Citation for published version:

DOI:
10.1080/02640414.2022.2051380

Publication date:
2022

Document Version
Peer reviewed version

Link to publication

This is an Accepted Manuscript of an article published by Taylor & Francis in Journal of Sports Sciences on 14/03/2022, available online: http://www.tandfonline.com/10.1080/02640414.2022.2051380

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The influence of exposure, growth and maturation on injury risk in male academy football players

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Key Words:
Soccer, Maturity, Adolescent, Prevention, Injury
Abstract

Adolescence is a period of increased injury risk in youth footballers; however, no studies have considered the influence of growth-related factors and exposure time upon injury risk. Forty-nine elite male youth footballers were prospectively monitored for growth, lower-limb growth, maturation, training volume and injury for one season. Generalised linear mixed-effects models were used to model growth rate, lower-limb growth rate, Percentage of Predicted Adult Stature, and smoothed week-to-week changes in exposure on time-loss injury risk. The relationship between growth rate and injury incidence was linear (P=0.031) and injury burden was non-linear (P=0.019). The relationship between lower-limb growth rate and injury incidence was linear and positive (P=0.098). A non-linear relationship was observed between lower-limb growth rate and injury burden (P=0.001). A non-linear relationship between Percentage of Predicted Adult Stature and both injury incidence and injury burden were found, with peak risk occurring at 92% and 95% Percentage of Predicted Adult Stature, respectively. There was a positive linear relationship between smoothed week-to-week changes in exposure and injury incidence (P=0.001), and a non-linear relationship between week-to-week change and injury burden (P=0.01). Practitioners should monitor the timing and rate of the growth spurt and exposure time to identify players at greater injury risk.
Introduction

It is common practice for football clubs worldwide to use academies to develop talented youth players (Jones et al. 2019). These academies aim to develop youth players into elite players, but injuries may negatively affect this development. A review by Jones et al. (2019) suggested that the likelihood of a high-level youth football player sustaining a time-loss injury during a season was 50%. Additionally, Jones et al. (2019) also suggested that non-contact injuries are prominent in high-level male youth soccer players; with 53% to 72% injuries being non-contact. Thus, the reduction of injuries to youth players in academies is of paramount importance (Read et al. 2018). Injuries at the youth level can also have long-term consequences, making players more susceptible to future injuries and long-term health risks (e.g. osteoarthritis) (Webborn 2012; Lohkamp, Kromer, and Schmitt 2017). During adolescence, many changes occur to the body, and so there are several potential causes of an increased injury risk, including the rapid growth of the body during peak height velocity (PHV) and changes to limb length, limb mass, and moments of inertia (Adirim and Cheng 2003; Hawkins and Metheny 2001). Consequently, adolescents might therefore experience temporary delays or regressions in sensorimotor mechanisms and motor control (Quatman-Yates et al. 2012), which may adversely impact injury risk.

To date, a limited number of studies in youth football academies have investigated the influence of adolescent growth rates upon injury (Kemper et al. 2015; Rommers et al. 2019). Kemper et al. (2015) reported that injured male adolescent footballers had a higher rate of growth compared to non-injured players. Rommers et al. (2019) also found that increases in leg length were associated with increased overuse injury risk in youth footballers. In adolescent track and field athletes, Wik, Martínez-Silván, et al. (2020) found that both overall growth rate and leg length growth rate were associated with a greater risk of bone and growth plate injuries. In accordance with these findings, research suggests an increase in injuries during the period of
peak height velocity (PHV) that accompanies puberty (Bult, Barendrecht, and Tak 2018; Van der Sluis et al. 2014; Maternea, Farooqb, and Johnson 2015). However, the aforementioned studies have employed the maturity offset protocol (Mirwald et al. 2002) which uses age, stature, mass and seated stature for estimating age at PHV, the validity and reliability of which has been questioned (Kozieł and Malina 2017; Kozieł and Malina 2018). Specifically, the offset method, and its variations, has been shown to under-estimate age at PHV in younger and late-maturing youth and overestimates age at PHV in older and early maturing youth (Kozieł and Malina 2018; Kozieł and Malina 2017). A recent study of player development in English academy footballers found that, at 13 years of age, the offset method was only able to correctly categorise 62% of players as being within or outside the + or -1 year band of their observed age at PHV (Parr et al., 2020). Using the percentage of predicted adult stature as an alternative indicator of maturation status, Johnson et al. (2019) found that players between 88 and 95% of predicted adult stature (i.e., circa PHV) presented a higher injury incidence rate and burden compared to pre-PHV. However, this work was limited by the fact that it only accounted for match exposure rather than total exposure (match and training). Monasterio et al. (2020) also demonstrated that growth-related injuries are grouped around PHV, and that these injuries occurred from distal to proximal body regions, following the pattern of growth (Malina, Bouchard, and Bar-Or 2004).

