DISSERTATION FROM THE
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Eirik Halvorsen Wik

Injuries in elite male youth football and athletics

- Growth and maturation as potential risk factors

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Eirik Halvorsen Wik

Doha/Oslo, March 2021

List of papers

This dissertation is based on the following original research papers, which are referred to in the text by their Roman numerals:

I. Wik EH, Materne O, Chamari K, Duque JDP, Horobeanu C, Salcinovic B, Bahr R, Johnson A. Involving research-invested clinicians in data collection affects injury incidence in youth football. *Scandinavian Journal of Medicine and Science in Sports*. 2019;29(7):1031-1039.

II. Martinez-Silvan D, Wik EH, Alonso JM, Jeanguyot E, Salcinovic B, Johnson A, Cardinale M. Injury characteristics in male youth athletics: a five-season prospective study in a full-time sports academy. *British Journal of Sports Medicine*. 2020:bjsports-2020-102373.

III. Wik EH, Lolli L, Chamari K, Materne O, Di Salvo V, Gregson W, Bahr R. Injury patterns differ with age in male youth football: a four-season prospective study of 1111 time-loss injuries in an elite national academy. *British Journal of Sports Medicine*. 2020:bjsports-2020-103430.

IV. Wik EH, Martinez-Silvan D, Farooq A, Cardinale M, Johnson A, Bahr R. Skeletal maturation and growth rates are related to bone and growth plate injuries in adolescent athletics. *Scandinavian Journal of Medicine and Science in Sports*. 2020;30(5):894-903.

V. Wik EH, Lolli L, Chamari K, Tabben M, Di Salvo V, Gregson W, Bahr R. Main and combined effects of growth rate and skeletal maturity status on injury risk in elite male youth football players. *Manuscript submitted to Scandinavian Journal of Medicine and Science in Sports, February 2021*.

Abbreviations

ACL	Anterior cruciate ligament
AE	Athlete exposures
AIC	Akaike information criterion
AIIS	Anterior inferior iliac spine
APHV	Age at peak height velocity
ASIS	Anterior superior iliac spine
BMI	Body mass index
CE	Competition exposures
CI	Confidence interval
GP	Greulich-Pyle
ICC	Intraclass correlation coefficient
IOC	International Olympic Committee
IRR	Incidence rate ratio
ISAK	International Society for the Advancement of Kinanthropometry
MDC	Minimal detectable change
OR	Odds ratio
OSTRC	Oslo Sports Trauma Research Center
OSTRC-O	OSTRC Overuse Injury Questionnaire
OSTRC-H	OSTRC Questionnaire on Health Problems
PHV	Peak height velocity
PWV	Peak weight velocity
QIC	Quasi-likelihood under independence model criterion
RUS	Radius, ulna and short bones
SD	Standard deviation
SEM	Standard error of the measurement
SMDCS	Sports Medicine Diagnostic Coding System
TE	Training exposures
TEM	Technical error of measurement
TW1-3	Tanner-Whitehouse 1-3

Summary

Background

Elite youth athletes participate in intense and structured training programmes to realise their performance potential, but their development may be interrupted by injuries. To reduce the impact of injuries we first need to know which injuries affect participation the most and what the risk factors are. Growth and maturation represent two potential non-modifiable intrinsic risk factors that are unique to adolescent athletes. The literature published on this topic is, however, considered of low quality and findings in earlier studies are inconsistent. The aim of this thesis was therefore to identify the most common and burdensome injuries in elite male youth athletes participating in football (soccer) and athletics (track and field) and to explore growth and maturation as risk factors.

Methods

All studies were based on data from routine monitoring of athletes at Aspire Academy, a national elite sports academy in Doha, Qatar. Participants were males aged 11 to 18 years participating in the football or athletics programmes. The first study (*Paper I*) was a methodological study where we investigated the effect on injury incidence when a broad medical-attention definition was used and recorders/supervisors were invested in research projects relying on the data. This study was based on injury data for the U16 through U18 squads from 2012/13 through 2016/17 (211 players). *Papers II* and *III* were descriptive epidemiological studies in athletics and football, respectively. Time-loss injuries were collected prospectively over five seasons in athletics (2014/15 through 2018/19, 179 athletes) and four seasons in football (2016/17 through 2019/20, 301 players) by physiotherapists. The most common (injury incidence) and burdensome (injury burden) combinations of injury location and type were identified, and injury patterns were examined for event groups (athletics; non-specialised, endurance, sprints, jumps, throws) and age groups (football; U13 through U18). In *Papers IV* and *V*, subsamples of athletes (74 in athletics, 103 in football) from the epidemiological studies with complete growth (anthropometric measures, i.e. height, leg length and body mass) and maturity (skeletal age, using the Fels method) assessments were included. Growth rates, maturity status and maturity tempo were then examined as risk factors for specific injury types.

Main results

The level of investment in the injury surveillance programme by the injury recorder (team physiotherapist) or supervisor had a large impact on the incidence of non-time-loss injuries and injuries with a minimal day loss (1-3 days), while time-loss injuries overall were unaffected (*Paper I*). In athletics (*Paper II*), the main concerns were bone and muscle injuries, with thigh muscle strains/ruptures, lumbar spine stress fractures and lower leg bone stress injuries as the most burdensome location-type combinations. Injury patterns were, however, specific to each event group. In football (*Paper III*), typical "football injuries" (knee sprains, thigh strains and ankle sprains) were the most burdensome, followed by lumbosacral bone stress injuries and physis injuries to the hip/groin. Older athletes sustained more injuries relative to exposure (hours); muscle injuries were increasingly common and physis injuries less common with age. In *Paper IV*, younger skeletal age and greater changes in height, leg length and skeletal age over a season were associated with a greater incidence of bone and growth plate injuries in athletics. No associations with injury risk were found for changes in body mass, trunk height or body mass index. In football (*Paper V*), growth rates over shorter periods were not related to injury risk when accounting for age (chronological age or skeletal age) and load (weekly exposure). Older skeletal age was associated with significantly greater overall, sudden onset, muscle and joint sprain injury risk. The associations could, however, not be considered practically relevant due to the uncertain estimates for the odds ratios.

Conclusion

Based on our findings, time-loss incidence should be used when multiple medical staff recorders are involved in the data collection. Injuries patterns in elite male youth athletes are specific to the sport, event group and age group; tailoring injury reduction programmes may therefore be possible. A large proportion of lost training and competition days were attributed to bone injuries; these should be targeted to a larger degree in risk factor studies and in injury reduction programmes. Skeletal maturity appears to affect the risk of sustaining certain injury types in football and athletics, while growth rates were only related to injury risk in athletics. Practitioners and researchers may need to consider the full growth and maturity process, rather than analysing short isolated periods, to better understand the relationship between growth, maturation and injury risk.

Sammendrag på norsk (Summary in Norwegian)

Bakgrunn

Unge eliteutøvere tar del i intensive og strukturerte treningsprogram for å realisere prestasjonspotensialet sitt, men utviklingen deres kan bli påvirket av skadeavbrekk. For å redusere skadeomfanget må vi først vite hvilke skader som har størst innvirkning på aktivitetsdeltagelse og hvilke faktorer som bidrar til økt skaderisiko. Vekst og modning er to potensielle ikke-modifiserbare interne risikofaktorer som er unike for unge utøvere, men studiene som er publisert innenfor dette feltet er av lav kvalitet og har rapportert sprikende funn. Målet med denne avhandlingen var derfor å identifisere de vanligste skadene og de med størst innvirkning, blant unge mannlige eliteutøvere i fotball og friidrett, og å utforske vekst og modning som risikofaktorer.

Metode

Alle studiene var basert på data fra den regelmessige overvåkingen av utøvere ved Aspire Academy, et nasjonalt eliteakademi i Doha, Qatar. Deltagerne var gutter i alderen 11 til 18 år som deltok i fotball- eller friidrettsprogrammene. Den første studien (*Artikkel I*) var et metodestudie, hvor vi undersøkte hvordan skadeinsidensen ble påvirket av at datainnsamleren (lagsfysioterapeut) eller dens overordnede var involvert i forskningsprosjekter som benyttet det innsamlede materialet. Studien var basert på skadedatabasen for U16, U17 og U18 lagene for sesongene 2012/13 gjennom 2016/17 (211 spillere). De neste to artiklene var deskriptive epidemiologistudier i friidrett (*Artikkel 2*) og fotball (*Artikkel 3*). Fraværsskader ble registrert prospektivt over fem sesonger i friidrett (2014/15 gjennom 2018/19, 179 utøvere) og fire sesonger i fotball (2016/17 gjennom 2019/20, 301 spillere) av lagsfysioterapeuter. Kombinasjoner av skadested og skadetype ble undersøkt for å identifisere de vanligste skadene (skadeinsidens) og de med størst innvirkning (skadebyrde), og skademønsteret ble undersøkt for ulike øvelses- (friidrett; ikke-spesialisert, utholdenhet, sprint, hopp, kast) og aldersgrupper (fotball; U13 gjennom U18). I *Artiklene IV* og *V* brukte vi utvalg av utøvere fra epidemiologistudiene som hadde fullstendige vekst- (antropometri, dvs. høyde, vekt og beinlengde) og modningsdata (skjelettalder, målt med Fels-metoden). Veksthastighet, modningsstatus og modningstempo ble deretter undersøkt som risikofaktorer for spesifikke skadetyper.

Hovedresultater

Det at en lagsfysioterapeut eller overordnet var involvert i innsamlingen av skadedata hadde stor påvirkning på insidensen av skader som ikke førte til fravær fra trening eller kamp, og skader av kort varighet (1-3 dager) (*Artikkel I*). Insidensen for fraværsskader ble derimot ikke påvirket. Skjelett- og muskelskader var de største problemene i friidrett (*Artikkel II*), og strekkskader i låret, stressfrakturer i korsryggen og stressreaksjoner i leggen var kombinasjonene av skadested- og type med den største skadebyrden. Skademønsteret var forskjellig for ulike øvelsesgrupper. I fotball (*Artikkel III*) stod typiske "fotballskader" (leddbåndskader i kne/ankel og strekkskader i låret) for den største skadebyrden, fulgt av stressreaksjoner i korsryggen og vekstsoneskader i hoften. Innvirkningen disse skjelettskadene har på deltagelse har ikke blitt godt beskrevet i tidligere studier. Eldre utøvere ble oftere skadet enn yngre; strekkskader var et større problem og vekstsoneskader var et mindre problem med økende alder. I *Artikkel IV* fant vi at yngre skjelettalder og større endringer i høyde, beinlengde og skjelettalder over en sesong var assosiert med høyere insidens av skjelett- og vekstsoneskader i friidrett. Endringer i vekt, overkroppshøyde og kroppsmasseindeks påvirket ikke skaderisikoen. I fotball fant vi ingen assosiasjoner mellom veksthastighet og skaderisiko etter å ha justert for alder (skjelettalder eller kronologisk alder) og belastning (timer per uke) (*Artikkel V*). Et mer modent skjelett var forbundet med økt risiko for alle skader, akutte skader, strekkskader og leddbåndskader. Estimatene for odds ratio var usikre og vi kunne derfor ikke karakterisere disse assosiasjonene som praktisk betydningsfulle, selv om de var statistisk signifikante.

Konklusjon

Basert på våre funn anbefaler vi bruk av fraværsskader dersom flere lagsfysioterapeuter (eller andre klinikere) benyttes til å samle inn skadedata. Skader blant unge mannlige eliteutøvere er idretts-, øvelses- og aldersspesifikke; det kan derfor være mulig å tilpasse skadereduserende tiltak. En stor andel fraværsdager skyldes skjelettskader; disse bør få mer oppmerksomhet i studier av risikofaktorer og når det utvikles skadeforebyggende programmer. Skjelettmodning ser ut til å påvirke risikoen for enkelte skadetyper og kan være et nyttig å overvåke i både fotball og friidrett. Veksthastighet var bare relatert til skaderisiko i friidrett; det kan være nødvendig for trenere, klinikere og forskere å ta hensyn til hele vekst- og modningsprosessen, ikke bare korte isolerte perioder, for i større grad å forstå sammenhengen mellom vekst, modning og skader.

