations between BM and LBS strongly support Hypotheses 1 and 6. PHV was moderately to strongly correlated with isokinetic strength at all velocities, particularly for quadriceps at 180°/s and 300°/s (r = 0.64–0.84), and with jump metrics like CMJFAJH and SQJJH (r = 0.63–0.78). These findings align with prior reports that muscle mass accrual and neuromuscular coordination increase significantly around the period of peak growth (Lloyd et al., 2014; Malina et al., 2015).

Significant between-group differences in isokinetic strength (H180, Q180) were found, with post-PHV athletes showing the highest values ($p < 0.001$, $d = 0.85–1.10$). This supports

H3 and H6 and suggests that maturity status should inform individualized strength programming. The data further confirm strength asymmetries tend to stabilize with age.

Research indicates that biological maturation significantly affects the development of lower limb isokinetic strength. Growing evidence suggests that as athletes progress through puberty, particularly during periods marked by PHV, their neuromuscular systems adapt and develop stronger muscle capabilities. For instance, Almeida-Neto et al. found that young male soccer players who reached advanced stages of puberty exhibited superior knee extension strength compared to their peers who matured later Almeida-Neto et al. (2020). This observation underscores the critical role of hormonal changes including increases in testosterone that accompany maturation, which positively influences muscle size and strength. Kaľata et al. support this notion, revealing that isokinetic strength in the KE and KF of elite youth soccer players correspondingly increases with age categories, confirming a developmental trajectory that aligns with maturation. Their study highlighted significant strength differences across age groups, demonstrating that older youth players possessed greater isokinetic strength than their younger counterparts (Kaľata et al., 2021). This increase in strength is likely a reflection of both enhanced motor unit recruitment and muscle hypertrophy stimulated by hormonal influences during adolescence. The interplay of BM with lean mass also plays a vital role in the development of lower limb strength. In a study conducted by Portella et al., significant gains in fat-free mass (FFM) after isokinetic training were positively correlated with peak torque production in Brazilian soccer players (Portella et al., 2014). The evidence suggested that increases in FFM contributed to enhanced lower limb strength capabilities, as stronger athletes generally possess a greater proportion of lean muscle mass. This highlights the importance of considering both biological maturation and changes in body composition when assessing strength development in young athletes. Moreover, Almeida-Neto et al. further emphasized the positive correlation between lean mass and muscle strength performance in elite young athletes, indicating that lean mass significantly impacts the relationship between BM and LBS (Almeida-Neto et al., 2020). Their findings suggest that lean mass acts as a mediator, illustrating the importance of developing muscle tissue during the maturation process to optimize strength potential. The implications of biological maturation on lower limb strength development extend to training and injury prevention for elite youth soccer players. Malý et al. reported that isokinetic assessments can be used to identify strength imbalances, which are critical for predicting potential injuries, especially during high-intensity training phases when maturation differences can lead to mechanical deficiencies (Malý et al., 2019). Understanding these differences allows trainers and coaches to implement individualized training programs that account for the distinct needs of immature athletes to minimize injury risk. Furthermore, findings by Gherghel et al. highlight the importance of explosive strength in performance, reinforcing that young athletes' development should prioritize strength training methodologies that enhance explosive capabilities without compromising safety during periods of rapid growth (Gherghel et al., 2021). Coaches must carefully consider both strength development and the timing of maturation-related changes to optimize performance while reducing injury risk in training cycles. In conclusion, the relationship between biological maturation and lower limb isokinetic strength development in elite youth soccer players is characterized by a strong methodological approach that incorporates hormonal influences, lean mass contributions, and strategic training adjustments.

