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The combined effects of growth and maturity status on injury risk in an elite football academy

Keywords

youth, adolescence, football, epidemiology, height, injury prevention

Abstract

Objectives

This study aimed to explore the interaction between growth rate on specific injury incidence and burden on pre-, circa- and post-peak height velocity (PHV) periods.

Material and methods

Injury and stature data collected during the 2000-2020 seasons in an elite football academy were retrospectively analysed. Only players with height measurements from childhood until the attainment of adult height were included in the study (N=84). Growth data were smoothed using a cubic spline to calculate daily growth rate and height. Growth rate was categorised into three groups: fast (>7.2 cm/year), moderate (3.5-7.2 cm/year) and slow (<3.5 cm/year). Percentage of observed adult height was used to classify players as pre-PHV (<88%), circa-PHV (88-95%) or post-PHV (>95%). Overall and specific injury incidence and burden and rate ratios for comparisons between growth rate groups were calculated on pre-, circa- and post-PHV periods, separately.

Results

Overall injury incidence and burden were greater in pre-PHV players with quicker growth rates compared to players growing moderately and slowly. All in all, players with more rapid growth-rates were at higher risk for growth-related injuries in all pre-, circa- and post-PHV periods. Post-PHV, the incidence and burden of joint/ligament injuries were 2.4 and 2.6-times greater in players growing slowly compared to players growing moderately.

Conclusions

Practitioners should monitor growth rate and maturity status and consider their interaction to facilitate the design of targeted injury risk reduction strategies.

Explanation letter

RESPONSE TO REVIEWERS

The authors would like to thank the anonymous reviewers for their helpful and constructive suggestions and comments. Following the suggestions, we have included several modifications in the manuscript. We have now addressed each comment. The changes in the manuscript are now indicated by track changes (one colour for each reviewer) to facilitate identification of their location. Also, we send a point-by-point response to the reviewers.

They would also like to thank the Editor for the comments and for giving us the opportunity to submit a revised version of our manuscript.

Please, consider citing the findings of recent studies if you find them relevant:

Massa M, Moreira A, Costa R, et al. Biological maturation influences selection process in youth elite soccer players. *Biol Sport*. 2022;39(2):435-441. doi:10.5114/biolSport.2022.106152.

Mandorino M, J. Figueiredo A, Gjaka M, Tessitore A. Injury incidence and risk factors in youth soccer players:

a systematic literature review. Part I: epidemiological analysis. *Biol Sport*. 2023;40(1):3-25.

doi:10.5114/biolSport.2023.109961.

Response (in green): Thanks for the suggestion. We have removed one of the references in the first manuscript version to add citation by Mandorino et al. However, due to limited number of references (40 according to journal standards for original investigation), we have not included reference by Massa et al.

Review 1 (Modifications in blue)
(this review has file attachment)

Dear Authors,

I would like to thank you for submitting your manuscript “THE COMBINED EFFECTS OF GROWTH AND MATURITY STATUS ON INJURY RISK IN AN ELITE FOOTBALL ACADEMY” in Biology of Sport and for the opportunity of the review. While I think the topic is great of interest and the experimental aspect of your work is appropriate and bring interesting novel information can be beneficial in professional youth male football academies, the manuscript requires several modifications and clarifications. The table must be revisited, and the figures are well done.

1. □ Title, key words and abstract:

a. □ I will suggest modifying the title to match better the content of the paper, but also to be more attractive (See below my comments in methodology and limitations part of the paper).

i. □ I’m suggesting that the “Two decades” must be in the title as it will attract readers and strengthen the paper.

ii. □ The “retrospective” aspect of the methodology should be there to be clear from the start with the readers.

iii. □ “Male” should be included as well in the title or as keywords.

iv. □ Title style suggestions:

1. □ Effect of growth and somatic maturity status on injury risk in an elite football academy: A retrospective study over 2 decades.

2. □ Effect of growth and somatic maturity status on injury risk in an elite football academy: A retrospective research over 20 years.

3. □ Growth and somatic maturity status injury risk in youth male elite football academy: A retrospective study over 2 decades.

Response: We absolutely agree with the reviewer, but journal standards allow a maximum of 60 characters in the title.

b. □ To increase the chance to be found in the literature, it’s better to not use words as keyword if they are already in the title. So, Growth, Maturity and Football must be changed for e.g. Youth, male, or PHV, etc...

Response: Keywords already included in the title have been replaced by “youth” and “injury prevention”.

c. □ Abstract:

i. Line 23: Rather to use “Injury prevention programs” use “Injury risk reduction strategy.”

Response: We agree with the reviewer. “Injury prevention programs” has been replaced by “Injury risk reduction strategy” throughout the text.

2. □ Introduction

a. □ Line 28: I suggest changing “youth” for “adolescence” and make the sentence as below:

i. “Injuries occurring during childhood and adolescence can also result in long-term consequences, ...”

Response: Sentence has been modified as suggested by the reviewer.

b. □ Lines 30-32: Rephrase the last sentence of the paragraph. Keep its simple and clear.

i. “Thus, injury prevention in youth footballers is vital to ensure the development of healthy professional players and ensure the long term health of adolescent players regardless of footballing success.”

ii. Suggestion:

iii. “Injury prevention in football academies is vital to ensure the development of healthy youth players and ensure the long-term health of the professional football players.”

Response: Sentence has been modified as suggested by the reviewer.

c. □ Line 86: Delete separately.

Response: The word “separately” has been removed as suggested by the reviewer.

3. □ Materials and Methods

a. □ The Retrospective aspect and the 20 consecutive seasons or two decades must be highlighted in the title or in key words.

4. □ Response: We absolutely agree with the reviewer, but journal standards allow a maximum of 60 characters in the title.

a. □ In study design and participants paragraph there is no indication about the chronological age of the cohort. Could the authors indicate descriptive information about the age of the whole cohort (e.g. youngest and oldest) to provide a better understanding beside of the age group

Response: Additional information about the chronological age-based teams included in the study has been added in the “study design and participants” section: “The academy has a team in each of the age-based levels or categories. In men, this includes U11, U12, U13, U14, U15, U16, U17, and U19 teams, in addition to 3rd and 2nd teams comprising 17–23-year-old players competing in the Spanish Fourth and Third Divisions, respectively”.

b. □ What was the oldest age group? Could the authors be more precise about that information as well?

Response: Additional information about the chronological age-based teams included in the study has been added in the “study design and participants” section: “The academy has a team in each of the age-based levels or categories. In men, this includes U11, U12, U13, U14, U15, U16, U17, and U19 teams, in addition to 3rd and 2nd teams comprising 17–23-year-old players competing in the Spanish Fourth and Third Divisions, respectively”.

5. □ Height measurement, growth-rate estimation, and maturity status assessment:

a. □ Could the author mention between brackets the brand of the portable stadiometer?

