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Title: Skeletal maturation and growth rates are related to bone and growth plate injuries in adolescent athletics

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ABSTRACT

Injuries are common in elite adolescent athletics, but few studies have addressed risk factors for injury. Growth and maturation are potential risk factors in this population; however, the current body of literature is both inconclusive and considered at high risk of bias. The aim of this study was therefore to examine if growth rate, maturity status and maturity tempo are associated with injury risk in an elite sports academy. Anthropometric, skeletal maturity and injury data collected prospectively over four seasons (117 athlete-seasons) were included in the analyses. Growth rate for stature was associated with greater risk of bone (Incidence rate ratio (IRR): 1.5 per one standard deviation increase above the mean; 95% CI: 1.1 to 1.9) and growth plate injuries (IRR: 2.1; 1.5 to 3.1). Growth rate for leg length was associated with greater overall injury risk (IRR: 1.3; 1.0 to 1.7) as well as the risk of bone (IRR: 1.4; 1.0 to 1.9) and growth plate injuries (IRR: 2.1; 1.4 to 3.0). Athletes with greater skeletal maturity, expressed as skeletal age (IRR: 0.6 per year; 0.5 to 0.9) and percentage of predicted mature height (IRR: 0.8 per percent increase; 0.7 to 1.0) were less prone to growth plate injuries. Rate of change in skeletal age was associated with an increased risk of bone injuries (IRR: 1.5; 1.0 to 2.3). The results of this study suggest that rapid growth in stature and leg length, skeletal maturity status and maturity tempo represent risk factors for certain injury types in adolescent athletics.

KEYWORDS

Track and field, youth, male, growth and development, epidemiology, sports medicine

INTRODUCTION

In elite youth athletics, approximately six out of ten athletes can expect to encounter an injury resulting in restricted participation or training modifications every season, with half of them leading to more than three weeks of absence from normal training.[1] Training interruptions due to injury or illness lower the chances of reaching high levels of performance substantially,[2] and therefore, better knowledge about injury risk factors and preventative strategies should be of interest to all invested parties. Still, confusion amongst coaches and parents on how to effectively and safely train growing children has been perceived as one of the important contributing factors to injuries in athletics.[3]

Growth and maturation are potential risk factors, unique to the adolescent population. Growth rate is used to describe changes in a physical dimension over a given time and it is typically assessed through anthropometric measures such as stature, body mass or limb lengths.[4,5] Growth rates are especially increased during the adolescent growth spurt, with the peak height velocity (PHV) observed around the age of 11 to 12 years in girls and 13 to 14 years in boys, although this varies between individuals.[4] Rapid growth and the period around PHV have been associated with an increased risk of injuries in elite sporting populations,[6-10] and suggested underlying mechanisms include decreased bone mineral density, increased tensile forces on vulnerable muscle attachments, decreased neuromuscular control and reduced flexibility.[4,7,11-16]

Maturation is a more complex concept, referring to the process towards a mature state.[4] The athlete's maturity status indicates where along this process a given tissue or organ system has reached at the time of measurement and is normally assessed through secondary sex characteristics or skeletal age derived from x-ray images.[4,17,18] As with growth rate, the timing and tempo of maturation varies greatly between individuals, where immature structures, underdeveloped neuromuscular control and mismatches in maturity status between athletes have been suggested as mechanisms through which maturation can affect the risk of injury.[13,15,19]

In athletics, Fourchet et al.[20] reported more injuries to the foot, ankle and lower leg in later maturing academy athletes when using the estimated age at PHV as a maturity indicator. Although this supports the finding of more stress fractures in high-school runners with late menarche by Tenforde et al.,[21] contrasting observations were made by Rejeb et al.[22] in a mixed sample of academy athletics and racquet sports athletes. In their cohort, early maturing athletes, determined by skeletal age, were at twice the risk of sustaining an injury over a season compared to late maturing athletes.

