The Influence of Biological Maturity on Hamstring:Quadricep Ratios and Asymmetries in Male Academy Footballers

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The candidate confirms that the work submitted is their own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Aim

The apparentness of inter-limb muscular asymmetries and intra-limb muscular imbalances within an adolescent population is currently under-researched. Failure to address such impairments may have substantial implications regarding both injury and performance presentations. This study aims to explore the impact of biological maturation (status and timing) on both knee extension (KE) and flexion (KF) peak isometric force asymmetries, alongside Hamstring:Quadricep (H:Q) ratios, within academy footballers.

Method

Forty-six adolescent academy footballers (aged 11-16) were examined, with players subsequently categorised based on their maturity status. The Khamis-Roche method was used to classify players into maturity groups, with the thresholds of <88%, 88-96%, and >96% of peak adult height corresponding to the periods of pre-, circa-, and post-peak height velocity. Isometric strength was recorded, with all players performing two prone isometric KE and KF contractions within a single session.

Results

Biological maturity had no significant impact on strength asymmetries for both KE and KF and H:Q ratios produced, yet, peak isometric strength was shown to increase significantly with maturity. Concerning the entire group, no difference in the extent of KE compared to KF asymmetry levels were produced but a significant difference was demonstrated between left and right H:Q ratio values. Injury data showed that the thigh exhibited the greatest injury incidence rate across the 2024/25 season, providing a rationale to focus on KE and KF peak isometric strength.

Conclusion

As biological maturation had no significant impact on asymmetries or H:Q ratios produced, clinicians should focus on the entire group when minimising inter-limb asymmetries and developing hamstring strength rather than focusing on a particular maturity group.

Additionally, the absence of maturational differences suggests that other factors responsible for altered asymmetries and H:Q ratios should be further investigated. Due to the novelty of this study, future research is needed to solidify findings.

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Abbreviations

Adolescent Awkwardness Phenomenon (AAP)

Biceps Femoris Long Head (BFlh)

Hamstring:Quadricep (H:Q)

Hamstring Injury (HSI)

Handheld Dynamometer (HHD)

Home-Grown Player (HGP)

Isokinetic Dynamometer (IKD)

Knee Extension (KE)

Knee Flexion (KF)

Muscle-Tendon Unit (MTU)

Osgood-Schlatters Disease (OSD)

Peak Adult Height (PAH)

Percentage of Peak Adult Height (%PAH)

Peak Height Velocity (PHV)

Rectus Femoris (RF)

Union of European Football Associations (UEFA)

Chapter 1 Introduction

‘Home-Grown Rule’

Football is the most popular sport in the world, with involvement from over 200 countries and more than half of the world’s population identifying as followers of the sport (Li & Mateos, 2022). Within England, approximately 1.5 million players compete in organised youth football; however, only around 180 of those will eventually play professionally in the Premier League (Kyeremateng, 2025). Consequently, players must maximise the available playing time to enhance their performance to make it as professional footballers. As a result, injury prevention and performance enhancement must be maximised to allow for the successful integration from youth to senior football.

Within European professional male football, teams must comply with the Union of European Football Associations (UEFA) ‘home-grown rule’; this rule states that each club must include a minimum of eight home-grown players (HGP) out of a 25-player squad (Bullough et al., 2016). A HGP is defined as a player who has played for at least three years between the ages of 15-21 at a club competing in the same national association as the senior club (Bullough & Jordan, 2017). The reasoning behind the rule was to encourage local training of young players, increase the fairness of European competitions, counter the trend of hoarding players, and promote a ‘local’ identity at clubs (Bullough, 2021). As a result, an increased emphasis is placed on football academies to reduce injuries and enhance the performance of adolescent players, allowing clubs to meet the required HGP requirements while also improving economic and performance outcomes for the club.

Avoiding injury is crucial for adolescents to maximise the potential of playing professional football. For example, disturbed physeal growth due to injury can cause significant long-term disability due to alterations in deformity and joint mechanics (Maffulli et al., 2010). The difficulty of making it as a professional footballer, regardless of injury, is a global issue, with just over 3% of players playing in Spain’s highest professional league within 10 years of leaving the academy, following a two-decade analysis of two professional clubs (Moran et al., 2024). This highlights the low proportion of players who make it as professional footballers and further emphasises the need to reduce injury risk. Additionally, Kelly et al., (2020) found that key performance categories (technical, tactical, physiological, and psychological) shown in 19-year-olds were also displayed by 15-year-olds, meaning that key performance attributes are developed during the period of adolescence, thus further demonstrating the detrimental impacts that injury may place if players are unable to get the opportunity to develop essential performance qualities.

Adolescent injuries within academy football have been researched in recent times, with literature centred on both injury incidence and burden. Light et al., (2021) explored injury incidence over four consecutive seasons within a national football academy. They reported a total of 603 time-loss injuries from 190 different players, resulting in an overall injury incidence rate of 2.4 per 1,000 hours per player. However, a greater injury rate was reported in Wik et al., (2021)'s longitudinal study, finding an incidence rate of 12/1000 hours per player, with an average burden of 255 days lost per 1000 hours. Furthermore, Materne et al. (2021) reported an average injury rate of 30 time-loss injuries per 25-player squad, with an injury burden of 574 days lost per squad season. There is, therefore, a clear need for practitioners to efficiently rehabilitate injuries, thereby reducing the overall burden and ultimately increasing a player's potential to perform at the highest level. Understanding likely injury risk factors is therefore paramount to prevent long-term pathologies.

Within academy football, muscular injuries, especially those to the thigh, are the most common type of injury, with an incidence of 0.62/1000 hours and a burden of 7.6 days lost per 1000 hours reported by Weishorn et al. (2023). Regarding specific musculature, past research has shown both the quadriceps and hamstring groups to be particularly susceptible to injury, with the literature somewhat contrasting regarding which muscular group has the highest incidence rate of injury. For example, Skomrlj et al. (2024) found a slightly higher rate of hamstring injuries compared to quadriceps within a U15 Croatian squad. In contrast, Read et al. (2018) reported a higher injury rate for quadriceps. This is of concern due to the high involvement of both muscle groups during football-related movements, such as sprinting (Garcia et al., 2022), thus highlighting the need to reduce the risk of injury to both muscle groups and to identify specific risk factors associated with thigh-related pathologies.

Biological Maturity

Although all adolescents have the potential to sustain an injury, it has been suggested that players of specific maturities are more susceptible to injuries than others. This refers to the concept of biological maturity, defined as the progression toward a mature state (Sherar et al., 2010). There are three different maturity statuses that a child can fall under; these are pre-, circa-, and post-peak height velocity (PHV), corresponding to before, during, and after a player's growth spurt. PHV is the period during which a player will experience the most significant rate of growth. All children mature at different rates, with some being deemed early or late maturers. Yet, typically, it is expected for a male child to undergo a growth spurt during the ages of 13-16 (Vist Hagen et al., 2022)., with age 14 initiating PHV for many individuals (Leite Portella et al., 2017).

Research has theorised about the physiological changes that occur during this period, with the term 'adolescent awkwardness phenomenon' (AAP) commonly used. This phenomenon has been theorised to disrupt postural control (John et al., 2019) due to a change in neurological and information processing; changes in neurological and information processing are suggested to be caused by a lack of ability to estimate internal bodily orientation, thus causing slower movement detection times which may have adverse effects on both injury and performance (Wachholz et al., 2020). It is, therefore, crucial that practitioners are aware of this phenomenon and take appropriate measures to reduce the risk of injury during this vulnerable stage.

Past research has highlighted the increased injury incidence within circa-PHV players compared to their counterparts, with these individuals generally displaying increased vulnerability towards growth-related conditions. Contrastingly, post-PHV players are often more susceptible to muscular injuries (Monasterio et al., 2023). As this study employed a single-testing approach, it is therefore impossible to accurately correlate injuries sustained throughout the season with maturity status due to the changes in players' biological maturity throughout the season. As a result, the purpose of recording injuries is not to explore injury patterns dependent on maturity but to aid in providing a potential rationale for focusing on knee extension (KE) and flexion (KF) asymmetry.

It may be questioned as to why the focus is centred on adolescent strength asymmetries and H:Q ratios rather than examining adults. Firstly, there is a significant gap in the literature regarding adolescents, with most research using adult participants. It is, therefore, increasingly invalid to adopt findings and subsequent concepts from studies using an adult sample towards an adolescent population, thus highlighting the need for further research involving children. Secondly, it has been shown that children have the potential to sustain a similar number of injuries compared to an adult population (Pfirrmann et al., 2016), with circa-PHV particularly vulnerable to injury (Monasterio et al., 2023). Although the link between strength asymmetries and injury may be questioned due to conflicting literature, this is not the case for the impact of reduced H:Q ratios and the potential increase in injury risk. As a result, maturity differences must be investigated to identify potentially vulnerable individuals who are at a higher risk of injury, thereby reducing the likelihood of injury and enhancing performance. Lastly, due to the recent emergence of the concept of ‘biobanding’, coaches may be unaware of the potential physical variations among individuals of the same chronological age. Resultingly, the findings produced will aid in clarifying the extent to which maturity has on strength asymmetries, which will either support or disprove the grouping of individuals based on biological rather than chronological age.

Strength Asymmetry

Various strength asymmetry parameters are available for analysis. It is crucial to examine inter-limb strength asymmetry values between limbs, in addition to intra-limb asymmetry variations among muscular groups, such as the hamstrings and quadriceps group. An asymmetry is generally considered a hindrance if there is at least a 10% difference in strength levels between the two limbs (Fort-Vanmeerhaeghe et al., 2016).

Within football, lower-limb asymmetries are often due to players relying more heavily on their dominant side, which means that limbs may adopt varied neural-motor patterns due to excessive unilateral load (Mala et al., 2020), potentially increasing injury risk. Due to being the preferred leg to stand on during a match, the non-dominant limb often adapts with greater strength and balance compared to enhanced coordination and skill adopted by the dominant side (McElveen et al., 2010). Therefore, it is generally accepted that asymmetries will be apparent. However, literature has suggested a positive correlation between injury and asymmetries succeeding the 10% limb symmetry index (LSI) (Fort-Vanmeerhaeghe et al., 2016), thus implying that asymmetries should be minimised to reduce injury risk.

Variations exist when comparing findings from previous research, thus providing ambiguity regarding the impact of maturation on asymmetry. Peek et al., (2018) demonstrated asymmetries in muscular strength when testing with a handheld dynamometer (HHD) in 110 male academy footballers. Quadriceps asymmetry appeared to be more prevalent compared to hamstring asymmetry, yet significant differences between age groups did not exist; one reason for this may be the reduced sample size of the older age players, which raises questions about the study's validity. However, Kalata et al., (2021) discovered that the U13 and U15 age groups showed significantly higher levels of asymmetry for both KE and KF strength compared to the U17 age group when using an isokinetic dyanmometer (IKD), thus showing the impact that maturity may have had within this study. The difference in methods and results is, therefore, a clear issue within the literature, as it reduces the generalisability and comparability of results to produce shared conclusions. As a result, one purpose of this project is to provide further research on maturity and asymmetries using an HHD, thereby increasing the generalisability of results to those who do not have access to 'gold standard' equipment.

Literature is lacking regarding the exploration of injury and hamstring/quadricep asymmetries within an adolescent population. A recent systematic review, conducted by Helme et al., (2021), included only three relevant studies suitable for this project. Results from the systematic review were varied, making it challenging to assume if a link between injury and asymmetry exists correctly.

Due to the nature of testing, it is not possible to directly explore the association between strength asymmetry and injury. This is due to testing taking place within a single session, which reduces the validity of the results if an injury that occurred either in the early or late season were to be associated with strength asymmetry and maturity results obtained at the midway point in the season. Due to the likelihood of players progressing to the next maturity group throughout the season, chronological age will, therefore, be used to group players when interpreting injury data. To clarify, injury findings within this study cannot be directly related to maturity findings. Therefore, the findings will be used to explore the occurrence of thigh-related pathologies, aiding in the rationale for the focus of this study.

The principle behind exploring the impact of maturity on KE and KF strength asymmetries is due to the unilateral nature of football, which can influence injury risk. It has been suggested that biomechanical differences exist between the limbs of players who rely heavily on their dominant side (Read et al., 2018), which may increase the risk of injury. Empirically, although research highlighting the relationship between injury and asymmetries is lacking, findings have suggested a link between isokinetic hamstring strength asymmetries and increases in injury rate (Fousekis et al., 2010; Knapik et al., 2021). Additionally, literature has suggested a positive correlation between injury and asymmetries succeeding the 10% limb symmetry index (LSI) (Fort-Vanmeerhaeghe et al, 2016). Further reasoning for the inclusion of asymmetry findings about maturity stems from the insufficiency of research centred on the impact of maturity status and timing on strength asymmetries. Although research has included adolescents, most studies fail to categorise participants based on their biological age compared to their chronological age. Furthermore, those that have accounted for maturity variations have been unable to include a circa-PHV group (Souza et al., 2024), which is arguably the group that may contain the most significant number of players vulnerable to injury during the period of PHV. Overall, due to the potential link between asymmetry and injury, alongside the lack of research focused on the impact of biological maturity on strength asymmetries, it, therefore, seems necessary that research investigates the possible effect of maturation on strength asymmetries to aid in the detection of vulnerable individuals subject to alterations in injury risk and performance deficits.

H:Q Ratios

Regarding normative values, research using the conventional method (concentric hamstring divided by concentric quadriceps strength) has generally agreed on an achievable ratio of 0.6 to strive for to reduce injury risk (Fritsch et al., 2023). However, a review of previous literature has shown that it may be appropriate to lower this threshold for adolescents to increase its achievability. A normative threshold for adolescents appears to have received little attention; therefore, this project may provide future research with average H:Q ratios sustained by adolescent individuals.

Similarly to asymmetry research, the literature surrounding H:Q ratios tends to favour senior players, with most studies using an IKD; therefore, this reduces the generalisability of the findings to this project. Research featuring adolescent H:Q ratios using an HHD was conducted by Peek et al., (2018), who found over a third of players aged 12-15 demonstrated an isometric H:Q ratio of less than 0.60. Additionally, they found that the largest reduction in the ratio was evident among players aged 11-12, with a drop from 0.82 to 0.65. This, therefore, suggests that maturation may have negatively lowered the player’s ratios. However, it is difficult to conclude whether other factors may have been responsible. Yet, contrasting literature, proposed by Ishoi et al., (2021), showed that out of 125 players from the U13 group to senior performers, the U15 category was the only age group to achieve a H:Q ratio of 0.62, thus exceeding the generally agreed-upon threshold of 0.6. This, therefore, contradicts the suggestion that maturity may influence H:Q ratios, and it is clear that further research is needed to explore the extent to which maturation affects the muscular imbalance between the hamstrings and quadriceps.

Unlike the ambiguous relationship between asymmetries and injury, the link between reduced H:Q ratios and injury appears to be more evident, with the non-dominant limb often producing lower ratios compared to the dominant side (Maly et al., 2016). For example, a significant relationship was found between H:Q ratios lower than 0.6 and an increased incidence of left leg injuries in 40 male and 42 female college basketball players (Kim & Hong, 2011), potentially highlighting the vulnerability of the non-dominant side. More specifically, Lee et al., (2017) discovered a strong link between lower H:Q ratios and hamstring injuries. It has also been proposed that a reduced H:Q conventional ratio is due to both strengthened quadriceps and weakened hamstrings (Fritsch et al., 2023), thus potentially increasing a player's susceptibility to injury due to the excessive quadriceps contraction (Pfeifer et al., 2018). Based on past research, it can, therefore, be assumed that lower H:Q ratios are potentially associated with an increased risk of injury.

The basis behind the analysis of H:Q ratios produced and how this is altered by maturity is due to the strong link between reduced H:Q ratios and injury rate in addition to the lack of research centred on the impact of biological maturity on ratios produced. From an injury perspective, literature has produced strong findings that solidify the link between reduced H:Q ratios and injury. Reduced H:Q ratios are often the result of weakened hamstrings (Fritsch et al., 2023), which has been suggested to have the potential to cause a variety of musculoskeletal pathologies, such as hamstring injuries (HSI) (Lee et al., 2018) and anterior cruciate ligament (ACL) pathologies (Holcomb et al., 2007). Additional reasoning for the inclusion of H:Q ratio findings impacted by maturity stems from the lack of literature discussing the impact of biological maturity on the ratios produced. Similarly to asymmetry research, when including adolescents, the literature tends to group participants based on chronological age rather than biological age, making it challenging to produce implications specific to certain maturity groups. Lastly, research involving adolescents has consistently shown the suggested 0.6 threshold to be somewhat unlikely to be achieved. Success in reaching the 0.6 H:Q ratio threshold has been proposed as a means to reduce injury risk (Fritsch et al., 2023); however, the literature has demonstrated that adolescents often fail to reach this normative value. As a result, the findings produced within this study can contribute to the potential notion that a lower threshold is more applicable to adolescents. It is, therefore, clear that there is a need for research to focus on the impact of maturity on H:Q ratios, allowing clinicians to identify potentially vulnerable individuals concerning injury risk and performance deficits.

Objectives

The primary purpose of this study is to investigate the extent of the impact of biological maturity status on strength asymmetry and H:Q ratio values in male adolescent footballers, with the impact of maturity timing being a secondary focus.

As a result, the following objectives will be directly measured:

1. Does maturity impact peak isometric KE and KF force produced?
2. What is the prevalence of asymmetry between the dominant and non-dominant limb when completing an isometric KE and KF contraction and is this influenced by maturity status?
3. What is the prevalence of reduced H:Q ratios when completing an isometric KE and KF contraction and is this altered by maturity status?
4. Does the timing of maturity impact the extent of strength asymmetries or H:Q ratios produced?

As stated previously, injury data regarding the commonality of injury occurrence within different bodily locations will be conducted throughout the 2024/2025 season, with a specific focus on hamstring and quadricep-related pathologies. The purpose of this data is to provide a ratione for the selection of exploring KE and KF strength.

Chapter 2 Literature Review

Biological Maturity

Within footballing academies, children are often categorised by their chronological age, defined as a single time point from the child's date of birth (Lloyd et al., 2014), yet it is crucial to take a holistic approach when exploring a child's physical development. A child's biological maturation, defined as the progression toward a mature state, must also be considered due to biological asynchrony between adolescents (Sherar et al., 2010), with some children growing at a faster rate compared to others (Sanders et al., 2017). During childhood, all children undergo a growth spurt where their tempo of growth reaches its greatest rate – this period is known as a child's PHV. Generally, PHV approximately occurs at the ages of 14 and 12 in males and females, respectively (Leite Portella et al., 2017). However, due to varying levels of biological maturity within individuals, it is generally assumed that the point of PHV occurs within males aged 13-16, yet, although uncommon, children can undergo their PHV either before or after this period (Vist Hagen et al., 2022).

Differences in biological maturation between individuals of the same chronological age result in physical discrepancies among them. During the time of PHV, adolescents undergo various physical changes, thus enhancing physical differences between players of the same chronological age. Within males, the duration of peak growth is approximately 3 years, with an average height advancement of 9.5 cm per year, as reported by Soliman et al., (2014). However, a reduced growth advancement figure has been produced, with Pichardo et al., (2019) suggesting that the maximum growth rate be 9 cm/year, in addition to the potential growth between ≥7.2 cm and ≥3.6 cm/year, as discussed by Johnson et al., (2023). Changes in muscular architecture have also been researched in adolescents, with Radnor et al., (2020) highlighting an increase in vastus lateralis and medial gastrocnemius thickness and pennation angle throughout biological maturation, with the greatest difference apparent between those before and those during their growth spurt. As a result, it therefore seems appropriate to predict that peak strength values obtained by participants will increase as maturity progresses.