Introduction

Reducing the impact of injuries in elite youth sports

The desire to develop future sporting stars has led to professional structures being put in place for younger athletes.[1,2] Children and adolescents are exposed to structured training programmes from an early age with the goal of systematically nurturing talent based on specific principles, often referred to as long-term athlete development.[3,4] While deliberate play and practice over time represents one important factor for achieving senior excellence,[5,6] excessive training may be associated with negative outcomes, such as burnout, psychological stress, injuries, long-term health problems and societal costs.[7-10]

The International Olympic Committee (IOC) consensus statement on youth athletic development states a clear goal - to develop healthy and resilient young athletes while attaining sustainable and enjoyable participation for all levels.[7] Injuries do not only affect athlete health, but also restrict participation, opportunities to develop and, ultimately, performance.[11,12] Growth and maturation are suggested to predispose some athletes to certain injuries;[7,8,13] however, the research underpinning these suggestions is considered as having a high risk of bias, resulting in conflicting and inconclusive evidence.[14] Prospective studies in larger samples with stronger designs and more robust methods are therefore needed to fill the knowledge gaps in this area.[8,14] This is a key element in the process of developing future sports champions at the Aspire Academy, an elite sports academy in Qatar. There, prospective monitoring of growth, maturity and injuries is used to drive sport science research and to inform training and prevention programmes. Although the academy programmes only cater for boys, this setting allowed us to address some of the gaps in the literature using a large sample of youth athletes participating in intense training programmes.

A framework for research into youth injury reduction

A systematic four-step approach, described by van Mechelen et al.,[15] is often used to guide research aimed at reducing the impact of sports injuries. First, the extent of the problem must be described (Step 1); then injury risk factors and mechanisms have to be identified (Step 2). Based on this knowledge, measures that may reduce injury risk and severity can be developed and introduced (Step 3) and their effectiveness can be evaluated by repeating the first step (Step 4). This model was later expanded by Finch[16] to better account for implementation issues relating to adoption and compliance among end users; still, the first two steps remain similar and form the basis of this thesis.

The extent of the problem is usually established through systematic injury surveillance.[15,16] Representing the foundation for the subsequent steps in the process, it is important that we are able to provide valid and reliable injury data. This is addressed in *Paper I*, where we examine methodological issues relating to the use of multiple medical staff members to record injuries, and how different levels of investment in the surveillance programme can affect the outcomes of a study. We could then subsequently examine the extent of the injury problem in the academy athletics (track and field - *Paper II*) and football (soccer - *Paper III*) programmes with greater confidence in our key outcome measures. The epidemiology of elite male youth athletes participating in athletics is not well researched, with only a handful prospective studies conducted in this population. A larger number of epidemiological studies have been published on elite male youth football players; however, differences in injury recording methods, outcome measures and injury classification limit our ability to identify the injuries that have the greatest impact on player participation.[17]

Effective injury reduction measures can only be developed after gaining a thorough understanding of why injuries occur (Step 2).[15,16] Meeuwisse[18] provided a multifactorial model for the aetiology of sports injuries, starting with intrinsic risk factors (which may predispose an athlete to injury), followed by exposure to external risk factors (making the athlete more susceptible) and an inciting event. This model has subsequently been expanded by Meeuwisse et al.[19] to include a dynamic component and Bittencourt et al.[20] suggest an even more comprehensive model to account for the complex interplay between risk factors. Growth and maturation are two potential non-modifiable intrinsic risk factors that are unique to the youth athletic population, and in *Papers IV* and *V* we aimed to improve our understanding of their associations with injury occurrence, knowledge that can be used to guide preventative efforts. In doing so, the hope is that a larger number of youth elite athletes can enjoy uninterrupted and enjoyable sports participation for a longer time, maximising their development and realising their own goals and potential.[7]

Background and theoretical framework

Injury surveillance methodology

In the first step of the sequence of injury prevention research we are asked to describe the extent of the problem. Our ability to accurately and reliably answer this question is highly dependent on the method chosen for recording injuries. In a systematic review of injury surveillance systems, Ekegren et al.[21] identified a wide range of methods applied, which is necessary to successfully obtain relevant injury data with the resources available in a given context. This does, however, require an understanding of how variations in surveillance methods can affect the study outcomes and researchers need to consider the presence, direction and magnitude of any biases or confounding factors.[22] Alongside specific[23-33] and general[34] consensus statements on the recommended injury surveillance procedures, validation studies and critical appraisals of methodology have been published to guide researchers. In this section, methodological considerations when defining, recording and reporting injuries will be more closely discussed.

Defining injuries

As the main outcome of surveillance studies, what constitutes an injury has to be clearly defined prior to data collection to avoid bias and to allow for clear interpretation of the results.[35] While this may appear straightforward, there are challenges associated with fitting simple and often dichotomous criteria to a complex phenomenon. There may not be much debate when an incident results in hospitalisation (e.g. fractures), but in cases with mild symptoms and less obvious impact on participation (e.g. tendinopathies) the decision to count an injury becomes more difficult. Different definitions have therefore been used, operating on a continuum from narrow (e.g. missed match) to broad (e.g. any complaint).[36] While the choice depends on the research question, each definition is associated with strengths and limitations that should be taken into account.

Narrow injury definitions

The narrowest definitions will only capture the most severe injuries, for example those resulting in insurance claims, hospitalisations or clinic treatments. Studies applying these are often interested in the impact of injuries at a societal level and benefits include accurate diagnoses by qualified medical staff and the ability to cross-check injuries using independent sources.[10,15,22,37,38] They do, however, miss out on the large proportion of injuries that are not acute or have delayed effects, and incidence measures are limited by the unknown population size, as the number of injuries will depend on the popularity and participation of a sport in a certain area.[10,15,22,37,38]

In consensus statements, the narrowest recommended definitions are those leading to time loss from training or competition. Time-loss definitions may involve a criterion for severity (e.g. any future session, >48 hours or >3 weeks) and have also been classified as semi inclusive or fully inclusive.[39] A semi-inclusive definition (competition time loss only) is considered reliable and practical, as it places minimal burden on recorders (who do not require medical training) and can be cross-checked with official reports.[36,39,40] On the other hand, it is vulnerable to differences in competition schedules, medical treatment practices and risk tolerance, does not pick up injuries impacting only training or athletes competing with pain, and is of limited use in individual sports where competitions are less regular.[36,39-42]

The fully-inclusive definition is the most common in long-term surveillance programmes and captures the injuries affecting participation in organised activities (i.e. training and/or competition).[36] These are considered important to capture, as they may affect athlete and team performance and be relevant for subsequent injuries.[42,43] Many of the strengths and limitations discussed for the semi-inclusive definition apply here as well; however, it is considered more prone to variation in recording.[40,43] Training frequency and the presence of recorders at sessions will play a role, and the distinction between "normal", "restricted", "partial" or "planned individualised" training has to be made clear; this is again especially challenging in individual sports.[22,34,36,40,41] Injuries are also somewhat sport-specific in terms of time loss;[39,41] for example, a finger fracture would likely restrict participation in volleyball, but perhaps not in football.

Broad injury definitions

Although considered practical and relatively reliable, time-loss definitions do not necessarily capture all the injuries we are interested in, possibly just the tip of the injury iceberg.[15,38,40,42,44] Broader definitions have therefore been applied to better account for injuries that do not restrict participation but still require treatment, cause pain and/or restrict performance. One example is the medical-attention definition, a popular approach in large-scale multisport events which is also applicable to other sporting contexts where medical staff are present.[26,36] In addition to capturing more problems, this is considered useful to inform the allocation of medical staff and resources.[15,22,36] Using medically trained personnel carries the benefit of detecting conditions with better diagnostic validity; however, inconsistent medical coverage will limit the ability to compare results and the extent of potentially recordable events places a large burden on recorders, which again may impair data completeness and accuracy.[36,37,39-42] Furthermore, reliability is threatened by not being able to cross-check injuries against training records, differences between medical staff in their motivation to record minor examinations and interpretation of which events qualify as recordable.[40] These differences have not been well described in the existing literature and form the basis for *Paper I* in this thesis.

The definition of an injury may not be the same for an athlete, coach or medical practitioner and injuries that do not require medical attention may still cause symptoms and impair performance.[44,45] Athlete-centred surveillance systems have therefore been developed and refined, relying on broad "any-complaint" definitions,[46,47] such as the questionnaires developed at the Oslo Sports Trauma Research Center (OSTRC). In the original OSTRC Overuse Injury Questionnaire (OSTRC-O),[46] the term "injury" was replaced by "problem" to reduce differences in interpretation among athletes and referred to problems that affected participation, led to reductions in training volume, affected performance and/or caused pain. This has been supplemented by a questionnaire (OSTRC Questionnaire on Health Problems; OSTRC-H) encompassing all health problems (e.g. illnesses and associated symptoms), both of which were recently updated (e.g. changing training "reduction" to "modification" to acknowledge alterations that only affect training mode or intensity).[47]

Using the athlete's own definition of an injury is considered relatively cost-efficient with modern technology, does not require medical staff and captures more problems than time-loss definitions.[36,46] Still, this is a definition that is prone to differences in interpretation of a recordable injury or health problem, relies on high response rates from athletes (who may not have any interest or incentive to report them) and does not secure diagnoses.[36,46] Validity can, however, be improved using follow-up interviews with medical staff, although this is logistically challenging and costly.[46]

Recording injuries

While the definition dictates "what" is reported, recording methods represent the "who" and "how" of injury surveillance. Few systems will be able to capture all injuries,[22] yet a precise recording system that does not miss injuries is considered a prerequisite for risk factor studies.[48] Medical staff have traditionally been responsible for recording injuries, but athlete reporting (e.g. using the OSTRC questionnaires) has gained popularity and the use of coaches, parents, match/technical officials and researchers has been explored.[47,49-55] Standard or sport-specific recording forms (paper or electronic) are recommended in most consensus statements to ensure complete and uniform data,[23-26,28-33] although technological advances now allow for more direct data collection using online platforms, text messaging and smart phone applications.[29-32,34,51,56] By comparing different combinations of injury definitions, recorders and tools, validation studies have provided insights into their strengths and limitations.

Comparisons of medical staff and athlete-reported injuries

Medical staff and athlete-reported methods have been directly compared in multiple settings. In professional male football, Bjørneboe et al.[50] compared injury records from medical staff for the final three months of a season to post-season player interviews. One of five injuries (19%) were missed by medical staff and only half (51%) were reported by both methods, even though a time-loss definition was applied. The majority of missed injuries were minor (<1 week lost), suggesting that these are the most challenging for medical staff to record. One third of injuries (29%) were, importantly, only recorded by the medical staff, which was likely due to recall bias associated with retrospective interviews. Similar conclusions were reached by Flørenes et al.,[49] where post-season interviews of international skiers and snowboarders were compared against medical staff records. Only 55% of time-loss injuries were recorded by both methods, 39% only by athletes and 6% only by medical staff. For medical-attention injuries, more than half (52%) were only recorded by athletes and 41% by both. Again, the majority of injuries (68%) missed by medical staff were minor (0-3 days lost); this was also the case for the injuries missed in the athlete interviews (77% were minor).

Nilstad et al.[51] expanded on the previous findings by using weekly in-season injury recording by text messaging in elite female football and comparing these to those reported by medical staff. With a high completion rate (90%), only 28% of injuries were recorded by both methods, 62% by athletes only and 10% by medical staff only. Surprisingly, only half the severe injuries were reported by medical staff, while nearly all were captured by athletes. The authors highlighted that the underreporting was consistent for all medical staff and not just related to a few recorders or teams. Weekly text message reporting was also applied by Møller et al.[56] over 12 weeks in Danish adolescent handball players, including questions from the OSTRC-O.[46] The comparison method used trained on-field recorders to initiate injury records and physiotherapists to complete them, and a large number of injuries (41%) were only captured by the athlete self-report method (12% only by observers/medical staff). Consistent with previous findings, two-thirds of the missed injuries by observers/medical staff were problems that did not lead to time loss.

The results from these comparison studies highlight the inability of any system to capture all injuries. Medical staff reporting provides more valid and detailed injury data, but a large proportion are missed and the collection is time-consuming for busy practitioners when broad definitions are applied.[46] Athlete-reported measures capture a larger number of injuries and online software makes data collection easier once set up, but are limited by different interpretation of recordable symptoms between athletes, the need for medical follow-up to accurately report injury details and the reliance on high response rates and honesty among players.[46,56] As a consequence, some researchers have combined methods to provide a more complete injury picture and overcome the limitations of studies using only one approach.[57,58] Finally, while these methodological studies provide insights into differences between recording systems, little evidence exists to describe biases within the same surveillance programme where the injury definition and recording method is assumed to be consistent. This research gap is addressed in *Paper I*, where we explore the challenges associated with combining medical staff recorders and a broad non-time-loss definition.