A systematic review by Swain et al.[5] from 2018 concluded that the available evidence was inconsistent and not strong enough to support a causal relationship between growth, maturation and injuries in adolescents. Furthermore, all the studies included were judged at high risk of bias, most commonly related to study attrition and not accounting for potential confounding variables. Given the high injury rates seen in young athletics athletes and the inconclusive pool of research addressing potential risk factors, we aimed to examine three concepts - growth rate, maturity status and maturity tempo - and their association to injuries in academy athletes.

MATERIAL AND METHODS

Study population

This study used growth, maturation and injury data collected prospectively over four seasons at Aspire Academy, an elite sporting academy in the Middle East. The participants were male full-time student athletes, enrolled in the athletics program for the 2014/15 through the 2017/18 seasons. This study was part of a larger study on growth, maturation and athletic development for which written informed consent was obtained from the athletes' guardians prior to data collection and ethics approval was granted from the Anti-Doping Lab Qatar Institutional Review Board (IRB Application #E20140000012).

Only athletes who had not yet specialized towards a single event-group were considered eligible for inclusion. These athletes followed a general athletics development program and typically participated in 8 training sessions per week over the academic year from September to June, while following a comprehensive educational curriculum. Specialized athletes were not included for analysis in this study, as the majority had reached or were near skeletal maturity.

Somatic growth assessment

Anthropometric screenings were conducted by ISAK (International Society for the Advancement of Kinanthropometry) Level 2 certified academy staff at the start and end of each season, which corresponded to the academic year. Measures were taken early in the morning prior to any activities to minimize diurnal variations, following ISAK-recommended procedures,[23] and were uploaded to a central academy anthropometry database. Stretch stature was measured using a wall-mounted stadiometer with a precision of 0.1 cm (Holtain Ltd., Crosswell, UK) and body mass using digital scales with a precision of 0.1 kg (ADE Electronic Column Scales, Hamburg, Germany). Body mass index (BMI) was calculated as body mass divided by squared height (kg/m^2). Trunk height was measured using a stadiometer with the athlete seated on a purpose-built table (Holtain Ltd., Crosswell, UK), and leg length was calculated as the difference between stature and trunk height.

Data on the intra-rater reliability of anthropometric measures taken at the academy have been published,[24] demonstrating good short-term reliability in this population for stretch stature (coefficient of variation (CV): 0.4%) and body mass (CV: 1.4%). The reliability of trunk height and leg length was indirectly assessed through the estimation of age at PHV (CV: 0.6%), which uses these components in the equation. The measures in the current study were taken by 7 different staff members introducing a potential for inter-rater differences. For ISAK Level 2 certified anthropometrists, the technical error of measurement (TEM) for length measures must be below 2% compared to a criterion measurer and intra-rater TEM has to be less than 1% for accreditation.

Assessments of skeletal maturation

Skeletal maturation was assessed at the beginning of each academic year, using x-ray images of the athlete's left hand and wrist complex taken at the Radiology Department at Aspetar Orthopaedic and Sports Medicine Hospital. The images were interpreted and entered into an academy maturation database by the same experienced assessor. Skeletal age was determined using the Fels method, following the procedures outlined by Roche et al.,[25] where a maximal skeletal age of 18.0 indicates full maturity. For prediction of mature height, the TW3 method developed by Tanner et al.[26] was used. The athlete's TW3 score (max. 1000 points/16.5 years), current stature and chronological age were entered into the prediction equation to estimate mature height. The intra-rater reliability for Fels skeletal age has previously been reported for this assessor (intraclass correlation coefficient (ICC), 95% CI: 0.998, 0.996 to 0.999)[27] and reliability data from the academy demonstrated an ICC of 0.95 (0.92 to 0.97) for the TW3 RUS (radius, ulna and short bones) overall score (unpublished data).