Alongside lower-limb muscle architecture, Hall et al., (2022) described additional changes in weight and trunk size, potentially leading to the impairment of coordination, movement mechanics, and motor task performance. A disruption in postural control (John et al., 2019) resulting from changes in neurological and information processing (Wachholz et al., 2020) has been termed the 'AAP'. Wacholz et al., (2020) proposed that neurological and information processing impairment may be due to a lack of ability to estimate internal bodily orientation, thus causing slower movement detection times, and may ultimately increase injury risk.

Biological maturation varies among children due to differences in status, timing, and tempo. Regarding status, children can be grouped into one of three categories depending on their current percentage of peak adult height (PAH; these consist of pre-, circa-, and post-PHV. Quantitatively, Monasterio et al., (2021) classified pre-PHV as being less than 88% of PAH, circa-PHV players as 88-96%, and post-PHV as greater than 96% of their PAH. However, the growth spurt thresholds of 88% to 92.8% of PAH and 88-95% were used by Johnson et al., (2023) and Johnson et al., (2022), respectively, thus displaying the varied levels of maturity within literature. Maturation timing refers to a child's specific maturational events in relation to age, such as a child's growth spurt (Vist Hagen et al., 2022). Children can be categorised as early, on-time, or late maturers (Monasterio et al., 2021). Lastly, tempo describes the rate of biological maturation, which, as stated previously, is at its greatest during the period of PHV. The consideration of a player's status, timing, and tempo is necessary to elicit correct injury monitoring and rehabilitation practices. However, due to the single-testing session used in this project, maturity status is the primary focus throughout this thesis, with timing also being discussed.

To assess biological maturity, literature has generally used a combination of skeletal, sexual, somatic, and dental procedures (Ruf et al., 2021). However, due to the invasiveness of such procedures, alongside the cost and safety risks associated with methods of skeletal age assessment, an increase in anthropometric estimates of biological maturity status has been produced (Malina et al., 2015). The Khamis-Roche method is an increasingly popular method for predicting a child's percentage of PAH. This method uses the participant's standing height, body mass, chronological age at the time of testing, and self-reported parental standing height (Ruf et al., 2021). Although the validity of this method can be questioned due to the self-reported parental stature alongside the absence of a child's parents in the minority of cases, the Khamis-Roche method is generally a simple procedure with the ability to predict adult stature to within 2.2 and 5.3 cm for the 50th and 90th percentile respectively (Salter et al., 2022), thus proving to be an accurate method for assessing a player's %PAH, therefore allowing practitioners to effectively calculate a child's biological maturity in comparison their counterparts.

Injury Trends Across Maturation in Football

As mentioned in the introduction section of this thesis, it is essential to note that injury incidence and severity were not directly studied. However, understanding common injury trends among adolescents and how these often present is crucial to successfully interpreting how findings from this study may impact injury risk. Additionally, examining which category of injury is the most common within the sample, alongside the body location most affected, can aid in determining the direction of focus for the muscular architecture being tested.

Adolescent injuries within academy football have been widely researched in recent times, with literature centred on both injury incidence and burden. Light et al., (2021) explored injury incidence over four consecutive seasons within a national football academy. They reported a total of 603 time-loss injuries from 190 different players, consequently providing an overall injury incidence rate of

2.4/1000 hours per player. However, a greater injury rate was reported in Wik et al., (2021)'s longitudinal study, finding an incidence rate of 12/1000 hours per player, with an average burden of 255 days lost per 1000 hours. Furthermore, Materne et al. (2021) reported an average injury rate of 30 time-loss injuries per 25-player squad, with an injury burden of 574 days lost per squad season. Interestingly, research conducted by Theisen et al. (2013) showed that injury incidence is greater in team sports compared to individual sports among adolescents, thereby raising attention regarding the need to create preventive strategies to reduce injury risk among vulnerable players.

In comparison to senior-level football, similar injury incidence rates appear apparent between senior and adolescent players. A mean match incidence rate of 7.75/1000 hours was suggested by Gurau et al., (2023) whereas Pfirrmann et al., (2016) displayed an injury incidence range of 8.7-65.9/1000 hours within senior players compared to 9.5-48.7/1000 hours in adolescents. Similarly, both adolescents and senior players have been shown to sustain a greater number of injuries during matches compared to training, with the incidence rate decreasing to 1.37-5.8 and 3.7-11.14 injuries per 1000 hours in adults and adolescents, respectively (Pfirrmann et al., 2016). Previous literature has, therefore, emphasised the impact that injuries can have on both a player and the team and that there is as much need to focus on adolescent injuries as there is within senior teams, thus sparking the need to develop interventions to successfully reduce the rate of injury for both contact and non-contact injuries due to their shared commonality within youth football (Mandorino et al., 2023). To enhance effective interventions, knowledge of injury trends among different age groups must be considered.

Regarding injury trends between age groups, Light et al., (2021) explained that burdensome injuries peak between the ages of 13-16, corresponding strongly to the period of PHV for most players. This result is supported by Monasterio et al., (2023) who found growth-related injuries to be more burdensome within circa-PHV players, with pre-PHV players having a 3.2x lower injury burden than those going through their growth spurt. Similarly, the injury rate was highest in the U12-U14 teams during the 2012–2013 season within an elite academy, thus highlighting the consistent injury patterns over the past decade (Renshaw & Goodwin, 2016). Additionally, the injury rate appears to have increased from the year before the year of PHV, which van der Sluis et al. (2015) suggested applied to both early and late-maturing individuals. As a result, past literature demonstrates the importance of preventing injury occurrence among players undergoing their growth spurt.

Understanding injury incidence among different age groups can help practitioners identify individuals who may be considered vulnerable and, therefore, require increased attention. As mentioned previously, PHV may have temporary adverse effects on both coordination and motor competence, as shown within the adolescent awkwardness phenomenon (Sheehan & Lienhard, 2019). This increased growth rate has been shown to have a positive, linear relationship with injury incidence, as well as a positive yet non-linear relationship with injury burden (Johnson et al., 2022). A widely accepted reason for the enhanced injury rate may be the vulnerability of growth plates within the growing bone to shearing injuries at the epiphyseal-metaphyseal junction (Caine et al., 2014), with another being the traction of tendons and repetitive strain caused by the pull of the muscle (Corbi et al., 2022) due to the reduced growth rate of tendon in comparison to the faster-growing bone (Launay, 2014). Resultingly, research has demonstrated a significant correlation between adolescents' growth spurt and injury incidence.

Although research has favoured a heightened injury risk in those during their growth spurt, it is vital to understand injury patterns between age groups to aid in the personalisation of prevention and rehabilitation programmes for specific cohorts. Literature has widely agreed that adolescents during their growth spurt are more subject to growth-related injuries, whereas players post-PHV have a greater incidence of soft tissue pathologies. Monasterio et al., (2023) performed a two-decade study using a Spanish academy and found post-PHV players to have a greater incidence of muscular and ligamentous injuries, with Hall et al., (2022) similarly reporting a higher incidence of growth-related injuries within pre-PHV compared to post-PHV players. Light et al., (2021) reported bone-related injuries peaking in the U13 players, whereas groin muscle strains peaked in the U15 players. Although similar, this finding may present differently if there was a greater percentage of later-maturing players compared to the 13% within the U15 sample used in this study. One reason for the greater rate of soft tissue injuries among post-PHV players may be due to the overall distance and quantity of high-intensity effort experienced in older age groups (Goto et al., 2015), thus increasing the risk of injury if individuals have not been subject to higher chronic training loads (Malone et al., 2018).

Although research often adopts maturity status as a primary dependent variable, it is also essential to understand how maturity timing may influence injury trends. To allow practitioners who are unable to access biological data to monitor performance and injury trends, it is important to be aware of the expected proportions of maturation timings across chronological age groups. When comparing literature, it is essential to note that various methods for establishing biological timing have been employed, so maturity timing comparisons must be conducted with caution. Past studies have compared the age of PHV to a chronological age, such as being younger than the age of 13 at the time of PHV resulting in a player being deemed an early maturer (Goto et al., 2019), with others using a player’s Z-score, defined as the standard deviation difference between current and expected maturity status (Sweeney et al., 2024). Regarding comparisons between literature, it seems agreed that the number of early and on-time matures within a particular age group outweighs the number of late maturers, often with most children being categorised as on-time maturers. This is shown by the average-early timing classification being the most common timing out of 159 elite youth soccer players (Hirose, 2009), alongside the classification displaying the highest incidence for both club and elite adolescent footballers (Figueiredo et al., 2016), with both studies reporting a substantially lower number of players of late maturity. Additionally, Atkins et al., (2016) found the on-time maturity group to dominate out of 105 players, with Goto et al., (2019) classing 81% of participants to be classed as an on-time maturer. It is, therefore, clear that practitioners can expect a higher quantity of on-time maturers, with players of late maturation sparsely included, which may aid practitioners when designing interventions to target the entire group.

As mentioned, children can be grouped based on the timing of maturation alongside the stage of growth; therefore, considering whether a player is an early, on-time, or late maturer is necessary to elicit correct injury monitoring and rehabilitation practices. Previous research appears to be less clear-cut compared to maturity status in determining which maturity timing is associated with the greatest injury risk. Although it is assumed that maturity timing may impact injury during specific stages of the maturation process, Johnson et al. (2020) found no significant differences between maturity timing and both injury incidence and burden when analysing maturity timing in 76 U11-16 academy footballers. Alternatively, van der Sluis et al., (2014) found that players maturing at an older age experienced significantly more overuse injuries than early-maturing players both before and during puberty, potentially due to a reduction in strength and power resulting from reduced game time compared to their early-maturing peers. Contrastingly, injury burden was found to be 2.8x and 3.6x higher in matches and training, respectively, in early compared to late matures within an U14 academy age group (Monasterio et al., 2022), with muscular injuries being 4x more burdensome in early matures, yet no significant differences were evident for growth-related injuries. Additionally, Monasterio et al., (2022) discovered that early maturers had six times higher hamstring injury burden than on-time maturers. One reason for the greater incidence of muscular injuries, rather than growth-related, may be due to the higher physicality of earlier maturing players. Saward et al. (2019) reported a higher number of tackles from early-maturing players compared to on-time players. Although injury risk will not be directly measured in this study, it can be predicted that early-maturing players will produce a greater force output compared to their later-maturing teammates, allowing for indirect assumptions to be made about individuals vulnerable to injury.

Prevalence of Hamstring and Quadricep Related Pathologies

When analysing literature, research may deviate in the terminology used, with the terms KE and quadriceps strength being used interchangeably, as is the case for KF and hamstring strength. Although only the quadricep group performs KE, and the hamstrings are the prime agonist for KF, the action of KF is also performed by gracilis, sartorius, gastrocnemius, plantaris, and popliteus (Mansfield & Neumann, 2023). As a result, the term "hamstring strength" used throughout this study refers to all knee flexors due to the impossibility of solely isolating the hamstring group.

Recent literature has focused on the incidence rate of adolescent injuries, with hamstring and quadriceps-related pathologies being of great significance due to their commonality in both adolescent and senior football.

Muscular injuries have been found to account for 28% of total injuries within an elite footballing academy in Germany (Weishorn et al., 2023), with the thigh muscles being particularly affected, which is also supported by Dias (2014) who found the thigh to be the most common injury site for time loss injuries when examining an U17 age group, some of whom may have been late-maturers. Similarly, Read et al., (2018) discovered muscle strains to account for the greatest percentage of all injuries when exploring injury incidence in six professional football academies. Specifically, Skomrli et al., (2024) discovered a slightly greater rate of hamstring injuries compared to quadriceps within an U15 Croatian squad, whereas Read et al., (2018) found the quadriceps to have the greater injury rate. Regardless of which muscle group has the greatest injury prevalence, adolescents are clearly at risk of injury to either area, thereby increasing the need for further research on epidemiology, risk factors, and, consequently, preventive measures.

Previous literature has generally found that the thigh is the most frequently injured area among adolescent footballers (Dias, 2014), with the area being subject to both muscular strains and apophyseal pathologies and also having the potential to disrupt the entire lower-limb kinetic chain further. As a result, this project will specifically focus on hamstring and quadriceps inter-limb asymmetries, as well as varied H:Q ratios, within youth players to aid in the detection of potential risk factors for lower-limb pathologies.

Regarding the severity of injuries, research on senior players is abundant compared to adolescents, again highlighting the need for further research on specific injury trends among adolescents. Nevertheless, research involving the analysis of 121 severe muscular lower limb injuries over three seasons within Serie A showed that the dominant side is more susceptible to a serious injury, with the quadriceps group often more at risk compared to the hamstrings (Della Villa et al., 2023); one reason for this finding may be due to the increased limb dominance for quadriceps injuries compared to other major muscle groups, thus exposing the quadriceps to more unilateral load compared to other musculature (Della Villa et al., 2023). However, it must be stated that 88% of severe muscle injuries within this study occurred during running, open and closed kinetic stretching, and kicking, all of which have the potential to cause either a quadricep or hamstring injury. This, therefore, highlights the consideration that should be taken during injury screening and return-to-play and that ‘sport-specific’ movements should be replicated to assess injury risk fully. Additionally, there is a clear need for increased research regarding the analysis of hamstring and quadriceps incidence and severity rates in adolescents, meaning that future literature does not have to base its findings on those using senior players.

Regarding discrepancies in injury rates between different hamstring musculature, a recent literature review by Kellis (2018) showed that the biceps femoris long head (BFlh) is the most vulnerable to injury due to the heightened peak muscle-tendon unit (MTU) strain during the late swing phase when sprinting, primarily because of its shortened fibre length. Contrastingly, SM is more commonly injured during excessive stretching compared to sprinting. Concerning ST, this appears to have the lowest injury rate, mainly due to its greater MTU length compared to the other hamstring muscles (Kellis, 2018).

The differences in hamstring mechanisms can be placed into categories. Type 1 injuries occur while sprinting, which entails the maximum eccentric muscle action occurring simultaneously with muscle elongation, with the BFlh being the most involved compared to the semimembranosus for type 2 pathologies. However, type 2 injuries involve excessive lengthening of the hamstrings when the hip is flexed and the knee is extended, such as during the late swing phase of a kick (Garcia et al., 2022), which is the most common mechanism (Danielsson et al., 2020). As hinted by the mechanisms of injury, an indirect mechanism is accountable for approximately 80% of hamstring injuries (Garcia et al., 2022).

Previous literature has reported a significantly higher incidence of quadriceps injuries resulting from kicking, rather than sprinting. Jokela et al., (2023) analysed 20 videos of rectus femoris (RF) injuries in 19 professional footballers and discovered that kicking was the most common mechanism, causing 80% of quadriceps injuries. In contrast, sprinting and change of direction accounted for 10% of injuries each, with sprinting injuries occurring at maximal speed. Additionally, Della Villa et al., (2023) showed that of the 16% of overall injuries, causing an injury burden of >28 days, obtained throughout three seasons within Italy's Serie A, 56% of these involved the quadriceps, with a total of 78% of quadricep injuries being the result of a non-contact mechanism. Regarding adolescents, Skomrlj et al., (2024) proved kicking to be the most common mechanism for quadriceps injuries when analysing U15 Croatian players. It is crucial to obtain quadriceps injury data from studies that have used adolescents as their sample. However, the literature using adolescents is sparse, so injury generalisations will have to consider injuries occurring in senior football alongside those in adolescents.

Due to RF crossing both the knee and hip, alongside its fusiform structure, it is well suited to allow the execution of movements requiring a high shortening velocity or significant change in length, alongside having a high proportion of type 2 muscle fibres, thus making it more prone to injury compared to other quadriceps musculature (Mendiguchia et al., 2013).

Within adolescents, it is crucial to consider apophyseal injuries as players undergo the period of PHV (van der Made et al., 2013). Generally, literature has proved that the anterior inferior iliac spine (AIIS) is the most common site for an apophyseal injury. The AIIS is located slightly proximal to the anterior superior acetabular rim, serving as an attachment point for RF; these injuries are known as a sprinter's fracture, as they often occur during hip hyperextension and KF (Sato et al., 2024). A 7-year longitudinal study featuring FC Barcelona's academy found that 43% of apophyseal injuries involved the AIIS, with only 10% of cases involving the ischial tuberosity (Gudelis et al., 2022). Similarly, the AIIS accounted for 39% of apophyseal injuries over four consecutive seasons within the U9-19 age groups (Materne et al., 2011), thus further demonstrating the domination of AIIS apophyseal injuries compared to other anatomical locations and highlighting the considerations that should be noted when differentiating between RF muscle strains and AIIS apophyseal injuries.

Avulsions of the ischium are becoming a commonly recognised injury, with the mechanism often being a forced eccentric contraction of the knee and hip flexion during kicking or sprinting (Neuschwander et al., 2015). Although uncommon, avulsion fractures of the ischial tuberosity occur due to the weakened and still developing secondary ossification centres, which are frequently overpowered by the hamstring tendon (Schoensee & Nilsson, 2014), and, similarly to hamstring muscle strains, occur proximally rather than distally (van der Made et al., 2013). Avulsion fractures are, therefore, due to failure through the secondary apophysis, and those with an IT avulsion fracture are often younger than others with pelvic avulsion pathologies, as the ossification centre forms early (Schiller et al., 2017). This concept is further supported by Beltran et al. (2012), who stated that the weakest link within the muscle-tendon-bone unit in children is at the apophyseal attachment of the muscle, compared to the MTJ in older athletes. Similarly to avulsions to the AIIS, practitioners must be cautious when diagnosing proximal hamstring strains, as the potential for an ischial apophyseal injury to be apparent may exist instead.

The average age of adolescents with avulsion fractures tends to be between 13-18 years of age (Schoensee & Nilsson, 2014). However, increasingly precise ages of 14.7 and 14.4 years have been reported by Vadhera et al., (2022) and Mitchell et al., (2021), respectively, which would seem appropriate given that this age marks the onset of the period of PHV (Leite Portella et al., 2017). Lastly, during a longitudinal study centred on apophyseal injuries, it was shown that hip apophyseal injuries were more common in 12–14-year-olds, whereas those in the leg occur more frequently in 10–12-year-olds (Gudelis et al., 2022). Therefore, although muscle strains are significantly more common than avulsion fractures, practitioners must be aware of apophyseal conditions to aid in injury diagnosis and prevention programmes.

To assess hamstring and quadricep strength, practitioners can take various approaches regarding cost, time available, and dependent variables. Generally, strength can be measured using a HHD or an IKD. An IKD is a computerised machine capable of providing multiple elements of measuring muscle strength. On the other hand, a HHD is a convenient, portable device that generally measures isometric strength in comparison to the isotonic contractions prevalent when using the IKD (Stark et al., 2011). Although significantly cheaper, a 19-study systematic review, composed by Stark et al.

(2011), found the HHD to demonstrate moderate-to-good reliability and validity when compared to isokinetic testing, indicating that the HHD is a clinically strong choice of equipment when cost, time availability, or location may be a concern.

Asymmetry and Injury Risk

Within sports that utilise unilateral movements, strength differences between limbs often become apparent due to one side being designated the 'dominant' side while the other is termed the 'non-dominant' side; these strength differences are known as strength asymmetries (Fousekis et al., 2010). Lower-limb asymmetries are not uncommon in sports; however, the literature has suggested that asymmetries exceeding the 10% limb symmetry index (LSI) have an association with injury (Fort-Vanmeerhaeghe et al., 2016), thus emphasising the need to minimise asymmetries.

Several methods for calculating strength asymmetries exist, each with its limitations and producing fluctuations when applied to the same data. Additionally, literature often employs various names for the same calculation, thereby making comparisons between formulas increasingly challenging.