Reporting injuries

Once the injuries of interest are defined and data collected, these have to be presented in a manner that provides useful information to the end-user. Usually, researchers, medical staff, coaches or athletes are interested in knowing something about the chances of sustaining certain injuries and if they occur more often than what is considered normal (e.g. compared to previous seasons, other countries or other sports). Incidence is preferred to measure how common a condition is in a sample or population, since absolute counts and proportions cannot provide information about risk.[39] This can be expressed as the number of injuries per athlete over a given time period (e.g. injuries per athlete per season) or as cumulative season prevalence (the number of athletes sustaining at least one injury, sometimes termed "incidence proportion"[59]), but these measures do not take the time spent at risk into consideration.[15] Sports injuries can only be sustained when participating in sports activities and it is therefore recommended to report them relative to the time spent in training and/or competition (e.g. injuries per 1000 h). This better indicates the extent of the problem and allows for direct comparisons between sports and settings, as differences in season duration, session frequency and duration, and absences for other reasons than injuries are considered in the calculation.[15,34,39,59]

Incidence may not always be the most appropriate measure, for example, if the goal is to describe the presence of injury problems in a group at a given time. Prevalence measures (e.g. through repeated cross-sectional questionnaires) have therefore been suggested as especially useful when overuse and long-term injuries dominate, as is often the case in individual sports.[34,44] Another limitation of only reporting incidence is that frequency measures do not say anything about the severity of each injury, which is important in terms of risk management.[60] The impact of serious but less common injuries (e.g. anterior cruciate ligament (ACL) tears) will be underestimated, while common but mild injuries (e.g. contusions) will appear a larger problem than they are for a player or team. Injury burden, expressed as the number of days lost per 1000 h, is therefore suggested as a more informative measure of impact, taking both incidence ("how often") and duration ("how severe") into account.[34,61,62]

Injuries in elite male youth football and athletics

Measures to reduce the impact of injuries in youth sports can only be introduced if we know which injuries we should focus on. Consensus statements have therefore been published (football in 2006[25] and athletics in 2014[29]) to improve the quality and comparability of epidemiological studies. Still, different combinations of injury definitions, recording methods, injury categories and outcome measures make attempts to reach definite conclusions difficult. Very few studies report injury burden to measure impact and most studies report injury locations and types separate. This has made it difficult for practitioners to target the specific injuries that have the greatest impact on participation in these populations.

Injuries in elite male youth football

To summarise the existing epidemiological literature on elite male youth football players, a systematic search in the PubMed database was conducted (Table 1), identifying 34 prospective studies satisfying the inclusion criteria published prior to 01.11.20.

Table 1. Search strategy for the literature review on injuries in elite male youth football.

Inclusion criteria	**Exclusion criteria**
✓ Male football (soccer) players	✓ Mixed sport or mixed gender samples
✓ Adolescents (10-19 years, U11-U20)	✓ Children, college or senior players
✓ High-level, elite or academy players	✓ Middle school or high school students
✓ Prospective data collection	✓ Cross-sectional, retrospective, case-series or intervention studies
✓ Minimum duration of 1 season/year	✓ Duration <1 season/year
✓ Overall injury outcome with incidence and/or burden	✓ Studies on specific injury types
✓ Full article available in peer-reviewed journal	✓ Abstract, conference paper, review, editorial, letter or chapter
✓ English language	✓ Non-English language
Domain (combined with AND)	**Keywords (combined with OR within each domain)**
Sport	football, soccer
Age	adolescen*, young, youth, boys, child*
Outcome	injur*
Analysis	incidence, prevalence, burden, surveillance, audit
Initial search results (PubMed 01.11.2020): 2149	
Studies included after screening titles, abstracts and reference lists: 34	

Overall incidence and prevalence

The cumulative season prevalence (players with minimum one injury) in the studies included ranged from 38% to 75% (median: 53%, 25th to 75th percentile: 40 to 68),[63-66] suggesting that for a given season, a coach can expect half the squad to sustain at least one injury. The range in the mean number of injuries per player per season was 0.4 to 2.5 (1.0, 0.7 to 1.6) in studies using time-loss definitions[64,65,67-76] and 0.9 to 2.2 (1.4, 1.3 to 1.5) in those applying broader definitions (any complaint or medical attention).[63,77-79] These numbers both demonstrate that many players sustain more than one injury and that broader definitions, as expected, detect more injuries than time-loss definitions. Both measures may, however, be biased by different time spent at risk.

In studies reporting injuries relative to exposure (Table 2), the overall incidence ranged from 1.3 to 12.1 (6.2, 2.7 to 8.3) time-loss injuries or 2.5 to 18.4 (6.1, 4.7 to 9.4) medical-attention or any-complaint injuries per 1000 h. The proportion of reinjuries ranged from 3% to 25% (6%, 3 to 10),[64,68,69,71,72,74,78,80,81] and match incidence was 1.6 to 16.1 times higher (4.3 times, 2.8 to 5.8) than training incidence (Table 2). The wide ranges of reported incidences, even when comparing narrow and broad definition separately, may reflect the different methods used to calculate exposure (e.g. estimation at a group vs. individual level) or the differences within these categories (e.g. different cut-offs for time loss). The variation in proportion of reinjuries likely reflects different definitions (e.g. within two months[69,72] vs. within 12 months[64,81] of return from the previous injury), study durations, players age and the consideration of injuries prior to entering the observation period.

Severity and burden

The severity of an injury is most commonly reported as the number of time-loss days, capturing the period a player is not available for full participation in training sessions and/or match selection.[25,34] The severity in the studies included ranged from 11 to 32 days per injury (17 days, 1 to 19) when reporting the mean [65,68,69,71,75,76,80,82,83] and 7 to 31 days when reporting the median.[64,76,84] The distribution of injuries in specific severity bands was often reported, with 7% to 72% (36%, 29 to 48) lasting 7 days or less, 16% to 67% (41%, 34 to 44) classified as moderate (8-28 days) and 2% to 34% (22%, 14 to 28) as severe (>28 days).[64,65,68,69,71-78,80,81,84-87] The differences in severity may again represent differences in injury definition and recording method, affecting the ability to detect injuries of lower severity; however, it appears that injuries of moderate duration are the most common and that every fifth injury will last more than four weeks. The impact of these injuries may have been underestimated since only two studies have reported injury burden. In Dutch football, Bult et al.[76] reported a mean 58.4 days lost per 1000 h, while the corresponding number by Raya-Gonzales et al.[87] for Spanish players was 37.6 days per 1000 h. This knowledge gap is addressed in *Paper III*.

Table 2. Prospective studies reporting overall, training and/or match incidence relative to exposure hours in elite male youth football over at least one year or season.

1st author (year) Duration	Level Country	Players	Age	Injury definition	Injury recorder	Injuries	Exposure	Incidence (per 1000 h) Overall	 Training	 Match
Hawkins (1999)[80] 2.5 years	Professional club England	Unclear	Youth	Time loss (>1d)	Medical staff	166	Estimated	N/A	4.1	37.2
Junge (2000)[67] 1 year	High level Multiple countries	193	14-18	Time-loss (>1wk) tissue damage	Medical staff/ Coach	131	Individual	2.0-2.5	N/A	N/A
Peterson (2000)[88] 1 year	High level Unclear	135	14-18	Tissue damage	Medical staff	262	Individual	6.0-6.6	N/A	16-19
*Le Gall (2006)[69] 10 seasons	National institute France	528	U14-16	Time loss (>48h)	Medical staff	1152	Estimated	4.8	3.9	11.2
Merron (2006)[85] 4 years	Academy England	112	16-18	Time loss (>2d)	Medical staff	236	Individual	8.1	6.1	25.0
*Le Gall (2007)[71] 10 seasons	National institute France	233	U14	Time loss (>48h)	Medical staff	588	Estimated	5.6	4.7	11.8
Timpka (2008)[89] 1 season	Elite Sweden	Unclear	U16-17	First time-loss match injury	Coach/ Interview	Unclear	Estimated	N/A	N/A	1.9-2.8
Johnson (2009)[90] 6 years	Academy England	292	9-16	Unclear	Medical staff	476	Individual	2.2	1.4	10.5
Brink (2010)[91] 2 seasons	National level Netherlands	53	15-18	Medical attention (>1d) & time loss	Medical staff	320	Individual	N/A	MA: 11.1 TL: 6.7	MA: 37.6 TL: 26.7
Ergün (2013)[81] 3 seasons	National team Turkey	52	U17-19	Medical attention & time loss	Medical staff	44	Individual	MA: 18.4 TL: 12.1	MA: 10.5 TL: 7.4	MA: 48.7 TL: 30.4
Tourny (2014)[77] 3 seasons	Professional club France	Unclear	U12-20	Any complaint	Medical staff	618	Estimated	1.5-4.8	1.0-3.8	9.4-42.2
van der Sluis (2014)[92] 4 seasons	Professional club Netherlands	26	11.9	Medical attention & time loss	Medical staff	178	Individual	N/A	MA: 2.6-4.2 TL: 1.6-2.8	MA: 12.5-23.1 TL: 9.4-15.9

*Sample represented in multiple studies. MA: Medical attention. TL: Time loss

1st author (year) Duration	Level Country	Players	Age	Injury definition	Injury recorder	Injuries	Exposure	Incidence (per 1000 h)		
								Overall	Training	Match
Kemper (2015)[63] 1 season	Academy Netherlands	101	U12-19	Medical attention (>1d)	Medical staff	134	Estimated	5.9	3.3	18.2
Bianco (2016)[72] 1 season	Academy Italy	80	13-19 yr.	Time loss	Researcher	107	Individual	1.3	1.2	2.8
Nilsson (2016)[73] 2 seasons	Elite team Sweden	43	15-19 yr.	Time loss	Medical staff	61	Individual	6.8	5.6	15.5
Bacon (2017)[86] 2 seasons	Academy England	41	U18-21	Unclear	Medical staff	85	Individual	10.6	3.7	5.8
Bowen (2017)[82] 2 seasons	Academy England	32	U18-21	Time loss	Medical staff	138	Individual	12.1	7.9	33.5
Tears (2018)[78] 6 seasons	Academy England	Unclear	U12-18	Medical attention	Medical staff	882	Estimated	2.5	1.5	24.1
Bult (2018)[76] 3 seasons	Academy Netherlands	170	U12-19	Time loss	Medical staff	620	Group	8.3	N/A	N/A
Delecroix (2019)[93] 4 seasons	Academy France	52	U19	Time loss	Unclear	182	Individual	7.6	N/A	N/A
Loose (2019)[94] 1 season	Elite division Germany	Unclear	U19	Time loss & Non-time loss	Player/ Medical staff	Unclear	Individual	10.4	N/A	N/A
Raya-Gonzales (2019)[87] 4 seasons	Academy Spain	Unclear	U14-19	Time loss	Medical staff	337	Individual	2.7	2.0	8.8
Cezarino (2020)[64] 1 season	Academy Brazil	228	10-20 yr.	Time loss	Medical staff	187	Group	1.9	1.4	8.1
Sieland (2020)[84] 2 seasons	Academy Germany	205	U12-19	Time loss	Medical staff	125	Individual	2.7	2.3	5.0

Location, type and diagnoses

The incidence, severity and burden provide a basic understanding of the injury extent; yet, information about the injured body part and injury type is required to tailor specific injury prevention programmes to the injuries causing the most problems. As football is a field-based team sport characterised by frequent high-intensity runs, duels and shooting/passing, it is not surprising that the lower extremity (including the hip/groin) is by far the most injured body region. Studies are relatively consistent in this regard, with proportions ranging from 71% to 93% (83%, 79 to 86) of all recorded injuries.[65,68-70,73,75-78,81,84,85,91,92] Although injury location categories were not consistent, the thigh, ankle, knee and hip/groin stood out as the most frequently reported, and roughly three out of four injuries could be expected to involve these body parts (Table 3).

Table 3. Proportion (%) of all recorded injuries per lower extremity body part in elite male youth football.