The development of explosive LBS, particularly as measured by VJ performance, is closely linked to an athlete's PHV status in elite adolescent soccer players. Explosive LBS is commonly assessed through VJ tests such as CMJ, which serves as a valid indicator of an athlete's explosive power. Studies indicate that VJ performance improves significantly as athletes' progress through their maturation stages. Perroni et al. observed that older and more mature soccer players significantly outperformed their younger and less mature counterparts in VJ assessments Perroni et al. (2024). This finding underscores a trend where maturation, especially post-PHV, correlates with increased lower limb strength. Marinho et al. further highlighted those physiological changes accompanying maturation, such as increases in muscle mass and strength, positively relate to improved motor performance, particularly in explosive activities like jumping (Marinho et al., 2020). These adaptations make post-PHV athletes capable of showcasing greater explosive power in their jumps during optimal maturation periods. The timing of PHV is crucial for influencing explosive strength development. Akbari et al. noted that maturity status significantly affects VJ performance, with those in the post-PHV group demonstrating superior performance compared to their pre-PHV counterparts (Akbari et al., 2018). Their research also indicates that plyometric exercises incorporated into training may have heightened effects on jump performance post-PHV due to the more developed neuromuscular systems.

Conversely, Hermassi et al. illustrated that younger player within the pre-PHV age group exhibited lower levels of performance in vertical jumps. Their findings suggest that BM correlates more strongly LBS than with chronological age, indicating that merely training based on age may not adequately enhance performance (Hermassi et al., 2024). The practical implications for training strategies are evident. Coaches should prioritize and tailor plyometric and strength training programs according to an athlete's maturity status. Behm et al. emphasize the importance of designing training interventions that consider biological maturity along with CA (Behm et al., 2017). Moreover, the relationship between strength training, including plyometric exercises, and VJ performance suggests that adolescence especially around PHV is a critical period for developing explosive strength (Asadi et al., 2018). Asadi et al. found that structured plyometric training can enhance not only jumping ability but also sprint performance, further linking lower limb strength to overall athletic capability (Asadi et al., 2018). In summary, the development of explosive lower limb strength as illustrated through VJ performance is significantly influenced by an athlete's PHV status in elite adolescent soccer players. As biological maturation progresses, particularly after PHV, athletes exhibit enhanced explosive power and strength, necessitating training programs that are tailored to the athlete's maturation level for optimal performance. The evidence supports a nuanced approach to performance training and assessment that prioritizes biological maturation as a critical factor in a young athlete's development.

The consistent improvements in isokinetic knee strength over the two seasons substantiate Hypotheses 3, 4, and 5. Both hamstring and quadriceps strength improved significantly, with quadriceps demonstrating higher absolute force yet hamstrings showing proportionally greater gains (Figure 7). This led to improved PTKF and PTKE, especially among older and biologically advanced players, mirroring findings by Lehance et al. (2009) and Croisier et al. (2008) on maturation-related improvements in muscular balance and injury resistance.

High correlations between Q180 and jump height ($r = 0.78–0.95$) further validate H7 and reinforce the role of high-velocity force production in explosive movements. These patterns align with biomechanical models emphasizing the stretch-shortening cycle in CMJs and SJs (Markovic & Mikulic, 2010).

Interestingly, the results of isokinetic strength, including KE and KF, varies significantly with age and maturation status due to physiological changes such as muscle hypertrophy, hormonal fluctuations, and neuromuscular adaptations (DiStefano et al., 2015; Maly et al., 2021; Pletcher et al., 2021; Pradhan et al., 2020). De ste Croix et al. (2003) indicate that while fat-free mass and muscle cross-sectional area are key contributors to isokinetic strength, other factors also influence its development. It is important to note that strength was assessed using relative values (normalized to body mass), which may be skewed for older players due to their greater body mass. Although stature and mass significantly predict knee extensors and flexors strength, age and maturity become non-significant when these factors are considered. The maturation and growth status of adolescent athletes are implicit factors in determining their physical performance development (Williams & Reilly, 2000).

8.3 Functional Movement Trends Across Maturation

Adolescence is a sensitive and complex period of biological and physical growth that cannot be handled with a monolithic evaluation, particularly in team sports like soccer. The findings suggest that younger adolescent soccer players may need to focus more on improving their individual development of FM and strength based on their BM. As adolescents progress through growth and development, their bodies undergo changes that can impact movement patterns and strength. It is well established that BM affects physical performance, largely due to changes in hormonal profiles, increases in lean body mass, myelination of motor neurons, and improved inter and intramuscular coordination, which contribute to the development of various physical and physiological characteristics (Faigenbaum et al., 2013; Lloyd et al., 2015; Malina et al., 2004). Although the study identified age group differences, optimizing physical loading necessitates recognizing individual variations and tracking changes within each age category (Deprez et al., 2013; Wrigley et al., 2014). FMS scores improved across the year, particularly in younger athletes (U13–U14), suggesting age-appropriate motor control enhancements, likely driven by exposure to training stimuli and neurological development. However, the limited association between FMS and strength/jump outputs ($r < 0.30$) corroborates critiques of its predictive power (Kiesel et al., 2011; Dorrel et al., 2018), partially validating H2.