A recent systematic review evaluated the functions of twelve asymmetry indices used to examine strength asymmetries (Parkinson et al., 2021). Out of the 12 formulas, only 4 overcame the limitations of selecting a reference limb. Two of the four formulas (referred to as index-11 and -12) produced non-linear outputs, meaning that identical magnitudes of changes to asymmetry scores do not correspond to identical changes in the magnitude of the raw input values. Furthermore, although suited to unilateral movements, another asymmetry calculation (index-9) required normalisation to a reference value, thus potentially leading to the artificial inflation of asymmetry scores. Lastly, index-10 is generally implemented when performing bilateral tasks. However, it has still often been used for single-leg isokinetic assessments despite this. In contrast to index-9, index-10 is more likely to deflate asymmetry scores because it divides the absolute difference by the sum of both limb values.

As a result, there is an apparent difficulty when selecting which asymmetry calculation to adopt. It is, therefore, essential to examine the methods employed in similar studies to ensure a reliable comparison of data. Unfortunately, it appears that most studies have failed to report the precise calculation used to assess asymmetry; however, upon expanding research criteria to apply to a variety of neuromuscular sporting movements, it appears that index-10, commonly referred to as the Symmetry Index, is frequently used, thus serving as a strong rationale to use within this project. See the formula method.

The commonality of lower-limb asymmetries necessitates a holistic approach, with asymmetries present across various fitness components, both kinematically and kinetically. For example, 21.4% of male participants between the ages of 10 and 16 exhibited limb symmetry of less than 90% during a single-leg countermovement jump (SLCMJ) (Ceroni et al., 2012). Additionally, Read et al., (2018) demonstrated reduced hip range of motion (ROM) alongside differences in hamstring and quadriceps isokinetic strength within a group of 347 male adolescents. The reasoning behind these asymmetries may be due to excessive unilateral load during specific movements, resulting in one limb adopting certain neural-motor patterns that lead to varied morphological and strength asymmetries (Mala et al., 2020). Specifically, regarding football, the non-dominant limb may, therefore, adapt with greater strength and balance. However, the dominant side may produce enhanced coordination and skill (McElveen et al., 2010). Therefore, it is generally expected that asymmetries will be apparent, especially in adolescents who rely significantly on their dominant side.

The link between lower-limb asymmetries and injury risk in the literature is unclear due to conflicting evidence; however, the proposed theories demonstrate logical reasoning between asymmetry and injury occurrence. A commonly agreed-upon concept in football is the distinction between a dominant and non-dominant limb, as players tend to rely more heavily on one limb, potentially leading to the non-dominant limb adapting with greater strength and balance while the dominant limb acquiring greater coordination and skill (McElveen et al., 2010). This may ultimately increase stability and force absorption on the non-dominant limb (Read et al., 2018), thereby leading to muscle recruitment efficiency or biomechanical differences between limbs, which may justify the increased incidence of injury. Additionally, force production asymmetries have been demonstrated to be partly due to reduced lean mass, thereby showing associations with greater joint laxity, which may again increase injury incidence (Bell et al., 2014). Although theories establishing the link between asymmetries and injuries are essential for drawing conclusions, incorporating evidence-based approaches is also crucial for establishing factual cause-and-effect relationships.

A recent systematic review conducted by Helme et al., (2021), analysed the statistical association between lower limb injury and asymmetry within 31 studies. Out of these, only three studies specifically focused on hamstring or quadriceps strength asymmetries while being classified as at least moderate quality on the Critical Appraisal Skills Programme (CASP) checklist. A link between KF asymmetries and the development of hamstring strains was found (Fousekis et al., 2010). A similar finding showed a positive correlation between KF strength asymmetries of over 15% and higher injury rates (Knapik et al., 2021). Although Fousekis et al., (2010) used only males, compared to the complete gynocentric sample used by Knapik et al. (2021), both studies showed no significant correlations between quadriceps asymmetry and injury, ultimately suggesting that prevention protocols should be hamstring-focused. Contrastingly, the third study within the systematic review demonstrated that asymmetries exceeding 10% did not increase the risk of a hamstring injury, as the correlation between KE asymmetry and injury was not investigated. These studies exhibit the ambiguity surrounding the link between strength asymmetries and injury risk, as they fail to use adolescents and employ a combination of isometric and isokinetic methods. Therefore, they should be studied further to aid in building solid conclusions within an adolescent population.

Previous research analysing quadriceps and hamstring asymmetries while comparing maturities is lacking, with a failure to produce shared conclusions, alongside most studies comparing age groups rather than maturities. No between-group differences were found by Peek et al., (2018), yet KE asymmetries appeared more prevalent compared to KF asymmetries. Contrasting research revealed that the U13 and U15 age groups exhibited significantly higher levels of asymmetry in quadriceps and hamstring strength compared to the U17 age group, indicating the impact that maturity may have had in this study (Kalata et al., 2021). Interestingly, 68% of U15 players exhibited hamstring strength asymmetries over the 10% threshold compared to the U13 and U17 groups. One reason for the difference in results between the two studies may be the increased U15 sample size, with Kalata et al., (2021) using 25 U15 players, compared to the eight used by Peek et al., (2018). Lastly, Maly et al., (2016) showed that more than 73.2% of players exhibited at least one strength asymmetry, with the hamstring group displaying larger asymmetries compared to the quadriceps group when analysing 41 U16 players. This result contrasts with the heightened quadriceps asymmetries found by Peek et al., (2018). However, it is worth noting that Maly et al., (2016) used only U16 players, which highlights that most of the sample would have consisted of post-PHV players. Overall, it is clear that ambiguity exists in the current literature regarding the impact of maturity on hamstring and quadriceps asymmetries, as well as the prevalence of asymmetries within the hamstring and quadriceps groups, highlighting the need for further research to clarify these conclusions.

Further research with similarities to this project examined bilateral KE and KF asymmetries, as well as H:Q ratios, in 80 Brazilian footballers aged 12-17 (Souza et al., 2024). Players were grouped into a pre-PHV and post-PHV group, with findings showing no links between maturity status and the H:Q ratio or knee extensor and flexor asymmetries and maturation. However, this study failed to incorporate a circa-PHV group alongside measuring isokinetic rather than isometric strength, therefore providing novelty grounds for this project. The findings suggest that no differences will be found between maturities. Nevertheless, this was a novel piece of research, thus meaning assumptions cannot be made due to a failure of supporting research. Additionally, children undergoing their PHV were not included in this study; therefore, this provides an opportunity for further research to build on the existing work. Previous research appears contradictory when discussing the impact of maturity on muscular asymmetries; as a result, it is increasingly complex to predict the outcome of this study.

To my knowledge, there is no current research examining the impact of maturity timing on muscular asymmetries as most of the focus is centred on maturity status. As a result, this can be understood as a piece of novel research. It is, therefore, difficult to predict if significant differences will prevail regarding hamstring and quadricep muscular asymmetries between different maturity timings within the same maturity status groups. By examining the timing of maturity within children in the same maturity status group, it can be suggested that there will be a similar impact on muscular asymmetries between maturity status and timing. Previous literature has shown an unclear link between the effect that maturity may have on hamstring and quadriceps asymmetries. In the absence of empirical evidence, no solid conclusions can be drawn when predicting the impact of maturity timing on muscular asymmetries.

H:Q Ratios and Injury Risk

A person's H:Q ratio is defined as the division of a person's hamstring strength by quadriceps strength (Fritsch et al., 2023). This is termed the conventional approach; however, research has shown variation in outcomes when using a conventional versus a functional approach. The conventional approach compares a hamstring and quadriceps concentric contraction, whereas the functional approach involves dividing eccentric hamstring strength by concentric quadriceps strength (Holcomb et al., 2007). Although the conventional ratio is generally the most common method, as only an isometric contraction is required, the functional method has gained recent popularity due to its functionality and better representation of the muscle requirements necessary in sports (Fritsch et al., 2023). Regarding normative values, research has generally agreed on an achievable ratio of 0.6 and 0.8 for the conventional and functional ratio within adults, respectively (Fritsch et al., 2023). Nevertheless, past literature has frequently demonstrated that adolescents achieve lower hamstring strength than the 0.6 conventional threshold, thus highlighting the potential for a reduced H:Q threshold for adolescents. Research is lacking regarding the production of a set of thresholds for adolescents; therefore, this study will adopt the 0.6 threshold.

Similarly to asymmetry research, current literature tends to focus on senior-age players rather than adolescents, thus reducing the generalisability of findings to adolescents. Available literature examining H:Q ratios in adolescents is somewhat mixed, with studies varying in their use of an IKD and HHD. Peek et al., (2018) explored H:Q ratios in 110 8-15-year-old academy footballers using an HHD and found that over one-third of players aged 12-15 demonstrated an isometric H:Q ratio of less than 0.60. Additionally, the largest reduction in the ratio was evident between players aged 11-12, with a drop from 0.82 to 0.65. Although it is difficult to explain this reduction fully, one reason may be that some players are beginning to go through the period of PHV; however, this study did not report on individual player maturities. Similarly, Mandroukas et al., (2023) found that U12 footballers exhibited smaller H:Q ratios than U20 players, thus suggesting that maturity status may partly determine H:Q ratios. However, contrasting literature has shown no links between maturity status and H:Q ratios in adolescent footballers, thus questioning the extent to which maturity affects strength differences between players (Souza et al., 2024). Additionally, Ishoi et al., (2021) demonstrated that out of 125 U13-senior-level players, the U15 category was the only age group to achieve an H:Q ratio of 0.62, thereby exceeding the generally agreed-upon threshold of 0.6. Surprisingly, the senior group demonstrated the lowest H:Q ratio, with a value of 0.44, thus again contradicting the theory that PHV may lower the ratio and highlighting the need for further research to clarify the vulnerability of certain players to hamstring and quadriceps muscular imbalances.

Additionally, a recent systematic review, conducted by Gao & Luo (2024), explored quadricep, hamstring, and H:Q ratios within 13 studies involving adolescents, yet only two studies involved male athletes whilst maintaining temporal validity. One paper in the review showed no significant differences in the conventional ratio between 14- and 18-year-olds (Nagai et al., 2021), thus contradicting the literature that displays maturity differences in ratios produced. The second study compared 10 15-year-olds and 14 senior players (Hadzić et al. 2013). Findings showed a significant difference between the two groups regarding the non-dominant side, with the adolescent group averaging a ratio of 0.53 compared to 0.68 in the senior group. This finding contrasts with that of Ishoi et al., (2021), who found that senior players exhibit a lower H:Q ratio; however, it supports previous studies that demonstrate the influence of maturation on H:Q ratios. As a result, it is clear that the current literature on adolescents has contrasting findings, which means that solid conclusions cannot be drawn. This, therefore, highlights the need for further research on the impact of maturation on H:Q ratios to aid in identifying vulnerable age groups, thereby enabling the development of targeted prevention programmes to reduce injury risk and enhance performance.

Similar to the deprivation of asymmetry research, a lack of research exists when exploring the impact of maturity timing on H:Q ratios. Literature has generally found that early maturing players are often physically superior (Fink et al., 2024) compared to their later maturing counterparts of the same chronological age (Ostojic et al., 2014). However, this does not necessarily correspond to having a greater H:Q ratio. Without data concerning isolated muscular group strength at different maturity timings, it is difficult to make accurate assumptions regarding the change in maturity timing and H:Q ratios. Although under-researched, the literature has shown that early maturers have a six times greater hamstring injury burden compared to on-time maturers (Monasterio et al., 2022). While lacking empirical evidence, due to the strong link between lower H:Q ratios and hamstring injuries (Lee et al., 2018), it may be suggested that the early maturers may be more susceptible to lower H:Q ratios, though due to the lack of supporting research, further research is needed to support this assumption.

Unlike the ambiguous relationship between asymmetries and injury, the link between reduced H:Q ratios and injury appears to be more evident. Various studies have shown that the non-dominant limb often exhibits reduced ratios compared to the dominant side. Maly et al., (2016) displayed an average reduced conventional H:Q ratio for the non-dominant side when analysing 41 U16 footballers. A similar finding was reported by Pellicer-Chenoll et al., (2017), who reported lower ratios in the non-dominant leg within their sample of 14 males and 14 females, with the dominant side showing an average of 9% higher values. Additionally, a significant relationship was found between H:Q ratios lower than 0.6 and an increased incidence of left leg injuries in 40 male and 42 female college basketball players (Kim & Hong, 2011), potentially highlighting the vulnerability of the non-dominant side. This, therefore, may support the presence of a positive relationship between lower-limb asymmetries and injury occurrence. However, injury occurrence is multifactorial, thus meaning that asymmetries cannot explain injury occurrence entirely.

It has been proposed that a reduced H:Q conventional ratio is due to both strengthened quadriceps and weakened hamstrings (Fritsch et al., 2023), which affects numerous parts of the musculoskeletal system. From a muscular perspective, Lee et al., (2018) showed a significant relationship between HSI and a conventional ratio below 50.5%. On the other hand, when discussing ligamentous injuries, reduced hamstring strength may lead to excessive tibial anterior translation, a key mechanism for ACL injury (Holcomb et al., 2007), as the hamstrings are unable to counteract the excessive quadriceps force (Pfeifer et al., 2018). Therefore, athletes must maintain significant hamstring strength to reduce their susceptibility to muscular and ligamentous injuries. In addition to soft tissue pathologies, growth-related issues may also be partly due to muscular imbalances. Research by Nasake et al. (2015) showed that a precise risk factor for Osgood-Schlatter's Disease (OSD) was increased quadriceps strength when comparing 10 adolescents with OSD to 60 control subjects. Theoretically, this would make sense due to the repetitive pull from the patellar tendon on the tibial tuberosity. However, this study failed to explicitly examine H:Q ratios, therefore making assumptions regarding the relationship between reduced H:Q ratios and OSD invalid. Additionally, this appears to be the only study examining the effect of quadriceps strength on OSD; therefore, future studies should investigate this link before solid conclusions can be drawn. It appears that reduced H:Q ratios can be partly associated with increased lower-limb injury incidence; however, injury incidence is a vast and complex topic, and therefore, cannot be explained solely by muscle imbalances.

Chapter 3 Method

Research Design

A quantitative experimental research design was employed, with testing conducted within a single session in a controlled laboratory environment. All sessions commenced at York St John University Sports Centre in early January, marking the midway point of the season. Testing took place in the morning and early afternoon, with each age group attending an allocated time slot in chronological order. Three groups were created, corresponding to each stage of biological maturation (pre-, circa-, and post-PHV groups), with each group completing all tests under the same conditions.

Participants, Sampling and Recruitment

Recruitment involved 46 male adolescent footballers, all of whom played for the same Junior Premier League Academy during the 2024-2025 season, competing within the U12-U16 age groups. See Table 1 for player anthropometrics. At the time of testing, all players involved were free from any lower-limb injury that may have impacted the amount of KE and/or KF strength exerted; my clinical judgement was used to assess whether a player was fully fit to complete the trials. Participants were selected if they were deemed fit enough for the trials, regardless of their playing position, and all participants spent the entirety of the 2024/25 season at the club.

A convenience sample was used in this study, as external recruitment strategies were not necessary due to the selected tests being included in the mid-season testing session at the Junior Premier League Club.

All parents and players at the Academy are required to complete a registration document at the start of each season (see Appendix A). On this, parents/guardians consented to the regular, periodic testing conducted by York St John University for research purposes. This is an electronic document that is signed by the player's parent or guardian at the start of the season, thereby acting as a form of passive consent from both the parent/guardian and the player. Additionally, in the week before the January testing period, players and parents were emailed an information sheet outlining the demands of the specific tests used in this project, along with relevant information. This ensured that informed consent was obtained and that an opportunity to ask any questions was available, either during training or on the day of testing. Due to parent involvement in the consensual processes, players' parents and/or guardians were deemed the appropriate gatekeepers for this project.

Ethical approval was granted, and a thorough risk assessment was conducted, thereby aiding in the protection of participants from harm (e.g., muscular injury). Ethics was reviewed by the YSJU Science, Technology, and Health Ethical Panel, with the reference number being ETH2324-0401.

Procedure

Upon arrival, player anthropometric measurements were taken by recording each player's standing height and weight. Standing height measurements involved players standing barefoot on a portable stadiometer. Each player was instructed to take a deep breath while their height was measured to the nearest 0.1 cm. To measure body mass, players were asked to stand barefoot on a set of portable weighing scales whilst wearing their normal training attire.

Due to the nature of testing, only dynamic stretching was deemed appropriate, given the potential link between static stretches and reduced muscular force (Chaabene et al., 2019). Due to time purposes, players completed a variety of self-directed stretches, ensuring that the quadriceps and hamstrings were predominately targeted to reduce injury risk.

Before performing the tests, players reported their names and the dominant leg they used to the researcher. Participants completed one submaximal familiarisation trial for each movement on both limbs. To complete the trials, participants were asked to lie in a prone position on a mat with one leg relaxed while the testing leg was flexed at 90 degrees at the knee joint. Testing procedures used by Peek et al., (2018) were adopted within this study due to it being described as both a reliable and valid method within literature; this involved an isometric hamstring and quadricep contraction performed in a prone position.

Players were first instructed to extend their left knee as hard as possible, with the researcher ensuring that their leg remained stationary so that an isometric contraction could be performed. Contractions were sustained for three seconds before resting, with a total of two trials performed for each movement on both legs. During the KE action, if the player started to overpower the researcher, began to extend their hip, or experienced any pain or discomfort, this was considered a false trial, and the movement was performed again. Once two successful left and right KE trials had been completed, players were then asked to perform the KF tests. This involved the players trying to bring their heel back as hard as possible, again for three seconds, whilst ensuring an isometric contraction was obtained. The same exclusion criteria were applied for KF alongside KE, with participants completing the trial again until two successful trials had been completed. Once testing had commenced on the left leg, testing then moved to the right leg, with the same principles applied. To increase the standardisation of testing, the same verbal instructions and encouragement were given to each participant.

Hand placements for KE entailed the HHD being placed on the player's anterior distal tibia, with the researcher applying a posterior force to counteract the KE movement. Regarding KF, the HHD was positioned on the posterior distal calf, with the researcher providing an anterior force to counteract the force applied from the KF. To enhance intra-rater reliability, the same researcher was utilised for each test, thus ensuring that hand placements remained consistent across trials.

Apart from using a researcher to apply a counter force rather than a leather harness, alongside players performing the testing on a mat rather than a massage plinth, testing protocols followed those shown by Peek et al., (2018), who displayed good-excellent levels of intra-tester reliability when using the same testing positions as shown in this study.

To minimise the potential for researcher bias, the researcher and player were not allowed to view results until all tests for the participant had been completed. Once completed, the results were documented on a paper-copy table, which was then converted to an electronic format after all players had been tested.

Measures

Muscle Strength Assessment

To retrieve data, the handheld Activforce 2 HHD was used for all testing; this was chosen over the use of an IKD due to a lack of time available and reduced practicality of using an IKD, alongside allowing a larger sample size due to the simplicity and ease of using a HHD. As mentioned previously, Stark et al., (2011) showed the HHD to demonstrate moderate-to-good reliability and validity when compared to isokinetic testing during a 19-study systematic review.

Peak isometric force data was recorded after each successful trial. An isometric contraction was analysed as for an isokinetic contraction to be recorded, an IKD would have to have been used. This is due to the lack of standardisation between trials, particularly if an isokinetic contraction had been involved, as the varied angular velocities between players could not be accurately controlled. Using a researcher to control the speed of movement would have been problematic, thereby reducing project validity and increasing human error.

Biological Maturity Calculations

To correctly group participants, each player's %PAH was calculated using the Khamis-Roche method. The Khamis-Roche method was used to predict a child's %PAH, thus providing each player's maturity status. This method uses the participant's standing height (cm), body mass (kg), chronological age (years) at the time of testing, and self-reported parental standing height (cm) (Ruf et al., 2021). Importantly, birth parent heights were corrected for overestimation before a figure for %PAH was produced. The parent's height was obtained at the beginning of the 2024/25 season through the online registration document, whereas the player's height and weight were recorded at the beginning of the testing session. The Khamis-Roche method is as follows: $\beta 0 + \beta 1$stature + $\beta 2$weight + $\beta 3$mid − parent stature. The $\beta 0$ represents the values of the intercepts, whilst $\beta 1$, $\beta 2$ and $\beta 3$ are values corresponding to stature, weight and mid-parent stature, respectively, which are then multiplied (Sweeney et al., 2024).