1st author (year)	Hip/groin	Thigh	Knee	Lower leg	Ankle	Foot
Hawkins (1999)[80]	16	23	10	9	17	8
Peterson (2000)[88]		10-16	14-16		17-21	
Price (2004)[68]	12	19	18	10	19	8
Le Gall (2006)[69]	2	25	15	5	18	8
Merron (2006)[85]	7	12	19	7	19	8
Deehan (2007)[70]		31	15		18	6
Ergün (2013)[81]	25	32	7		9	2
Tourny (2014)[77]	16-19	23-32	12-15	6	10-20	6-10
Bianco (2016)[72]	21	34	18	11		
Nilsson (2016)[73]	33	26			18	
Renshaw (2016)[74]	13	35	17	6	13	4
Bacon (2017)[86]	16	11	16	2	31	7
Read (2018)[75]		16	20		18	
Tears (2018)[78]	15	20	14	11	15	9
Bult (2018)[76]	17	17	17	9	20	7
Raya-Gonzales (2019)[87]	17	23	18	10	23	3
Cezarino (2020)[64]	12	26	23	4	19	3
Hall (2020)[65]	~8	~22	~20	~5	~14	~6
Median	**16**	**23**	**17**	**7**	**18**	**7**
25th to 75th pct.	**(12 to 17)**	**(18 to 27)**	**(15 to 18)**	**(5 to 10)**	**(15 to 19)**	**(5 to 8)**

While information about the injured body part is relatively easy to report and relate to for non-medically trained players and staff, it is of limited use without knowing the type of injury. A lower leg injury could, for example, be a bone stress injury or a muscle strain, which require different preventative approaches. As for injury location, identifying the most common injury types is complicated by the different categories used; however, muscle strains, ligament sprains and contusions were consistently among the most frequent types and, together, accounted for approximately seven out of ten injuries (Table 4). Again, this information alone does not give a good picture of which injuries to focus on. First, a ligament sprain to the knee should be seen as different to a sprained wrist and only a handful of studies report injuries in more detail. For example, hamstring injuries accounted for 4% to 14% (11%, 6 to 12),[64,65,70,74,75,81,85,86] quadriceps injuries for 7% to 21% (9%, 8 to 11)[64,70,74,75,81,86] and adductor injuries for a 8% to 25% of all injuries (8%, 8 to 17).[64,70,81] Second, even though contusions were identified as common, we might not want to focus all our efforts towards preventing them if they only lead to one or two days lost. Resources may then be more effectively used to reduce the impact of muscle strains and ligament sprains, which occur with a similar frequency but typically restrict participation for a longer duration. The lack of location-specific injury reporting was highlighted as a limitation in the IOC consensus statement, where the example data also includes sport-specific diagnoses with their associated incidence, severity and burden.[34] The identification of the most common and burdensome location-specific injury types is therefore one of the main aims of *Paper III*.

Table 4. Proportion (%) of all recorded injuries per injury type in elite male youth football.

1st author (year)	Muscle strain	Joint/ ligament sprain	Contusion/ haematoma	Fracture	Tendon	Growth related/ Osteochondroses
Hawkins (1999)[80]	36	20	27	4		
Price (2004)[68]	31	20		4		
Le Gall (2006)[69]	15	17	31	6	9	6
Deehan (2007)[70]	37	18	10		6	
Brink (2010)[91]	38	25	26			
Ergün (2013)[81]	61	9	20		2	
van der Sluis (2014)[92]	57	21	13			
Kemper (2015)[63]	~18	~22	~28	~3	~6	~19
Bianco (2016)[72]	87				13	
Nilsson (2016)[73]	53	24				
Renshaw (2016)[74]	46	16				
Bacon (2017)[86]	14	19	12	6		
Read (2018)[75]	21	17		3	4	7
Tears (2018)[78]	31	20	22	4	12	
Bult (2018)[76]	28	13	28	9	13	
Raya-Gonzales (2019)[87]	26	37	3	4		
Cezarino (2020)[64]	26	24	16	7	10	
Hall (2020)[65]	30	20	~9	~6	4	~9
Median	**31**	**20**	**20**	**4**	**8**	**8**
25th to 75th pct.	**(26 to 44)**	**(17 to 22)**	**(12 to 27)**	**(4 to 6)**	**(5 to 12)**	**(7 to 12)**

A category specific to youth players is osteochondroses, a group of conditions affecting the growth plates.[95] This term is used interchangeably with "growth-related disorders" in the literature, but were not included as a separate injury type in the football consensus statement from 2006 (most fall into the category "other bone injuries").[25] The extent of these injuries is therefore largely unexplored, although some studies have created a new category and indicate that these account for less than every tenth injury.[63,65,69,75] Osgood-Schlatter disease (apophysitis of the tibial tubercle) and Sever's disease (apophysitis of the calcaneus) are two frequently mentioned diagnoses within this injury type,[95] each accounting for 2% to 3% of the reported time-loss injuries.[68-70] The lack of data on the impact these injuries have on young football players is another research gap addressed in *Paper III*.

Onset and mechanism

In addition to identifying which injuries we should target, it is important to understand how they are sustained,[96] and researchers are encouraged to report both the type of onset and mechanism.[25] The terms "overuse" or "gradual onset" have been used to describe similar aetiologies in the included studies, accounting for 17% to 48% (25%, 21 to 32) of injuries,[65,69,76,78,79,81,86,87] although time-loss definitions were mostly used, meaning the extent is likely underestimated.[44] The proportion of non-contact injuries ranged from 42% to 77% (64%, 59 to 69) which suggests that these represent more than half of all injuries.[64,65,70,74,75,77,78,84,86,93] There is no unified classification system for specific mechanisms and pooling results was therefore challenging. The majority of injuries do, however, appear to be related to duels and competing for the ball (i.e. tackled, tackling, kicked)(27%, 17 to 38),[68,70,73,80] running and sprinting (19%, 14 to 24)[68,73,80] or kicking actions (i.e. shooting, passing)(11%, 10 to 12).[68,73,80] In saying this, it should also be acknowledged that studies did not verify mechanisms using video footage or other tools and the results should therefore be interpreted with care.

Age group differences

A noteworthy feature of youth football is that game demands and physical capacity are expected to increase as players get older,[97,98] which could have implications for injury risk. In the majority of the studies included, injury incidence was indeed greater in older players,[64,68,70,74,75,77,84] although this was not always clear[67,69,81,87,88] and some studies identified peaks in incidence around the age groups U14 to U16.[70,76,83] Injury severity also appears to change with age, as demonstrated by Read et al.[75] who reported the greatest number of days lost per injury in U14 and U15 players and the largest number of severe injuries in the U15 age group. Similar trends were observed by Hall et al.,[65] with the greatest proportion of severe injuries in the U14, U15 and U16 age groups. The two studies reporting injury burden both reported a peak for the U16 age group,[76,87] suggesting that players of this age are more likely to lose training and match time due to injury. No significant age group differences were reported by Le Gall et al.[69] for injury location, although they did report significantly more osteochondroses in U14 players compared to the U15 and U16 age groups. This is in line with the findings by Hall et al.,[65] who found that growth-related injuries were the most common in the age groups U9 through U13, while muscle strains, tears and cramps were the most common in the older age groups (U14 through U18). Both Price at al.[68] and Read et al.[75] observed a peak incidence of Sever's disease and Osgood-Schlatter disease in the U13 and U14 age groups. In general, detailed descriptions of injury patterns across age groups and the extent of growth-related injuries are not well described, an area we specifically target in *Paper III*.

Injuries in elite male youth athletics

The existing literature on injuries in elite male youth athletics was audited in a similar manner as for football, where a systematic search of the PubMed database (Table 5) returned only six prospective articles satisfying the inclusion criteria published before 01.11.20. The low number of included studies could be due to the many studies based on middle or high school programmes and larger competitive events, but may also reflect fewer structured elite programmes (e.g. academies) than in football. The sport itself is also challenging in terms of prospective injury surveillance, as discussed by Edouard et al.[99] First, they point out that athletics is comprised of different events (disciplines) that differ in terms of training and competition demands. Second, the non-professional structure, often without close medical coverage, provides a challenge for monitoring athletes. This is compounded by remotely located athletes for training camps and a tendency to trust the athlete's own medical providers (although this is less of a problem with youth athletes). Finally, individual sports are challenging in general, as the training content can be easily modified on a daily basis without affecting other athletes. It is therefore difficult to draw a clear line for when an athlete is injured and when he/she is not (e.g. when using a time-loss definition).[36]

Table 5. Search strategy for the literature review on injuries in elite male youth athletics.

Inclusion criteria	Exclusion criteria
✓ Male athletics (track and field) athletes ✓ Adolescents (10-19 years, U11-U20) ✓ High-level, elite or academy athletes ✓ Prospective data collection ✓ Minimum duration of 1 season/year ✓ Overall injury outcome with incidence, burden and/or weekly prevalence ✓ Full article available in peer-reviewed journal ✓ English language	✓ Mixed sport or mixed gender samples ✓ Children, college or senior athletes ✓ Middle school or high school students ✓ Cross-sectional, retrospective, case-series or intervention studies ✓ Duration <1 season/year ✓ Studies on specific injury types ✓ Abstract, conference paper, review, editorial, letter or chapter ✓ Non-English language
Domain (combined with AND)	**Keywords (combined with OR within each domain)**
Sport	track and field, athletics, runn*, throw*, jump*, sprint*
Age	adolescen*, young, youth, boys
Outcome	injur*
Analysis	incidence, prevalence, burden, surveillance, audit
Initial search results (PubMed 01.11.2020): 10 394 Studies included after screening titles, abstracts and reference lists: 6	

Overall incidence and prevalence

Athletes sustained 1.4 to 4.4 injuries per season,[100-102] with two studies reporting the cumulative season prevalence at 64% and 76%.[101,103] The number of injuries relative to training and competition exposure ranged from 3.9 to 13.8 per 1000 h (median: 5.3, 25th to 75th percentile: 4.4 to 8.0), depending on the events included (Table 6). It should be noted that these studies mainly used broad injury definitions, which may explain the greater proportion of injured players compared to football. Incidence is, as mentioned in the earlier section on injury reporting, a less useful measure in sports where long-standing and overuse problems dominate. To better describe the extent of the injury problem, repeated cross-sectional prevalence measures are therefore suggested for athletics.[29] Two studies reported this (Table 6), where 20% and 39% struggled with any injury problem in a given week and 9% and 23% with a substantial injury. This suggests that at least one out five athletes trained or competed in the presence of an injury problem at any given time. For at least one in ten athletes, these problems moderately or severely restricted training volume or performance, or completely hindered participation.

Table 6. Prospective studies reporting overall incidence relative to exposure hours or average weekly prevalence in elite male youth athletics over at least one year or season.

1st author (year) Duration	Level Country	Athletes	Age	Events	Injury definition	Injury recorder	Injuries	Exposure	Incidence (per 1000 h)	Weekly prevalence
Jacobsson (2013)[103] 1 year	Top-10 ranked Sweden	55	17 yr.	Track & field (mixed)	Affected training/ competition	Athlete	85	Individual	3.9	N/A
Martinez-Silván (2017)[100] 1 season	Academy Qatar	5	14-18 yr.	Middle- distance	Medical attention	Medical	22	Individual	13.8	N/A
Rejeb (2017)[104] 5 years	Academy Qatar	Unclear	12-18 yr.	Track & field (mixed)	Medical attention	Medical	Unclear	Estimated	~6	N/A
von Rosen (2017)[102] 1 year	Elite Sweden	18	16-19 yr.	Endurance (800m-10km)	Health problem (OSTRC-O)	Athlete	26	Individual	4.6	All: 39% Subst.: 23%
Carragher (2019)[101] 1 season	National level Ireland	37	16-19 yr.	Track & field (mixed)	Health problem (OSTRC-H)	Athlete	64	None	N/A	All: 20% Subst.: 9%

Subst.: Substantial injuries. OSTRC-O: Oslo Sports Trauma Research Center Overuse Injury Questionnaire. OSTRC-H: Oslo Sports Trauma Research Center Questionnaire on Health Problems.