This disconnect underscores the utility of FMS more as a movement quality screen than a performance predictor, a view supported by meta-analyses (Bonazza et al., 2017). Nonetheless, the modest association with PHV ($r = 0.21$–0.26) implies some maturational underpinning to movement efficiency (Figures 14–16). While FMS scores improved modestly over time and with maturation (supporting H2), their predictive power for strength or jump performance was limited ($r = 0.20$–0.35), aligning with prior findings (Kiesel et al., 2007; Lloyd & Oliver, 2012). This suggests that while maturation enhances gross movement proficiency, FMS might be better suited for screening dysfunction rather than predicting athletic performance. Coaches should use FMS for identifying limitations in mobility and stability rather than performance forecasting. FMS scores improved modestly over time, especially in post-PHV players (H2). However, the relationship between FMS and power/strength was weak ($r = 0.25$), indicating FMS may reflect movement quality rather than neuromuscular capacity. Thus, FMS is better seen as a baseline screening tool than a performance predictor (Kiesel et al., 2007).

Research indicates that FM quality, as measured by assessments like the FMS, can correlate with various measures of athletic performance, including speed, agility, and jump capability. For instance, Davies et al. highlight that while FMS scores have been associated with athletic performance measures, many studies have not adequately considered the role of BM in these assessments, potentially leading to skewed results Davies et al. (2022). The systematic review underscores the importance of maturation as a determining factor in how well FMS scores can predict athletic performance among adolescents. Similarly, findings by Mijalković et al. support the assertion that athletes at different maturity stages perform variably across athletic disciplines. Their research shows that biological maturity significantly influences success in explosive sports compared to endurance events, suggesting that early maturers may inherently excel in various athletic tasks, including those evaluated through FMS (Mijalković et al., 2024). This internal variability within maturity groups can thus influence the reliability of FMS as a predictor of performance. The effectiveness of FM assessments as predictors of athletic performance appears contingent upon adjusting for biological maturation. Alexe et al. present evidence that younger athletes demonstrate a stronger relationship between FM quality and performance metrics compared to their more mature peers, who may rely more on strength and power attributes as they mature (Alexe et al., 2024). This emphasizes the necessity of considering maturation when interpreting FMS results, as poorly timed assessments may lead to misguided training interventions or athlete development paths.

Furthermore, Zhang et al. reinforce this notion by analyzing FMS scores in relation to sprint and jump performance in youth soccer athletes. Their study found a positive albeit modest correlation between FMS scores and athletic outputs, suggesting that as athletes mature, the influence of FM quality may diminish relative to their physical capabilities (Zhang et al., 2022). As noted by Lloyd et al., the relationships between FMS scores and physical performance measures in young soccer players significantly vary depending on their maturation stage (Lloyd et al., 2014). This knowledge informs coaches that implementing FMS evaluations without considering biological maturity may lead to inappropriate conclusions regarding an athlete's potential. Additionally, Kramer et al. demonstrate that imbalances identified through FMS can be predictive of injury risk and thereby influence athletic performance (Kramer et al., 2019).

This finding underscores the necessity for coaches to integrate maturation timing into their training regimens. By improving movement quality early in an athlete's development, coaches can potentially mitigate injury risks and enhance long-term performance trajectories. In summary, while FM assessments like the FMS provide valuable insights into movement quality and its relationship with athletic performance, their predictive reliability is significantly heightened when adjusted for BM status.