Recording of injuries and athletic exposures

Injuries were recorded prospectively by academy medical staff, following the consensus procedures for athletics outlined by Timpka et al.[28] All physical complaints were recorded by the designated squad physiotherapist based on a standardized injury report form and entered into the Aspire Athletics Injury Surveillance Programme database by the senior physiotherapist. Only time-loss injuries were included in the analyses, defined as the athlete not being able to fully take part in athletics training and/or competition the day after the incident occurred (min. 1 day lost). Time-loss injuries were preferred to minimize the potential bias when using multiple injury recorders covering different squads over several seasons.[29] During the study period, 6 different physiotherapists covered the athletics program, with the same senior physiotherapist in charge of the injury database quality assurance. The number of training and competition sessions (athlete exposures; AE) were entered into a central academy database (Smartabase, Fusion Sport, Boulder, CO) by the coaching staff and reviewed case-by-case by the senior physiotherapist after each season.

Data classification

Three main concepts of growth and maturation were examined in this study: growth rate, maturity status and maturity tempo. Growth rate was defined as the difference in an anthropometric variable from the start to the end of the season, maturity status as the skeletal age and percentage of predicted mature height at the start of the season, and maturity tempo as the change in skeletal age from the start of one season to the start of the next.

Classification of maturity status followed procedures previously described,[30] based on the difference between skeletal age and chronological age (Mature: skeletal age 18.0, Early: skeletal age >1 year advanced of chronological age, On-time: skeletal age and chronological age within 1 year, Late:

skeletal age >1 year delayed compared to chronological age). Passport copies were screened to verify date of birth and nationality, which was used to classify into geographical regions following the United Nation standards.[31]

Entries in the injury database were classified as either "sudden onset" or "gradual onset" based on the consensus definitions.[28] Sudden onset injuries that did not originate from athletics training sessions or competitions were excluded from analyses. The number of days lost was calculated based on the date of clinical examination and the date of return to full participation and categorized according to severity (Minor: 1 to 7 days lost, Moderate: 8 to 28 days lost, Serious: >28 days lost). Using the final diagnosis, as confirmed by the academy physicians, the injured structure was coded based on the Sports Medicine Diagnostic Coding System,[32] while the injured body part and injury type were classified according to the athletics consensus categories.[28] The structures "Bone" and "Bone-spine" were combined to one "Bone injury" category.

Statistical analysis

Descriptive statistics for growth and maturation variables are reported as mean ± standard deviation (SD). Injuries are reported as frequencies and percentages, and incidence was computed as the number of injuries per 1000 AE.

Indicators of maturity status were absolute skeletal age and percentage of predicted mature height. Absolute changes in anthropometric measures (growth rate) and skeletal age (maturity tempo) were calculated as the difference between the values at follow-up and baseline. Relative change (percentage of change per year) was computed based on the absolute change and the time between the start and follow-up tests. The relative change was then standardized based on the sample distribution so that one unit represents one standard deviation.

Generalized estimating equations (GEE) were used with the frequency of injuries as the dependent variable and growth and maturation variables as independent factors after adjusting for chronological age at the start of the season. The incidence rate ratio (IRR) with 95% confidence intervals (CI) was derived by setting the log-transformed number of AE as the offset variable and allowing exchangeable correlation for repeated athlete seasons. This procedure was performed using Poisson and negative binominal regression separately and Quasi likelihood under independence model criterion (QIC) values were used to select the model with best fit. The negative binominal regression demonstrated the lowest QIC values and the output from these analyses are therefore reported with *P*-values < 0.05 indicating significant associations. All statistical analyses were performed in SPSS ver. 21 (IBM, Armonk, NY).

RESULTS

Inclusion of athletes

Across the four academic seasons, 129 complete athlete-seasons from 85 unique athletes were considered eligible for inclusion (Figure 1). For the analyses of growth rates, 86 athlete-seasons from 60 athletes (1.3±0.5 seasons per athlete; range 1 to 3) satisfied the inclusion criteria. Maturity status could be analyzed for 108 athlete-seasons from 71 athletes (1.4±0.6; 1 to 3), where 64 athlete-seasons from 42 athletes (1.4±0.6; 1 to 3) also satisfied the criteria for analysis of maturity tempo.