Severity and burden

In terms of injury severity, Jacobsson et al.[103] found that 23% of injuries lasted less than 7 days, which was lower than the 53% reported by Carragher et al.[101] These differences can most likely be attributed to the different injury definitions, as a broad definition will capture more problems of lower severity. The proportion of moderate injuries was similar between the two studies: 29% (lasting 8 to 21 days) in Jacobsson et al.[103] and 33% (lasting 8 to 28 days) in Carragher et al.[101] Severe injuries accounted for the majority (47%) of injuries in the study by Jacobsson et al.[103] (>21 days), while these represented the least frequent (14%) category for Carragher et al.[101] (>28 days). It is difficult to base any conclusions on these two studies, which only covered one year, applied different surveillance approaches and used different severity classifications; we aimed to provide a better understanding of the severity and impact of injuries in *Paper II*.

Onset, location and type

Overuse or gradual onset injuries were common in this population, accounting for 49% of all injuries across events in Jacobsson et al.,[103] 48% in Martinez-Silván et al.[100] and 58% in Carragher et al.[101] The greater proportion of these injuries compared to football likely reflects differences in training and competition demands; however, it may also be the result of applying broader definitions and athlete reported recording systems.

As most athletics events are based on running, jumping or generating force through the lower limbs, it is not surprising that the lower extremity accounted for the greatest proportion of injuries (median 78%, 77 to 87), followed by the trunk (12%, 6 to 13) and upper extremities (11%, 6 to 11%). In terms of body parts, Jacobsson et al.[103] reported 60% of injuries to the thigh/hip/groin, 32% to the knee/lower leg and 18% to the Achilles/ankle/foot, while Carragher et al.[101] reported the thigh as the most common (25%), followed by the knee (16%) and lower leg (14%). Similarly, Fourchet et al.[105] reported the foot/ankle/lower leg as the most common location (38%), followed by the hip/pelvis/lumbar spine (30%) and thigh (14%). The same argument as presented for football applies here, where inconsistent categories limit comparisons (e.g. the pelvis/hip/groin area could be considered as the lower limbs or trunk) and no detail is provided on the injury types within each location. This is an area we address in *Paper II*.

Inconsistent categories also made comparisons of injury types difficult. In the study by Jacobsson et al.,[103] almost all injuries were categorised as either muscle strain/ligament sprain (49%) or inflammation/pain (47%). A large proportion of muscle injuries was also observed by Carragher et al.,[101] where 47% were muscle cramps and 13% muscle strains. Conditions concerning tendons were the second most common, accounting for 19%, while other bone injuries and ligament sprains both accounted for 8%. While these findings suggest muscle injuries as the most common, we have no indication of which injury types have the greatest impact and where these are located. Again, this is a gap in the literature we address in *Paper II*.

Injury patterns for event groups

With different movement patterns, training demands and competition formats, it is logical to assume that injury patterns may differ between event groups. This has, for example, been demonstrated in high school athletes[106] and in competitions.[107] In Swedish youth, Jacobsson et al.[103] observed the greatest cumulative season prevalence for throwers (73%), followed by jumpers (69%), sprinters (59%), middle/long distance runners (58%) and combined event athletes (50%). Similarly, Carragher et al.[101] reported a greater proportion for explosive events (89%) than for endurance events (63%) in Irish youth. The weekly prevalence was, however, greater in endurance athletes (22% with any and 14% with substantial injuries) compared to those participating in explosive events (17% with any and 6% with substantial injuries). In Swedish youth, von Rosen et al.[102] reported an even higher weekly prevalence for distance runners: 39% for all injuries and 23% for substantial problems. Overall, these findings suggest that while athletes in explosive events sustain more new injuries, endurance athletes may be suffering from more long-standing problems and train or compete with pain more often. This could also be supported by the greater proportion of overuse injuries observed by Carragher et al.[101] for endurance athletes (68%) compared to explosive events (51%) and by Martinez-Silván et al.[100] for middle-distance runners (76%) compared to the athletics group overall (48%). The latter study is also the only one where injury burden could be calculated (for middle-distance runners only), equating to 22.6 days lost per 1000 h.

The level of detail provided in the included studies for injury location and types is limited. von Rosen et al.[102] found that distance runners sustained 31% of injuries to the foot, followed by the lower leg and knee (both 19%). Carragher et al.[101] reported patterns for injury location and type, but with a broad distinction of endurance and explosive athletes. Here, endurance athletes sustained the majority of injuries to the knee (28%), followed by the lower leg and foot (both 24%). Tendon-related injuries were the most common (40%), followed by muscle strains and cramps (36%). The most common acute diagnosis was lower leg strain/tear, and the most common overuse diagnosis was knee tendinopathy. For explosive athletes, thigh injuries (33%) were the most common, with the knee, lower leg and hip/groin each accounting for 8%. Muscle strains and cramps made up three quarters of all injuries (74%), followed by ligament sprains (10%). The most common acute injury was trunk muscle cramp/spasm, and the most common overuse condition was hamstring muscle cramp/spasm. The limited knowledge about the most burdensome location-specific injury types for different event groups makes it difficult for practitioners to base their prevention programmes on scientific evidence. This is something we aimed to provide in *Paper II*.

Growth, maturation and injury risk

When the extent of the injury problem has been established, step two of the research process involves the identification of injury risk factors. It is a common saying that we should not treat young athletes as mini-adults, based on an underlying assumption that certain characteristics and traits differ in adolescents compared to seniors and are important to take into consideration in daily practice. Inconsistent and interchangeable use of terminology has, however, created confusion and difficulties when summarising and disseminating research. Two of the three main concepts described by Malina, Bouchard & Bar-Or;[108] *growth* and *maturation*, will therefore be described in detail in this section, creating a framework for understanding the complex transition from a child to an adult and how this may relate to sports injuries. The third concept, *development*, will not be explored in depth in this thesis, but has a broader use relating to either the biological processes leading to functional organs and tissues or to the development of behaviour and functional motor skills.[108]

Growth – changes in physical dimensions

Growth is defined as a change in the size of the whole body or a body part.[108] In other words, growth is used to describe changes in physical dimensions, such as height (stature), body mass (weight), limb lengths, circumferences, skinfold thickness or derivatives like body mass index (BMI) or percentage of body fat. Interpreting growth is common practice in clinical and research settings, where the growth status for an individual or a group can be tracked and compared to reference values from larger samples, usually for height and weight.[108-110] Growth charts (visual representations of reference data) are used to identify abnormal growth and also provide a picture of normal growth progression.[108,109] These can be presented as absolute attainment or growth velocity as a function of age, where growth velocity (growth rate) is typically calculated as the absolute change per year (Figure 1).[108,109]

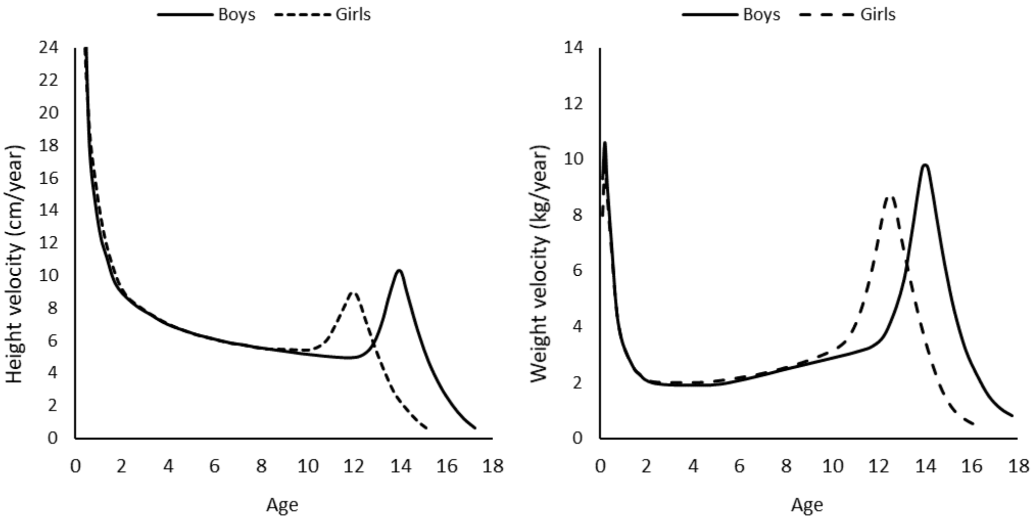

Figure 1. Growth velocities for the 50th centile for height (left) and weight (right). Adapted by permission from BMJ Publishing Group Limited. Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children, 1965. Part I. Tanner JM, Whitehouse RH, Takaishi M. Archives of disease in childhood. 1966;41(219):454-471.[111]

Looking at the growth velocity curve for height, it is clear this is not a linear process. High growth velocities are seen in the first years of life, before stabilising in the childhood years.[108] During adolescence, growth rates again accelerate, a phenomenon known as the "adolescent growth spurt".[108] Mean values from longitudinal studies indicate that initiation of the growth spurt ("take-off") occurs around the age of 8 to 10 years in girls and somewhat later in boys, at 10 to 12 years of age.[108] The point of maximal adolescent growth, peak height velocity (PHV), is observed around the age of 11 to 12 years in girls and 13 to 14 years in boys, with mean growth rates around 7 to 9 cm/year and 8 to 10 cm/year in girls and boys, respectively.[108] Following PHV, growth decelerates before adult height is attained around the age of 16 years in girls and 18 years in boys, although individuals may not reach their final height until their early 20s.[108] Ethnicity and socioeconomic status of the sample should be taken into account when interpreting growth studies.[110]

Both the timing and intensity of the adolescent growth spurt varies greatly between individuals, exemplified by Malina et al.[108] using data from Swiss[112] and British[113] children. Within these samples, the range in age at take-off was 6.6 to 12.9 years in girls and 7.8 to 13.5 years in boys. Age at PHV (APHV) occurred from 9.3 to 15.0 years in girls and 11.9 to 16.2 years in boys, with maximal growth rates of 5.0 to 10.1 cm/year in girls and 5.6 to 12.4 cm/year in boys. This highlights that while girls on average experience their growth spurt at an earlier age and boys on average have a more intense growth spurt, there is considerable variation and overlap at the individual level. It is also worth noting that variations are seen between body segments within the same individual, with the growth spurt of the lower extremities typically preceding the growth spurt of the trunk and upper extremities.[108]

While growth in height ceases in adults, body mass can change throughout life. Still, a point of maximal weight gain is observed during adolescence: peak weight velocity (PWV). Mean ages at PWV are reported around 12 to 13 years (0.3 to 0.9 years after PHV) for girls and 14 to 15 years (0.2 to 0.4 years after PHV) for boys, with mean weight velocities from approximately 7 to 9 kg/year in girls and 9 to 10 kg/year in boys.[108] Again, individual variations can be expected with standard deviations for age at PWV ranging from 0.7 to 1.6 years for girls and 0.9 to 1.5 years in boys and standard deviations in weight velocity from 1.2 to 2.4 kg in girls and 1.9 to 2.3 kg in boys.[108] The sources of weight gain also differs between genders, with boys gaining more mass from skeletal growth and muscle, and girls proportionally more from fat mass.[108] Change in BMI differs from the growth and weight curves and is characterised by a low point around the age of 5 of 6 years, followed by a relatively linear increase through adolescence.[108]

Measuring growth rates and estimating PHV

Studies assessing growth rates and the growth spurt in athletic populations use two main approaches: 1) directly measuring growth rates or 2) estimating the period of PHV. Both approaches rely on anthropometry: techniques for measuring body dimensions including, but not limited to, measures of lengths, breadths, girths, body mass and skinfold thickness.[108,114] Measurement protocols should be standardised to reduce random and systematic error related to the measurement itself and natural biological variation (e.g. diurnal variation, nutritional status, physical activity).[108,115] Measurement error is unavoidable, but can be minimised by following internationally accepted protocols (e.g. those outlined by ISAK: International Society for the Advancement of Kinanthropometry[114]), regularly calibrating measurement instruments, training assessors adequately, using a small number of assessors, ensuring data quality routines are in place and taking every measure twice (a third measure is recommended if the difference exceeds a set threshold).[108,110,114,115] To calculate growth rates, an anthropometric measure is recorded on two separate occasions, dividing the absolute difference by the time elapsed (typically expressed per year, e.g. cm/year). This is the approach we selected for the risk factor analyses in *Papers IV* and *V*. Although this is straightforward in theory, variability in growth measures and the potential for negative values complicate interpretations in practice.[109]

An alternative approach to identify periods of rapid growth is to estimate the period around PHV. Identifying this period requires repeated longitudinal measures throughout the growth process,[116] which has limited utility if practitioners want to be ahead of potential problems associated with it. Equations aiming to predict the PHV period with a one-off measure have therefore gained traction in sports settings.[117,118] One of the most common equations was published by Mirwald et al.,[119] based on a Canadian sample from the Saskatchewan Pediatric Bone Mineral Accrual Study.[120] The basis of this equation is the relationship between leg length and sitting height around the years of PHV, with gender-specific equations developed to predict "maturity offset" (the number of years from PHV) using only measures of the athlete's current age, leg length, sitting height, body mass and height.[119] These equations have subsequently been modified,[121,122] yet significant limitations regarding validity have been highlighted, making them less useful for researchers and practitioners. While attractive due to its non-invasive nature and time-efficiency, predicted APHV appears accurate only in average maturing boys ±1 year from observed PHV[123] and the equations are neither considered accurate for individuals nor stable over time.[124] For these reasons, we did not apply these methods when examining growth and maturation as a risk factors in *Papers IV* and *V*.