Maturity category thresholds were determined by the player's %PAH. Players were classed as pre-PHV if they were <88% of PAH. Alternatively, players placing between 88-96% of their PAH were placed in the circa-PHV group, whereas those players >96% of their PAH were categorised as post-PHV (Monasterio et al., 2021).

Participants were further divided based on their biological timing. To complete this, a maturity z-score for each participant was produced using the formula $Z = (X - \mu) / \sigma$; within the formula, X represents the individual score, μ represents the mean of the population, whereas σ represents the standard deviation of the population. Thresholds for categorisation entailed a score between -0.5-+0.5 indicated a player was an on-time maturer, whereas a score lower or high than the mentioned scores corresponded to a player being deemed a late or early maturer, respectively (Sweeney et al., 2024). When interpreting maturity timing data, players have been grouped into timing categories within each maturity status group. Although it would have been beneficial to group players based on chronological age when exploring maturity timing differences, this was not possible due to a saturated sample size within certain age groups, thus significantly reducing the sample size.

Asymmetry Analysis

As stated previously, literature has used a variety of different asymmetry calculations, all of which have both strengths and weaknesses (see literature review for an analysis of asymmetry calculations). For this project, the formula commonly referred to as the 'Symmetry Index' was used. Reasoning for this selection over other methods included the absence of having to select a reference limb, the simplicity to implement the formula, alongside the formula being more likely to deflate asymmetry values rather than inflating them, thus reducing the chance of a type 1 error occurring. Please see the formula below:

$$SI = \left(\frac{(\text{larger value} - \text{smaller value})}{\text{sum of values}} \times 100 \right)$$

Previous literature has used the 10% asymmetry threshold as an indicator for an increased injury risk (Fort-Vanmeerhaeghe et al, 2016). As a result, this study will also use the 10% threshold, with player's who score over this threshold being assumed to have an increased risk of injury.

H:Q Ratio Analysis

To calculate the H:Q Ratio for each player, a mean value for peak force for both KE and KF was calculated. Next, the average peak hamstring force was divided by the average peak quadricep force (Fritsch et al., 2023).

The conventional H:Q ratio calculation was used in this project compared to the functional ratio, with the main difference involving a concentric hamstring contraction used in the conventional ratio compared to an eccentric hamstring contraction used within the functional ratio (Holcomb et al., 2007). Although the functional ratio has been suggested to be more ‘sport-specific’, the conventional ratio is more commonly used within literature, featuring in research by both Souza et al., (2024) and Peek et al., (2018), therefore increasing the generalisability of results to other findings.

The 0.6 threshold will be used as a realistic aim for players to meet, thus meaning that the KF force should be at least 60% as strong as the KE force. The 0.6 threshold has been used in abundance throughout literature, with a clear link between reduced H:Q ratios and injury risk apparent (Kim & Hong, 2011), therefore acting as an appropriate reference point to be used within this study.

Injury Recording

As the purpose for inclusion of injury data is to provide a rationale for the analysis of thigh-related asymmetries, the focus on injury trends throughout the season is not a primary objective of this study. Resultingly, injury findings will appear in Appendix C.

Throughout the season, injury occurrence (i.e. number of injuries) and severity (i.e. time missed until match-fit) were monitored throughout. Injuries throughout the 35-week season were documented using an online software (Medinotes) to track injuries for all players at the club.

Any injury that caused a time-loss from training/match play was recorded (Fuller et al., 2006), therefore, any hard or soft tissue pathology that resulted in no time loss from training and/or a match was not recorded for use in this project. Although all time-loss injuries were recorded, only pathologies related to hamstring and quadricep musculature, alongside growth-related conditions occurring at the thigh, have been focused on. Specifically, this included hamstring and quadricep muscular strains and tendinopathies, with growth-related conditions including those involving the AIIS, inferior pole of the patella, and the tibial tuberosity.

Injury severity was determined by the quantity of days disrupted due to the injury. Using the classification system suggested by Walden et al., (2023), the following time frames were used for when assessing injury severity: 1–3 days, 4–7 days, 8–28 days, 29–90 days, 91–180 days and >180days.

Due to the likelihood of players progressing to the next maturity group throughout the season, chronological age was used to group players when interpreting injury data. To increase the quantity of injury data, all players who had spent the entire 2024/2025 season at the club were included, producing a sample of 70 players ranging from U12-U16 ages. This figure is greater than the quantity of participants involved in testing due to the unavailability of several players to attend the mid-season testing session. To clarify, injury findings within this study cannot be related to maturity findings and have been used to explore the occurrence of thigh-related pathologies to aid in the rationale for the focus of this study.

Statistical Analysis

All data was visually inspected for a normal distribution through Q-Q plots and presented as mean and standard deviation. Data analysis took place using Jeffreys Amazing Statistics Programme (JASP, v0.19.3 Intel, Amsterdam). When comparing group (pre-, circa-, and post-PHV) differences for all variables, a between groups ANOVA was used, whereas a Paired Samples T-Test was performed when comparing the dominant and non-dominant side whilst grouping all participants together, regardless of maturity. Similarly, when analysing maturity timing, a between groups ANOVA was used when comparing early, on-time, and late maturers within the pre-PHV group, although an Independent Samples T-Test was performed when comparing the early and on-time maturers within the circa- and post-PHV group due to the absence of any late developers. Effects size thresholds consisted off <0.2, 0.2, 0.5, and 0.8 for trivial, small, moderate, and large. Lastly, statistical significance for testing was set at $p \leq 0.05$ using the Bonferroni threshold. (Page, 2014)

Reliability Measures

To ascertain the reliability of the methodology and allow suitable interpretations, within-session reliability was calculated using intraclass correlation coefficient (ICC) and Coefficient of Variation (CV%), alongside 95% confidence intervals. ICC thresholds were 0.1, 0.3, 0.5, 0.7, 0.9, and 1.0 for low, moderate, high, very high, nearly perfect, and perfect, respectively (Hopkins et al., 2001). Additionally, each variable's reliability score was deemed 'acceptable' for an ICC ≥ 0.75 and a CV of ≤ 10%, or 'moderate' when the ICC failed to meet both the ICC and CV thresholds. Furthermore, potential 'learning effects' and bias between both trials for all movements were analysed using The Bland-Altman (BA) Limits of Agreement.

Chapter 4 Results

Descriptives

Initially, 50 participants participated in baseline testing. However, 4 participants had to be disregarded due to the impact of a result-altering injury as true peak values could not be recorded, thus leaving a total sample of 46 participants. As all players completed two trials for both left and right KE and KF values, each player therefore completed 8 trials, meaning that a total of 368 observations were recorded. Although players have been grouped concerning maturity status, in terms of chronological age, eight U12, six U13, thirteen U14, ten U15, and nine U16 players were included.

Table 1. Anthropometric data for each biological maturity status group

	Pre-PHV	Circa-PHV	Post-PHV
Participants (n)	12	17	17
Stature (cm)	151.97 ± 6.00	166.23 ± 6.80	180.93 ± 5.03
Body Mass (kg)	40.55 ± 5.95	52.82 ± 8.41	66.11 ± 8.03
Chronological Age	12.22 ± 0.53	13.99 ± 0.71	15.38 ± 0.79
Biological Age	12.46 ± 0.41	14.19 ± 0.60	16.59 ± 0.77
%PAH	85.34 ± 1.52	92.21 ± 2.37	98.54 ± 1.32
Left Side Dominant	2	5	3
Right Side Dominant	10	12	14

Within-session reliability

Within-session reliability for peak strength variables regardless of maturity are presented in Table 2. All four variables demonstrated ‘very high’ (ICC 0.7-0.9) reliability (Hopkins et al., 2001), with Bland-Altman analysis displaying minor within-session biases which marginally favoured Trial 2 for each variable. All variables demonstrated a CV percentage of ≥10%, thus providing ‘moderate’ reliability.

Table 2. Within-session reliability measures for peak isometric force variables

Dependent Variables	Trial 1 (Mean ± SD)	Trial 2 (Mean ± SD)	Mean Diff (%)	CV%	ICC (95% CI)	B-A Bias	LOA 95% CI (lower)	LOA 95% CI (upper)
Left KE Peak Force (N)	19.38 ± 3.54	17.96 ± 3.47	7.61	18	0.77 (0.63-0.87) Very high	1.42	17.69	19.65
Right KE Peak Force (N)	18.48 ± 3.66	17.82 ± 3.54	3.64	19	0.76 (0.61-0.86) Very high	0.65	17.15	19.15
Left KF Peak Force (N)	11.38 ± 2.32	11.07 ± 2.63	2.76	21	0.83 (0.72-0.90) Very high	0.31	10.52	11.93
Right KF Peak Force (N)	12.29 ± 2.78	11.83 ± 2.48	3.81	21	0.83 (0.71-0.90) Very high	0.46	11.32	12.81

Standard Deviation (SD), Confidence Interval (CI), Intraclass Correlation Coefficient (ICC), Bland-Altman (B-A), Limits of Agreement (LOA)

Maturity-specific within-session reliability measures are reported in Table 3. Each maturity group displayed at least 'high' (ICC 0.5-0.7) reliability for each strength variable, and all scored a CV percentage of ≥10%. Bland-Altman analysis showed trivial within-session biases which marginally favoured Trial 2 for each variable, apart from left KF for the post-PHV group, therefore displaying slight 'learning effects' due to the improvements gained in the second trial.

Table 3. Bio-banded (pre-PHV, mid-PHV and post-PHV) within-session reliability for peak isometric force variables

	Dependent Variables	Trial 1 (Mean ± SD)	Trial 2 (Mean ± SD)	Mean diff (%)	CV%	ICC (95% CI)	B-A Bias	LOA 95% CI (lower)	LOA 95% CI (upper)
Pre-PHV (<88% PAH, N = 12)	Left KE Peak Force (N)	17.32 ± 3.07	15.13 ± 2.82	13.50	17	0.68 (0.20-0.90) High	2.18	14.51	17.94
	Right KE Peak Force (N)	16.13 ± 3.57	15.77 ± 3.72	2.26	21	0.74 (0.31-0.92) Very high	0.37	13.80	18.10
	Left KF Peak Force (N)	9.16 ± 1.79	9.13 ± 1.94	0.33	20	0.87 (0.60-0.96) Very high	0.04	8.00	10.29
	Right KF Peak Force (N)	10.41 ± 2.25	9.90 ± 2.53	5.02	23	0.94 (0.79-0.98) Nearly perfect	0.51	8.66	11.65
Circa-PHV (88-96% PAH, N = 17)	Left KE Peak Force (N)	18.30 ± 2.85	17.09± 2.82	6.84	14	0.57 (0.14-0.82) High	1.21	16.41	18.99
	Right KE Peak Force (N)	18.15 ± 2.71	17.38 ± 3.19	4.33	16	0.86 (0.66-0.95) Very High	0.77	16.30	19.23
	Left KF Peak Force (N)	11.62 ± 1.37	10.74 ± 2.09	7.87	14	0.64 (0.24-0.85) High	0.88	10.36	12.01
	Right KF Peak Force (N)	12.34 ± 1.80	11.79 ± 1.54	4.56	12	0.60 (0.18-0.83) High	0.55	11.30	12.84
Post-PHV (>96% PAH, N = 17)	Left KE Peak Force (N)	21.91 ± 3.07	20.82 ± 2.21	5.10	12	0.70 (0.34-0.88) Very high	1.09	20.10	22.63
	Right KE Peak Force (N)	20.45 ± 3.64	19.72± 2.88	3.63	14	0.55 (0.11-0.81) High	0.74	18.60	21.57
	Left KF Peak Force (N)	12.70 ± 2.32	12.77 ± 2.55	0.55	18	0.82 (0.56-0.93) Very high	-0.07	11.54	13.93
	Right KF Peak Force (N)	13.57 ± 3.26	13.23 ± 2.39	2.54	20	0.77 (0.47-0.91) Very high	0.33	12.02	14.78

Peak Strength Analysis

Bonferonni's Post Hoc Test correction for multiple comparisons revealed that the mean left knee extensor peak force was significantly different between the circa- and post-PHV groups ($p = <.001$, 95% C.I. = [-5.84, -1.49]) and the pre-and post-PHV groups ($p = <.001$, 95% C.I. = [2.75, 7.53]). Mean right knee extensor peak isometric force was significantly different between pre- and post-PHV groups ($p = 0.002$, 95% C.I. = [1.31, 6.96]) whilst the mean left knee flexor peak isometric force was significantly different between pre- and circa-PHV groups ($p = 0.02$, 95% C.I. = [0.22, 3.86]) and the pre- and post-PHV groups ($p = <.001$, 95% C.I. = [1.77, 5.41]). Lastly, the mean right knee flexor peak isometric force was significantly different between pre- and post-PHV groups 2 ($p = 0.001$, 95% C.I. = [1.16, -5.33]). Regarding effect sizes, all comparisons between peak strength variables demonstrated at least a moderate effect size, with all comparisons between the pre-PHV and post-PHV group showing a large effect size. See Table 4.

Table 4. Maturity-specific peak isometric force differences

Peak Force Variables (N)	Pre-PHV (<88% PAH) Mean ± SD (95% CI) N = 12	Pre-PHV vs Circa-PHV p (Cohen-d)	Circa-PHV (88-96% PAH) Mean ± SD (95% CI) N = 17	Circa-PHV vs Post-PHV p (Cohen-d)	Post-PHV (>96% PAH) Mean ± SD (95% CI) N = 17	Pre-PHV vs Post-PHV p (Cohen-d)
Left KE	16.23±2.70 (14.51-17.94)	0.4 (0.57†)	17.70±2.51 (16.41-18.99)	<.001* (-1.47‡)	21.36±2.46 (20.10-22.63)	<.001* (2.00‡)
Right KE	15.95±3.39 (13.80-18.10)	0.35 (0.59†)	17.77±2.86 (16.30-19.23)	0.09 (-0.81‡)	20.09±2.89 (18.60-21.57)	0.002* (1.36‡)
Left KF	9.14±1.80 (8.00-10.29)	0.02* (1.21‡)	11.18±1.60 (10.36-12.01)	0.07 (-0.78†)	12.73±2.32 (11.54-13.93)	<.001* (1.69‡)
Right KF	10.16±2.35 (8.66-11.65)	0.08 (1.01‡)	12.07±1.50 (11.30-12.84)	0.26 (-0.61†)	13.40±2.68 (12.02-14.78)	0.001* (1.27‡)

*p <.001
‡Large. †Moderate. §Small. ǁTrivial.

Dominant vs Non-Dominant Asymmetry Analysis

For each asymmetry variable, each maturity group produced a mean value below the 10% threshold associated with an increased risk of injury (Fort-Vanmeerhaeghe et al, 2016).

For KE, the pre-PHV group produced an average asymmetry percentage of 4.77%, whilst the circa- and post-PHV groups scored 7.07% and 4.66% on average respectively. For KF, the pre-and circa-PHV group scored similar values with an average of 6.48% and 6.42% correspondingly, with the post-PHV group averaging a percentage of 4.26. As highlighted by the asymmetry percentages, no significant difference between asymmetry values produced between KE and KF when examining the group as a whole; $t(45)=-0.07$, p 0.95, C.I. = [-1.85, 1.73]), with a trivial effect size displayed ($d = -0.01$). Reduced effect sizes were seen when analysing asymmetry variables, with a combination of trivial-moderate effect sizes being prevalent (See Table 5).

Regarding the percentage of participants to produce asymmetry values succeeding 10%, 9.09% of pre-PHV players, 25% of the circa-PHV group, whereas 17.65% of the post-PHV group excelled past the 10% threshold concerning KE. For KF, 27.27% and 12.5% of pre- and circa-PHV players exceeded the 10% threshold, respectively, whilst all players in the post-PHV group recorded asymmetry values below 10%.

Table 5. Maturity-specific asymmetry differences

Asymmetry Variable	Pre-PHV Mean ± SD (95% CI) N = 12	Pre-PHV vs Circa-PHV p (Cohen-d)	Circa-PHV Mean ± SD (95% CI) N = 17	Circa-PHV vs Post-PHV p (Cohen-d)	Post-PHV Mean ± SD (95% CI) N = 17	Pre-PHV vs Post-PHV p (Cohen-d)
KE (%)	4.77±4.66 (1.81-7.73)	0.54 (0.55†)	7.08±3.79 (5.12-9.03)	0.37 (0.55†)	4.66±4.97 (2.11-7.22)	1.00 (-0.02‖)
KF (%)	6.48±4.63 (3.54-9.43)	1.00 (-0.01‖)	6.42±4.04 (4.34-8.50)	0.32 (0.62†)	4.26±2.85 (2.80-5.73)	0.39 (-0.60†)

*p <.001
‡Large. †Moderate. §Small. ‖Trivial.

Hamstring:Quadricep Ratios

All three maturity categories displayed a greater quantity of players failing to reach the 0.6 threshold on their left side compared to their right side. As 78% of participants were right-side dominant, it can therefore be assumed that the non-dominant side produced a lower H:Q ratio compared to the dominant side across all maturities.

For the pre-PHV group, 64% of players scored below 0.6 when using their left limb compared to 36% when using their right limb. This trend prevailed into the circa- and post-PHV groups, with 44% and 53% failing to reach a H:Q ratio of 0.6 on their left side, compared to 25% and 35% on their right side.

Although maturity made no significant difference when comparing H:Q ratio between groups, a paired samples T-test demonstrated a significant difference between the left (M=0.61, SD=0.12) and right (M=0.68, SD=0.16) H:Q ratio when examining players regardless of maturity; t(45)=-3.6, p <.001, C.I. = [-0.11, -0.03]), with a moderate effect size displayed (Cohen's d = -0.531).

Table 6. Maturity-specific H:Q ratio differences

H:Q Ratio Variable	Pre-PHV (<88% PAH) Mean ± SD (95% CI) N = 12	Pre-PHV vs Circa-PHV p (Cohen-d)	Circa-PHV (88-96% PAH) Mean ± SD (95% CI) N = 17	Circa-PHV vs Post-PHV p (Cohen-d)	Post-PHV (>96% PAH) Mean ± SD (95% CI) N = 17	Pre-PHV vs Post-PHV p (Cohen-d)
Left H:Q Ratio	0.58±0.14 (0.49-0.67)	0.47 (0.51†)	0.64±0.12 (0.58-0.70)	0.91 (0.38§)	0.60±0.10 (0.55-0.65)	1.00 (0.19‖)
Right H:Q Ratio	0.66±0.19 (0.54-0.78)	1.00 (0.21§)	0.69±0.11 (0.64-0.75)	1.00 (0.60†)	0.68±0.18 (0.59-0.77)	1.00 (0.12‖)

*p <.001
‡Large. †Moderate. §Small. ‖Trivial.

Maturity Timing

When categorising players dependent on maturity timing, comparing players to other participants within the same maturity status group was deemed the most appropriate approach. Grouping players based on chronological age rather than maturity status may have increased the diversity of results due to a greater variety of biological maturities within a group, however, some chronological age groups had a reduced sample size compared to others (e.g. six U13 players were used compared to thirteen within the U14 group) which would have impacted the validity of results.