Combined, the three samples included 117 different athlete-seasons from 74 athletes (1.4±0.6; 1 to 3). Chronological age at the start of the season was 13.4±1.0 years (11.7 to 17.2), with a stature of 163±11 cm (137 to 184) and body mass of 53±16 kg (28 to 112). Based on nationality, 91.5% of the athlete-seasons represented Western-Asian countries, while the remaining 8.5% represented Northern-African countries.

******* INSERT FIGURE 1 NEAR HERE *******

Growth and maturation

Baseline values and absolute and relative changes in growth and maturation are reported in Table 1. For the athlete-seasons with a complete skeletal age assessment at the start of the season, 5.6% were classified as mature, 68.5% as early maturing, 23.1% as on time and 2.8% as late maturing.

***** INSERT TABLE 1 NEAR HERE *****

Injuries

A total of 87 time-loss injuries (0.7±0.9; 0 to 3 per athlete-season) were recorded for 18 287 AE, equating to an injury incidence of 4.8 injuries per 1000 AE. Over one season, 51.3% sustained at least one injury (32.5% with only one injury, 14.5% with two injuries and 4.3% with three injuries). The total number of days lost was 1254 (10.7±24.7; 0 to 165 per athlete-season), corresponding to an injury burden of 68.6 days lost per 1000 AE.

The majority of injuries were minor (65.5%; 3.1 per 1000 AE), fewer were moderate (17.2%; 0.8 per 1000 AE) or serious (17.2%; 0.8 per 1000 AE). There were more injuries reported with a gradual onset (59.8%; 2.8 per 1000 AE) than with a sudden onset (40.2%; 1.9 per 1000 AE) and the lower extremities were most commonly injured (66.7%; 3.2 per 1000 AE), followed by injuries to the head and trunk (25.3%; 1.2 per 1000 AE) and the upper extremities (8.0%; 0.4 per 1000 AE). Detailed injury characteristics for location and type are presented in Table 2 and the effects of growth rate, maturity status and maturity tempo on injury rates are reported in Table 3 and 4.

***** INSERT TABLE 2, 3 & 4 NEAR HERE *****

DISCUSSION

Observational data from four seasons in a general athletics program revealed greater rates of bone and growth plate injuries in athletes with larger relative changes in stature and leg length over a season. Rapid growth in leg length was also associated with an increased overall risk of injuries. Furthermore, it was demonstrated that athletes with higher skeletal age and percentage of predicted mature height at the start of the season sustained fewer growth plate injuries while a greater change in skeletal age over a year was associated with an increased risk of bone injuries.

Rapid growth is associated with greater injury rates

Almost half of the injuries in this study were bone injuries, with growth plate disturbances and avulsions being the most common injury type. A large proportion of bone-related injuries has also been reported in Australian elite youth track and field, where bone stress injuries, fractures and avulsions together accounted for 47% of the total injuries.[33] The percentage of stress fractures seen in the current study (5.7%) was also similar to observations among Swedish top-ranked track and field athletes (6%),[1] although this is not directly comparable due to differences in injury definition and classification of injury types.

The incidence of bone and growth plate injuries increased when athletes experienced larger changes in stature and leg length over a season. Using the average height for this sample, an increase of one standard deviation above the mean represented an absolute growth rate of approximately 8.9 cm per year or 0.7 cm per month, which is within the expected range during the adolescent growth spurt.[4] The observations of increased injury incidence and burden around PHV[7-10] and with absolute monthly growth rates above 0.6 cm per month[6] from other elite sports therefore seem to apply also in athletics, at least for bone and growth plate injuries. While rapid growth in leg length also impacted the overall injury rates, changes in trunk height were not associated with any of the injury categories. It can therefore be suggested that monitoring changes in lower extremity segment lengths provides additional value when aiming to identify vulnerable athletes.