To date, no studies have evaluated the relationship between changes in exposure and injury risk in adolescent football players, although positive moderate-to-large associations between training volume (pitch counts) and injury risk have been observed in adolescent baseball players (Olsen et al. 2006; Lyman et al. 2002). Training load research recommends avoiding large changes in training load particularly in developing athletes (Soligard et al. 2016); one method to do this is to monitor week-to-week changes (Lazarus et al. 2017). Accordingly, the primary aim of this study was to explore the association between growth, maturity, and total
(match and training) exposure related risk factors and injury risk (incidence and burden) in a group of elite male academy football players.
Method

Participants

A total of 49 male football players, across four age groups (U13 – U16) within an English football club’s academy agreed to participate in this study. No a priori sample size calculation was conducted, however, Bahr and Holme (2003) suggest that 20–50 injury cases are needed to detect moderate-to-strong associations between risk factors and injury, and thus this sample size was deemed adequate for this purpose. These age groups were selected for analysis as the aim of this study was to understand the influence of growth, maturation, and exposure variables upon injury risk. Therefore, these groups provided a range of players pre-, circa- and post-PHV. Data from one full competitive season (2018/19) were analysed. This study gained ethical approval from the Research Ethics Approval Committee for Health at the University of Bath. All parents and guardians provide consent and assent for routine data collection as part of the enrolment in the academy and agreed to the potential use of this data for research purposes.

Measurements

Players’ stature, seated stature and mass were measured by one ISAK trained sports science staff member and researcher on a regular basis (3 to 5 times per year). The definitions and instructions in the measurement of stature, seated stature and mass are consistent with the International Society for the Advancement of Kinanthropometry (ISAK) guidelines. The staff member’s absolute and relative intra-rater typical error of measurement for standing stature was 0.03 cm and 0.02 %, and for seated stature was 0.02 cm and 0.02 %, respectively (Perini et al. 2005). Growth rate was calculated for each player as the change in stature over the change in time, giving a rate in cm per year. This rate was then inputted on the midpoint between the two measurement dates and smoothed using a Bessel spline to provide an estimated growth rate for each day. The calculation of the spline allowed an estimate of growth rate for each, which
allowed the growth and maturation data to match with daily observations of day training exposure, the spline would fit a curve across the whole time period using the multiple measurement points and subsequently, a growth rate per day could be estimated from this curve. The players’ stature, mass, chronological age, and mid-parent stature were also used to predict the adult stature of each player (Khamis and Roche 1994). Each player's parents completed a self-report form to provide their stature, this was adjusted for over-estimation using the equations in Epstein et al. (1995). For all players included in the study, it was possible to obtain the stature of both parents. Each player's current stature was then expressed as a percentage of their predicted adult stature, which was used as an index of somatic maturation (Roche, Tyleshevski, and Rogers 1983). This method has a median error between the actual and the predicted adult stature of males (4 to 17 years old) that ranges from 0.8 to 2.8 cm (Khamis and Roche 1994). The maturity status (pre-, circa- and post-PHV) and maturity timing (early, on-time and late) were calculated for each measurement point. A Bessel spline was used to provide a data point for each day within the season, for maturity status.