Table 7. Anthropometric for each maturity timing group with all maturity status groups

	Pre-PHV			Circa-PHV			Post-PHV		
	Early	**On-Time**	**Late**	**Early**	**On-Time**	**Late**	**Early**	**On-Time**	**Late**
Participants (n)	4	6	2	8	9	0	14	3	0
Stature (cm)	155.08±7.95	152.15±3.29	145.20±4.67	169.78±4.48	163.08±7.16	0	181.52±5.35	178.17±1.51	0
Body Mass (kg)	44.15±8.80	38.43±3.53	39.70±3.82	56.60±7.9	49.47±7.73	0	67.04±7.9	61.73±8.69	0
Chronological Age	11.95±0.37	12.16±0.42	12.97±0.63	13.70±0.75	14.24±0.59	0	15.36±0.83	15.45±0.72	0
Biological Age	12.71±0.38	12.31±0.41	12.42±0.47	14.33±0.64	14.06±0.56	0	16.77±0.69	15.78±0.63	0
%PAH	86.28±1.50	84.76±1.44	85.16±1.67	92.74±2.51	91.73±2.28	0	98.85±1.15	97.11±1.28	0
Z Score	1.05±0.40	-0.02±0.23	-0.7±0.14	0.96±0.48	-0.06±0.32	0	1.04±0.55	0.4±0.1	0

Table 7, 8, and 9 compares dependant variable values between players of varied biological timings. Table 7 corresponds to pre-PHV players, whereas table 8 and 9 relate to the circa- and post-PHV group, respectively. To clarify, there were no late maturers within the circa- and post-PHV group, meaning that only early and on-time maturation sections have been included.

No significant findings were produced when examining the impact of biological timing on peak strength, strength asymmetry, and H:Q ratios. This was the case for all three maturity status groups. Although insignificant, it is worth noting the significance for right knee extension peak force and right H:Q ratio within the circa-PHV group, with both variables recording a p-value of 0.07 and 0.06, respectively, and displaying a large effect size. While insignificant, when exploring trends for all maturity groups, it appears somewhat ambiguous, with a combination of all timing groups for each maturity status recording the highest values for varied variable.

Table 8. The comparison of dependant variable values between early, on-time, and late maturing players within the pre-PHV group

Variable	Early Maturation Mean ± SD (95% CI) N = 4	Early vs On-time p (Cohen-d)	On-time Maturation Mean ± SD (95% CI) N = 6	On-time vs Late p (Cohen-d)	Late Maturation Mean ± SD (95% CI) N = 2	Early vs Late p (Cohen-d)
Left Knee Extension Peak Force (N)	15.68±2.66 (11.45-19.90)	1.00 (-0.36§)	16.73±3.06 (13.52-19.93)	1.00 (-0.31§)	15.82±3.07 (-11.75-43.39)	1.00 (-0.05‖)
Right Knee Extension Peak Force (N)	16.05±3.86 (9.91-22.19)	1.00 (0.06‖)	15.82±3.64 (12.00-19.64)	1.00 (0.09‖)	16.16±3.88 (-18.72-51.03)	1.00 (-0.03‖)
Left Knee Flexion Peak Force (N)	7.91±0.98 (6.35-9.46)	0.51 (-0.96‡)	9.48±1.93 (7.46-11.50)	1.00 (0.69†)	10.61±1.70 (-4.64-25.86)	0.27 (-1.65‡)
Right Knee Flexion Peak Force (N)	8.87±1.34 (6.74-11.00)	0.47 (-1.00‡)	11.17±2.79 (8.24-14.10)	1.00 (-0.64†)	9.69±1.83 (-6.80-26.14)	1.00 (-0.35§)
Knee Extension (%)	5.15±2.33 (1.44-8.86)	1.00 (-0.08‖)	5.55±6.30 (-1.06-12.15)	1.00 (-0.79†)	1.68±1.12 (-8.36-11.72)	1.00 (0.71†)
Knee Flexion (%)	5.55±7.31 (-6.09-17.18)	1.00 (-0.44§)	7.71±3.30 (4.24-11.17)	1.00 (-0.62†)	4.69±1.48 (-8.59-17.96)	1.00 (0.18‖)
Left H:Q Ratio	0.51±0.05 (0.44-0.58)	1.00 (-0.56†)	0.58±0.14 (0.44-0.73)	1.00 (0.83‡)	0.70±0.25 (-1.53-2.92)	0.43 (-0.39§)
Right H:Q Ratio	0.57±0.08 (0.43-0.70)	0.64 (-0.86‡)	0.73±0.22 (0.50-0.97)	1.00 (-0.53†)	0.63±0.37 (-1.78-3.04)	1.00 (-0.33§)

*p <.001
‡Large. †Moderate. §Small. ‖Trivial.

Table 9. The comparison of dependant variable values between early and on-time maturing players within the circa-PHV group

Variable	Early Maturation Mean ± SD (95% CI) N = 8	Early vs On-time p (Cohen-d)	On-time Maturation Mean ± SD (95% CI) N = 9
Left Knee Extension Peak Force (N)	17.57±3.17 (14.91-20.22)	0.85 (-0.10‖)	17.82±1.94 (16.32-19.31)
Right Knee Extension Peak Force (N)	16.45±2.85 (14.07-18.83)	0.07 (-0.94‡)	18.94±2.44 (17.06-20.81)
Left Knee Flexion Peak Force (N)	11.41±1.84 (9.88-12.95)	0.59 (0.27§)	10.98±1.43 (9.88-12.08)
Right Knee Flexion Peak Force (N)	11.99±1.28 (10.92-13.06)	0.84 (-0.10‖)	12.14±1.74 (10.81-13.48)
Knee Extension (%)	8.44±4.15 (4.97-11.91)	0.17 (0.70†)	5.86±3.19 (3.41-8.31)
Knee Flexion (%)	7.11±3.48 (4.21-10.02)	0.52 (0.32§)	5.81±4.60 (2.27-9.35)
Left H:Q Ratio	0.67±0.15 (0.54-0.79)	0.45 (0.38§)	0.62±0.08 (0.56-0.68)
Right H:Q Ratio	0.74±0.10 (0.66-0.82)	0.06 (0.97‡)	0.65±0.10 (0.57-0.72)

*p <.001
‡Large. †Moderate. §Small. ‖Trivial.

Table 10. The comparison of dependant variable values between early and on-time maturing players within the post-PHV group

Variable	Early Maturation Mean ± SD (95% CI) N = 14	Early vs On-time p (Cohen-d)	On-time Maturation Mean ± SD (95% CI) N = 3
Left Knee Extension Peak Force (N)	21.64±2.54 (20.17-23.19)	0.34 (0.63†)	20.08±1.87 (15.43-24.72)
Right Knee Extension Peak Force (N)	20.35±3.13 (18.55-22.16)	0.43 (0.52†)	18.85±0.14 (18.50-19.20)
Left Knee Flexion Peak Force (N)	12.53±2.45 (11.12-13.94)	0.45 (-0.49§)	13.68±1.55 (9.80-17.56)
Right Knee Flexion Peak Force (N)	13.09±2.71 (11.52-14.66)	0.31 (-0.66†)	14.86±2.41 (8.88-20.85)
Knee Extension (%)	5.00±5.20 (1.99-8.00)	0.57 (0.37§)	3.10±4.15 (-7.22-13.42)
Knee Flexion (%)	4.26±2.69 (2.71-5.81)	0.99 (-0.01‖)	4.29±4.25 (-6.28-14.86)
Left H:Q Ratio	0.58±0.10 (0.52-0.64)	0.12 (-1.04‡)	0.68±0.06 (0.54-0.83)
Right H:Q Ratio	0.66±0.19 (0.55-0.77)	0.28 (-0.72†)	0.79±0.12 (0.48-1.09)

*p <.001
‡Large. †Moderate. §Small. ‖Trivial.

Injury Data

When recording injury data, as mentioned previously, a greater sample size was used with every player within the Junior Premier League being included, with only those who had not spent the entire season at the club being excluded. This produced a total of 70 players across the U12-U16 teams. When exploring injury data, participants were grouped concerning their chronological rather than biological age; as a result, findings regarding asymmetry and H:Q ratio results are analysed and interpreted separately compared to injury findings. Due to the injury findings relating to the entire season, no anthropometrics have been recorded due the fluctuations in recordings throughout the season, with age group being the only consistent marker.

It was found that the thigh recorded the most injuries compared to other bodily locations, with the hamstring group obtaining a greater quantity of injuries in comparison to the quadriceps group.

Due to not being the prime purpose of this thesis, please see Appendix C for detailed injury findings.

Chapter 5 Discussion

The current study examined KE and KF peak isometric force in male academy footballers, with data providing information regarding peak force, asymmetry, and H:Q ratio values for a pre-, circa-, and post-PHV group. In addition, injury data was recorded throughout the season regarding bodily location, with a focus on quadricep and hamstring specific pathologies.

The findings highlighted, as expected, that significant differences existed between groups for peak force produced; this was true for both left and right KE and KF, with the post-PHV group scoring the highest for all variables. Significant differences were also apparent when comparing left and right H:Q ratios regardless of maturity. No significant between-group differences were found regarding KE and KF asymmetry values alongside H:Q ratio scores.

When analysing injury findings throughout the U12-U16 age groups, it was found that the thigh was the bodily location with the greatest injury incidence, with the hamstring group being subject to a higher injury incidence than the quadriceps group. Regarding severity, 50% of time-loss muscular injuries recorded a severity of 4-7 days, with 50% of hamstring strains producing a severity of 8-28 days.

Peak Isometric Muscle Strength

Results demonstrated a significant difference in muscle force exhibited between the different maturity groups. The post-PHV group scored significantly higher results compared to the pre-PHV group for both KE and KF on each limb. There was a significant difference in strength between the circa- and post-PHV groups for left KE, while a significant difference was evident between the pre-and circa-PHV groups for left KF. All comparisons between peak strength variables demonstrated at least a moderate effect size, with all comparisons between the pre-and post-PHV groups showing a large effect size, thus further highlighting the increase in strength throughout maturity.

The finding that KE and KF strength increased significantly from pre- to post-PHV is not unexpected, given the abundance of past research that has arrived at the same conclusion (Peek et al., 2018), with the shared idea that strength increases throughout adolescence. In a recent study, an apparent increase in peak knee extensor and flexor strength was observed between a pre-and post-PHV group of adolescent footballers (Souza et al., 2024). However, the study failed to incorporate a circa-PHV group, meaning that the findings obtained from this study may help to understand muscle strength tempo throughout adolescence, whereas other studies have been unable to consider this aspect.

The results obtained imply that the relationship between biological maturity and increased strength is rather individualistic, with the development of muscle strength occurring earlier for left KF compared to extension. The boost in flexor strength in the circa-PHV group may be attributed to the finding that muscle thickness and pennation angle increase throughout biological maturation, with the most significant difference occurring between those before and those during their growth spurt (Radnor et al., 2020). However, it must be noted that Radnor et al., (2020) found this to be the case for vastus lateralis and medial gastrocnemius. While it can be argued that the medial gastrocnemius aids in KF, vastus lateralis is a clear knee extensor, thus potentially meaning that increases in medial gastrocnemius strength may be responsible for the significant difference between the pre-and circa-PHV groups, yet this should be examined further before arriving at conclusions. On the other hand, the difference in left knee extensor strength between the circa- and post-PHV group may be attributable to the proposed theory of the ‘window of opportunity’ where post-PHV players gain an increase in androgen concentrations (Peña-Gonza´lez et al., 2019), yet, it would be assumed that this would impact both limbs rather than just the left side. A more likely reason is that, due to being the preferred leg to stand on during a match, the non-dominant limb may have developed greater strength and balance compared to the dominant side (McElveen et al., 2010). Understanding that the development of muscle strength is not directly proportional to biological maturation can enhance practitioners' receptiveness to the varying maturation rates among players, thereby helping to explain why some players mature at different rates.

Regarding maturity timing, it was predicted that early-maturing, circa- and post-PHV players would produce greater strength scores for all peak strength variables compared to their later-maturing counterparts. The reasoning for this prediction was due to the widespread assumption that early maturing players display increased physicality levels compared to later-developed players (Fink et al., 2014) due to increased muscular thickness throughout biological maturation, with the greatest difference often occurring between those before and those during their growth spurt (Radnor et al., 2020). Additionally, the theory of the ‘window of opportunity’ where post-PHV players gain an increase in androgen concentrations (Peña-Gonza´lez et al., 2019) suggests that players maturing earlier will be subject to enhanced physiological adaptations before those who are yet to develop. However, the findings produced showed no significant difference between maturity timing and peak strength scores when examining each maturity status. This discovery contradicts theoretical findings yet may be due to the reduced sample size and lack of late-maturing players, meaning that the results primarily examined the difference between early and on-time maturers. As a result, future research must examine the impact of maturity timing on peak strength values using a large sample size with varying levels of biological maturity.

KE and KF Asymmetry

Results from this study showed that maturation status and timing had no significant impact on the extent of strength asymmetry differences between groups. This was true for both KE and KF asymmetry differences, with only a trivial effect size present for all asymmetry variables, further highlighting the lack of difference between maturity groups. Additionally, all groups produced a mean value below the 10% threshold associated with an increased risk of injury.

Although previous research suggested a reduced likelihood of a significant difference between maturity groups and asymmetries produced, past research and theoretical assumptions proposed that asymmetries would exist regardless of maturity. For example, Maly et al., (2016) demonstrated that more than 73.2% of players exhibited at least one strength asymmetry. Additionally, Kalata et al. (2021) found that 68% of U15 players in their study exhibited hamstring strength asymmetries exceeding the 10% threshold. Similarly, from a theoretical perspective, it could be argued that asymmetries would have existed. This is due to the popular theory of players often favouring the dominant limb when playing, therefore meaning that the nondominant limb adapts with greater strength due to an increased amount of unilateral load placed through the standing limb during kicking, whereas the dominant limb acquires greater coordination and skill (McElveen et al., 2010). However, all groups within this study produced a mean value below the 10% threshold associated with an increased risk of injury, with only 17.4% and 10.9% of players exceeding the 10% threshold for KE and KF, respectively. This finding, therefore, implies that strength asymmetries may not be as prevalent within adolescents as previously thought and that other factors may have a greater responsibility for enhancing injury risk.

Maturity-specific results were not entirely unexpected, with insignificant conclusions generally aligning with those in previous literature. Past research has largely failed to yield significant results when examining strength asymmetry differences among maturity groups. Findings produced by Souza et al., (2024) showed no significant difference between a pre- and post-PHV maturity group and isokinetic KE and KF asymmetry values. It was initially suggested that including a circa-PHV group might have elicited a different outcome; however, the same conclusion was produced when a circa-PHV group was included, thus further solidifying the claim that maturity does not play a significant role in the extent of muscular asymmetry. Furthermore, Peek et al., (2018) showed no significant differences between age groups when exploring muscular asymmetry differences between adolescent footballers using a HHD. Again, the validity of the methodology used was questioned due to the small sample size within the U15 group (8 players), which we can assume most likely contained a combination of both circa- and post-PHV players; however, participants within this study involved 17 participants within both the circa- and post-PHV group and still arrived at the same conclusion that maturity plays no significant role in muscular asymmetries. Nevertheless, Kalata et al., (2021) demonstrated that the U13 and U15 groups within their study showed significantly higher levels of asymmetry for both quadriceps and hamstring strength compared to the U17 age group, thus implying that maturity influences asymmetries. However, the reason for the difference in results may be due to the type of muscular contraction performed; this further emphasises the need for future research to include isometric contractions to cater for practitioners who do not have access to an IKD.

When examining the impact of maturity timing on strength asymmetries, accurate predictions were difficult to generate due to the limited previous literature surrounding the topic. The findings produced showed no significant difference between maturity timing categories within each maturity status group and both KE and KF strength asymmetries. This finding suggests that practitioners should take a whole-group approach when testing for muscular asymmetries rather than focusing on a particular cohort of players. Nevertheless, due to the lack of similar research, it is incorrect to draw concrete conclusions based on this finding, especially given the reduced sample size and the absence of any late-maturing players within the circa- and post-PHV group. As stated previously, future research is needed to support or dismiss the notion that no significant strength asymmetries are apparent among players of varied maturity timings.

When comparing the extent of KE asymmetry with KF asymmetry, the findings showed no significant difference in asymmetry values produced between KE and KF when examining the entire group. This finding was predicted due to the discrepancy between previous literature regarding the potential difference in hamstring and quadricep strength asymmetries. Regarding previous literature, Peek et al., (2018) showed quadricep asymmetry to be more prevalent compared to hamstring asymmetry, whereas Maly et al., (2016) discovered that the hamstring group displayed greater asymmetries compared to the quadriceps group. On the contrary, although not explicitly commented on, asymmetry results produced by Kalata et al., (2021) showed similar extents of quadricep and hamstring asymmetry within the U13, U15, and U17 groups. Nevertheless, no significant difference was observed within this study; however, different results may have been obtained with a larger sample size, thereby highlighting the need for increased attention to this area using a greater number of participants. With no significant difference between KE and KF asymmetries, clinicians should focus equally on screening both quadriceps and hamstring asymmetry.

H:Q Ratios

Results from this study showed that maturation status and timing had no significant impact on the H:Q ratio differences between groups, with group comparisons displaying a combination of trivial to moderate effect sizes. Moreover, half of all players failed to score over the 0.6 threshold for the left limb, whereas a greater number of participants exceeded the threshold on their right limb.

When comparing H:Q ratios between maturity groups, the results demonstrated no significant differences, and no significant differences were present within H:Q inter-limb asymmetries between groups. This finding was largely expected, given the varying levels of agreement in the literature regarding the impact of maturity on H:Q ratios. In support of this study’s findings, it was found that there were no significant links between maturity status and H:Q ratio within pre- and post-PHV adolescent footballers (Souza et al., 2024); similarly, Nagai et al., (2021) demonstrated no significant differences in the conventional ratio between 14 through to 18-year-olds, ultimately suggesting that the PHV phase has no impact on H:Q ratios exhibited. However, contradicting research has shown the U12 group to display increased vulnerability to lower H:Q ratios compared to other age groups, with Peek et al., (2018) showing the largest reduction in ratio to be between players aged 11-12, in addition to Mandroukas et al., (2023) who found U12 footballers to exhibit smaller H:Q ratios than U20 players. Although it could be suggested that these studies contained early maturing U12 players who fell within the circa-PHV groups, thus potentially implying that the phase of PHV may reduce H:Q ratios, all U12 players were yet to experience a growth spurt (shown within anthropometric testing), therefore reducing the likelihood that the reduced ratio in U12 players within research by Peek et al., (2018) and Mandroukas et al., (2023) were due to players undergoing a growth spurt. Additionally, findings from Ishoi et al., (2022) repelled those mentioned with the finding that the senior group displayed the lowest H:Q ratio compared to adolescent groups. As a result, it can be suggested that maturity appears to have a minimal impact on a player's H:Q ratio; therefore, players subject to lower ratios should follow an individualised plan suited to the individual rather than their maturity. Additionally, clinicians should screen all players for reduced H:Q ratios regardless of biological maturity.

Similarly to when exploring the impact of maturity timing on strength asymmetries, it is increasingly difficult to make solid predictions when testing the effect of maturity timing on H:Q ratios due to a reduction in related prior research. Although under-researched, research has suggested that a potential link between lower H:Q ratios and hamstring injuries exists (Lee et al., 2018), with early maturers often proving to have a greater hamstring burden compared to on-time maturers (Monasterio et al., 2022), it can therefore be implied that early maturers may be more susceptible to lower H:Q ratios. However, the findings from this study showed no significant difference in maturity timing within each maturity status group when examining both the left and right H:Q ratio among players. This ultimately contradicts the assumption that early-maturing players may produce reduced H:Q ratios and, therefore, suggests that practitioners should aim to develop hamstring strength in all players, regardless of their maturity timing. However, it is crucial to remember that this is an under-developed research focus which requires further research to aid in the solidification of accurate conclusions.