Response: The band of the portable stadiometer (Añó Savol, Spain) has been added in the “Height measurement, growth-rate estimation, and maturity status assessment” section.

b. □ Line 98 – 102: The few sentences must be rephrased for clarity.

i. E.G. standing stature was taken by trained Doctors at least twice annually using a portable stadiometer (Add the brand). Participants stood barefoot with feet together and their head in the Frankfort plane. They were required to take a deep breath and hold their head while measuring. Two of the four doctors worked in the academy during the 20 years, reducing chance of bias. The intra-rater typical error of measurement for standing stature of these two doctors was 0.23 cm while the inter-rater error was 0.29 cm.

Response: Sentence has been modified as suggested by the reviewer.

c. □ Line 101: “Similar equipment was used over the study” must be deleted

Response: Sentence has been deleted as suggested by the reviewer.

6. □ Injury definition, exposure, and recording procedures:

a. There is no any clinical details on how the apophyseal injuries have been diagnosed and differential diagnosis has been executed.

i. Could the author add one paragraph to provide more clarity the diagnosis process?

Response: More detailed information about the diagnosis of growth-related injuries has been added in the “Injury definitions, exposure, and recording procedures” section.

7. □ Results:

a. Line 156: Change the sentence as below:

i. The mean (SD) exposure for each player was 1932.3 (\pm 439.9) hours. The mean (SD) values for the percentage of observed adult stature and growth rate were 92.38 (\pm 6.64) % and 5.57 (\pm 3.35) cm/year, respectively.

Response: Sentence has been modified as suggested by the reviewer.

8. Discussion:

a. Line 199: the sentence “All in all, our results demonstrated that players with higher growth-rates were at higher risk for growth-related injuries in all pre-, circa- and post-PHV periods.” Can be change to: All in all, our results demonstrated that players with higher growth-rates were at higher risk for growth-related injuries independently to the somatic maturation status.”

Response: Sentence has been modified as suggested by the reviewer.

b. The below references can be a valuable adding in the discussion:

i. The below reference can be a valuable adding in the discussion:

Survival analysis of lower-limb apophyseal injuries in youth elite soccer in association with growth and skeletal maturation.

<http://dx.doi.org/10.1136/bjsports-2021-IOC.2>

ii. Relationship between injuries and somatic maturation in highly trained youth soccer players.

Materne, O., Farooq, A., Johnson, A., Greig, M., McNaughton, L. Routledge A, ed. Science and soccer II; 2016. In: Favero T, Drust B, Dawson B, eds. International Research in Science and Soccer II.

Response: We would like to thank the reviewer for the suggestion. Even though we found this conference papers interesting and have already cited them in previous papers, the journal standards only allow to include 40 references in original papers.

Considering that available literature has already studied and discussed how somatic maturity (pre- vs. circa- vs. post-PHV) affects injury risk, the discussion of this paper was more focused in how growth-rates affect specific injury risk in each of the somatic maturation periods.

Therefore, we did not include papers suggested by the reviewer or other papers discussing injury risk in each of the somatic maturation periods (e.g., Bult et al. and Van der Sluis et al.) and discussed our results with either papers that studied the impact of growth rates or risk for specific injuries.

c. Line 199: The sentence “Besides, a higher incidence/burden for joint/ligament injuries in players with slow growth rate post-PHV compared to players with moderate growth rate was found.” Change to “Slow growth rate post-PHV players had a higher incidence and burden of joint/ligament injuries.”

Response: Sentence has been modified as suggested by the reviewer.

d. Line 202: remove first, just keep as “The major finding...”

Response: “First” has been removed as suggested by the reviewer.

e. Line 209-2012: the sentence must be rephrased.

“Considering that the growth related injuries have the highest incidence and burden..”

Response: Sentence has been modified as suggested by the reviewer.

f. Line 2016: Delete “accounting for”

Response: “accounting for” has been removed as suggested by the reviewer.

9. Methodological considerations:

a. Could you mention in the limitation of a retrospective aspect in study in regards of injury surveillance? In regards of quality diagnosis, etc...

Response: We have added that “injury data was analysed retrospectively and classification by the FIFA Consensus was not considered since the start of the study” in the “methodological considerations” section.

10. Conclusion:

a. Line 314: could you delete “Besides” and split “incidence/burden” by “and” as it’s two different

indicator.

Response: Sentence has been modified as suggested by the reviewer.

11. □References

a. I do believe that the reference in the text must be at the end of the sentences after the dot between square bracket (e.g. the end of the sentence. [1]).

Response: We have reviewed some papers which have been recently published in this journal (Mandorino et al. 2023) and the reference in the text appear at the end of the sentence and before the dot between square brackets.

12. □Table 1

a. □Delete “percentage of” and add “(%)”

b. □For injury count add “(n)”.

c. □Change “Mean severity” to “mean time loss” as you are displaying the data by the number of days.

d. □I would advise to remove the Exposure (hours) from the table 1 and keep it only in the manuscript in the beginning of your results part.

e. □Could you add a symbol and link it with the data description:

i. □Anthropometrical variables are shown as mean \pm SD.

ii. □Incidence, severity, and injury burden are expressed with 95% confidence intervals.

Response: Table has been modified as suggested by the reviewer. However, we believe that exposure (hours) in each somatic maturity status period suits better in the table.

13. □Figures:

a. Could you delete all incidence and burden for all figures?

i. It will be clearer for the reader if the right figures are “Incidence” and the left “Burden” and make it as title on top of each side.

Response: Figures have been modified as suggested by the reviewer.

Review 2:

Thank you for the opportunity to review this manuscript . The manuscript is well-written, has scientifically sound methodology and addresses all relevant literature. The limitations of the study are appropriately acknowledged, and the main findings are well presented with unique visualisation that is likely to be useful to practitioners and academic readers. I have no major concerns regarding this work and would only suggest some minor proof-reading before publication to identify a couple of typos within the text. Overall, the work is a good addition to this field of research and is unique in the ability of the authors to capture data across a significant time period (20 seasons), something which is extremely difficult to achieve for most studies on this topic.

Response: We thank the reviewer for the positive comments. Manuscript has been re-read and minor corrections have been made.

1 **TITLE:** THE COMBINED EFFECTS OF GROWTH AND MATURITY STATUS ON
2 INJURY RISK IN AN ELITE FOOTBALL ACADEMY

3 **HEAD TITLE:** THE COMBINED EFFECTS OF GROWTH AND MATURITY STATUS
4 ON INJURY RISK

5 **ABSTRACT**

6 Objectives: This study aimed to explore the interaction between growth rate on specific injury
7 incidence and burden on pre-, circa- and post-peak height velocity (PHV) periods.

8 Material and methods: Injury and stature data collected during the 2000-2020 seasons in an
9 elite football academy were retrospectively analysed. Only players with height measurements
10 from childhood until the attainment of adult height were included in the study (N=84). Growth
11 data were smoothed using a cubic spline to calculate daily growth rate and height. Growth rate
12 was categorised into three groups: fast (>7.2 cm/year), moderate (3.5-7.2 cm/year) and slow
13 (<3.5 cm/year). Percentage of observed adult height was used to classify players as pre-PHV
14 (<88%), circa-PHV (88-95%) or post-PHV (>95%). Overall and specific injury incidence and
15 burden and rate ratios for comparisons between growth rate groups were calculated on pre-,
16 circa- and post-PHV periods, separately.