Exposure time in minutes was calculated as the total training, match, and gym time within the academy and recorded daily by the age group coach. Total training, match, and gym time were included to fit with the consensus statement on football injuries which suggest physical activities under the control of the team’s coaching or fitness staff that are aimed at maintaining or improving players’ football skills or physical condition should be included. Participants with exposure two standard deviations below the mean were excluded as outliers before analysis (Hopkins et al. 2009), a low exposure was due to players being released, signed by another club or recently signed to the academy. The total daily exposure, total weekly exposure and the week-to-week change were also calculated. Total weekly exposure was calculated on a rolling basis including the current day and the previous six days. The smoothed week-to-week change in exposure was calculated as the change in total weekly exposure between the previous and
current week; this value was then exponentially smoothed as described in Equation 1 (Lazarus et al. 2017):

$$\text{Week } - \text{to- week change}_{\text{today}} = \text{Week } - \text{to- week change}_{\text{yesterday}} \times \lambda_a + ((1 - \lambda_a) \times EMW_{\text{yesterday}})$$

Where \( \lambda_a \) represents the degree of time decay. Time decay will be calculated by:

$$\lambda_a = 2/(N + 1)$$

Where \( N \) is the chosen time decay constant. A decay factor representing a time constant of 7 days (0.069) was used. Activities outside the academy including both at home or school were not registered (Bult, Barendrecht, and Tak 2018).

Academy medical staff recorded time-loss injuries using the club’s online database. A time-loss injury was defined as a player being unable to take part in full football training or match play (Fuller et al. 2006). Only injuries that occurred during training, gym or football competition were counted, those unrelated to academy activities were not recorded (Fuller et al. 2006). Only non-contact injuries were analysed; these were defined as those sustained by a player without extrinsic contact by another player or other object on the field of play (Marshall 2010). Injuries are represented as a total value (cumulative value) and as the number of injuries per 1,000 player-hours (Fuller et al. 2006). Injury severity was given by the number of days elapsed between the initial injury date and the player’s return to full availability for training and/or matches (Fuller et al. 2006). The injury burden was given by the injury incidence rate multiplied by the mean days missed per injury, giving the days of absence per 1000 hours per (Fuller 2018).

**Statistical analysis**

All estimations were performed using \( R \) (version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria). Generalized linear mixed-effects models were fitted using the \textit{lme4} package (Bates et al. 2014), to model the association between growth rate, maturity status and week-to-
week changes in exposure upon estimated injury likelihood, using a binomial distribution and log-link function.

For analysis of injury burden, data were transferred into weekly values, with the dependent variable being the count of days absent each week. For week-to-week changes in exposure, the injury burden data was lagged by one week so that the week-to-week change was associated with burden incurred in the subsequent week. Generalized linear mixed-effects models with a Poisson distribution, log-link function and exposure offset were used, with the same predictor variables input to model their association with injury burden.

Predictor variables were modelled as continuous fixed effects. The growth rate variable was also parsed into two categories to explore the difference between a high growth rate (>7.2 cm/year) and a low growth rate (<7.2 cm/year) (Kemper et al. 2015). Player ID was included as a random effect to account for repeated observations. Each continuous predictor variable was independently modelled as both a linear and nonlinear effect by including a polynomial term in the model (Hulin et al. 2013; Cross et al. 2016). For non-linear effects, polynomial terms were retained in the model where P < 0.10. Rate ratio (RR) values were presented as the change in risk per two standard deviation increase (2SD↑) in the predictor variable (Hopkins et al. 2009). For non-linear relationships, the ‘estimate smooth’ function from the ‘model based’ package was used to summarise non-linear curves in terms of linear segments and the region of peak risk (Makowski, Ben-Shachar, and Lüdecke 2020).
Results

Player demographics and maturity data between age groups are presented in Table 1. There were 53 injuries and 8,843 hours of total exposure. The mean exposure for each player was 180.4 (± 40.6) hours, furthermore, the mean (SD) values for Percentage of Predicted Adult Stature = 92.14 (± 4.89), growth rate = 5.39 (± 3.54) cm/year, lower-limb growth rate = 3.06 (± 2.53) cm/year and week-to-week change in total exposure = 3.52 (± 117.62) minutes. The overall injury incidence rate was 6.0 injuries per 1,000 hours (95% CI 4.6-7.8), the mean severity of injuries was 31 days (95% CI 24 – 40) and injury burden was 184.1 days absent per 1,000 hours (95% CI 140.6-241.0). A comparison between age groups for injury incidence, severity, and burden can be found in Table 2; injury burden in the U16 age group was lower than all other age groups.