Biological maturation – progressing towards a mature state

Maturation is closely related to growth but is a more complex concept, defined as the progress toward the mature state.[108] This implies a definite end point (a functional and developed biological system), such as a fully ossified skeleton (skeletal maturity), full reproductive capability (sexual maturity) or the attainment of final adult height (somatic maturity).[108] The level of maturation at a given point, maturity status, therefore varies depending on the biological system and maturity indicator.[125]

Similar to growth, maturation is not a linear process and individuals differ in terms of maturity status, maturity timing (when maturational events occur) and maturity tempo (rate of maturational progression).[108] Depending on the maturity indicator, reported mean or median ages for onset of puberty range from 8.8 to 12.1 years in girls and 9.2 to 13.4 years in boys.[108] Maturational events occur around two years earlier in girls compared to boys when using similar indicators,[125] with ethnicity also playing a role.[13] Interquartile ranges for pubertal onset were around 1 year in the American Third National Health and Nutrition Examination Study[126] while around 3 to 4 years separated the 10th to 90th percentile in a longitudinal study of Dutch youth,[127] highlighting large inter-individual differences similar to those discussed for age at PHV.[108] Two individuals of the same chronological age may therefore differ considerably in biological age - maturing earlier or later, faster or slower, and with different combinations of these (Figure 2).[128] This has implications for sports where training and competition groups are based on chronological age, especially during early- and mid-adolescence in events where size and strength are central for performance.[129]

The level of maturation also differs within an individual, who can be at different stages of maturation depending on the biological system and indicator used. Kozieł & Malina[123] use examples from the Zurich longitudinal study[130,131] and Wroclaw Growth Study,[132] where individuals at the time of PHV (somatic maturation) were at very different stages of sexual and skeletal maturation. Differences can also be found within the same biological system, as can be seen in the skeletal system where a rough distal to proximal maturation pattern is observed.[133]

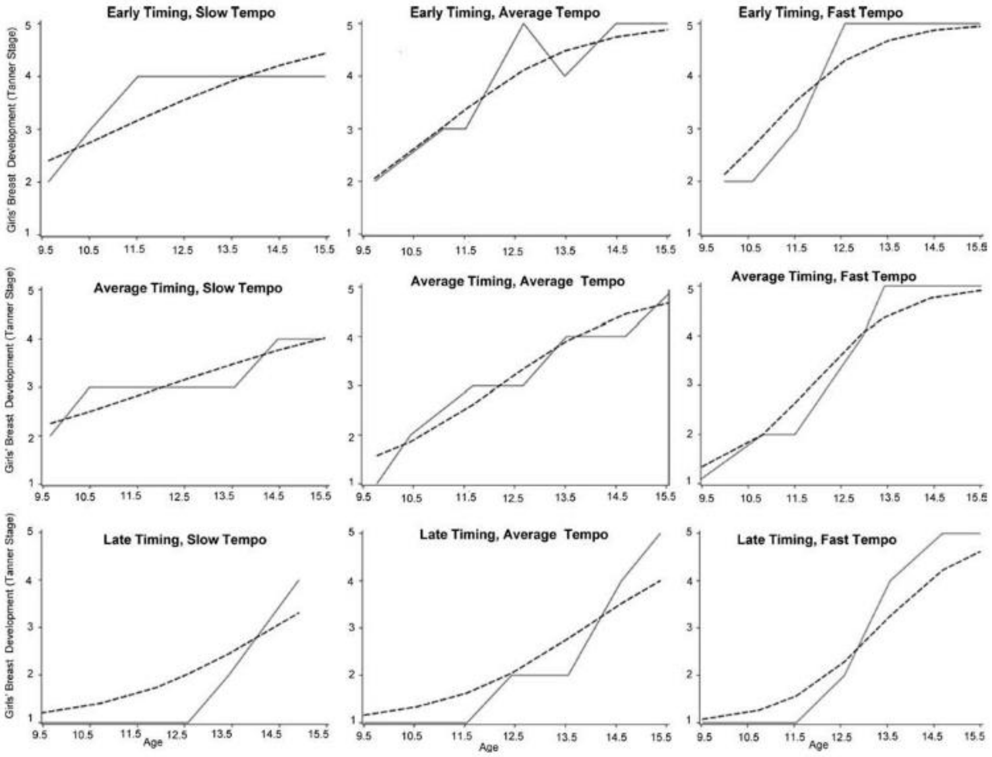

Figure 2. Observed and predicted pubertal development (girls' breast development) demonstrating combinations of early, average and late timing, slow, average and fast tempo. Each figure represents one individual, with the observed pubertal stage in grey (solid line) and the fitted curve in black (dashed line). Copyright © 2011 by American Psychological Association. Reproduced with permission. Marceau K, Ram N, Houts RM, Grimm KJ, Susman EJ. Individual differences in boys' and girls' timing and tempo of puberty: modeling development with nonlinear growth models. Dev Psychol. 2011;47(5):1389-1409.[128]

Assessing maturation

Assessing maturation can be challenging, since different biological systems require different indicators. Although difficult in practice, Beunen et al.[125] explain that a reliable and valid indicator of maturity has to: 1) reflect the maturation of a biological system, 2) occur and reach the same endpoint in all individuals, 3) ideally be independent of growth and 4) ideally be applicable throughout the process of maturation. In sporting contexts, the skeletal, sexual and somatic systems have received the most attention.

Skeletal maturation is considered the single best maturity indicator, as the start (skeleton of cartilage) and endpoints (skeleton of mature bone) are known and can be followed throughout the maturation process with precise and reliable estimates.[108,125] The most common methods use a single x-ray of the hand-wrist complex, as it typically resembles the maturity of the whole skeleton.[108] The level of ossification, shape of bones and union of epiphyses (growth plates) follow a regular order and by comparing the image to criteria from reference samples a skeletal age (bone age) can be estimated.[108,134] Three main methods are used:[108,134] Greulich-Pyle (GP),[135] Fels[136] and Tanner-Whitehouse (TW 1-3).[137-139] The GP and Fels methods are both based on white American boys and girls from Ohio (USA), while the TW1-2 methods are based on British children.[108] In the TW3 method, a broader sample is used to account for ethnic variation, including British, Belgian, Italian, Spanish, Argentinian, Japanese and American children.[108] Although considered the best maturity indicator, limitations with skeletal age assessment include exposure to low-level radiation, the need for specialised equipment and trained technicians and discretisation of a continuous process.[125,134] This makes skeletal age a challenging and costly approach for most practices; however, in our context this was in place as part of the annual medical screening. This allowed us to use the arguably best indicator for our risk factor studies (*Papers IV* and *V*) and to extend on the literature (that has mainly used somatic prediction equations) with a more valid and reliable measure.

Sexual maturation is based on the reproductive system with puberty representing the transition from child to adult.[108] Assessment of sexual maturation is based on secondary sex characteristics, such as pubic hair in both genders, breast development and menarcheal status in girls and genital development in boys.[108,125] The five-point scales provided by Tanner et al.[140] are often used, with stage 1 indicating the prepubertal state, stage 2 the onset of puberty and stage 5 the mature state.[108] While these are best examined directly by a trained clinician, self-assessment has also been used with a tendency for overestimation of early stages and underestimation of later stages.[108,141] Although secondary sex characteristics are relatively easy to use and are related to hormonal processes, they are limited by their invasive nature, exclusive applicability to puberty and somewhat arbitrary discrete categories which limit the ability to pinpoint the exact age of transition between pubertal stages.[108,125] These considerations excluded sexual maturity as a potential maturity indicator in our studies.

In most practical and scientific sport settings, assessment of skeletal age or secondary sex characteristics are not considered feasible options.[117] Assessment of somatic maturation is therefore common, representing a non-invasive and cost-efficient alternative.[117] This can be done using anthropometric equations, by predicting the age at PHV (e.g. using the Mirwald equation described earlier) as a measure of maturity timing or by predicting adult height.[125] The latter is often calculated using the Khamis-Roche method,[142] based on reference data from American children in the Fels Longitudinal Study.[143] In addition to the athlete's current weight and height, midparent height (average height of the two parents) is added to predict adult height at a given chronological age (reference values for adult height were measured at 18 years). The percentage of predicted adult height is a measure of maturity status, which again can be used to classify athletes into maturity groups.[144] The equation can also be used to estimate the time around PHV which is typically observed around 91-92% of adult height and occurs in most athletes between 88-96%, which also seems to represent the year before and after PHV.[118,144] While simple, this approach depends on accurate anthropometric measures and some error must be expected in the prediction of adult height (1-3% depending on the age and growth percentile).[117,144] The distinction between the growth and maturity processes may also not be as clear when basing indicators on anthropometric measures. Considering our ability to assess skeletal maturity, an arguably superior option, we did not include measures derived from somatic prediction equations in *Papers IV* or *V*.

Theoretical link between growth, maturation and injuries

In the previous section, the concepts of growth and maturation were presented, and it was clear that children enter puberty, mature, and experience periods of rapid increases in height and weight at different chronological ages and with different tempo. This has implications for injury risk, and researchers often highlight the presence of immature structures, the impact of rapid growth, and mismatches in maturity status between athletes when discussing injuries in youth athletes.

Immature structures

Certain structures and tissues are highlighted as especially vulnerable in immature athletes. The mechanical properties of joint surfaces and cartilage change with maturity,[13,95,145] while the developing brain is more susceptible to injury and requires longer time for recovery following concussions.[95,145] It is, however, the immature skeletal system that has received the greatest attention in terms of sports injuries. The epiphyseal growth plates, a unique feature of immature athletes, are weaker than mature bone and are especially vulnerable to shearing and tensile forces.[95,146] Given their role in longitudinal growth and shaping the skeleton, there is concern that injuries to the growth plates lead to alterations in growth.[7] Epiphyseal growth plate fractures may lead to growth interruptions and while fractures involving joint surfaces (Salter-Harris type III and IV) represent the greatest risk of complications,[95] type I and II fractures may also lead to alterations if circulation to the growth plate is compromised.[146] Cases of extreme repetitive loading have also been associated with temporary and chronic stress-related injuries and widening of the growth plates.[146] This has especially been a worry in the radial epiphysis of young gymnasts following high compression loads from weightbearing through the hand and wrist, but is also seen in other sports, such as baseball and long distance running.[146] These injuries should be taken seriously as they in some cases can lead to deformities and premature closure of the growth plate.[146]

Several conditions related to the primary and secondary ossification centres (osteochondroses) are seen in young athletes. This group of disorders includes Sever's disease and Osgood-Schlatter disease, in addition to diagnoses that receive less attention in epidemiological studies of athletic populations, such as Scheuermann's lesion (spine), Kohler's lesion (navicular) and Perthes' disease (femoral head).[95,147] Irritations to the insertion points for the muscle-tendon complex (apophyses) are common as they are associated with cartilaginous secondary ossification centres and represent a relatively weak link in the movement chain prior to maturation.[95] The apophyses may be particularly vulnerable to repetitive traction and compression forces,[95,148] although the underlying mechanisms are not well understood. In addition to the aforementioned Sever's disease and Osgood-Schlatter disease, common locations include the anterior inferior iliac spine (AIIS apophysitis), anterior superior iliac spine (ASIS apophysitis), ischial tuberosity (ischium apophysitis), pubic bone (pubic apophysitis) and the medial epicondyle (humerus) of the elbow ("Little League elbow").[95,147,149,150]