17 Results: Overall injury incidence and burden were greater in pre-PHV players with quicker
18 growth rates compared to players growing moderately and slowly. All in all, players with more
19 rapid growth-rates were at higher risk for growth-related injuries in all pre-, circa- and post-
20 PHV periods. Post-PHV, the incidence and burden of joint/ligament injuries were 2.4 and 2.6-
21 times greater in players growing slowly compared to players growing moderately.

22 Conclusions: Practitioners should monitor growth rate and maturity status and consider their
23 interaction to facilitate the design of targeted injury [risk reduction strategies](#).

Keywords: youth, adolescence, football, epidemiology, height, injury prevention.

INTRODUCTION

Injuries can result in long absences from training and matches in academy football players, reducing the opportunity for players to develop their fitness and skills [1]. Consequently, injuries negatively impact players' academy progression [2]. Injuries occurring during [childhood and adolescence](#) can also result in long-term consequences, making players more susceptible to future injuries and long-term health risks (e.g., osteoarthritis) [3]. Thus, [injury risk reduction strategies in youth footballers are vital to ensure the development of healthy youth players and ensure the long-term health of the professional football players.](#)

During adolescence, players experience a marked and rapid period of somatic growth [4], leading to evident changes in limb length, limb mass, and moments of inertia [4]. As a consequence of these changes, temporary delays or regressions in sensorimotor mechanisms and motor control may be observed during this period [5], adversely impacting injury risk. Accordingly, the International Olympic Committee [6] and league governmental bodies (e.g., English Premier League) [7] have highlighted the importance of assessing and monitoring inter-individual variations in growth and maturity.

Growth rate is used to describe changes of a physical dimension (e.g., standing height) over a given time [4]. During the adolescence there is an increase in the rate of growth, with highest point known as peak height velocity (PHV). PHV is observed around the age of 13–14 years in boys, reaching maximal growth rates of 5.6–12.4 cm/year [4]. To date, a limited number of studies in youth football academies have investigated the influence of adolescent growth rates upon injury [8–11]. Kemper et al. [8] and Rommers et al. [9] observed that injured male adolescent players had a higher rate of growth compared to non-injured players. Similarly, Johnson et al. [11] reported that players with a rate of growth rate >7.2 cm/year were more likely to be injured than players growing less than 7.2 cm/year. Not only that, but they also

49 showed that there was a linear increase in injury risk associated with growth rate [11].
50 Concerning the risk for specific types of injuries, Wik et al.[12] found that overall growth rate
51 was associated with a greater risk of bone and growth plate injuries in adolescent athletics.

52 Biological maturation is a separate and more complex concept. The level of biological
53 maturation at a given point, defined as maturity status, indicates where along the process
54 towards a mature state a given tissue or organ system (somatic, skeletal, or sexual) is at the time
55 of measurement [4]. The percentage of adult height at the time of observation is an indicator of
56 somatic maturity that is increasingly used in youth athletes and allows to easily classify players
57 as pre- (<88%), circa- (88-95%), or post-PHV (>95%) [13]. Available research has suggested
58 that injury incidence and burden is higher in circa-PHV compared to pre-PHV period [14],
59 whilst a recent study has found that the occurrence of specific injuries varies according to the
60 percentage of adult height [15]. Growth-related injuries were more frequent in percentages
61 around PHV (91.2%) while muscle and joint/ligament injuries were more common in post-PHV
62 [15]. Interestingly, growth-related injuries occurred from distal to proximal body regions,
63 following the pattern of growth and maturation [15]. As a result, growth-related injuries
64 occurring on distal segments (e.g., Sever's and Osgood-Schlatter's disease) peaked in pre- and
65 circa-PHV periods while proximal injuries (e.g., spondylolysis) peaked in post-PHV [15].

66 To date, only one study has analysed the interaction between growth-rate and maturity status
67 upon injury risk. Johnson et al. [11] showed that there is an increase in estimated injury
68 likelihood at a high growth rate circa-PHV. However, they found an increase in estimated injury
69 burden likelihood at a lower growth rate and a higher percentage of predicted adult stature (post-
70 PHV). Despite the novel results found by Johnson et al. [11], this study has potential limiting
71 factors. First, the data were recorded over a single season period, making it impossible to follow
72 individuals during a sufficient interval of time to model individual growth curves and account
73 for the non-linear characteristic of growth [16]. Further, the Khamis-Roche equation was used

74 to estimate adult height. If measured accurately, this equation is reported to predict adult height
75 to within 2.2 and 5.3 cm for the 50th and 90th percentile, respectively; therefore, the use of
76 Khamis-Roche equation might have led some players to be misclassified as pre-, circa- or post-
77 PHV due to errors associated with the prediction [13]. Most importantly, this research did not
78 study the interaction between growth-rate and injury risk of specific injuries in pre-, circa- and
79 post-PHV periods. Considering that growth-rates [4] and injury patterns [15,17] differ
80 according to maturity status, studying the impact of growth-rate on specific injury risk in each
81 period seems vital.

82 The present study builds upon the abovementioned limitations by using height and injury data
83 recorded in an elite football academy over two decades. This permits a more accurate estimation
84 of growth rate and percentage of the observed adult height of players and affords the
85 opportunity to explore potential interactions between growth rate (cm/year) and risk for specific
86 types of injuries (incidence and burden) in pre-, circa- and post-PHV periods, separately.

87 **MATERIALS AND METHODS**

88 **Study design and participants**

89 This retrospective analysis studied height and injury data recorded longitudinally for 20
90 consecutive seasons (2000–2020) in XXXXXX's elite soccer academy whose professional
91 male team plays in XXXXX. The academy has a team in each of the age-based levels or
92 categories. In men, this includes U11, U12, U13, U14, U15, U16, U17, and U19 teams, in
93 addition to 3rd and 2nd teams comprising 17–23-year-old players competing in the Spanish
94 Fourth and Third Divisions, respectively. Among the 1123 players who were followed, only
95 players who were ≤U12 when they entered the academy and continued until they attained adult

96 height were included in the study (n=84) attempting to equally represent pre-, circa- and post-
97 PHV periods.

98 The study was conducted in accordance with the National Health Council resolution (466/2012)
99 and was approved by the Ethics Committee of the XXX. Written informed consent to use
100 regularly collected data for research purposes was obtained from the players.

101 **Height measurement, growth-rate estimation, and maturity status assessment**

102 Standing stature was measured by trained doctors at least twice annually using a portable
103 stadiometer (Añó Savol, Spain). Participants stood barefoot with feet together and their head in
104 the Frankfort plane. They were required to take a deep breath and hold their head still while
105 measuring. Two of the four doctors worked in the academy during the entire study period,
106 thereby reducing chance of bias. The intra-rater typical error of measurement for standing
107 stature of these two doctors was 0.23 cm while the inter-rater error was 0.29 cm.