In the study of growth rates in Dutch footballers by Kemper et al.,[6] a BMI increase exceeding 0.3 kg/m² per month was identified as an injury risk factor. This was not seen in the current study, where injury rates were unaffected by relative increases in body mass (approximately 0.9 kg per month) and BMI (approximately 0.2 kg/m² per month). Measuring whole-body mass does therefore not seem to be relevant in terms of injuries in athletics, perhaps due to different demands for training and competition compared to team sports. Assessing specific changes in limb mass and identifying the sources of weight gain (e.g. through a heavier skeleton, increased muscle mass or increased fat percentage) may be required to understand the relationship between changes in body mass and injury risk.

Fewer growth plate injuries near skeletal maturity

The average skeletal age was 1.8 years advanced compared to chronological age in this athletics development program and the majority of athletes were classified as early maturing. This could reflect maturity-associated performance benefits in early maturing individuals, which has been considered especially important in athletics during early and mid-adolescence in events based on speed, power and size.[34] Selection bias among coaches favoring individuals of larger size[35] and the use of broader age group bands in athletics championships (e.g. U14, U16, U18)[36] may have further amplified these differences, explaining the skewed distribution.

More advanced maturity status, expressed as greater skeletal age and a higher attained percentage of predicted mature height, was associated with a lower rate of growth plate injuries with no differences in overall or bone injuries. This supports the observations of increased injury risk in later maturing athletes in previous athletics studies,[20,21] and is in line with trends in other elite youth sports. In French academy football, players classified as late or on-time sustained more osteochondral injuries than early maturing players, with no significant differences in overall incidence.[37] Similarly, immature players displayed a greater incidence of apophyseal injuries compared to mature players in Spanish elite handball, again with similar overall rates.[38]

Based on these results, skeletal maturity status appears to only have implications for certain injury types and supports previous claims that growth plates are especially vulnerable structures in immature athletes. It could also explain the contrasting findings in studies using more general injury outcome categories,[10,20,22,27] although the underlying mechanisms require more comprehensive study designs to address. A degree of overlap between maturity status and growth rates as concepts should be considered, as athletes closer to full skeletal maturity are more likely to have passed their growth spurt. It is therefore unclear if it is maturity status *per se*, or the combined effects of immature structures and rapid growth that are responsible for the increased injury rates.

Skeletal maturity tempo as a risk factor

Traditional maturity indicators, such as secondary sex characteristics, can only assess the status at the time of observation and not the exact entry to or duration of a pubertal stage.[18] Furthermore, few institutions or federations with large enough athletic cohorts have access to skeletal x-rays and trained assessors. As a consequence, maturity tempo is not commonly considered as an injury risk factor. In this study, the advancement in skeletal age over one calendar year was used to indicate maturity tempo and large variations were observed, ranging from 0 to 3.1 years.

Greater change in skeletal age was associated with an increased rate of bone injuries, although the underlying mechanisms remain unclear. One potential explanation could be that an athlete experiencing a three-year increase in skeletal age, e.g. from 15 to 18 years, would have a larger potential for maturation and begin the season further from skeletal maturity than an athlete progressing from 17 to 18 years. As discussed earlier, starting the season with a lower skeletal age affects the rate of growth plate injuries. A link between rapid skeletal maturation and rapid growth could also be suggested, although the correlation between changes in skeletal age and stature was low (r=0.45) in this sample. The correlation between changes in skeletal age and leg length was even lower (r=0.22) and therefore growth rate and maturity tempo seem to represent different aspects of growth and maturation. Risk factors related to psychological traits and behavior or associated maturational changes of other organ systems and tissues,[15] beyond the scope of this article, may also be implicated.