Table 1. Stature, Body Mass, Percentage of Predicted Adult Stature and Maturity Timing (mean ± SD)

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Stature (cm)</th>
<th>Body Mass (kg)</th>
<th>Percentage of Predicted Adult Stature</th>
<th>Maturity Timing (z-score)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U13</td>
<td>157.7 ±7.5</td>
<td>45.2 ±6.1</td>
<td>87.7 ±2.2</td>
<td>0.25 ±0.79</td>
</tr>
<tr>
<td>U14</td>
<td>163.4 ±10.9</td>
<td>49.9 ±8.6</td>
<td>91.9 ±3.1</td>
<td>0.34 ±0.66</td>
</tr>
<tr>
<td>U15</td>
<td>170.5 ±6.9</td>
<td>56.0 ±9.3</td>
<td>95.9 ±1.9</td>
<td>0.41 ±0.43</td>
</tr>
<tr>
<td>U16</td>
<td>179.9 ±6.5</td>
<td>70.1 ±8.1</td>
<td>99.2 ±0.6</td>
<td>0.76 ±0.30</td>
</tr>
</tbody>
</table>

Table 2. Injury counts, incidence rates, mean severity, and injury burden for each age group (95% Confidence Intervals Lower – Upper)

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Exposure (Hours)</th>
<th>Injury count</th>
<th>Injury Incidence (per 1,000 hours)</th>
<th>Mean Severity (days)</th>
<th>Injury Burden (per 1,000 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U13</td>
<td>3873</td>
<td>23</td>
<td>5.9 (3.9 – 8.9)</td>
<td>36 (24 – 54)</td>
<td>213.8 (142.1 – 321.7)</td>
</tr>
<tr>
<td>U14</td>
<td>1797</td>
<td>16</td>
<td>8.9 (5.5 – 14.5)</td>
<td>17 (10 – 27)</td>
<td>148.0 (90.7 – 241.6)</td>
</tr>
<tr>
<td>U15</td>
<td>1376</td>
<td>10</td>
<td>7.3 (3.9 – 13.5)</td>
<td>48 (26 – 89)</td>
<td>347.4 (186.9 – 645.7)</td>
</tr>
<tr>
<td>U16</td>
<td>1797</td>
<td>4</td>
<td>2.22 (0.8 – 5.9)</td>
<td>14 (5 – 37)</td>
<td>31.2 (11.7 – 83.0)</td>
</tr>
</tbody>
</table>
A linear relationship between growth rate (cm/year) and the estimated likelihood of injury was found (RR per 2SD↑: 1.73, 95% CI: 1.05–2.85, \( P=0.031 \)) (Figure 1A). There was a greater estimated likelihood of injury for players with a growth rate >7.2cm/year (RR: 1.74, 95% CI: 1.03-2.94, \( P=0.037 \)). A non-linear relationship was observed between growth rate and estimated injury burden (\( P=0.019 \)), with peak injury burden occurring at 4.17 cm/year (Figure 1B). There was a RR per 2SD↑ of 1.05 in injury burden between 0.00 cm/year and 4.21 cm/year, and a RR per 2SD↑ of 0.87 between 4.21 cm/year up to 19.94 cm/year.

There was a non-linear relationship between Percentage of Predicted Adult Stature and the estimated likelihood of injury incidence (\( P=0.082 \)). Peak estimated injury likelihood occurred at 92% Percentage of Predicted Adult Stature (Figure 2A). There was a RR per 2SD↑ of 1.10 in estimated injury likelihood between 83% and 92% Percentage of Predicted Adult Stature,
and a RR per 2SD↑ of 0.93 in the estimated injury likelihood between 92% and 100%. There
was also a non-linear relationship between Percentage of Predicted Adult Stature and estimated
injury burden \( (P<0.001) \). The peak estimated injury burden occurred at 95% Percentage of
Predicted Adult Stature (Figure 2B). There was a RR per 2SD↑ of 1.22 in estimated injury
likelihood between 83% and 95% Percentage of Predicted Adult Stature, and a RR per 2SD↑
of 0.82 in the estimated injury burden likelihood between 95% and 100% Percentage of
Predicted Adult Stature. The combined effects of growth rate and Percentage of Predicted
Adult Stature on estimated injury likelihood and injury burden are displayed in Figure 5 A and
B, respectively. The combined effects of growth rate and Percentage of Predicted Adult Stature
on injury incidence and burden are displayed in Figure 3.