108 Growth rate was calculated as the change in stature over the change in time (cm/year). Growth
109 data were smoothed using a Cubic spline. The spline would fit a curve across the whole time
110 period using the multiple measurement points and subsequently, a growth rate and height per
111 day could be estimated from this curve [18]. The calculation of the spline allowed an estimate
112 of growth rate for each training/match day, which allowed the growth and maturation data to
113 match with daily observations of daily training/match exposure.

114 Growth rate was categorised into three groups: fast (>7.2 cm/year), moderate (7.2-3.5 cm/year)
115 and slow (<3.5 cm/year), based on previous literature [8,11] and to achieve an approximately
116 equal number of observations per group.

117 The percentage of observed adult height was used as a maturity status indicator [4]. A player
118 was considered to have attained final height once growth-velocity was <1 cm/year for one year
119 [4]. The observed adult height allowed to calculate percentage of adult height using estimated

120 height. Players were classified as: pre-PHV (<88%), circa-PHV (88-95%) or post-PHV (>95%)
121 [11,13].

122 **Injury definitions, exposure, and recording procedures**

123 Time-loss injuries were recorded in the club's online database by [academy's doctors](#) when a
124 player was unable to take part in full football training or match due to a physical complaint
125 [19]. Absence days were calculated as the number of days elapsed between the initial injury
126 date and the player's return to full availability for training and matches [19].

127 From the 2007–2008 season onward, injuries were described following the International
128 Federation of Association Football (FIFA) Consensus [19]. [For each injury, the date of injury,](#)
129 [injury type, session type, contact type and specific mechanism were reported.](#) In the previous
130 seasons, specific injury diagnosis and absence days of time-loss injuries were recorded. This
131 allowed to categorise type of injuries (e.g., muscle injury) recorded before the publication of
132 the FIFA Consensus. As the Consensus by Fuller et al. [19] did not explicitly consider growth-
133 related injuries, [the injury surveillance system was customised by adding a category for](#)
134 [“growth-related injuries”, which were defined](#) as “unique injuries not seen in adults but
135 common in skeletally immature athletes (e.g., growth plate fractures, apophysitis, apophyseal
136 avulsion fractures, and greenstick fractures)” [20]. [Growth-related injuries were classified](#)
137 [according to physical examination \(e.g., pain at insertional points on palpation, passive](#)
138 [movements and stretches, and active movements including resistance testing\) and imaging](#)
139 [diagnosis \(ultrasound and/or magnetic resonance imaging\).](#) Two of the four doctors worked in
140 the academy since the start of the study, thereby reducing the chance of bias, differences in
141 injury interpretation, and changes in observation methods between doctors.

142 Daily exposure in matches and training sessions in available non-injured players was estimated
143 based on the number and duration of matches and trainings, squad size and the number of
144 players on the pitch in each category [21]. Players had 3 (U11-U12) or 4 (U13-Reserves) 90-
145 minutes training sessions per week and played a match every weekend. Match length was 70
146 minutes for U11-U14, 80 minutes for U15-U16 and 90 minutes for older age-groups. The
147 number of players on the pitch was 11 for all categories except for U11-U12, in which 7 players
148 played in each team.

149 **2.1 Data analysis**

150 Injury incidence (number of time-loss injuries/1000 hours) and injury burden (number of days
151 lost/1000 hours) were calculated with 95% CI assuming a Poisson distribution [22].
152 Generalized linear mixed-effects models (GLMM) were used to compare incidence and burden
153 between growth-rate groups (fast vs. moderate vs. slow) in each maturity status period (pre-,
154 circa- or post-PHV) using a Poisson distribution and log-link function. The predictor variables
155 were modelled as categorical fixed effects and player ID was included as a random effect to
156 account for repeated observations. Statistical significance was accepted at $p < 0.05$ for
157 incidences, while significant differences for injury burden were considered when the 95%
158 confidence intervals did not overlap [23]. Bonferroni adjustments were performed to control
159 the Type I error rate when making multiple comparisons. All analyses were performed using R
160 version 4.1.2 (R Core Team 2021, R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Player demographics, growth, and maturity data according to maturity status are presented in Table 1. There were 782 injuries and 162,314 hours of total exposure. The mean (SD) exposure for each player was 1932.3 (\pm 439.9) hours. The mean (SD) values for the percentage of observed adult stature and growth rate were 92.38 (\pm 6.64) % and 5.57 (\pm 3.35) cm/year, respectively. The overall injury incidence rate was 4.82 injuries per 1,000 hours (95% CI 4.49–5.17), the mean time-loss of injuries was 23 days (95% CI 21–26) and injury burden was 113 days absent per 1,000 hours (95% CI 105–121). Injury incidence, time-loss, and burden in each maturity status period are shown in Table 1.

Overall injury incidence was 1.65- and 2.38- times greater in pre-PHV players with fast growth rates (4.1 injuries/1000h, 95% CI: 2.8-5.2/1000h) compared to players growing moderately (2.6 injuries/1000h, 95% CI: 1.9-3.0/1000h) and slowly (1.8 injuries/1000h, 95% CI: 0.8-3.1/1000h), respectively. Similarly, overall injury burden in pre-PHV players growing fast (86 days lost/1000h, 95% CI: 59-125/1000h) was 2.9- and 4.4-times higher compared to pre-PHV players with moderate (33 days lost/1000h, 95% CI: 25-44/1000h) and slow (20 days lost /1000h, 95% CI: 8-46/1000h) growth rates (Figure 1).

Concerning growth-related injuries, in the pre-PHV period, incidence and burden were 2.5- and 5.4-times higher in players with fast growth rates (1.9 injuries/1000h, 95% CI: 1.2-2.8/1000h and 58 days lost/1000h, 95% CI: 34-101/1000h) compared to players growing moderately (0.9 injuries/1000h, 95% CI: 0.5-1.1/1000h and 14 days lost/1000h, 95% CI: 9-23/1000h). In the same line, circa-PHV players growing fast showed 2.8- and 3.4-times greater injury incidence and burden (2.5 injuries/1000h, 95% CI: 1.7-3.2/1000h and 96 days lost/1000h, 95% CI: 68-136/1000h) compared to players growing moderately (0.9 injuries/1000h, 95% CI: 0.4-1.6/1000h and 24 days lost/1000h, 95% CI: 10-57/1000h) (Figure 2). In post-PHV, growth-

185 related injury incidence was 2.4-times higher in players growing fast (0.8 injuries/1000h, 95%
186 CI: 0.2-3.4/1000h) compared to players growing slowly (0.3 injuries/1000h, 95% CI: 0.2-
187 0.5/1000h) (Figure 2). Concerning injury risk for specific growth-related injuries, pre-PHV
188 players growing fast showed a 4.4-times higher Osgood-Schlatter's disease incidence (0.2
189 injuries/1000h, 95% CI: 0.1-1.2/1000h) compared to players growing moderately (0.1
190 injuries/1000h, 95% CI: 0.1-0.3/1000h) (Figure 3). Moreover, post-PHV players growing fast
191 had a higher incidence of anterior inferior iliac apophyseal injuries (0.4 injuries/1000h, 95%
192 CI: 0.1-3.9/1000h) compared to players growing slowly (0.2 injuries/1000h, 95% CI: 0.1-
193 0.2/1000h) (RR: 257.9) (Figure 3).