8.4 Practical Applications for Training and Talent Development

This study reinforces the critical need for BA informed training approaches in elite youth soccer, particularly by considering PHV when designing and adjusting training programs. Relying solely on CA overlooks the significant physiological and neuromuscular differences that exist between pre-, circa-, and post-PHV athletes. Coaches should adopt individualized programming that reflects an athlete’s current stage of maturation to optimize physical development, reduce injury risk, and support long-term performance outcomes.

For example, post-PHV athletes, who typically demonstrate enhanced strength and jump capabilities, may benefit from more intensive strength and power training. Conversely, pre-PHV athletes should focus on neuromuscular control, coordination, and movement competency. This aligns with LTAD principles, which advocate age- and stage-appropriate progression to minimize overtraining and promote efficient skill acquisition. Movement competency should be treated as a distinct performance attribute, not just a byproduct of strength. As shown in this study and supported by previous work (Morris et al., 2021; Woods et al., 2016), maturity status significantly affects motor control and training responsiveness. Athletes who mature later may initially lag in strength but can achieve considerable improvements through well-targeted neuromuscular training. Similarly, differences in force–velocity profiles across maturity stages (Jiménez-Reyes et al., 2018) suggest that certain athletes may excel more in either force or velocity-dominant tasks depending on their biological development, warranting specialized programming.

To apply this effectively, regular assessment of both maturity status and movement quality is essential. FMS, when used alongside strength and performance tests, provide valuable insight into movement efficiency and physical readiness. These tools can help coaches identify deficits, apply targeted interventions, and track progress over time even in environments with limited resources.

In practice, this means moving beyond age-group training models toward developmentally responsive systems. Coaches should:

- Monitor PHV and BA regularly to contextualize performance metrics.
- Use FMS as a supplementary not standalone assessment alongside power and strength testing.
- Introduce targeted hamstring training during the PHV window to mitigate ACL injury risk and promote balanced knee strength (Fort-Vanmeerhaeghe et al., 2016).
- Avoid one-size-fits-all training plans in favor of adaptable strategies that evolve with the athlete's growth and maturation status (Lloyd & Oliver, 2012).

Ultimately, maturity-informed coaching empowers practitioners to make evidence-based decisions that align with each player's individual development pathway. By integrating biological and functional assessments into training design, clubs can enhance both performance outcomes and injury resilience, supporting long-term success in elite soccer development.

9 Conclusion

This longitudinal study provides strong evidence that BM particularly PHV is a critical determinant of neuromuscular performance in elite youth soccer players. By analyzing movement quality, LBS, and VJ capacity across U13 to U16 age groups over two competitive seasons, the research demonstrates that BA, not just CA, should guide training decisions and talent development strategies.

The findings confirm that players transitioning through or beyond PHV experience the most significant gains in strength and power. Strong correlations ($r = 0.48–0.78$) between PHV and both isokinetic knee strength and VJ performance support this, validating Hypotheses H1, H3, H5, H6, and H7. In contrast, FMS scores while improving modestly with age exhibited limited predictive validity for explosive strength outcomes, partially supporting H2. However, FMS remains a valuable tool for identifying movement inefficiencies and supporting injury prevention.

Analysis of PTKE and PTKF results at varying velocities (60°, 180°, 300°/s) revealed consistent improvements with maturation, reinforcing the performance and injury-prevention benefits of targeted strength development. Notably, players classified as circa- or post-PHV outperformed their pre-PHV peers in both Q and H strength across all testing velocities, emphasizing the importance of tailoring strength programs to maturation status rather than age group alone. The use of maturity offset calculations alongside objective physical assessments allowed for a nuanced profile of individual development. This maturity-informed approach supports the application of bio-banding and developmentally appropriate training loads, ensuring that young athletes are challenged and protected based on their biological readiness. The study further underscores the need for regular monitoring of maturation status (e.g., PHV estimates) to contextualize performance trends and guide individualized training interventions.

Ultimately, this thesis advances the understanding that maturity status should be central to youth athlete development. Programs aligned with BA can better optimize performance outcomes, reduce injury risk, and support long-term progression within elite development pathways. Future research should build on these findings by testing targeted training interventions across maturity stages and exploring how maturation interacts with technical and tactical skill development in youth soccer.