Figure 2. The relationship between Percentage of Predicted Adult Stature and A) injury incidence, with peak
estimated injury likelihood occurring at 91.84%, and B) Injury Burden, with peak risk occurring at 95.24% (The
black line represents the estimated likelihood and grey shaded area represents the 90% confidence intervals).
Figure 3. A heat map showing the combined effects of Growth Rate and Percentage of Predicted Adult Stature on estimated A) injury likelihood and B) injury burden.
The relationship between lower-limb growth rate (cm/year) and estimated injury likelihood was linear (RR per 2SD↑: 1.51, 95% CI:0.92–2.49, \( P=0.098 \)) (Figure 3A). A non-linear relationship was observed between lower-limb growth rate (cm/year) and injury burden (\( P<0.001 \)) (Figure 3B). Peak estimated injury burden likelihood occurred at 5.27 cm/year. There was a RR per 2SD↑ of 1.11 in estimated injury burden between 0.00 cm/year and 5.27 cm/year and a RR per 2SD↑ of 0.90 between 5.27 cm/year and 11.78 cm/year.

Figure 4. The relationship between lower-limb Growth Rate (cm/year) and A) the likelihood of injury incidence and B) Injury Burden, with peak risk occurring at 5.27 cm/year (The black line represents the estimated likelihood and grey shaded area represents the 90% confidence intervals).
There was a linear relationship between week-to-week change in total exposure and the likelihood of injury incidence (RR per 2SD↑: 2.68, 95% CI:1.60 – 4.49, \(P<0.001\)). A non-linear relationship between week-to-week change and injury burden \((P=0.01)\) was observed; the peak estimated injury burden occurred at -68 minutes. There was a RR per 2SD↑ of 2.03 in injury burden between -273 minutes and -68 minutes and a RR per 2SD↑ of 0.31 between 68 minutes to 287 minutes.

Figure 5. The relationship week-to-week change in exposure and A) the likelihood of injury incidence and B) Injury Burden (The black line represents the estimated likelihood and grey shaded area represents the 90% confidence intervals).
Discussion

This study aimed to investigate the effects of growth rate, lower-limb growth rate, percentage of adult stature and week-to-week changes in exposure on the likelihood of injury in adolescent academy footballers. The overall injury incidence rate in this study was 6.0 injuries per 1,000 hours (95% CI 4.6-7.8), the mean severity of injuries was 31 days (95% CI 24 - 40) and overall injury burden was 184.1 days absent per 1,000 (95% CI 140.6-241.0) hours. A linear relationship between growth rate and estimated injury likelihood, and a non-linear relationship between growth rate and injury burden, was observed. There was also a non-linear relationship between Percentage of Predicted Adult Stature and the likelihood of injury, with peak estimated injury likelihood occurring at 92% Percentage of Predicted Adult Stature. The association between Percentage of Predicted Adult Stature and injury burden was non-linear, with peak estimated injury burden likelihood occurring at 95% Percentage of Predicted Adult Stature. The relationship between lower-limb growth rate and the likelihood of injury incidence was found to be linear, whilst a non-linear relationship was observed between lower-limb growth rate and injury burden. There was a positive linear relationship between smoothed week-to-week changes in total exposure and the likelihood of injury incidence, and a non-linear relationship between week-to-week change and injury burden.