194 Significant differences for incidence and burden of muscle injuries were not found between any
195 of the growth rates groups in pre-, circa- and post-PHV periods. Nevertheless, the incidence
196 and burden of joint/ligament injuries were 2.4 and 2.6-times greater in post-PHV players
197 growing slowly (1.7 injuries/1000h, 95% CI: 1.3-2.1/1000h and 62 days lost/1000h, 95% CI:
198 47-81/1000h) compared to those growing moderately (0.7 injuries/1000h, 95% CI: 0.4-
199 1.1/1000h and 24 days lost/1000h, 95% CI: 12-45/1000h) (Figure 2).

200 **DISCUSSION**

201 This is the first research studying the main and interactive effects of growth rate and maturity
202 status on risk for specific types of injuries in academy football. We improved upon the
203 limitations of previous research by using longitudinal height data from childhood to adulthood
204 to estimate daily growth rate and percentage of observed adult height to study how growth rate
205 influences overall and specific incidence and burden in pre-, circa- and post-PHV periods. **All**
206 **in all, our results demonstrated that players with higher growth-rates were at higher risk for**

207 growth-related injuries independently to the somatic maturation status. Besides, slow growth
208 rate post-PHV players had a higher incidence and burden of joint/ligament injuries.

209 The major finding of this study is that growth-rate affects overall injury risk in pre-PHV period,
210 which highlights the importance of regular growth monitoring from an early age. Multiple
211 injury mechanisms may explain increased injury risk in pre-PHV players with fast growth rates.
212 Rapid growth might lead to larger changes to limb length, limb mass, and moments of inertia
213 [24], alterations in motor control [5], which may adversely impact injury risk. Rapid
214 longitudinal skeletal growth is also associated with a temporary decrease in bone mineral
215 density and weakness of the epiphyseal growth plates [25], and may facilitate the appearance
216 growth-related conditions [26]. Considering that the growth-related injuries have the highest
217 incidence [15] and burden [17] in pre-PHV period, increased growth-related injury risk in
218 players growing fast might have contributed to increased overall injury risk. Another reason
219 that could explain the higher risk in pre-PHV players growing fast, might be that pre-PHV
220 players with faster growth-rates could be earlier maturers [4]. Players maturing earlier usually
221 have faster growth rates [4] and might be physically superior to their peers [27]. Thus, they may
222 develop a more physical way of playing football [28] exposing them to a higher injury risk in
223 pre-PHV [17]. Future research should consider maturity timing when studying the interaction
224 of growth-rate, maturity, and injury risk.

225 The results of the current investigation showed a higher incidence and burden of growth-related
226 injuries in players with fast growth rates compared to those growing moderately in pre- and
227 circa-PHV, and a higher incidence in players with moderate growth rates compared to those
228 growing slowly in post-PHV. The small number of playing growing slowly (<3.5 cm/year) in
229 pre- and circa-PHV might have led to not finding significant differences in those groups. In the
230 same line, the lack of players growing fast in post-PHV period may explain why significant
231 differences compared to this group were not found; however, players growing quick had the

232 highest incidence of growth-related injuries in this period. The combination of altered
233 sensorimotor mechanisms and motor control [5] and vulnerability of apophyses [25] might
234 result in increased injury growth-related injury incidence and burden in players growing fast
235 [26], which is in line with previous research by Wik et al. [12]. Besides, it was not surprising
236 to find that faster growth rates lead to higher risk for growth-related injuries in all pre-, circa-
237 and post-PHV periods, as previous research has already shown that these injuries can occur all
238 along the maturation process [15,17]. Interestingly, our results showed that growth-rate affected
239 risk for specific types of growth-related injuries differently according to maturity status, which
240 is in accordance with the distal to proximal pattern of growth-related injuries found in previous
241 research [15,17].

242 No significant results between incidence and burden of muscle injuries were found between
243 growth rate groups (fast vs. moderate vs. slow) in pre-, circa- and post-PHV. These results are
244 in line with previous research by Wik et al. [12], who only found an association between growth
245 and risk of bone and growth-plate injuries. More research is needed to better understand if
246 neuromuscular alterations that appear around PHV [29] are related to the higher muscle and
247 joint/ligament injury risk in circa- and post-PHV periods [15,17].

248 Concerning injury risk for joint/ligament injuries, players growing slowly had a higher
249 incidence and burden compared to those with fast/moderate growth rates in post-PHV. Our
250 results are in accordance with recent results found by Monasterio et al. [17], who found a higher
251 injury burden for joint/ligament injuries in adult players (growth rate <1cm/year), compared to
252 post-PHV players who may have been growing at higher rates. Considering that post-PHV
253 players growing slow may be more mature (and older) than players growing fast and
254 moderately, our results might be explained by the accumulation of multiple seasons of training
255 and competition throughout their careers [30], with previous injury increasing the risk of
256 subsequent injury [31].

257 **Practical application**

258 In light of the results above, we recommend academy practitioners to measure players height
259 every 3–4 months [32] to model individual growth curves and estimate growth velocities. In
260 order to monitor maturity status (percentage of predicted adult height), an x-ray of the hand-
261 wrist complex is considered the best method to use [4]. However, exposure to low-level
262 radiation, the need for specialised equipment and trained technicians makes it impractical in
263 academies. Thus, other non-invasive and cost-efficient alternatives such as the Khamis-Roche
264 method (somatic maturity) [33] or SonicBone BAUSPORT system (skeletal maturity via
265 ultrasound) [34] could be used to estimate percentage of adult height.

266 Once estimated each player's growth rate and maturity status (pre-, circa-, post-PHV), Figure
267 4 could be used in a practical setting to identify players at higher risk (red colour). This figure
268 will be helpful to facilitate the interpretation of our results to key decision-makers in football
269 academies (players, coaches, and directors), who may be unfamiliar with scientific figures and
270 data analysis. As a result, it may improve communication with key decision-makers and
271 increase their engagement in injury management strategies. Practitioners may choose the adjust
272 training content and training and competition load during periods of heightened injury risk (i.e.,
273 adolescent growth spurt) to mitigate injury risk. Jan Willem Teunissen, a former movement
274 scientist at Ajax Football Club describes an innovative bio-banding (i.e., maturity matching)
275 strategy whereby the player's entering the adolescent growth spurt were prescribed a training
276 programme that emphasised core strength, balance, coordination, the re-training of fundamental
277 and sport-specific motor skills, and the maintenance mobility, in addition to a reduction in
278 training and competition load [35]. The purpose of this programme was to reduce injury risk
279 and aid transition through this phase of development.