Methodological considerations

This study is based on systematic prospective assessments of growth and maturation combined with a consistent injury recording methodology in a relatively large and controlled athletics cohort. Some of the weaknesses identified for earlier research on growth, maturation and injuries were addressed, such as controlling for a potential confounding effect of chronological age and accounting for different baseline values.[5] Yet, some important methodological limitations must be acknowledged.

First, the anthropometric measures were taken by different assessors and could have included more detailed measures of segment lengths together with assessments of body composition. Measuring changes in, for example, tibia and femur length and relating changes to injuries in the surrounding tissues should be considered in future studies. Similarly, the skeletal age determination was based on the maturity of the hand and wrist, which does not necessarily reflect the maturation of other bones, tissues and organ systems. Second, the wrist x-rays were only available annually, and therefore, the injury and exposure data for the academic year (September to June) did not perfectly match the period for maturity tempo (September to September). This also resulted in a loss of athletes to follow-up, either due to graduation or dismissal from the athletics program. Third, incomplete recording for athletic exposures, mostly associated with training camps abroad, introduced some uncertainty which limited the possibility of assessing growth rates over shorter periods of time. Finally, using a time-loss definition influenced the injuries that were included in the analyses. Many overuse conditions may not be captured using narrow definitions if they only require treatment around the normal training sessions or just small adjustments to the training plan, even if they impair training and competition performance.[39]

PERSPECTIVES

This is the first study to examine growth rates and skeletal maturation as injury risk factors in a relatively large cohort of adolescents involved in athletics. Rapid growth in stature and leg length, younger skeletal age and faster maturity tempo were significantly associated with increased risk of bone and growth plate injuries. This provides a rationale for monitoring anthropometric variables and indicators of skeletal maturity in athletics to identify athletes who are particularly vulnerable. Changes in body mass, BMI and trunk height were, on the other hand, not associated with injury.

Although growth rates and skeletal maturation were shown to influence injury rates, they are considered non-modifiable risk factors and there is little anyone can do to affect these processes in healthy, well-nourished individuals.[4,40] Increased awareness of risk factors among clinicians, parents and athletes should be considered an important first step; what a clinician, coach, parent or athlete can do to reduce the incidence and burden of these injuries is less clear.

While consensus is lacking on the best approach to reduce the injury risk of growing athletes, it seems reasonable to focus on load management during critical phases, exposing young athletes to varying movement patterns and ensuring safe progression with sufficient rest and recovery.[41] The limitation is that specific loading parameters are not defined, beyond the general advice. Future work should therefore include more detailed reporting of training load, at the same time using injury recording methods capable of capturing how symptoms fluctuate with changes in load.

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TABLES

Table 1. Baseline values and seasonal change for the growth and maturation variables included in the analyses. Absolute changes represent the actual change from baseline to follow-up while relative changes represent the annual percentage change.

	Baseline value		**Absolute change**		**Relative change (%)**
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
Growth rate					
Chronological age (a)	13.3 ± 0.9	11.8 to 15.7	0.6 ± 0.0	0.6 to 0.7	7.5 ± 0.5
Stature (cm)	162.6 ± 11.1	136.6 to 184.3	3.4 ± 2.0	-0.2 to 11.7	3.4 ± 2.1
Body mass (kg)	51.4 ± 13.8	28.4 to 100.4	3.3 ± 3.3	-4.1 to 14.1	11.1 ± 11.0
BMI (kg/m²)	19.2 ± 3.5	14.6 to 33.1	0.4 ± 1.1	-2.3 to 4.7	3.7 ± 9.2
Trunk height (cm)	83.2 ± 6.3	70.3 to 95.9	1.7 ± 1.6	-1.5 to 6.3	3.4 ± 3.3
Leg length (cm)	79.4 ± 5.9	66.3 to 93.8	1.7 ± 1.6	-1.4 to 5.4	3.5 ± 3.3
Maturity status					
Chronological age (a)	13.4 ± 1.0	11.7 to 17.1			
Skeletal age (a)	15.2 ± 1.9	10.0 to 18.0			
SA-CA (a)	1.8 ± 1.5	-2.2 to 5.4			
Predicted mature height (%)	92.5 ± 5.6	80.2 to 101.7			
Maturity tempo					
Chronological age (a)	13.4 ± 0.9	11.8 to 15.6	1.0 ± 0.1	0.9 to 1.1	7.5 ± 0.5
Skeletal age (a)	15.2 ± 1.9	10.0 to 18.0	1.1 ± 0.8	0.0 to 3.1	7.7 ± 5.1