The first major finding of this study is the linear relationship between growth rate and injury incidence (RR per 2SD↑: 1.73, 95% CI:1.05–2.85, \( P=0.031 \)), with higher growth rates associated with a greater estimated likelihood of injury (Figure 1A). It should be noted that the confidence interval for this effect estimate ranged from trivial to large. Kemper et al. (2015) found a similar association, showing that injured players had a greater rate of growth than uninjured players. In Kemper et al. (2015) the injured players had a mean rate of growth of 7.2 cm/year; the present study also found the players with a rate of growth rate >7.2 cm/year were 74% more likely to be injured than players growing less than 7.2 cm/year (\( P<0.05 \)). It should
be noted that the current study used generalized linear mixed-effects models to account for repeated observations within players, whereas Kemper et al. (2015) violated the assumption of independence in their models, which may have resulted in Type I errors (Windt et al. 2018). It is likely that growth rate is specifically associated with the risk of bone and growth plate injuries, as evidenced by Wik, Martínez-Silván, et al. (2020) in adolescent athletics athletes. This study also found a non-linear relationship between growth rate and estimated injury burden, with the peak burden estimated at 4.17 cm/year. There was a 5% increase in injury burden per 7.08 cm increase in growth rate between 0.00 cm/year and 4.21 cm/year, but a 13% decrease between 4.21 cm/year up to 19.94 cm/year. This finding is potentially due to players post-growth spurt slowing down in growth but having a high injury burden due to more severe injuries seen in older age groups (Bult, Barendrecht, and Tak 2018). Players post-PHV with a moderate growth rate, approximately 4.17 cm/year, are more likely to miss days with an injury.

For maturity status (Percentage of Predicted Adult Stature) and injury incidence, there was a non-linear relationship between Percentage of Predicted Adult Stature and the likelihood of injury incidence ($P=0.082$) and the peak likelihood of injury occurred at 92% (Figure 2A). The likelihood of injury increased by 10% per 2SD increase in Percentage of Predicted Adult Stature between 83% and 92%, which is equivalent to moving from pre-PHV to circa-PHV. The likelihood of injury decreased by 7% per 2SD↑ when moving from 92% (circa-PHV) to 100% (post-PHV). This corresponds to previous research that has shown an increased risk of injury incidence at 88% and 95% compared to pre and post PHV (Johnson et al. 2019). There was also a non-linear relationship between Percentage of Predicted Adult Stature and injury burden ($P<0.001$) (Figure 2B). The peak risk for injury burden occurred at 95%, which is a higher Percentage of Predicted Adult Stature than the peak for injury incidence. Furthermore, there was a 22% increase in the estimated injury burden per 2SD↑ between 83% and 95% Percentage of Predicted Adult Stature, followed by an 18% decrease in estimated burden.
between 95% and 100% Percentage of Predicted Adult Stature. This result is in agreement with Johnson et al. (2019), who found that there was a greater injury burden circa-PHV (88-95%) and post-PHV (95-100%) when compared to pre-PHV. Other literature has shown similar findings regarding injury risk during PHV; Bult, Barendrecht, and Tak (2018) found 3 to 6 months post-PHV had the highest risk of injury incidence and burden. These findings show that peak risk could occur later than PHV, as per the finding for burden in this study. Similarly to the current study, Van der Sluis et al. (2014) found the year of PHV was associated with a greater number of injuries compared to pre- and post-PHV. However, this study also demonstrated that the days absent were higher during PHV than pre- and post-PHV, contrasting with the present findings. A possible reason for this contrast is that the present study used a different method to calculate the timing of PHV to both Van der Sluis et al. (2014) and Bult, Barendrecht, and Tak (2018). These studies used the maturity offset method, which has been shown to have major limitations with early and late maturing boys (Kozieł and Malina 2018; Kozieł and Malina 2017). The likelihood of injury could be due to an increased vulnerability of tissue during this period, in particular growth sites (Monasterio et al. 2020) or due to changes in motor and postural control (Quatman-Yates et al. 2012; John et al. 2019).