280 The growth/maturity heat maps also highlight the most burdensome injuries [36] in each
281 quadrant and may guide practitioners to design targeted injury **risk reduction strategies**. As
282 shown in previous research [15,17], reducing the impact of growth-related injuries seems vital
283 in pre- and circa-PHV periods. Further, this research highlights the need for special attention to
284 those players growing at velocities >7.2 cm/year. Strategies such as controlling week-to-week
285 changes in load [11,37], changing training content [35] or monitoring symptoms of
286 musculoskeletal complaints to detect early growth-related conditions [38] may be of the utmost
287 importance in those players. Due to the distal to proximal patterns of growth-related injuries,
288 special awareness to symptoms in the ankle/ knee should be taken in pre-PHV period, while
289 focussing on complaints on the hip/pelvis and lower back is essential in circa- and post-PHV,
290 respectively. On the other hand, reducing the impact of spondylolysis, muscle and
291 joint/ligament injuries seems vital in post-PHV. For instance, controlling training load [37] or
292 neuromuscular training programmes [39] might be beneficial to reduce injury risk during this
293 period.

294 **Methodological considerations**

295 The principal strength of this study is its longitudinal design over two decades, which allowed
296 to model growth rates and estimate daily growth rate and percentage of observed adult height.
297 This research has improved on previous data that recorded growth during short periods [8–12],
298 not allowing to account for the non-linear characteristic of growth [16]. Besides, this study used
299 percentage of observed adult height as a maturity status indicator, while previous studies
300 calculated percentage of predicted adult height [11,14]. Most importantly, this is the first study
301 investigating the interaction between growth rate and injury risk (incidence and burden) for
302 specific types of injuries according to maturity status (pre-, circa- and post-PHV).

303 However, the limitations of the current investigation should also be noted. Firstly, we did not
304 account for individual exposure. Thus, as suggested by the latest international Olympic
305 Committee consensus statement [21], exposure was estimated based on the number and
306 duration of matches and training sessions, squad size and the number of players on the pitch in
307 each category. Besides, our findings apply to a single elite soccer academy, and only players
308 who attained adult height were included in the study. Considering that injuries have a negative
309 impact on academy progression [2], players who sustained severe injuries may have been
310 missed. [Moreover, injury data was analysed retrospectively and classification by the FIFA
311 Consensus was not considered since the start of the study.](#) Further, there were no protocols to
312 check intra- and inter-tester reliability of all the doctors that recorded injuries during the whole
313 study period.

314 Further, many factors such as equipment used to measure height or diagnose players' injuries,
315 preventive strategies and training content might have changed over the study period and were
316 not controlled for in analyses. Another limitation is that our sample size was not large enough
317 to detect association with all specific injuries [40], and the limited number of specific injuries
318 resulted in wide confidence intervals for the injury incidence and burden of many injuries. Thus,
319 we only studied the most frequent injuries in our dataset. Future studies should build on this
320 work by conducting multi-team collaborative studies with a sufficiently powered sample size.

321 CONCLUSIONS

322 Our results demonstrated that players with higher growth-rates were at higher risk for growth-
323 related injuries in all pre-, circa- and post-PHV periods. A higher [incidence and burden](#) for
324 joint/ligament injuries in players with slow growth rate post-PHV compared to players with
325 moderate growth rate was found. Thus, practitioners in football academies should consider the

326 combined effects of growth rate and maturity status when designing targeted injury risk
327 reduction strategies.

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460 **FIGURE CAPTIONS**

461 **Figure 1:** Overall [injury burden \(A\)](#) and [incidence \(B\)](#) according to growth rate and
462 percentage of observed adult height.

463 **Figure 2:** [Injury burden and incidence](#) of growth-related (A, B), muscle (C, D) and
464 joint/ligament injuries (E, F) according to growth rate and percentage of observed adult height.

465 **Figure 3:** [Injury burden and incidence](#) of specific growth-related injuries according to growth
466 rate and percentage of observed adult height.

467 **Figure 4:** Ranking for most burdensome type of injuries according to growth rate and maturity
468 status.

Table 1: Stature, growth velocity, % of observed adult height, injury counts, exposure, incidence rates, mean severity, and injury burden according to maturity status.

Maturity status	Stature (cm) ^a	Growth velocity (cm/year) ^a	% of observed adult height ^a	Injury count (n)	Exposure (hours)	Injury incidence (per 1000 hours) ^b	Mean time loss (days) ^b	Injury burden (per 1000 hours) ^b
Pre-PHV	149.7 ± 6.0	5.8 ± 2.5	83.5 ± 2.6	147	51544	2.85 (2.43-3.35)	15.4 (12.6-18.2)	43.9 (37.3-51.6)
Circa-PHV	165.9 ± 6.3	7.7 ± 2.7	92.4 ± 2.4	234	40417	5.79 (5.09-6.58)	23.5 (19.7-27.3)	136.0 (119.6-154.6)
Post-PHV	176.8 ± 5.2	2.0 ± 1.9	98.4 ± 1.1	401	70353	5.70 (5.17-6.29)	26.5 (21.8-31.2)	151.1 (137.0-166.6)

^a Anthropometrical variables are shown as mean ± SD.

^b Incidence, severity, and injury burden are expressed with 95% confidence intervals