Rapid growth

Rapid growth has in itself been proposed as an underlying mechanism for injuries. In a biomechanical review, Hawkins & Metheny[151] suggest that longer and heavier limbs with growth increase moments of inertia and require larger forces to complete the same movement tasks. If the relative adaptation to these new requirements is faster in muscle tissue compared to tendons and apophyses, this will lead to greater stress on the muscle attachment sites. As mentioned above, the apophyses are already considered vulnerable structures during growth and are at their thickest and most fragile during the growth spurt.[95] Furthermore, they hypothesise that rapid lengthening increases "preload", a stretched position of the muscle-tendon unit leading to chronic increases in force through tendons and apophyses. This may be related to flexibility, although the association with injuries is unclear.[13,95,145,151] Rapid longitudinal skeletal growth has also been associated with a temporary decrease in bone mineral density and a period of relative skeletal weakness, which again has been linked to a greater incidence of fractures.[152,153] Finally, large changes in height and weight over short periods of time may lead to "adolescent awkwardness",[154] a period of reduced neuromuscular control that may be associated with increased lower extremity injury risk.[145,155]

Variation within chronological age groups

With the large variations in maturity status between individuals, mismatches in sports where training and competitions are based on chronological age have been a concern, especially in contact and collision sports, for later maturing and physically smaller athletes.[13,95,144] Inappropriate training load in groups of athletes with mixed maturity and developmental status is another related worry.[13] Grouping athletes based on their maturity status or size (bio-banding) has therefore been promoted.[144] Although this may counteract the potentially harmful differences between late and early maturing athletes, the effect on injury risk remains unclear and considerations should also be given to tactical, technical, psychological and social aspects.[144,156,157]

Growth, maturation and injury risk in elite youth athletes

To understand the existing literature on growth, maturation and injury risk in elite youth sports, a systematic literature search was performed in the PubMed database (Table 7); 21 studies were included and are summarised in Table 8. The samples in the included studies were heterogenous in terms of sports, with football (soccer) as the most common (n=13, 62%). The vast majority of studies only included boys (n=17, 81%) and covered a broad chronological age range using a variation of growth and maturity indicators. The concepts introduced above will be used as a framework to discuss the findings, broadly separating studies examining growth (growth rates or the period around PHV) or maturation (absolute or relative).

Table 7. Search strategy for the literature review on growth, maturation and injury risk in elite youth athletes.

Inclusion criteria	Exclusion criteria
✓ Adolescents (10-19 years, U11-U20) ✓ High-level, elite or academy athletes ✓ Prospective data collection ✓ Quantitative measure of growth and/or maturation ✓ Injury as outcome ✓ Association between growth/maturation and injury or comparison of injured/non-injured athletes ✓ Full article available in peer-reviewed journal ✓ English language	✓ Children, senior or college players ✓ Middle school or high school students, performance arts or general population ✓ Cross-sectional, retrospective or case-series ✓ Chronological age only ✓ Only illness as outcome ✓ No examination of association between growth/maturation and injury outcome ✓ Abstract, conference paper, review, editorial, letter, or chapter ✓ Non-English language
Domain (combined with AND)	**Keywords (combined with OR within each domain)**
Age	adolescent*, young, youth, child*
Sport	sport*, athletic*
Exposure	growth, maturation, maturity, bone age, skeletal age, body size, peak height velocity, Tanner stage, Tanner staging, puberty*
Outcome	injur* OR pain
Initial search results (PubMed 01.11.2020): 3562	
Studies included after screening titles, abstracts and reference lists: 21	

Growth rate and injury

Associations between growth rate and injuries were examined in three studies. Kemper et al.[63] reported that Dutch football players with a monthly change in height ≥0.6 cm or change in BMI ≥0.3 kg/m² were at greater risk of medical-attention injuries. A near significant association (p=0.06) was also observed for decreases in BMI ≥0.4 kg/m² per month. In Belgium, Rommers et al.[79] found that younger football players (U10-12) with a greater change in leg length from the start to the end of a season had a higher risk of overuse medical-attention injuries. In contrast, a lower change in height was related to a greater risk of acute medical-attention injuries in older players (U13-15). In a sample of Austrian alpine skiers, Steidl-Müller et al.[158] reported that greater changes in height and leg length over a season were significant risk factors for sustaining a time-loss injury (in a binary logistic regression model); however, no significant differences were observed when values for injured and non-injured athletes were compared (using independent t-tests). While providing an indication that growth rates may be related to injuries, these studies are limited in number and by using very broad injury categories as their outcome. We therefore aimed to examine growth rates with more specific injury outcomes, for which there may be a stronger theoretical rationale, in *Papers IV* and *V*.

Table 8. Studies with prospective data collection over minimum one season or year, examining the relationship between growth, maturation and injury risk in elite youth sports.

1st author (year)	Sample	Growth/maturity indicator	Injury outcome	Main findings
Le Gall (2007)[71] Football, 10 seasons	233 boys (U14) National institute France	Skeletal maturation (Greulich-Pyle) Early/Normal/Late Normal: SA ±1 yr. of CA	Time loss (>48h) 588 injuries	No difference in overall, training or match incidence between groups. Greater incidence of major injuries and lower incidence of tendinopathies in late maturing players. Greater incidence of reinjuries and groin strains and lower incidence of osteochondral disorders in early maturing players.
Johnson (2009)[90] Football, 6 years	282 boys (9-16 yr.) Academy England	Skeletal maturation (Fels) Early/Normal/Late Normal: SA ±1 yr. of CA	Unclear 476 injuries	No difference in incidence between groups when accounting for mean playing time, mean playing time, mean height and position played.
Fourchet (2011)[105] Athletics, 3 years	110 boys (13-18 yr.) Academy Qatar	Somatic maturation (Mirwald) Early/Normal/Late Normal: APHV ±1 yr. of sample mean	Time loss Foot/ankle/lower leg 74 injuries	Greater incidence of foot/ankle/lower leg injuries in late maturing athletes.
*van der Sluis (2014)[92] Football, 4 seasons	26 boys (11.9 yr. at start) Academy Netherlands	Peak height velocity (Mirwald) pre-PHV/PHV/post-PHV Year of PHV: APHV ±6 mo.	Medical attention 178 injuries	Greater incidence of traumatic injuries in the year of PHV vs. pre-PHV. No difference in overuse injuries, missed days or training/match incidence.
Kemper (2015)[63] Football, 1 season	101 boys (U12-19) Academy Netherlands	Growth rate (Anthropometry) Height, body mass index Monthly	Medical attention (>1d) 134 injuries	Higher injury risk for players with a monthly change in height ≥0.6 cm or a monthly change in BMI ≥0.3 kg/m^2.
*van der Sluis (2015)[159] Football, 4 seasons	26 boys (11.9 yr. at start) Academy Netherlands	Somatic maturation (Mirwald) Earlier/Later Median split based on APHV Peak height velocity (Mirwald) pre-PHV/PHV/post-PHV Year of PHV: APHV ±6 mo.	Medical attention 178 injuries	Greater incidence of overuse injuries pre- and circa-PHV for later maturing players. No difference between groups for traumatic injuries.
*Müller (2017a)[160] Alpine skiing, 2 seasons	51 boys, 31 girls (9-14 yr.) Elite level Austria	Somatic maturation (Mirwald) Early/Normal/Late Normal: APHV ±1 SD of sample mean	Time loss 69 injuries	No difference in traumatic or overuse injuries between groups.
*Müller (2017b)[161] Alpine skiing, 2 seasons	51 boys, 31 girls (9-14 yr.) Elite level Austria	Somatic maturation (Mirwald) Early/Normal/Late Normal: APHV ±1 SD of sample mean	Time loss 69 injuries	APHV was not a predictive risk factor. Lower injury severity with lower APHV (earlier maturing).

*Sample represented in multiple studies. SA: Skeletal age. CA: Chronological age. APHV: Age at PHV. PHV: Peak height velocity. BMI: Body mass index.

1st author (year)	Sample	Growth/maturity indicator	Injury outcome	Main findings
Bult (2018)[76] Football, 3 seasons	170 boys (U12-19) Professional club Netherlands	Peak height velocity (Mirwald) 6 PHV periods of 3 mo. each	Time loss 620 injuries	Greater incidence and burden 0-6 months post-PHV compared to the overall incidence and burden. Lower incidence >12 months pre-PHV and lower burden >6 months pre-PHV compared to the overall incidence and burden.
*Read (2018)[162] Football, 1 season	356 boys (U11-18) 6 Academies England	Somatic maturation (Mirwald) Maturity offset	Time loss (>48h) Non-contact lower limb Unclear number	Maturity offset was a risk factor for U13/14 players and injured players were further from APHV. Maturity offset was not a risk factor for U11/12, U15/16 or U18 players.
Horobeanu (2019)[163] Squash, 6 years	21 boys (U13-19) Academy Qatar	Skeletal maturation (Fels): Early/Normal/Late Normal: SA ±1 yr. of CA Peak height velocity (Mirwald) pre-PHV/PHV/post-PHV Year of PHV: APHV ±1yr	Medical attention 212 injuries	No significant differences reported between groups.
Monaco (2019)[164] Handball, 2 seasons	133 boys (U14-18) Academy Spain	Sexual maturation (Testicular volume) Mature/Immature Mature: ≥15 cm^3	Time loss 142 injuries	No difference in overall incidence between mature/immature players. Greater incidence of apophysitis in immature players.
Rejeb (2019)[165] Multiple sports, 4 seasons	67 boys (11-18 yr.) Academy Qatar	Skeletal maturation (Fels) Mature/Early/Normal/Late Mature: SA = 18.0 yr. Normal: SA ±1 yr. of CA Somatic maturation (Mirwald) Early/Normal/Late Normal: APHV ±1 yr. of sample mean	Medical attention 212 injuries	Greater risk of injury in early vs. late maturing athletes based on skeletal age. No difference between groups based on APHV.
Johnson (2020)[83] Football, 2 seasons	76 boys (U11-16) Academy England	Peak height velocity (Khamis-Roche) pre-PHV/circa-PHV/post-PHV circa-PHV: 88-95% POAH Somatic maturation (Khamis-Roche) Early/On-time/Late On-time: Z-score ±0.5 based on POAH at measurement age vs. the Berkley longitudinal study.	Time loss Non-contact 88 injuries	Greater incidence and burden in circa-PHV vs. pre-PHV players. Greater burden in post-PHV vs. pre-PHV players. No difference between early, on-time and late groups after accounting for PHV-status.

*Sample represented in multiple studies. PHV: Peak height velocity. APHV: Age at PHV. SA: Skeletal age. CA: Chronological age. POAH: Percentage of predicted adult height.

1st author (year)	Sample	Growth/maturity indicator	Injury outcome	Main findings
Monasterio (2020)[166] Football, 21 years	63 boys (U11-19) Academy Spain	Somatic maturation (Adult height) % adult height Peak height velocity (Adult height) pre-PHV/circa-PHV/post-PHV circa-PHV: 88-96% adult height	Time loss (>7d) 509 injuries	Growth-related injuries occurred at an earlier percentage of adult height and were more frequent pre- and circa-PHV. Muscle and joint/ligament injuries occurred at a later percentage of adult height and were most frequent post-PHV.
*Oliver (2020)[167] Football, 1 season	355 boys (U11-18) 6 Professional clubs England	Somatic maturation (Mirwald) Maturity offset	First time loss (>48h) Non-contact lower limb 99 injuries	Maturity offset was not associated with injury in the univariate analysis and not a predictor in the multivariate analyses.
*Read (2020)[168] Football, 1 season	346 boys (Unclear age) 6 Professional clubs England	Somatic maturation (Mirwald) Maturity offset Peak height velocity (Mirwald) pre-PHV/circa-PHV/post-PHV circa-PHV: APHV ±0.5 yr. pre-/post-PHV: APHV -1/+1 yr.	First time loss (>48h) Non-contact lower limb 99 injuries	Maturity offset was not associated with injury in pre-, circa- or post-PHV players.
*Rommers (2020a)[79] Football, 1 season	314 boys (U10-15) 4 Professional clubs Belgium	Growth rate (Anthropometry) Height, leg length, body mass Start to end of season	Medical attention 296 injuries	Younger players (U10-12) with a greater change in leg length were at greater risk of sustaining overuse injuries. Older players (U13-15) with a smaller change in height were at greater risk of sustaining acute injuries.
*Rommers (2020b)[169] Football, 1 season	734 boys (U10-15) 7 Professional clubs Belgium	Somatic maturation (Mirwald) Maturity offset	First medical attention 368 injuries	Higher APHV (late maturing) was the most important predictor for injury. Lower APHV (early maturing) was related to overuse injuries.
Schoeb (2020)[170] Alpine skiing, 1 season	96 boys, 59 girls (12-14 yr.) High level Switzerland	Somatic maturation (Mirwald) Maturity offset	OSTRC-H (every 2 wk.) End-season interview 379 injuries	Maturity offset was related to occurrence of all acute and substantial acute injuries and severity score of acute injuries. No association between maturity offset and overuse injuries.
Steidl-Müller (2020)[158] Alpine skiing, 1 season	50 boys, 39 girls (10-14 yr.) Elite boarding school Austria	Growth rate (Anthropometry) Height, leg length, sitting height, body mass, body mass index Start to end of season Somatic maturation (Mirwald) Maturity offset	Time loss (>1d) 53 injuries	Maturity offset (closer to PHV), greater change in height and leg length were significant risk factors for injury, but there were no differences between injured and non-injured athletes.