To the authors' knowledge, this is the first study to analyse the combined effects of growth rate and Percentage of Predicted Adult Stature on estimated injury likelihood and injury burden are displayed in Figure 5 A and B, respectively. As discussed above, these figures show that there is a different relationship between these risk factors and injury incidence or burden. Figure 5A shows an increase in estimated injury likelihood at a high growth rate during PHV, whereas, figure 5B shows an increase in estimated injury burden likelihood at a lower growth rate and higher Percentage of Predicted Adult Stature. These heat maps could be used in a practical setting to track an individual’s growth rate and percentage of adult stature and identify when they are at a greater likelihood of injury. There are several potential explanations for the
increased injury burden at a higher Percentage of Predicted Adult Stature. The first is that the types of injuries could change; the current study used all time-loss injuries but the timing of growth-related injuries at various body regions differ (Monasterio et al. 2020). The timing of the injuries would likely follow the pattern of growth and progress from distal to proximal (Malina, Bouchard, and Bar-Or 2004; Hermanussen 2016). The types and locations of injuries were not analysed in the present study due to sample size limitations, but this should be a consideration of future research. The greater injury burden post-PHV could be due to the higher incidence and burden of muscle injuries in older ages groups (Wik, Lolli, et al. 2020), which could potentially be attributed to the increased physical demands at these ages (Goto, Morris, and Nevill 2015a). In contrast, at the high Percentage of Predicted Adult Stature, there are likely to be fewer growth-related injuries. Wik, Martínez-Silván, et al. (2020) found that athletes with greater maturity, using both skeletal age and Percentage of Predicted Adult Stature, were less prone to growth plate injuries. Thus, practitioners should use injury prevention strategies that are appropriate for each player’s stage of development. Practitioners should consider the increased prevalence of muscle injuries and injuries attributed to sprinting in older ages groups (Wik, Lolli, et al. 2020). Another consideration is the demands of training; both increased age and maturity have been associated with increased match running performance (Buchheit and Mendez-Villanueva 2014). Additionally, a player at this stage could still be vulnerable to injury and growing, although less rapidly. Players could, therefore, experience more severe injuries because of the combined effects of a vulnerable musculoskeletal system and an increase in training load demands (Goto, Morris, and Nevill 2015b). Another possible explanation is that at older ages, medical staff are more conservative with return-to-play protocols as players’ values are increased and professional contracts are potentially offered at these ages. However, at the adult level, the opposite has been shown, where sports science and medical staff could be under pressure from coaching and management
staff to allow players to return to sport sooner (Law and Bloyce 2019). Finally, there is also the possibility that the higher injury burden could be due to a greater likelihood of having sustained a previous injury during their career so far (Krabak et al. 2021).

Regarding lower-limb growth rate, there was a linear relationship with the likelihood of injury incidence (RR per 2SD↑: 1.51 95% CI:0.92–2.49, $P=0.098$). This shows that for a two standard deviation increase in lower-limb growth rate (5.06 cm/year) there was a 51% increase in estimated injury likelihood, though the associated confidence intervals were wide and crossed the null. Additionally, a non-linear relationship was observed between lower-limb growth rate and injury burden ($P<0.001$), with peak estimated injury burden likelihood occurring at 5.27 cm/year. As per the findings for overall growth rate, it appears that players post-growth spurt, who have a low-to-moderate lower-limb growth rate, have a higher injury burden. Again, this highlights a distinction between the effect of this risk factor on injury incidence and burden, respectively. This finding is in agreement with Rommers et al. (2019), who found the lower-limb growth rate across a season to be associated with a higher risk of overuse injury. Moreover, in a sample of athletics athletes, Wik, Martínez-Silván, et al. (2020) found that leg length growth rate was associated with greater overall injury risk, as well as bone and growth plate injuries. Monitoring the rate of growth of the lower limbs is therefore important, especially in sports where lower limb injuries are common (Jones et al. 2019). Furthermore, if practitioners are already measuring stature and seated stature it is straightforward to measure this variable without additional procedures or equipment.

Another novel finding from this study is that week-to-week changes in exposure were associated with an increase in estimated injury likelihood. No previous studies have analysed the relationship between changes in exposure and injury risk in adolescent football players. This finding shows that for a 2 SD increase in week-to-week change in exposure (235 minutes), there was a 168% increased estimated injury likelihood (RR: 2.68, 95% CI:1.60 – 4.49,
This finding is difficult to compare with other studies as the number of studies considering both youth populations and this metric are limited. In adolescent baseball players, studies have shown that a larger exposure of activity is associated with a greater risk of injury (Olsen et al. 2006; Lyman et al. 2002). The method of quantifying week-to-week changes in the current study was suggested by Lazarus et al. (2017), where it was used to examine the training-performance relationship. Furthermore, the authors suggested performance staff should avoid prescribing high weekly and substantially increased exposure during the season.