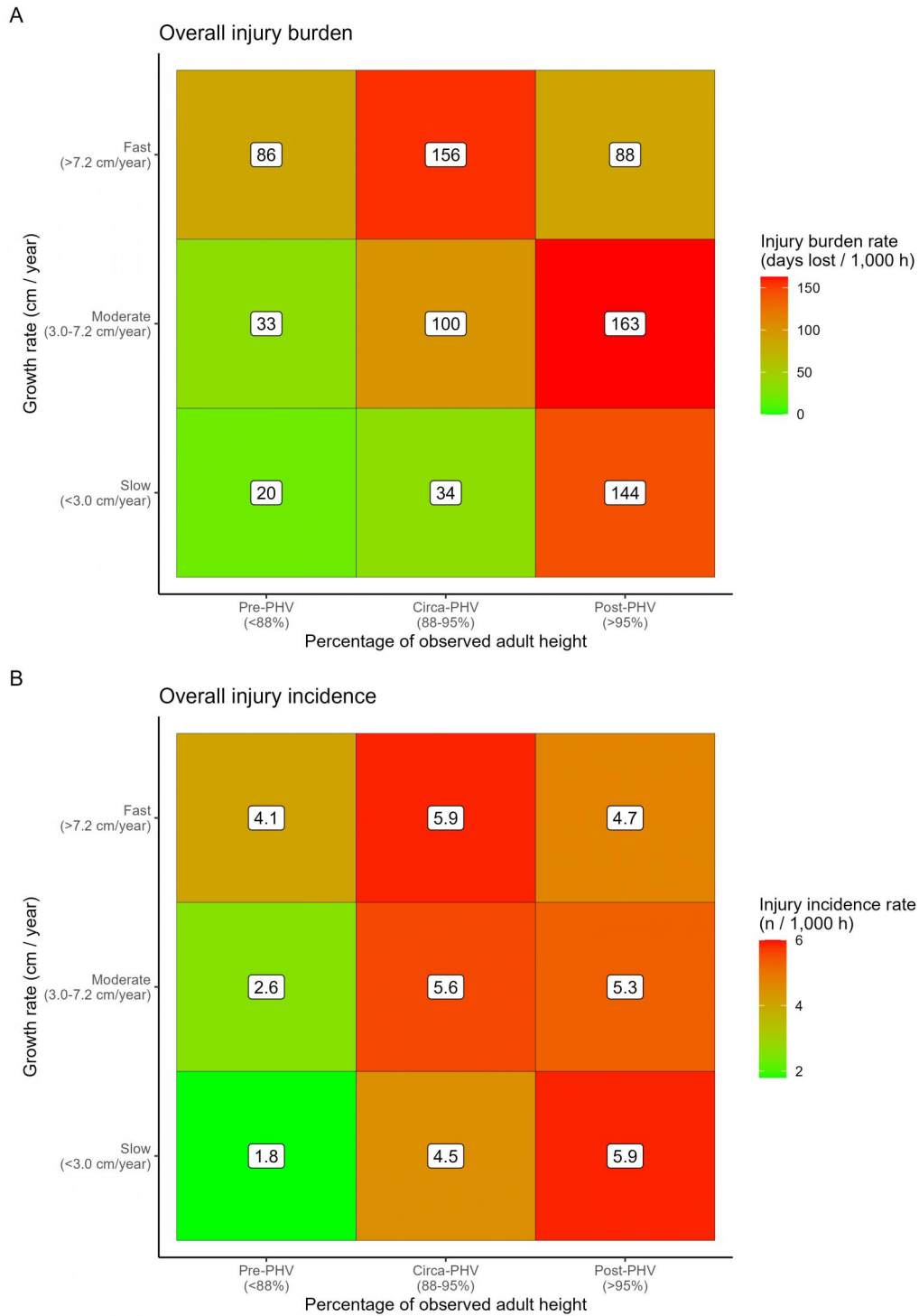


Figure 1: Overall injury burden (A) and incidence (B) according to growth rate and percentage of observed adult height.

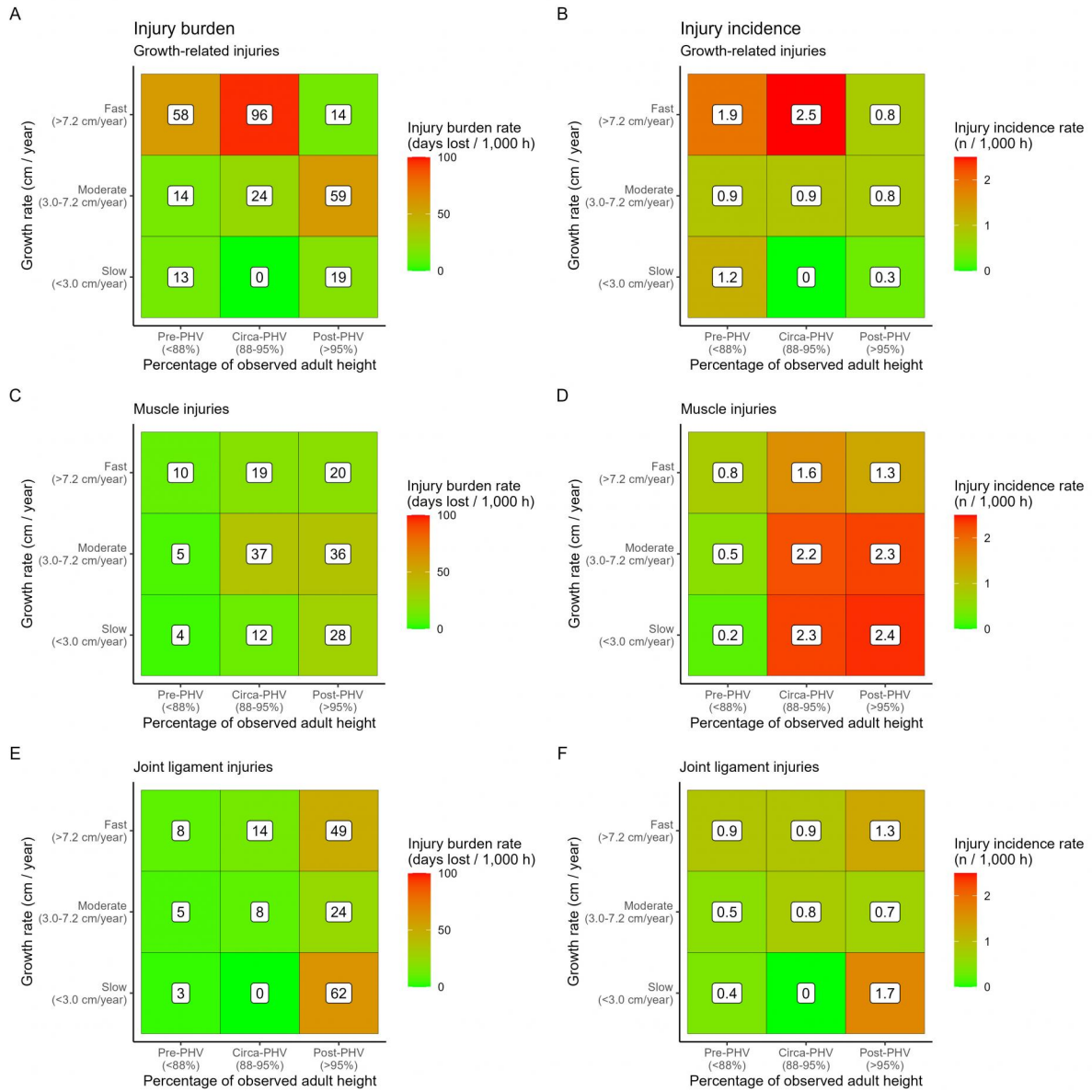


Figure 2: Injury burden and incidence of growth-related (A, B), muscle (C, D) and joint/ligament injuries (E, F) according to growth rate and percentage of observed adult height.