Table 2. Injury characteristics for the total sample of non-specialized academy athletes (n=117 athlete-seasons).

		Bone injuries				Other structures			
	No. (%)	Growth plate	Acute fracture	Stress fracture	Other bone	Muscle	Joint & ligament	Tendon	Misc.
Head & trunk									
Neck/cervical	1 (1.1)	0	0	0	0	0	0	0	1
Thoracic/upper back	1 (1.1)	0	0	0	0	0	0	0	1
Lumbar/low back	7 (8.0)	0	0	4	0	0	0	0	3
Abdomen	2 (2.3)	0	0	0	0	2	0	0	0
Pelvis/sacrum/buttock	11 (12.6)	11	0	0	0	0	0	0	0
Upper extremity									
Shoulder/clavicle	2 (2.3)	0	0	0	0	0	0	0	2
Elbow	1 (1.1)	0	0	0	0	0	1	0	0
Forearm	1 (1.1)	0	1	0	0	0	0	0	0
Wrist	2 (2.3)	0	0	0	0	0	0	0	2
Hand	1 (1.1)	0	1	0	0	0	0	0	0
Lower extremity									
Thigh	11 (12.6)	0	0	0	2	8	0	0	1
Knee	12 (13.8)	3	0	0	0	0	0	3	6
Lower leg	7 (8.0)	0	0	1	4	1	0	0	1
Achilles tendon	3 (3.4)	0	0	0	0	0	0	2	1
Ankle	10 (11.5)	2	1	0	0	0	6	0	1
Foot/toe	15 (17.2)	5	2	0	2	0	0	0	6
Total no.	87	21	5	5	8	11	7	5	25
(%)	(100.0)	(24.1)	(5.7)	(5.7)	(9.2)	(12.6)	(8.0)	(5.7)	(28.7)

Table 3. Incidence rate ratios (IRR) adjusted for chronological age for different injuries in association with annual standardized relative change in anthropometric variables amongst adolescent athletics athletes.