For injury burden, there was a non-linear relationship with week-to-week change, showing the peak estimated injury burden likelihood occurred at -68 minutes. There was a 103% increase in injury burden per 2SD↑ in week-to-week change between -273 minutes and -68 minutes, and a corresponding 69% decrease between 68 minutes to 287 minutes. This finding was unexpected, as it suggests that reducing the total exposure from one week to the next resulted in an increased burden of injury in the subsequent week. It is important to note that in figure 5B the confidence intervals are wide, representing large variation within the model. Furthermore, the density of values for week-to-week was greatest at the middle values, approximately 0 minutes. This demonstrates that at the extreme ends of the relationships, large increases or decreases in week-to-week changes had fewer observations and therefore may have been overly influenced by a small number of observations. A potential alternative method to measure the injury burden would be using median severity rather than mean severity (Bult, Barendrecht, and Tak 2018). This would reduce the influence of skewed data, where values of very high injury burden could inflate the mean severity.

The findings of this study should be considered alongside contextual and potentially limiting factors. The data were recorded from one academy over a one season period. As such, whilst the current study was powered to detect moderate-to-strong associations, it was likely underpowered to detect smaller associations with injury risk (Bahr and Holme 2003).
Moreover, this sample size resulted in wide confidence intervals for many of the reported effects, such that the true population value could range from trivial to large associations with injury risk. Future studies should build on this work by conducting an *a priori* sample size calculation to ensure adequate power for detecting effects of interest; it may be the case that a multi-team, collaborative project is required to achieve this. In addition, the results of this work cannot be generalised to other teams and settings, as differences in factors such as resources and training methods may alter these associations. Future studies should investigate the possibility of using interventions and adapting training protocols to reduce injuries during the adolescent growth spurt. Another consideration for future research is using training load rather than exposure, which could be measured through Session RPE (time x RPE) or Global Navigation Satellite Systems metrics (e.g., total distance, accelerations, decelerations, and high speed running). Understanding both the internal and external training demands could aid in the quantification of specific physical demands during adolescence (Impellizzeri, Marcora, and Coutts 2019). The training load and intensity of the session could have differed between players and groups in our study, but this information was not registered at the individual level. The final consideration is that outside the academy activity was not considered in this analysis; future studies should consider how much activity youth footballers do both inside and outside of the academy environment to understand the complete ‘load-injury’ relationship.

Based on the present findings, the authors recommend that football academies and other youth sports coaches measure growth rate, lower-limb growth rate and maturity status to identify at-risk individuals. Clubs should also monitor large increases in exposure to avoid a rapid overload of players that might lead to a greater likelihood of injury. Clubs should aim to develop interventions targeted at reducing the injury incidence and burden observed during these high-risk phases of adolescence. For example, adaptions to training load (Savelsbergh and Wormhoudt 2018), strength programmes (Kaya et al. 2013; Rathleff et al. 2020),
fundamental movement skills (Savelsbergh and Wormhoudt 2018) or other potential solutions could be investigated. Furthermore, practitioners should develop appropriate injury prevention strategies, to reduce the increase in injury risk seen during PHV. One example of this is Horobeanu, Jones, and Johnson (2017), who demonstrated that monitoring maturation and symptoms of overuse injury, and reducing training load in response to these ‘flags’, reduced the days missed due to Osgood Schlatter’s disease in adolescent squash players. However, this study was limited in terms of sample size and further research is required to validate these findings. Overall, examples of empirically-based and well-controlled interventions in this area are currently lacking, and so the authors recommend that practitioners take a pragmatic approach to potential strategies using the current evidence available.

Overall, this study has provided further evidence for the relationships between growth rate, lower-limb growth rate, maturity status and changes in total exposure with injury incidence and injury burden. Furthermore, this study has shown how understanding the interaction between growth rate and Percentage of Predicted Adult Stature with injury, which can be used in practice to identify adolescent academy football players at a greater likelihood of injury.


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