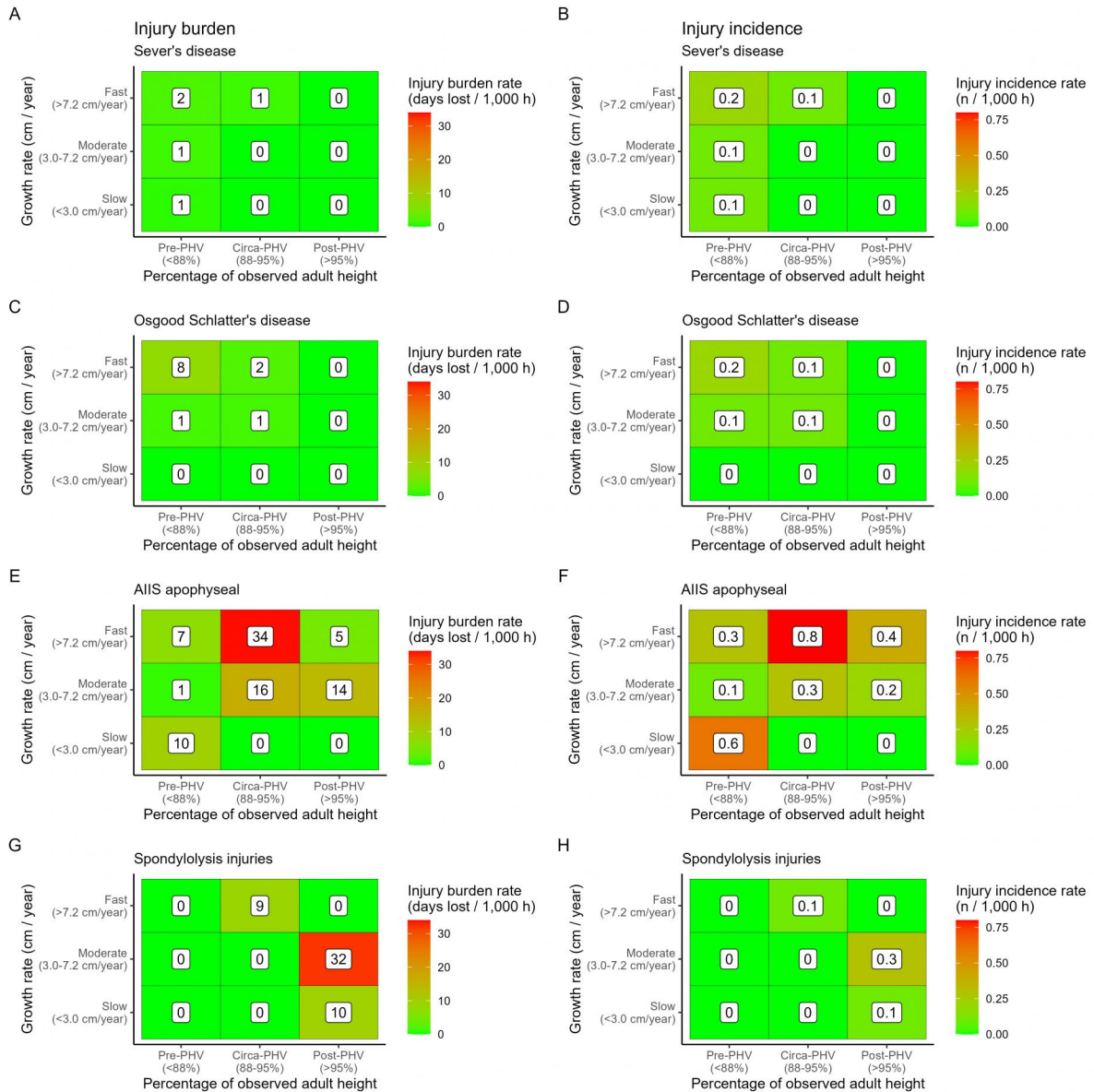


Figure 3: Injury burden and incidence of specific growth-related injuries according to growth rate and percentage of observed adult height.

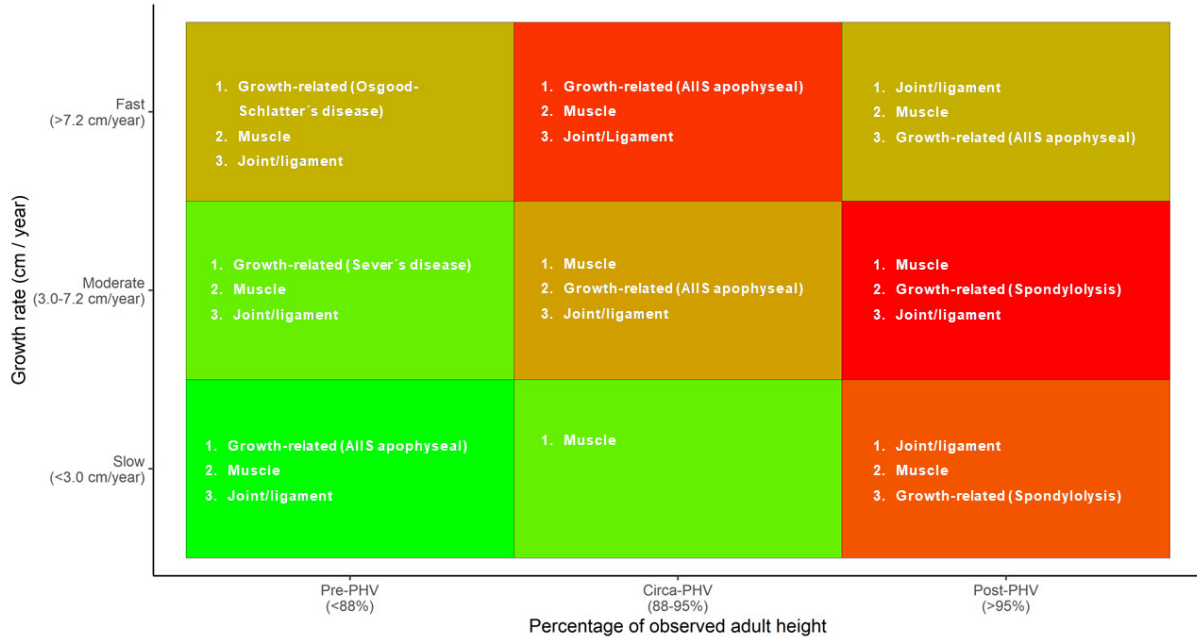


Figure 4: Ranking for most burdensome type of injuries according to growth rate and maturity status.

Manuscript body

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Tables

[Download source file \(13.88 kB\)](#)

Table 1: Stature, growth velocity, % of observed adult height, injury counts, exposure, incidence rates, mean severity, and injury burden according to maturity status.

Figures

Figure 1 - [Download source file \(341.11 kB\)](#)

Figure 1: Overall injury burden (A) and incidence (B) according to growth rate and percentage of observed adult height.

Figure 2 - [Download source file \(612.21 kB\)](#)

Figure 2: Injury burden and incidence of growth-related (A, B), muscle (C, D) and joint/ligament injuries (E, F) according to growth rate and percentage of observed adult height.

Figure 3 - [Download source file \(772.33 kB\)](#)

Figure 3: Injury burden and incidence of specific growth-related injuries according to growth rate and percentage of observed adult height.

Figure 4 - [Download source file \(176.45 kB\)](#)

Figure 4: Ranking for most burdensome type of injuries according to growth rate and maturity status.