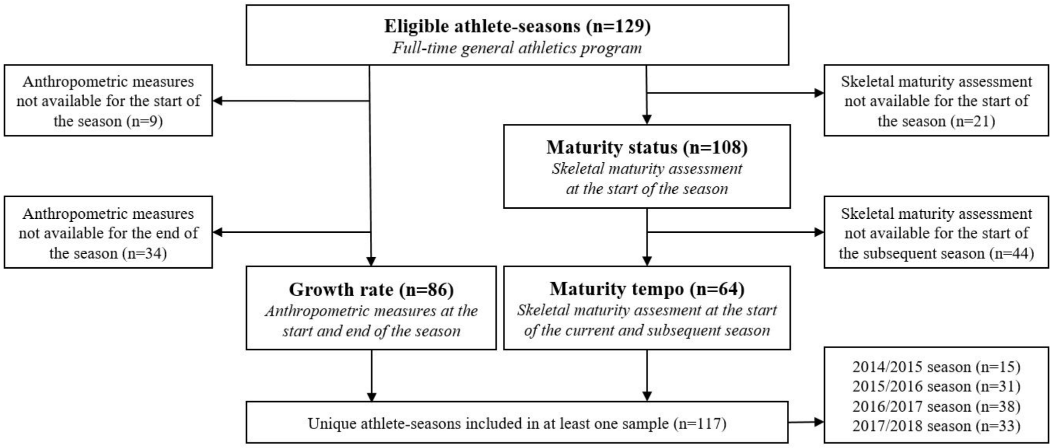
	IRR (95% CI)	*P*
Overall injuries (n=73)		
Δ Stature	1.10 (0.86 to 1.40)	0.46
Δ Body mass	1.04 (0.69 to 1.57)	0.86
Δ Body mass index	1.01 (0.67 to 1.52)	0.96
Δ Trunk height	0.87 (0.59 to 1.27)	0.46
Δ Leg length	1.30 (1.01 to 1.67)	*0.039*
Gradual onset injuries (n=46)		
Δ Stature	1.25 (0.97 to 1.61)	0.08
Δ Body mass	1.11 (0.77 to 1.62)	0.57
Δ Body mass index	1.01 (0.66 to 1.54)	0.97
Δ Trunk height	1.04 (0.79 to 1.37)	0.77
Δ Leg length	1.29 (0.99 to 1.68)	0.06
Sudden onset injuries (n=27)		
Δ Stature	0.80 (0.50 to 1.30)	0.37
Δ Body mass	0.81 (0.41 to 1.61)	0.55
Δ Body mass index	0.89 (0.51 to 1.54)	0.68
Δ Trunk height	0.64 (0.30 to 1.38)	0.25
Δ Leg length	1.26 (0.76 to 2.10)	0.37
Bone injuries (n=36)		
Δ Stature	1.47 (1.11 to 1.94)	*0.007*
Δ Body mass	1.13 (0.75 to 1.71)	0.55
Δ Body mass index	1.03 (0.65 to 1.65)	0.89
Δ Trunk height	1.16 (0.85 to 1.57)	0.36
Δ Leg length	1.41 (1.04 to 1.92)	*0.029*
Growth plate injuries (n=19)		
Δ Stature	2.14 (1.46 to 3.13)	*<0.001*
Δ Body mass	1.23 (0.68 to 2.26)	0.49
Δ Body mass index	1.02 (0.47 to 2.24)	0.96
Δ Trunk height	1.31 (0.91 to 1.88)	0.15
Δ Leg length	2.06 (1.43 to 2.97)	*<0.001*

Table 4. Incidence rate ratios (IRR) adjusted for chronological age for different injuries in association with maturity status and annual standardized relative change in skeletal age amongst adolescent athletics athletes.

	Total inj.	IRR (95% CI)	*P*
Overall injuries			
Skeletal age	76	0.99 (0.85 to 1.15)	0.89
% Predicted height	76	0.99 (0.94 to 1.05)	0.82
Δ Skeletal age	48	0.99 (0.70 to 1.39)	0.94
Gradual onset injuries			
Skeletal age	44	1.03 (0.84 to 1.28)	0.77
% Predicted height	44	1.00 (0.93 to 1.07)	0.92
Δ Skeletal age	31	1.13 (0.77 to 1.65)	0.53
Sudden onset injuries			
Skeletal age	32	0.95 (0.78 to 1.16)	0.61
% Predicted height	32	1.00 (0.93 to 1.08)	0.99
Δ Skeletal age	17	0.78 (0.51 to 1.19)	0.25
Bone injuries			
Skeletal age	34	0.88 (0.70 to 1.11)	0.29
% Predicted height	34	0.95 (0.87 to 1.03)	0.22
Δ Skeletal age	20	1.54 (1.03 to 2.29)	*0.035*
Growth plate injuries			
Skeletal age	18	0.64 (0.48 to 0.85)	*0.002*
% Predicted height	18	0.83 (0.73 to 0.96)	*0.009*
Δ Skeletal age	12	1.12 (0.74 to 1.69)	0.60

FIGURE LEGENDS

Figure 1. Flow diagram describing the inclusion of athlete-seasons from the academy athletics program to the final study samples, with the number of athlete-seasons excluded due to missing anthropometric or skeletal maturity assessments.



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