As stated previously, this study used 0.6 as the threshold to aid in the detection of players vulnerable to injury (Kim & Hong, 2011). Findings demonstrated that 50% and 30.43% of players failed to score over the 0.6 threshold for the left and right limbs, respectively. This supports previous literature, which has consistently demonstrated the failure of adolescents to achieve the 0.6 threshold, suggesting that a lower target value may be necessary; however, research has yet to establish a more realistic value. Research by Ishoi et al., (2021) demonstrated that only the U15 group, out of 125 U13-senior-level players, achieved a ratio over 0.6; however, the mean value reached only 0.62, further highlighting the difficulty in clearing the 60% threshold. Similarly, Peek et al., (2018) found that over one-third of 110 players aged 8-15 years scored less than 0.6 for an isometric H:Q ratio. Although the 0.6 threshold should not be altered due to its relationship with injury, only six time-loss hamstring strains occurred out of seventy players throughout the entire season. Out of the 46 players who participated in testing, 50% and 30.43% of players failed to score over the 0.6 threshold for the left and right limbs, respectively. This represents a significant proportion of players who would typically be deemed vulnerable to injury, as they failed to reach the 0.6 threshold; yet, this does not correspond with the substantially low number of HSI throughout the season. As a result, from analysing previous literature and in addition to the findings produced within this study, the assumption that adolescents commonly fail to reach the suggested 0.6 threshold is supported. Consequently, a lower threshold should be considered in future research.

Focusing on the entire group, findings showed a significant difference between limbs when analysing H:Q ratios, with a moderate effect size shown. Overall, 64, 44, and 53% of players failed to reach the 0.6 threshold on their left limb, with each percentage corresponding to the pre-, circa-, and post-PHV group; however, a reduced 36, 25, and 35% of players did not surpass the 0.6 threshold on their right limb. Notably, 78% of the players included were right-side dominant, suggesting that the non-dominant side was subject to lower ratios. This result was expected, as previous literature had arrived at the same conclusion. A reduced conventional H:Q ratio for the non-dominant side was shown by both Maly et al., (2016) and Pellicer-Chenoll et al., (2017) when analysing 41 U16 footballers and 14 male and female soccer players, respectively. Additionally, Kim & Hong (2011) displayed a significant relationship between H:Q ratios lower than 0.6 and increased incidence of left leg injuries within 40 male and 42 female college basketballers, thus implying that the left limb, which can be assumed to be the non-dominant limb, showed reduced H:Q ratios. As the results of this study support previous literature, it is suggested that the non-dominant limb has a greater risk of producing reduced H:Q ratios. Consequently, clinicians should particularly focus on developing hamstring strength in the non-dominant side to aid in injury reduction.

Injury Findings

The primary purpose of including injury data was to investigate the prevalence of thigh-related time-loss pathologies within an adolescent football population. If the proportion of thigh-related injuries is higher compared to other bodily locations, then the findings support the rationale for focusing on asymmetry and ratio data around the thigh musculature.

When analysing injury findings, it was decided that players would be grouped by chronological age rather than based on biological maturity. This was due to the high probability that several players would have progressed into a higher maturity group throughout the season, thereby reducing the validity of the results if maturity groups had been used. Additionally, only time-loss injuries were recorded, meaning that the incidence rate may be lower than that reported in previous literature, which may have included all injury complaints, regardless of severity. Importantly to note, due to the absence of relation to asymmetry data alongside the increase in the number of participants, all players who had spent the entire season within the U12-U16 age groups at the Junior Premier club were included when analysing injury trends, thus providing a greater sample than that used for examining asymmetries.

The bodily location most exposed to injury was the thigh, accounting for over 20% of time-loss injuries throughout the season across the U12-U16 age groups, with the ankle and knee closely following. See Table 10 within Appendix C. This finding was not unexpected, given the lower-limb dominance displayed in football. Previous literature generally agrees with the commonality of muscular injuries in academy football, with the thigh being particularly vulnerable to injury. Muscular injuries have been shown to account for a significant proportion of injuries with adolescent football, with Weishorn et al., (2023) showing that 28% of total injuries within a German academy to be muscular, in addition to Read et al., (2018) discovering muscle strains to account for the greatest percentage of all injuries within six footballing academies. Furthermore, in relation to injury location, the thigh was shown to be particularly impacted by both Weishorn et al., (2023) and Dias (2014), with the latter suggesting that the thigh is susceptible to both muscular and apophyseal pathologies. Due to the agreement between literature, it is therefore vital that clinicians target lower-limb strength in preparation for and throughout the season, with the intention of reducing injury incidence, with a particular focus on thigh muscular pathologies.

Results showed that the hamstring group sustained more injuries compared to the quadriceps group, with six hamstring strains recorded in contrast to one quadriceps strain. Regarding, tendinopathies, one proximal rectus femoris strain was recorded, whilst no hamstring tendinopathies occurred. See Table 15 within Appendix C. The increased number of hamstring strains fits with the large number of participants who failed to reach the 0.6 threshold associated with injury, with half of all participants scoring a ratio lower than 0.6. However, it must be noted that this study cannot solely account for cause-and-effect relationships, and with only six time-loss hamstring strains recorded throughout the season, it seems appropriate to question the validity of the link between reduced H:Q ratios and hamstring injuries within this study. Regarding past literature, the increased incidence of hamstring strains compared to quadriceps strains aligns with previous research. Skomrlj et al., (2024) found a slightly greater rate of hamstring compared to quadricep injuries. Additionally, the hamstring group produced almost double that of the quadriceps group from findings from Materne et al., (2021), with Price et al., (2004) recording slightly below 10% more hamstring injuries. The increased hamstring incidence rate may be attributed to the greater number of HSI mechanisms, which expose the hamstring musculature to vulnerability during both kicking and sprinting (Garcia et al., 2022). As a result, clinicians should place more attention towards the prevention of hamstring injuries in all players to reduce the chance of injury and ultimately enhance performance.

Moving towards apophyseal injuries, 60% of time-loss growth-related issues involved the AIIS (see Table 15). This finding was expected due to the concurrence with previous literature. It was found that 43% and 39% of apophyseal injuries involved the AIIS in a seven-year and four-year longitudinal study, respectively, conducted by Gudelis et al., (2022) and Materne et al., (2011). Furthermore, findings from Gudelis et al. (2022) showed that only 10% of growth-related issues over a 7-year period at FC Barcelona's academy involved the ischial tuberosity, thus highlighting the increased vulnerability of AIIS growth-related pathologies compared to the ischial tuberosity. As a result, practitioners should place a particular focus on reducing the burden of growth-related conditions, especially involving the AIIS, to maximise playing time and reduce the impact on football development.

When exploring injury severity for thigh-related issues, the existing literature tends to focus on senior-level players, often disregarding findings in adolescents. As a result, it seemed necessary to report severity findings regarding thigh musculature and growth-related conditions in the sample used in this study. For muscular pathologies, 50% of time-loss injuries recorded a severity of 4-7 days, with 50% of hamstring strains producing a severity of 8-28 days. See Table 16 within Appendix C. Due to the reduced frequency of injuries recorded, with only one season included, comparisons between injury severity must be made cautiously when drawing comparable conclusions to other research. In addition, previous literature comparing the burden of both hamstring and quadriceps pathologies has suggested that quadriceps injuries tend to have higher severity levels; however, due to only recording one quadriceps pathology, it seems inappropriate to make solid conclusions regarding this. Nevertheless, the severity of hamstring strains produced aligns with that found by previous researchers. It was found that the average time lost due to a hamstring injury was 21 days over three consecutive seasons at the Barcelona FC Academy (Valle et al., 2018). Similarly, Cloke et al., (2012) discovered an average burden of 12 days for a thigh muscular injury over a 5-year period across 41 English professional footballing academies. As a result, this highlights the expectation that thigh time-loss pathologies will fall within the 8-28 recovery period and that this must be considered by clinicians when administering rehabilitation protocols in collaboration with the multidisciplinary team.

Results, alongside those from previous literature, clearly highlight the commonality of thigh-related time-loss pathologies in adolescent footballers compared to other bodily areas; this appears to be the case for both muscular and apophyseal conditions. As a result, there is a clear rationale for focusing on the thigh when examining potential strength differences in asymmetry between various biological maturities.

Chapter 6 Conclusion

To summarise, it was first found that maturity status significantly influenced the peak isometric KE and KF forces produced, with the post-PHV group scoring higher than the pre-PHV group for all variables. Regarding asymmetry, the findings showed that all maturity groups achieved an average strength asymmetry percentage below the 10% threshold associated with injury (Fort-Vanmeerhaeghe et al., 2016). Additionally, it was found that maturity status had no significant impact on asymmetry values. Regarding maturity timing, no significant differences were present between maturity timing within all three maturity status groups and all peak strength, asymmetry, and H:Q variables. Alternatively, when analysing H:Q ratios, a greater proportion of players failed to exceed the 0.6 thresholds associated with injury (Fritsch et al., 2023), with 50% and 30.43% of players failing to score over the 0.6 thresholds for the left and right limb, respectively. However, proving consistent with asymmetry testing, maturity was found to play no significant role in the H:Q ratios produced. Lastly, when recording injury data, the thigh was found to have the greatest incidence of injury compared to other body areas, with the hamstring group experiencing a higher number of injuries than the quadriceps group.

Implications

Results, as expected, highlighted that peak isometric strength values increased with maturity status. This was demonstrated by the post-PHV group scoring higher peak values compared to the pre-PHV group for all strength variables. This indicates to practitioners the expectation that players with a greater biological age will display enhanced physicality compared to more biologically immature players. This promotes the use of the recent concept of bio-banding. Bio-banding categorises adolescents based on their biological rather than chronological age (Towlson et al., 2022) due to the varied physicality that can appear within an age group. The importance of bio-banding is shown due to the advancement of player's physical and cognitive development compared to their later-maturing counterparts (Ludin et al., 2022), thus often leading to developed anthropometric and performance characteristics contributing to maturity selection bias, which ultimately involves a greater selection of early maturers (Towlson et al., 2021). Therefore, it may potentially be beneficial to begin implementing bio-banding within training and matches to encourage fair game time whilst reducing injury risk.

Reduced strength asymmetry values were present for all maturity status and consequent timing groups, with maturity having no significant impact on results. Due to the ambiguity of previous research, it is, therefore, incorrect to draw implications solely from the results of this study. However, based on the findings produced, it is suggested that practitioners should focus on other factors that are partly responsible for injury occurrence or reduced performance rather than placing unnecessary effort on comparing inter-limb strength asymmetries. Nevertheless, it cannot be completely ruled out that excessive asymmetry levels are responsible for decrements in injury or performance occurrences; as a result, practitioners should place equal attention on all players regardless of maturity.

Regarding H:Q ratios, the overall trend showed a large proportion of players producing low ratios on each limb, with the non-dominant limb more susceptible to lower values. Similarly to the findings on asymmetry, maturity status and timing had no significant impact on the ratios produced. The reduced ratios for the entire group were shown by 50% and 30.43% of players failing to score over the 0.6 threshold for the left and right limbs, respectively. This indicates an apparent concern among adolescent athletes regarding injury risk, with the literature emphasising the link between failing to achieve the 0.6 threshold and increased injury risk (Fritsch et al., 2023). This suggests that practitioners should aim to develop hamstring strength in adolescents to limit the gap between KE and KF strength. Although both limbs should be targeted, focus should be placed on the non-dominant side as all three maturity categories produced a lower average ratio on the left side compared to the right side, with the left side being deemed the non-dominant side for 78% of participants within this study. Due to the absence of an impact on results caused by maturity, it is therefore suggested that practitioners target all players when improving hamstring strength regardless of maturity.

When recording injury incidence by bodily location, it was found that over 20% of total injuries occurred at the thigh, with two-thirds of thigh injuries occurring during match play. From this, practitioners must take appropriate measures to prevent thigh-related injuries, especially those to the hamstring group, due to its higher incidence of injury compared to the quadriceps group. The commonality of thigh-related pathologies provides a rationale for future studies to focus on thigh musculature to produce beneficial and relevant findings.

Limitations

One limitation of this research is that an androcentric sample of U12-U16 academy footballers was used. This demographic was included to aid in advancing knowledge regarding asymmetry and H:Q ratios within the area of adolescent football, which can be understood as an underdeveloped focus compared to senior-level players. Nevertheless, findings can only be applied to this population, thereby reducing the generalisability of the results to females, other sports, different experience levels, and other age groups (Peek et al., 2018). As a result, future research is encouraged to focus on varied groups to increase the generalisability of results to a broader population.

A further point to note, yet not necessarily a negative, is that testing involved an HHD rather than the use of an IKD. Reasoning for favouring the use of an HHD over an IKD has been mentioned previously. The HHD is a significantly cheaper and quicker option, with the device's portability adding to its convenience. Additionally, the HHD has been shown to demonstrate moderate-to-good reliability and validity when compared to isokinetic testing (Stark et al., 2011). However, it must be noted that an IKD allows practitioners to assess both concentric and eccentric strength, which are far more prevalent in football movements compared to isometric contractions. This challenges the external validity of the results; however, it must be emphasised that most practitioners will not have access to an IKD, thereby reducing the replicability of the results if an IKD were used. For that reason, using a HHD should not be viewed as a negative; instead, it should be seen as a cheaper and practical alternative method for assessing muscular strength.

An additional limitation entails the reliability of this study. Although a ‘very high’ level of within-session reliability was present for all dependent variables tested, other reliability parameters must be questioned due to the absence of multiple testing sessions and researchers. As only one testing session commenced, a between-session reliability figure cannot be calculated, making it challenging to assume that the results truly reflect the players' strength levels at the midpoint of the season. Secondly, only one researcher conducted the tests. Although this was due to the time available and allowed for a consistent approach among individuals, a second researcher would have been beneficial when determining a level of inter-rater reliability, thus aiding in the overall reliability of the study. As a result, if future research were to replicate this study, it is suggested that an additional testing session be conducted close to the existing session to assess between-session reliability, with an additional researcher used to provide a level of inter-rater reliability.

A final criticism of this study is the lack of control over extraneous variables. Due to the high frequency of children involved, controlling factors such as diet, sleep, and overall mental and physical well-being were deemed unrealistic; therefore, it is difficult to predict the impact this may have on peak forces produced. Specifically, focusing on the day of testing, players were asked to complete a self-directed warm-up due to the limited time available for the researcher to perform several warm-ups for each age group. As a result, some players may have performed a higher-quality warm-up compared to others, which could have impacted the peak forces produced. Lastly, all players were instructed to perform a maximum isometric contraction, however, this does not necessarily mean that all players attempted the tests with maximum effort levels which, therefore, questions the validity of results. As a result, while controlling the rate of perceived exertion may be difficult, future research should make attempts to control extraneous variables, such as diet and sleep, to provide a stronger level of consistency between players.

Future Research

Although not a direct criticism of the testing parameters used, it must be noted that the value of the findings would be enhanced if a direct association between maturity, strength asymmetries, or H:Q ratios and injury had been included. Unfortunately, this would have required a longitudinal approach with multiple testing periods throughout the season, which was increasingly difficult to perform due to the limited time and resources available. Instead, this research still recorded injury data, but findings were used to provide a rationale for the increased emphasis on thigh-related strength rather than aiding in the exploration of a potential link between injury and independent and dependent variables. As a result, it is strongly recommended that future research adopts a longitudinal approach, potentially throughout consecutive seasons, to aid in the discovery of the possible involvement of either strength asymmetries or reduced H:Q ratios on injury parameters within varied biological maturities, which, to my knowledge, would have a strong content of originality in comparison to previous research.

Rather than centred on injury occurrence, future research may also focus on the impact of asymmetry on performance tasks. According to a previous systematic review, available data suggested a negative relationship between inter-limb asymmetries in jumping and kicking (Bishop et al., 2018), which is relevant to football. However, it was recommended that future research adopts a longitudinal approach as well as testing a variety of populations. Similarly to the previous points made, it, therefore, seems necessary that testing is not confined to a single session to provide temporal fluctuations across the season while comparing this change across multiple demographics.

As discussed in the limitations section, the reasoning for including an HHD rather than an IKD has been clarified, with an HHD being the cheaper and more efficient option. However, if resources allow, it is suggested that future research include the analysis of concentric and eccentric movements to increase the applicability of the findings to real-life situations. Research appears more apparent when comparing isokinetic strength asymmetries between chronological age groups, yet this often fails to account for individual biological differences among individuals belonging to the same chronological group. As a result, it would be beneficial for future research to study isokinetic strength asymmetries to improve the external validity of implications.

A further direction for future research involves identifying an improved, realistic normative H:Q ratio threshold for adolescents to aim for. As predicted, a high proportion of players throughout all maturities failed to reach the 0.6 threshold associated with injury risk (Fritsch et al., 2023). For the pre-PHV group, 64% of players scored below 0.6 when using their left limb compared to 36% when using their right limb. This was further shown by the circa- and post-PHV groups, with 44% and 53% failing to reach a H:Q ratio of 0.6 on their left side, compared to 25% and 35% on their right side. These findings align with previous literature, which suggests that the 0.6 threshold is unrealistic for adolescents to achieve. As a result, future research should aim to identify an improved threshold, enabling practitioners to use the updated threshold to draw accurate conclusions regarding injury vulnerability.

Lastly, as discussed previously, it would be beneficial for future research to focus on diverse populations. Examples include expanding the study to include females, other sports, and various age groups (Peek et al., 2018).

Bibliography

Atkins, S.J., Bentley, I., Hurst, H.T., Sinclair, J.K. and Hesketh, C. (2016a) 'The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages', *The Journal of Strength & Conditioning Research,* 30(4), pp. 1007–1013.

Atkins, S.J., Bentley, I., Hurst, H.T., Sinclair, J.K. and Hesketh, C. (2016b) 'The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages', *The Journal of Strength & Conditioning Research,* 30(4), pp. 1007–1013.

Bell, D.R., Sanfilippo, J.L., Binkley, N. and Heiderscheit, B.C. (2014) 'Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes', *The Journal of Strength & Conditioning Research,* 28(4), pp. 884–891.

Bishop, C., Turner, A. and Read, P. (2018) 'Effects of inter-limb asymmetries on physical and sports performance: A systematic review', *Journal of Sports Sciences,* 36(10), pp. 1135–1144.

Bullough, S. and Jordan, J. (2017) 'Youth academy player development in english football: The impact of regulation since 2006', *Sport, Business and Management: An International Journal,* 7(4), pp. 375–392.

Bullough, S., Moore, R., Goldsmith, S. and Edmondson, L. (2016) 'Player migration and opportunity: Examining the efficacy of the UEFA home-grown rule in six european football leagues', *International Journal of Sports Science & Coaching,* 11(5), pp. 662–672.

Bullough, S.J. (2021) *Evaluating the efficacy of UEFA's home-grown rule in european football.* Sheffield Hallam University (United Kingdom).

Caine, D., Purcell, L. and Maffulli, N. (2014) 'The child and adolescent athlete: A review of three potentially serious injuries', *BMC Sports Science, Medicine and Rehabilitation,* 6, pp. 1–10.

Ceroni, D., Martin, X.E., Delhumeau, C. and Farpour-Lambert, N.J. (2012) 'Bilateral and gender differences during single-legged vertical jump performance in healthy teenagers', *The Journal of Strength & Conditioning Research,* 26(2), pp. 452–457.

Chaabene, H., Behm, D.G., Negra, Y. and Granacher, U. (2019) 'Acute effects of static stretching on muscle strength and power: An attempt to clarify previous caveats', *Frontiers in Physiology,* 10, pp. 489981.

Cloke, D., Moore, O., Shab, T., Rushton, S., Shirley, M.D. and Deehan, D.J. (2012) 'Thigh muscle injuries in youth soccer: Predictors of recovery', *The American Journal of Sports Medicine,* 40(2), pp. 433–439.

Corbi, F., Matas, S., Álvarez-Herms, J., Sitko, S., Baiget, E., Reverter-Masia, J. and López-Laval, I. (2022) 'Osgood-Schlatter disease: appearance, diagnosis and treatment: a narrative review', *Healthcare.*MDPI, pp. 1011.

Danielsson, A., Horvath, A., Senorski, C., Alentorn-Geli, E., Garrett, W.E., Cugat, R., Samuelsson, K. and Hamrin Senorski, E. (2020) 'The mechanism of hamstring injuries–a systematic review', *BMC Musculoskeletal Disorders,* 21, pp. 1–21.

Della Villa, F., Massa, B., Bortolami, A., Nanni, G., Olmo, J. and Buckthorpe, M. (2023) 'Injury mechanisms and situational patterns of severe lower limb muscle injuries in male professional football (soccer) players: A systematic video analysis study on 103 cases', *British Journal of Sports Medicine,* 57(24), pp. 1550–1558.

Dias, R.J.A. (2014) 'No title', *Musculoskeletal Injuries in Young Footballers and Associated Risk Factors,* .

Figueiredo, A.J., Gonçalves, C.E., Coelho e Silva, M.J. and Malina, R.M. (2009) 'Characteristics of youth soccer players who drop out, persist or move up', *Journal of Sports Sciences,* 27(9), pp. 883–891.

Fink, B., Freitas, T.T., De Marzo, C., Spyrou, K., Pereira, L.A., Loturco, I. and Zabaloy, S. (2024) 'Relative age, biological maturation, body composition, and physical performance in under-16 academy soccer players: Differences and associations among early and late born athletes', *Sport Sciences for Health,* 20(1), pp. 165–176.

Fort-Vanmeerhaeghe, A., Gual, G., Romero-Rodriguez, D. and Unnitha, V. 'Lower limb neuromuscular asymmetry in volleyball and basketball players', *Journal of Human Kinetics,* 50(1), pp. 135–143.

Fousekis, K., Tsepis, E. and Vagenas, G. (2010) 'Lower limb strength in professional soccer players: Profile, asymmetry, and training age', *Journal of Sports Science & Medicine,* 9(3), pp. 364.

Fousekis, K., Tsepis, E., Poulmedis, P., Athanasopoulos, S. and Vagenas, G. (2011) 'Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: A prospective study of 100 professional players', *British Journal of Sports Medicine,* 45(9), pp. 709–714.

Fritsch, C.G., Dornelles, M.P., Oliveira, G.d.S. and Baroni, B.M. (2023) 'Poor hamstrings-to-quadriceps torque ratios in male soccer players: Weak hamstrings, strong quadriceps, or both?', *Sports Biomechanics,* 22(7), pp. 811–821.

Fuller, C.W., Ekstrand, J., Junge, A., Andersen, T.E., Bahr, R., Dvorak, J., Hägglund, M., McCrory, P. and Meeuwisse, W.H. (2006) 'Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries', *Scandinavian Journal of Medicine & Science in Sports,* 16(2), pp. 83–92.

Gao, H. and Luo, X. (2024) 'Effect of sex and age on knee strength in young athletes: A systematic review and meta-analysis', *International Journal of Exercise Science,* 17(6), pp. 1461–1477.

Garcia, A.G., Andrade, R., Afonso, J., Runco, J.L., Maestro, A. and Espregueira-Mendes, J. (2022) 'Hamstrings injuries in football', *Journal of Orthopaedics,* 31, pp. 72–77.

Goto, H., Morris, J.G. and Nevill, M.E. (2015) 'Motion analysis of U11 to U16 elite english premier league academy players', *Journal of Sports Sciences,* 33(12), pp. 1248–1258.

Goto, H., Morris, J.G. and Nevill, M.E. (2019) 'Influence of biological maturity on the match performance of 8-to 16-year-old, elite, male, youth soccer players', *The Journal of Strength & Conditioning Research,* 33(11), pp. 3078–3084.

Gudelis, M., Perez, L.T., Cabello, J.T., Leal, D.M., Monaco, M. and Sugimoto, D. (2022) 'Apophysitis among male youth soccer players at an elite soccer academy over 7 seasons', *Orthopaedic Journal of Sports Medicine,* 10(1), pp. 23259671211065063.

Gurau, T.V., Gurau, G., Voinescu, D.C., Anghel, L., Onose, G., Iordan, D.A., Munteanu, C., Onu, I. and Musat, C.L. (2023) 'Epidemiology of injuries in men’s professional and amateur football (part I)', *Journal of Clinical Medicine,* 12(17), pp. 5569.

Hadžić, V., Erčulj, F., Bračič, M. and Dervišević, E. (2013) 'Bilateral concentric and eccentric isokinetic strength evaluation of quadriceps and hamstrings in basketball players', *Collegium Antropologicum,* 37(3), pp. 859–865.

Hall, E.C., Larruskain, J., Gil, S.M., Lekue, J.A., Baumert, P., Rienzi, E., Moreno, S., Tannure, M., Murtagh, C.F. and Ade, J.D. (2022) 'Injury risk is greater in physically mature versus biologically younger male soccer players from academies in different countries', *Physical Therapy in Sport,* 55, pp. 111–118.

Helme, M., Tee, J., Emmonds, S. and Low, C. (2021) 'Does lower-limb asymmetry increase injury risk in sport? A systematic review', *Physical Therapy in Sport,* 49, pp. 204–213.

Hirose, N. (2009) 'Relationships among birth-month distribution, skeletal age and anthropometric characteristics in adolescent elite soccer players', *Journal of Sports Sciences,* 27(11), pp. 1159–1166.

Holcomb, W.R., Rubley, M.D., Lee, H.J. and Guadagnoli, M.A. (2007) 'Effect of hamstring-emphasized resistance training on hamstring: Quadriceps strength ratios', *The Journal of Strength & Conditioning Research,* 21(1), pp. 41–47.

Hopkins, W.G., Schabort, E.J. and Hawley, J.A. (2001) 'Reliability of power in physical performance tests', *Sports Medicine,* 31, pp. 211–234.

Ishøi, L., Krommes, K., Nielsen, M.F., Thornton, K.B., Hölmich, P., Aagaard, P., Penalver, J.J. and Thorborg, K. (2021) 'Hamstring and quadriceps muscle strength in youth to senior elite soccer: A cross-sectional study including 125 players.', *International Journal of Sports Physiology & Performance,* 16(10).

John, C., Rahlf, A.L., Hamacher, D. and Zech, A. (2019) 'Influence of biological maturity on static and dynamic postural control among male youth soccer players', *Gait & Posture,* 68, pp. 18–22.

Johnson, D., Williams, S., Bradley, B. and Cumming, S.P. (2023) 'Can we reduce injury risk during the adolescent growth spurt? an iterative sequence of prevention in male academy footballers', *Annals of Human Biology,* 50(1), pp. 452–460.

Johnson, D.M., Cumming, S.P., Bradley, B. and Williams, S. (2022) 'The influence of exposure, growth and maturation on injury risk in male academy football players', *Journal of Sports Sciences,* 40(10), pp. 1127–1136.

Johnson, D.M., Williams, S., Bradley, B., Sayer, S., Murray Fisher, J. and Cumming, S. (2020) 'Growing pains: Maturity associated variation in injury risk in academy football', *European Journal of Sport Science,* 20(4), pp. 544–552.

Jokela, A., Mechó, S., Pasta, G., Pleshkov, P., García-Romero-Pérez, A., Mazzoni, S., Kosola, J., Vittadini, F., Yanguas, J. and Pruna, R. (2023) 'Indirect rectus femoris injury mechanisms in professional soccer players: Video analysis and magnetic resonance imaging findings', *Clinical Journal of Sport Medicine,* 33(5), pp. 475–482.

Kalata, M., Hank, M., Bujnovsky, D., Michalek, J., Varjan, M., Kunzmann, E., Zahalka, F. and Maly, T. (2021) 'Bilateral strength asymmetry in elite youth soccer players: Differences between age categories', *Symmetry,* 13(11), pp. 1982.

Kellis, E. (2018) 'Intra-and inter-muscular variations in hamstring architecture and mechanics and their implications for injury: A narrative review', *Sports Medicine,* 48(10), pp. 2271–2283.

Kelly, A., Wilson, M.R., Jackson, D.T. and Williams, C.A. (2020) 'Technical testing and match analysis statistics as part of the talent development process in an english football academy', *International Journal of Performance Analysis in Sport,* 20(6), pp. 1035–1051.

Kim, D. and Hong, J. (2011) 'Hamstring to quadriceps strength ratio and noncontact leg injuries: A prospective study during one season', *Isokinetics and Exercise Science,* 19(1), pp. 1–6.

Knapik, J.J., Bauman, C.L., Jones, B.H., Harris, J.M. and Vaughan, L. (1991) 'Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes', *The American Journal of Sports Medicine,* 19(1), pp. 76–81.

Konefał, M., Chmura, P., Zając, T., Chmura, J., Kowalczuk, E. and Andrzejewski, M. (2019) 'A new approach to the analysis of pitch-positions in professional soccer', *Journal of Human Kinetics,* 66, pp. 143.

Kyeremateng, D. (2025) *Football academies: When chasing a dream becomes a nightmare.* Available at: https://www.bbc.co.uk/news/articles/c0egr1nj9qpo (Accessed: .

Launay, F. (2015) 'Sports-related overuse injuries in children', *Orthopaedics & Traumatology: Surgery & Research,* 101(1), pp. S139–S147.

Lee, J.W., Mok, K., Chan, H.C., Yung, P.S. and Chan, K. (2018) 'Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of 146 professional players', *Journal of Science and Medicine in Sport,* 21(8), pp. 789–793.

Leite Portella, D., Arruda, M., Gómez-Campos, R., Checkin Portella, G., Andruske, C.L. and Cossio-Bolaños, M.A. (2017) 'Physical growth and biological maturation of children and adolescents: Proposed reference curves', *Annals of Nutrition and Metabolism,* 70(4), pp. 329–337.

Li, Y. and Mateos, G. (2022) 'Networks of international football: Communities, evolution and globalization of the game', *Applied Network Science,* 7(1), pp. 59.

Light, N., Johnson, A., Williams, S., Smith, N., Hale, B. and Thorborg, K. (2021) 'Injuries in youth football and the relationship to player maturation: An analysis of Time-Loss injuries during four seasons in an english elite male football academy', *Scandinavian Journal of Medicine & Science in Sports,* 31(6), pp. 1324–1334.

Lloyd, R.S., Oliver, J.L., Faigenbaum, A.D., Myer, G.D. and Croix, M.B.D.S. (2014) 'Chronological age vs. biological maturation: Implications for exercise programming in youth', *The Journal of Strength & Conditioning Research,* 28(5), pp. 1454–1464.

Lüdin, D., Donath, L., Cobley, S. and Romann, M. (2022) 'Effect of bio-banding on physiological and technical-tactical key performance indicators in youth elite soccer', *European Journal of Sport Science,* 22(11), pp. 1659–1667.

Maffulli, N., Longo, U.G., Spiezia, F. and Denaro, V. (2010) 'Sports injuries in young athletes: Long-term outcome and prevention strategies', *The Physician and Sportsmedicine,* 38(2), pp. 29–34.

Mala, L., Maly, T., Cabell, L., Hank, M., Bujnovsky, D. and Zahalka, F. (2020) 'Anthropometric, body composition, and morphological lower limb asymmetries in elite soccer players: A prospective cohort study', *International Journal of Environmental Research and Public Health,* 17(4), pp. 1140.

Malina, R.M., Rogol, A.D., Cumming, S.P., e Silva, M.J.C. and Figueiredo, A.J. (2015) 'Biological maturation of youth athletes: Assessment and implications', *British Journal of Sports Medicine,* 49(13), pp. 852–859.

Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K. and Gabbett, T.J. (2018) 'High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk?', *Journal of Science and Medicine in Sport,* 21(3), pp. 257–262.

Maly, T., Zahalka, F. and Mala, L. (2016) 'Unilateral and ipsilateral strength asymmetries in elite youth soccer players with respect to muscle group and limb dominance.', *International Journal of Morphology,* 34(4).

Mandorino, M., Figueiredo, A.J., Gjaka, M. and Tessitore, A. (2023) 'Injury incidence and risk factors in youth soccer players: A systematic literature review. part I: Epidemiological analysis', *Biology of Sport,* 40(1), pp. 3–25.

Mandroukas, A., Michailidis, Y. and Metaxas, T. (2023) 'Muscle strength and hamstrings to quadriceps ratio in young soccer players: A cross-sectional study', *Journal of Functional Morphology and Kinesiology,* 8(2), pp. 70.

Mansfield, P.J. and Neumann, D.A. (2023) *Essentials of kinesiology for the physical therapist assistant e-book: Essentials of kinesiology for the physical therapist assistant e-book.* Elsevier Health Sciences.

Materne, O., Chamari, K., Farooq, A., Weir, A., Hölmich, P., Bahr, R., Greig, M. and McNaughton, L.R. (2021) 'Injury incidence and burden in a youth elite football academy: A four-season prospective study of 551 players aged from under 9 to under 19 years', *British Journal of Sports Medicine,* 55(9), pp. 493–500.

McElveen, M.T., Riemann, B.L. and Davies, G.J. (2010) 'Bilateral comparison of propulsion mechanics during single-leg vertical jumping', *The Journal of Strength & Conditioning Research,* 24(2), pp. 375–381.

Mendiguchia, J., Alentorn-Geli, E., Idoate, F. and Myer, G.D. (2013) 'Rectus femoris muscle injuries in football: A clinically relevant review of mechanisms of injury, risk factors and preventive strategies', *British Journal of Sports Medicine,* 47(6), pp. 359–366.

Mitchell, B.C., Bomar, J.D., Wenger, D.R. and Pennock, A.T. (2021) 'Classifying ischial tuberosity avulsion fractures by ossification stage and tendon attachment', *JBJS,* 103(12), pp. 1083–1092.

Monasterio, X., Bidaurrazaga-Letona, I., Larruskain, J., Lekue, J.A., Diaz-Beitia, G., Santisteban, J.M., Martin-Garetxana, I. and Gil, S.M. (2022) 'Relative skeletal maturity status affects injury burden in U14 elite academy football players', *Scandinavian Journal of Medicine & Science in Sports,* 32(9), pp. 1400–1409.

Monasterio, X., Gil, S.M., Bidaurrazaga-Letona, I., Lekue, J.A., Santisteban, J., Diaz-Beitia, G., Martin-Garetxana, I., Bikandi, E. and Larruskain, J. (2021) 'Injuries according to the percentage of adult height in an elite soccer academy', *Journal of Science and Medicine in Sport,* 24(3), pp. 218–223.

Moran, D., Taylor, J. and Macnamara, Á (2024) 'Understanding the pedagogic underpinning and knowledge sources of game form coaching in high-level team sport coaches', *Sports Coaching Review,* , pp. 1–32.

Nagai, T., Bates, N., McPherson, A., Hale, R., Hewett, T. and Schilaty, N.D. (2021) 'Effects of sex and age on quadriceps and hamstring strength and flexibility in high school basketball athletes', *International Journal of Sports Physical Therapy,* 16(5), pp. 1302.

Nakase, J., Goshima, K., Numata, H., Oshima, T., Takata, Y. and Tsuchiya, H. (2015) 'Precise risk factors for Osgood–Schlatter disease', *Archives of Orthopaedic and Trauma Surgery,* 135, pp. 1277–1281.

Neuschwander, T.B., Benke, M.T. and Gerhardt, M.B. (2015) 'Anatomic description of the origin of the proximal hamstring', *Arthroscopy: The Journal of Arthroscopic & Related Surgery,* 31(8), pp. 1518–1521.

Opar, D.A., Williams, M.D., Timmins, R.G., Hickey, J., Duhig, S.J. and Shield, A.J. (2015) 'Eccentric hamstring strength and hamstring injury risk in australian footballers', *Medicine & Science in Sports & Exercise,* 47(4), pp. 857–865.

Ostojic, S.M., Castagna, C., Calleja-González, J., Jukic, I., Idrizovic, K. and Stojanovic, M. (2014) 'The biological age of 14-year-old boys and success in adult soccer: Do early maturers predominate in the top-level game?', *Research in Sports Medicine,* 22(4), pp. 398–407.

Page, P (2014) ‘Beyond Statistical Significance: Clinical Interpretation of Rehabilitation Research Literature’ *International Journey of Sport Physical Therapy,* 9(5), pp. 726-736.

Parkinson, A.O., Apps, C.L., Morris, J.G., Barnett, C.T. and Lewis, M.G. (2021) 'The calculation, thresholds and reporting of inter-limb strength asymmetry: A systematic review', *Journal of Sports Science & Medicine,* 20(4), pp. 594.

Peek, K., Gatherer, D., Bennett, K.J., Fransen, J. and Watsford, M. (2018) 'Muscle strength characteristics of the hamstrings and quadriceps in players from a high-level youth football (soccer) academy', *Research in Sports Medicine,* 26(3), pp. 276–288.

Pellicer-Chenoll, M., Serra-Añó, P., Cabeza-Ruiz, R., Pardo, A., Aranda, R. and González, L.M. (2017) 'Comparison of conventional hamstring/quadriceps ratio between genders in level-matched soccer players', *Revista Andaluza De Medicina Del Deporte,* 10(1), pp. 14–18.

Peña-González, I., Fernández-Fernández, J., Cervelló, E. and Moya-Ramon, M. (2019) 'Effect of biological maturation on strength-related adaptations in young soccer players', *PloS One,* 14(7), pp. e0219355.

Pfeifer, C.E., Beattie, P.F., Sacko, R.S. and Hand, A. (2018) 'Risk factors associated with non-contact anterior cruciate ligament injury: A systematic review', *International Journal of Sports Physical Therapy,* 13(4), pp. 575.

Pfirrmann, D., Herbst, M., Ingelfinger, P., Simon, P. and Tug, S. (2016) 'Analysis of injury incidences in male professional adult and elite youth soccer players: A systematic review', *Journal of Athletic Training,* 51(5), pp. 410–424.

Pichardo, A.W., Oliver, J.L., Harrison, C.B., Maulder, P.S., Lloyd, R.S. and Kandoi, R. (2019) 'The influence of maturity offset, strength, and movement competency on motor skill performance in adolescent males', *Sports,* 7(7), pp. 168.

Price, R.J., Hawkins, R.D., Hulse, M.A. and Hodson, A. (2004a) 'The football association medical research programme: An audit of injuries in academy youth football', *British Journal of Sports Medicine,* 38(4), pp. 466–471.

Radnor, J.M., Oliver, J.L., Waugh, C.M., Myer, G.D. and Lloyd, R.S. (2020) 'The influence of maturity status on muscle architecture in school-aged boys', *Pediatric Exercise Science,* 32(2), pp. 89–96.

Radnor, J.M., Oliver, J.L., Waugh, C.M., Myer, G.D. and Lloyd, R.S. (2020) 'The influence of maturity status on muscle architecture in school-aged boys', *Pediatric Exercise Science,* 32(2), pp. 89–96.

Read, P.J., Oliver, J.L., De Ste Croix, M.B., Myer, G.D. and Lloyd, R.S. (2018) 'An audit of injuries in six english professional soccer academies', *Journal of Sports Sciences,* 36(13), pp. 1542–1548.

Renshaw, A. and Goodwin, P.C. (2016) 'Injury incidence in a premier league youth soccer academy using the consensus statement: A prospective cohort study', *BMJ Open Sport & Exercise Medicine,* 2(1), pp. e000132.

Ruf, L., Cumming, S., Härtel, S., Hecksteden, A., Drust, B. and Meyer, T. (2021) 'Construct validity of percentage of predicted adult height and BAUS skeletal age to assess biological maturity in academy soccer', *Annals of Human Biology,* 48(2), pp. 101–109.

Salter, J., Cumming, S., Hughes, J.D. and De Ste Croix, M. (2022) 'Estimating somatic maturity in adolescent soccer players: Methodological comparisons', *International Journal of Sports Science & Coaching,* 17(1), pp. 11–17.

Sanders, J.O., Qiu, X., Lu, X., Duren, D.L., Liu, R.W., Dang, D., Menendez, M.E., Hans, S.D., Weber, D.R. and Cooperman, D.R. (2017) 'The uniform pattern of growth and skeletal maturation during the human adolescent growth spurt', *Scientific Reports,* 7(1), pp. 16705.

Sato, V.N., Moriwaki, T.L., Ikawa, M.H., Sugawara, L.M., da Rocha Correa Fernandes, A., Skaf, A.Y. and Yamada, A.F. (2024) 'Apophyseal injuries in soccer players', *Skeletal Radiology,* , pp. 1–15.

Schiller, J., DeFroda, S. and Blood, T. (2017) 'Lower extremity avulsion fractures in the pediatric and adolescent athlete', *JAAOS-Journal of the American Academy of Orthopaedic Surgeons,* 25(4), pp. 251–259.

Schoensee, S.K. and Nilsson, K.J. (2014) 'A novel approach to treatment for chronic avulsion fracture of the ischial tuberosity in three adolescent athletes: A case series', *International Journal of Sports Physical Therapy,* 9(7), pp. 974.

Sheehan, D.P. and Lienhard, K. (2019) 'Gross motor competence and peak height velocity in 10-to 14-year-old canadian youth: A longitudinal study', *Measurement in Physical Education and Exercise Science,* 23(1), pp. 89–98.

Sherar, L.B., Cumming, S.P., Eisenmann, J.C., Baxter-Jones, A.D. and Malina, R.M. (2010) 'Adolescent biological maturity and physical activity: Biology meets behavior', *Pediatric Exercise Science,* 22(3), pp. 332–349.

Skomrlj, J., Modric, T., Sekulic, D., Uljevic, O., Kesic, M.G., Bandalovic, A., Turic, A., Becir, B. and Versic, S. (2024) 'Muscle injuries in elite youth football academy: A six-year longitudinal study on the U15 football team', *Applied Sciences,* 14(11), pp. 4422.

Soliman, A., De Sanctis, V. and Elalaily, R. (2014) 'Nutrition and pubertal development', *Indian Journal of Endocrinology and Metabolism,* 18(Suppl 1), pp. S39–S47.

Souza, N.M.d., Ramos-Silva, L.F., Borges, P.H., Moura, F.A., Ronque, E.R.V. and Costa, J.C.d. (2024) 'Bilateral asymmetries and the performance profile in isokinetic knee assessment in young soccer players according to peak height velocity', *Revista Brasileira De Ciências do Esporte,* 46, pp. e20230058.

Stark, T., Walker, B., Phillips, J.K., Fejer, R. and Beck, R. (2011) 'Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review', *PM&R,* 3(5), pp. 472–479.

Sweeney, L., MacNamara, Á, Taylor, J. and Lundberg, T.R. (2024) 'Selection of reference data significantly influences biological maturity timing classification in national youth soccer players', *International Journal of Sports Science & Coaching,* 19(6), pp. 2356–2365.

Theisen, D., Frisch, A., Malisoux, L., Urhausen, A., Croisier, J. and Seil, R. (2013) 'Injury risk is different in team and individual youth sport', *Journal of Science and Medicine in Sport,* 16(3), pp. 200–204.

Towlson, C. and Cumming, S.P. (2022) 'Bio-banding in soccer: Past, present, and future', *Annals of Human Biology,* 49(7-8), pp. 269–273.

Vadhera, A.S., Knapik, D.M., Gursoy, S., Perry, A.K., Kunze, K.N., Singh, H., Westrick, J.C. and Chahla, J. (2022) 'Avulsion fractures of the ischial tuberosity in the pediatric athlete: A systematic review and return to sport analysis', *Journal of Pediatric Orthopaedics B,* 31(5), pp. 508–516.

Valle, X., Malliaropoulos, N., Párraga Botero, J.D., Bikos, G., Pruna, R., Mónaco, M. and Maffulli, N. (2018) 'Hamstring and other thigh injuries in children and young athletes', *Scandinavian Journal of Medicine & Science in Sports,* 28(12), pp. 2630–2637.

Van Der Made, A.D., Reurink, G., Gouttebarge, V., Tol, J.L. and Kerkhoffs, G.M. (2015) 'Outcome after surgical repair of proximal hamstring avulsions: A systematic review', *The American Journal of Sports Medicine,* 43(11), pp. 2841–2851.

van der Sluis, A., Elferink-Gemser, M.T., Brink, M.S. and Visscher, C. (2015) 'Importance of peak height velocity timing in terms of injuries in talented soccer players', *International Journal of Sports Medicine,* 36(04), pp. 327–332.

Van Der Sluis, A., Elferink-Gemser, M.T., Coelho-e-Silva, M.J., Nijboer, J.A., Brink, M.S. and Visscher, C. (2014) 'Sport injuries aligned to peak height velocity in talented pubertal soccer players', *International Journal of Sports Medicine,* 35(04), pp. 351–355.

Vist Hagen, R., Haga, M., Sigmundsson, H. and Lorås, H. (2022) 'The association between academic achievement in physical education and timing of biological maturity in adolescents', *Plos One,* 17(3), pp. e0265718.

Wachholz, F., Tiribello, F., Mohr, M., van Andel, S. and Federolf, P. (2020) 'Adolescent awkwardness: Alterations in temporal control characteristics of posture with maturation and the relation to movement exploration', *Brain Sciences,* 10(4), pp. 216.

Waldén, M., Mountjoy, M., McCall, A., Serner, A., Massey, A., Tol, J.L., Bahr, R., D'Hooghe, M., Bittencourt, N. and Della Villa, F. (2023) 'Football-specific extension of the IOC consensus statement: Methods for recording and reporting of epidemiological data on injury and illness in sport 2020', *British Journal of Sports Medicine,* 57(21), pp. 1341–1350.

Weishorn, J., Jaber, A., Trefzer, R., Zietzschmann, S., Kern, R., Spielmann, J., Renkawitz, T. and Bangert, Y. (2023) 'How does age affect injury characteristics in young elite footballers?—A prospective cohort study of a german youth academy', *Journal of Clinical Medicine,* 12(21), pp. 6938.

Wik, E.H., Lolli, L., Chamari, K., Materne, O., Di Salvo, V., Gregson, W. and Bahr, R. (2021) 'Injury patterns differ with age in male youth football: A four-season prospective study of 1111 time-loss injuries in an elite national academy', *British Journal of Sports Medicine,* 55(14), pp. 794–800.

Appendix A. Registration Consent Form Example

York City FC Academy | Registration Consent Form 2022/23

Welcome to York City FC Academy for the 2022/23 season, we're really looking forward to working with you. To support a number of projects across the club, we need your consent to capture photos, videos, and data regarding your child. Please complete this short form below to provide your consent.

* Required

1. Name of parent/guardian *

   Enter your answer

2. Name of player *

   Enter your answer

3. 2022/23 age group *

   ◯ U9

   ◯ U10

   ◯ U11

   ◯ U12

   ◯ U13

   ◯ U14

Appendix A. Registration Consent Form Example (Continued)

- ◯ U15
- ◯ U16
- ◯ U18 (York College and/or Pool Squad)
- ◯ U19 (Youth Team)

4. I consent for photos and video footage of my son to be shared within York City Academy to help monitor his development *

- ◯ Yes
- ◯ No

5. I consent for personal data collected on my son to be shared within York City Academy to help monitor his development *

- ◯ Yes
- ◯ No

6. To enable us to accurately estimate the maturity status of your son to help with their development, we require an indication of birth parent heights. Therefore, please provide us with the birth parent heights as accurately as possible in centimetres.

   If for any reason either/both birth parent heights cannot be provided accurately, please leave this blank.

   Birth Mother height:

   Enter your answer

Appendix A. Registration Consent Form Example (Continued)

7. To enable us to accurately estimate the maturity status of your son to help with their development, we require an indication of birth parent heights. Therefore, please provide us with the birth parent heights as accurately as possible in centimetres.

   If for any reason either/both birth parent heights cannot be provided accurately, please leave this blank.

   Birth Father height:

   Enter your answer

8. I consent for personal data collected on my son to be shared with researchers from York St John University and I understand that if my son's personal data is used for research this will be anonymised

   ◯ Yes

   ◯ No

9. I understand that I can withdraw from son's personal data from any research without giving an explanation, and that this will not have any negative impact on his future care and treatment within York City Academy *

   ◯ Yes

   ◯ No

10. Is there anything else you'd like to let us know?

Appendix B. Raw Peak Strength Values

Table 11. Raw peak isometric force data for the pre-PHV group

Participant	Age Group	Dominant Side	Left Knee Extension (N)			Right Knee Extension (N)			Left Knee Flexion (N)			Right Knee Flexion (N)		
			Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean
1	U12	Right	12.81	12.31	12.56	10.41	10.87	10.64	7.62	6.33	6.98	7.41	6.57	6.99
2	U12	Right	19.95	18.79	19.37	21.04	19.31	20.18	10.69	10.71	10.70	12.25	13.52	12.89
3	U12	Right	20.04	15.59	17.82	14.88	22.14	18.51	12.48	11.60	12.04	15.45	15.02	15.24
4	U12	Right	18.64	13.09	15.87	17.76	15.81	16.79	6.92	7.74	7.33	10.17	10.09	10.13
5	U12	Left	17.46	13.86	15.66	12.08	9.74	10.91	10.34	10.00	10.17	11.86	11.54	11.70
6	U12	Left	13.62	13.64	13.63	11.98	14.25	13.12	8.03	8.69	8.36	10.80	9.78	10.29
7	U12	Right	16.26	14.21	15.24	17.82	16.13	16.98	8.83	7.43	8.13	9.10	8.88	8.99
8	U12	Right	20.18	17.88	19.03	20.23	19.34	19.79	9.59	8.77	9.18	10.50	8.23	9.37
9	U13	Right	21.78	19.54	20.66	19.08	17.20	18.14	6.84	6.24	6.54	7.60	6.63	7.12
10	U13	Right	16.66	10.64	13.65	14.20	12.62	13.41	11.49	12.13	11.81	11.60	10.36	10.98
11	U13	Right	12.45	13.99	13.22	14.62	13.48	14.05	8.56	9.59	9.08	9.77	9.77	9.77
15	U14	Right	17.93	18.04	17.99	19.49	18.30	18.90	8.55	10.27	9.41	8.39	8.39	8.39

Table 12. Raw peak isometric force data for the circa-PHV group

Name	Age Group	Dominant Side	Left Knee Extension (N)			Right Knee Extension (N)			Left Knee Flexion (N)			Right Knee Flexion (N)		
			Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean
12	U13	Right	22.64	19.69	21.17	16.26	16.55	16.41	12.45	9.47	10.96	13.43	12.34	12.89
13	U13	Right	16.32	13.59	14.96	13.47	11.04	12.26	13.44	11.99	12.72	10.41	11.09	10.75
16	U14	Left	20.94	21.24	21.09	19.74	18.86	19.30	11.89	12.04	11.97	12.81	13.32	13.07
17	U14	Left	23.54	23.24	23.39	19.80	17.82	18.81	12.49	10.99	11.74	14.27	14.43	14.35
18	U14	Left	18.10	14.60	16.35	16.51	13.99	15.25	10.30	9.23	9.77	9.00	9.00	9.00
19	U14	Right	20.68	18.51	19.60	21.25	23.31	22.28	12.75	10.57	11.66	11.79	12.34	12.07
20	U14	Right	17.21	14.56	15.89	12.89	11.31	12.10	9.22	10.93	10.08	9.46	11.33	10.40
21	U14	Right	14.71	13.62	14.17	17.68	16.34	17.01	11.47	10.82	11.15	12.74	10.31	11.53
22	U14	Right	20.19	17.77	18.98	18.97	16.70	17.84	10.27	7.65	8.96	14.29	10.89	12.59
23	U14	Left	14.80	16.75	15.78	16.41	18.21	17.31	10.32	8.03	9.18	10.56	8.54	9.55
24	U14	Right	17.71	17.31	17.51	16.51	17.00	16.76	12.83	13.25	13.04	15.25	13.17	14.21
25	U14	Right	12.61	18.47	15.54	21.60	18.10	19.85	11.33	10.28	10.81	14.06	11.47	12.77
26	U14	Right	19.11	16.21	17.66	19.73	19.13	19.43	10.17	10.44	10.31	11.40	12.81	12.11
28	U15	Right	19.24	13.67	16.46	19.83	18.67	19.25	12.02	10.18	11.10	12.58	12.68	12.63
29	U15	Right	17.58	14.53	16.06	16.84	16.84	16.84	10.50	7.93	9.22	11.16	11.39	11.28
30	U15	Right	18.87	19.18	19.03	22.75	22.41	22.58	11.67	12.98	12.33	13.76	13.03	13.40
31	U15	Left	16.85	17.58	17.22	18.33	19.14	18.74	14.44	15.82	15.13	12.85	12.34	12.60

Appendix B. Raw Peak Strength Values (Continued)

Table 13. Raw peak isometric force data for the post-PHV group

Name	Age Group	Dominant Side	Left Knee Extension (N)			Right Knee Extension (N)			Left Knee Flexion (N)			Right Knee Flexion (N)		
			Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean	Attempt 1	Attempt 2	Mean
14	U13	Right	21.66	19.37	20.52	22.75	15.53	19.14	10.66	12.39	11.53	14.17	13.75	13.96
27	U14	Right	24.53	21.44	22.99	15.32	17.98	16.65	15.29	17.38	16.34	22.91	16.27	19.59
32	U15	Left	20.77	18.03	19.40	20.34	17.43	18.89	14.04	15.08	14.56	15.17	13.62	14.40
33	U15	Right	26.03	22.19	24.11	23.86	24.07	23.97	11.70	11.60	11.65	13.28	12.19	12.74
34	U15	Right	21.67	21.67	21.67	20.79	23.22	22.01	10.40	9.37	9.89	9.65	10.23	9.94
35	U15	Right	18.34	17.42	17.88	17.24	17.77	17.51	9.27	7.53	8.40	9.63	9.27	9.45
36	U15	Right	18.22	19.05	18.64	20.12	17.25	18.69	11.54	12.21	11.88	13.66	11.77	12.72
37	U15	Left	18.21	18.55	18.38	14.15	17.44	15.80	11.10	12.30	11.70	9.81	12.07	10.94
38	U16	Right	19.40	20.78	20.09	22.00	20.10	21.05	16.82	14.29	15.56	14.52	15.21	14.87
39	U16	Right	19.87	21.39	20.63	18.97	16.38	17.68	12.31	11.04	11.68	12.54	12.23	12.39
40	U16	Right	18.13	18.24	18.19	18.46	19.34	18.90	12.91	12.48	12.70	12.56	14.54	13.55
41	U16	Right	26.37	21.57	23.97	26.02	25.05	25.54	10.87	10.79	10.83	12.22	11.65	11.94
42	U16	Left	26.47	23.55	25.01	21.87	22.98	22.43	18.04	15.94	16.99	15.53	15.99	15.76
43	U16	Right	21.02	20.02	20.52	21.44	21.44	21.44	11.61	10.60	11.11	9.91	10.04	9.98
44	U16	Right	23.00	21.37	22.19	20.05	17.87	18.96	13.70	15.52	14.61	16.91	18.02	17.47
45	U16	Right	22.62	25.25	23.94	16.26	19.73	18.00	13.19	13.82	13.51	13.44	13.38	13.41
46	U16	Right	26.08	24.00	25.04	28.05	21.60	24.83	12.41	14.67	13.54	14.74	14.74	14.74

Appendix C. Injury Findings

Injury Findings

Table 14 represents the location of time-loss pathologies that occurred throughout the 2024/25 season, with injuries subsequently divided into match and training injuries.

When examining injury occurrence across all age groups, over 20% of injuries occurred at the thigh, with the ankle following closely with 18.61%. Importantly, 11.63% of injuries involved the hip, with 60**%** of these entailing a growth-related issue of the AIIS.

When exploring differences in match and training injury incidence occurrence, a paired samples T-test demonstrated a significant difference between match (M=2.50, SD=2.15) and training (M=1.08, SD=1.31) injury occurrence; t(11)=2.33, p=0.04, C.I. = [0.08, 2.76]), with a moderate effect size displayed (Cohen's d = -0.67).

Table 14. Injury incidence per location and match or training occurrence across the 2024/25 season

Location	All Injuries (n=43)		Match Injuries (n=30)		Training Injuries (n=13)	
	No	%	No	%	No	%
Thigh	9	20.93	6	20	3	23.08
Ankle	8	18.61	7	23.33	1	7.69
Knee	6	14	2	6.67	4	30.77
Hip	5	11.63	4	13.33	1	7.69
Groin	4	9.3	2	6.67	2	15.38
Lower Leg	3	6.98	3	10	0	0
Foot	3	6.98	2	6.67	1	7.69
Lumbar Spine	1	2.33	1	3.33	0	0
Head	1	2.33	0	0	1	7.69
Thumb	1	2.33	1	3.33	0	0
Shoulder	1	2.33	1	3.33	0	0
Chest	1	2.33	1	3.33	0	0

Table 15 represents the quantity of quadricep and hamstring-related time-loss pathologies that occurred throughout the 2024/25 season, with only players who were involved throughout the entire season being included. It is also important to emphasise that only time-loss injuries were recorded, thus meaning that the incidence rate may be lower than previous literature which may have included all injury complaints, regardless of the severity.

Over the five age groups included, 70 players competed throughout the entire season. Only one time-loss quadricep strain occurred during the season compared to six hamstring time-loss strains. Regarding, tendinopathies, one rectus femoris strain was recorded, with no hamstring tendinopathies prevailing. Importantly to note, one thigh-related issue with Table 14 involved adductor magnus so has therefore not been recorded in Table 15.

In relation to growth-related injuries, three growth-related injuries involving the AIIS, one involving the inferior pole of the patella (Sinding-Larsen-Johansson Syndrome), and one involving the tibial tuberosity (OSD), occurred throughout the season.

Of the six hamstring pathologies, 4 occurred during match-play compared to during training, with the one quadricep strain occurring during match-play. Each age group sustained at least one hamstring injury throughout the season, with the U13 groups being the only group to experience a quadricep time-loss strain. Additionally, the U13 group produced the greatest quantity of growth-related time-loss injuries.

Table 15. Injury incidence per age group across the 2024/25 season

	U12 (n=13)	U13 (n=14)	U14 (n=15)	U15 (n=13)	U16 (n=15)
Quadricep Muscle Strain		1			
Quadricep Tendinopathy					1
Hamstring Strain	2	1	1	1	1
Hamstring Tendinopathy					
Growth-Related: AIIS		2		1	
Growth-Related: Sinding Larsen Johansson Syndrome					1
Growth-Related: Osgood Slatters		1			

Injury severity varied across the 13 thigh-related pathologies, see Table 16. Using the burden categories suggested by Walden et al., (2023), the 4–7-day category recording the greatest number of injuries, with the 29-90 category producing no injuries.

The U12 group recorded one injury within the 4-7 category, with the other recording a greater severity of 8-28 days. Four of the five injuries within the U13 group had a severity of 4-7 days, with one injury having a reduced severity of 1-3 days. The U14 group recorded one injury within the 4-7 category, with the U15 group recording one injury in both the 8-28- and 91-180-day severity category. Lastly, the U16 injury recorded the greatest severity of all hamstring and quadricep-related pathologies, with a severity exceeding over 180 days.

Table 16. Injury severity for hamstring and quadricep-related time-loss pathologies

	Severity (days)					
	1-3	**4-7**	**8-28**	**29-90**	**91-180**	**>180days**
Quadricep Muscle Strain		1				
Quadricep Tendinopathy		1				
Hamstring Strain	1	2	3			
Hamstring Tendinopathy						
Growth-Related: AIIS		2			1	
Growth-Related: Sinding Larsen Johansson Syndrome						1
Growth-Related: OSD		1				