*Sample represented in multiple studies. PHV: Peak height velocity. APHV: Age at PHV. OSTRC-H: Oslo Sports Trauma Research Center Questionnaire on Health Problems.

Peak height velocity and injury

Four studies examined the period around PHV and injury risk, three using the Mirwald equation and one the Khamis-Roche method. In Dutch footballers, van der Sluis et al.[92] compared players in the year around PHV (predicted age at PHV ±6 months) to the year pre- and post-PHV. Significantly more traumatic medical-attention injuries were recorded in the year of PHV compared to the year before PHV, with no differences between periods for overuse injuries, number of missed days, training incidence or match incidence. In another Dutch football study, Bult et al.[76] created three-month time periods relative to predicted APHV. A significantly greater time-loss incidence and burden was seen in the six-month period following PHV compared to the overall incidence and burden, in addition to a lower incidence >12 months and burden >6 months prior to PHV. Horobeanu et al.[163] did not report any significant associations between PHV periods and medical-attention injuries in their sample of squash players in Qatar. Using the Khamis-Roche method, Johnson et al.[83] grouped English academy footballers into PHV groups, defining PHV as 88-95% of predicted adult height. Both non-contact injury incidence and burden were greater in circa-PHV players compared to pre-PHV players, while burden was also greater post-PHV compared to pre-PHV. The findings from these studies suggest that the time during and following PHV represents a period of relative vulnerability; however, they did not account for chronological age as a potential confounder (older players are assumed to sustain more injuries, as explored in the section on football epidemiology) and are based on estimation equations with questionable validity[123,124] as opposed to observations of the actual PHV. Firm conclusions can therefore not be drawn.

Absolute maturity and injury

Maturity status has been examined using two main approaches: 1) based on the absolute maturity status (how far along in the maturation process the athlete is) and 2) relative maturity status (athletes maturing earlier or later than what is considered normal). The distinction between the two is not always clear and there is some overlap in the use of terms in the literature.

Studies examining absolute maturity status used skeletal, sexual and somatic maturity indicators. Monaco et al.[164] reported greater time-loss incidence of apophysitis in immature Spanish handball players (testicular volume <15 cm^3), with no differences in overall incidence between immature and mature players. In three studies on English football players, Read et al.,[162] Oliver et al.[167] and Read et al.[168] used maturity offset (years from PHV) in risk factor analyses, an approach where the effects of rapid growth and maturation cannot be clearly distinguished. In two of these,[167,168] maturity offset was not related to time-loss non-contact lower extremity injuries, while one study[162] reported that maturity offset was an injury risk factor for U13/14 players but not in other age groups. Schoeb et al.[170] used a similar approach in Swiss alpine skiers and found that maturity offset was related to athlete-reported acute injuries, but not to overuse injuries. In Austrian alpine skiers, Steidl-Müller et al.[158] reported that maturity offset was a risk factor in their binary logistic regression analysis, although values were not statistically different for injured and non-injured athletes. Using the actual adult height (measured at 18 years), Monasterio et al.[166]examined the occurrence of time-loss injuries (>7 days) in relation to the percentage of adult height in Spanish academy footballers. Players sustained growth-related injuries at a lower percentage of adult height and these were more common pre- and circa-PHV (88-96% of adult height). Muscle injuries and ligament/joint sprains (ankle and knee) were, in contrast, observed at a higher percentage of adult height and were more common post-PHV. Furthermore, growth-related diagnoses followed a distal to proximal pattern, with Sever's disease appearing earlier in the somatic maturation process (median % of adult height: 85.6%) than Osgood-Schlatter disease (88.5%) and injuries to the AIIS (91.0%), ischial tuberosity (91.2%) and ASIS (98.1%). The inconsistent findings in this area could reflect difficulties in accounting for the many potentially confounding variables that are present in the complex maturation process, compounded by variations in maturity indicators and different injury outcomes. In *Papers IV* and *V,* we address some of these issues to better understand the relationship between absolute maturity status and risk of specific injury types.

Relative maturity and injury

The most common question asked in the literature is whether early, normal or late maturing athletes are at greater risk of injury. Four studies addressed this using skeletal age and defined normal maturing athletes as those with a skeletal age within one year of chronological age.[71,90,163,165] Only the study by Rejeb et al.,[165] in a multisport sample in Qatar, reported significant differences in overall incidence, with a greater risk of medical-attention injuries in early vs. late maturing athletes. The study by Le Gall et al.[71] in French football players did, however, find differences in time-loss injury incidence at the level of injury type. Earlier maturing players had a greater incidence of reinjuries and groin strains and a lower incidence of osteochondral injuries, while late maturing athletes had a greater incidence of major injuries (>28 days lost) and lower incidence of tendinopathies. These players were all in the same age group (U14) and the findings can therefore also be seen in relation to absolute maturity status. This again would indicate that maturation primarily has an effect on specific injury types, with less clear implications for overall injury risk.

In six studies, somatic prediction equations were used to classify athletes, with conflicting findings. Late maturing athletes (APHV 1 year delayed of the sample mean) were at greater risk of time-loss foot/lower leg/ankle injury in an athletics study from Qatar by Fourchet et al.[105] Later maturing Dutch football players (below the median APHV in the sample) were also at greater risk of medical-attention overuse injuries in a study by van der Sluis et al.,[159] although only in the pre- and circa-PHV periods and without differences in traumatic injury incidence. Rommers et al.[169] reported that that higher APHV (later maturing) was the most important predictor for medical-attention injuries, although lower APHV (earlier maturing) was related to overuse injuries. In English academy football, Johnson et al.[83] did not find differences between maturity groups (early, on-time or late) when adjusting for PHV period (pre-, circa- or post-PHV). Two publications on alpine skiers by Müller et al.,[160,161] reported that APHV was not a predictive risk factor for time-loss injury and no differences were observed between maturity groups for traumatic or overuse injuries. The severity of injuries was, however, lower with younger APHV (earlier maturing). As mentioned earlier, the use of anthropometric equations does not clearly distinguish the effects of maturation from rapid growth, which makes interpretations challenging. The bias towards selection of early maturing athletes represents an additional problem in youth academy settings,[171] and it is difficult to include a large enough number of athletes in the late maturing category. For this reason, we focused on maturity in absolute terms in *Papers IV* and *V*.

Aims of the thesis

The overall aim of this thesis was to identify the most common and burdensome injuries in youth academy athletes and examine growth and maturation as injury risk factors. To achieve this, three main areas were targeted. First, methodological aspects relating to injury surveillance in a youth academy setting were addressed (*Paper I*). Second, the main injury problems were identified for academy football players and athletics athletes (*Papers II* and *III*). Finally, growth and maturation were examined as potential injury risk factors for adolescent athletes participating in elite football and athletics programmes (*Papers IV* and *V*).

The specific aims for each paper included in the thesis were:

1. To examine the effect on time-loss and non-time-loss incidence in a youth injury surveillance programme when medical staff recorders are more or less invested in the process (*Paper I*).

2. To describe the most common and burdensome injuries in elite male youth athletics, with a special focus on event group differences (*Paper II*).

3. To describe the most common and burdensome injuries in elite male youth football, with a special focus on age group differences (*Paper III*).

4. To investigate growth rate and skeletal maturation as risk factors for injuries in elite male youth athletics (*Paper IV*).

5. To explore the main and combined effects of growth rate and skeletal maturation on injury risk in elite male youth football (*Paper V*).

Methods

Context and study design

The projects included in this thesis were all conducted at a single national elite sports academy: Aspire Academy in Doha, Qatar. The academy aim is to develop future sports champions that can compete for Qatar at the international level and to promote a healthy, active lifestyle within the country.[172] The academy is a boarding school for full-time student athletes who alongside their training complete an internationally recognised educational curriculum, while part-time athletes attend different local schools and participate in after-school sessions at the academy. The sports programme is broadly structured in two: football and Olympic sports (athletics, fencing, squash, table tennis and other federation sports). Medical staff at the Aspire Academy Sports Medicine Center are employed and managed by Aspetar Orthopaedic and Sports Medicine Hospital, the provider of medical services for clubs and federations in Qatar. Medical staff members include full-time sports physicians, sports physiotherapists, massage therapists and nurses. Furthermore, the academy provides each squad with full-time technical coaches, physiologists, strength & conditioning coaches in addition to other support staff (e.g. analysts and recovery specialists).

Routine monitoring of full-time and part-time athletes is an integral part of the academy's strategy to constantly provide the best clinical and sport science support to the athletes and at the same time generate high quality research. The studies in this thesis were all based on monitoring data that were primarily collected for practical and clinical use, focusing on the injury surveillance programmes and periodic assessments of growth and maturation (Figure 3). *Paper I* was a methodological study where prospectively collected injury data were audited to assess the reliability of the existing football surveillance programme. *Papers II* and *III* were descriptive epidemiology studies, based on prospectively collected injury and training data in athletics and football. *Papers IV* and *V* built on the data from the epidemiology papers while adding data on growth and maturation to examine them as potential risk factors for injury in athletics and football.

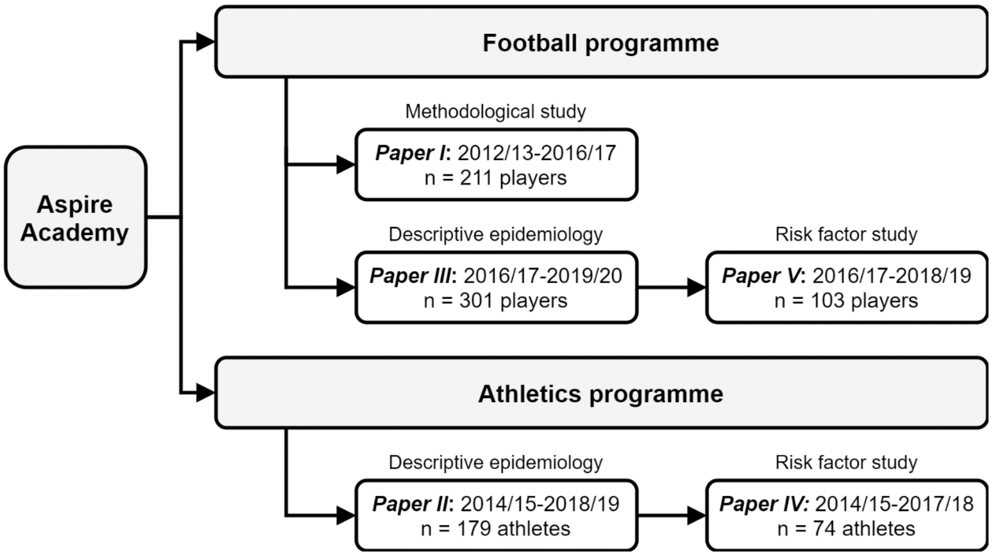

Figure 3. Overview of the academy programmes and studies included in the thesis.

Participants and ethics

Participants were male athletes enrolled in the Aspire Academy football or athletics programmes, aged 11 to 18 years. The academy season typically lasted from September through May, where full-time athletes typically participated in eight morning and/or afternoon sessions and part-time athletes in five afternoon sessions. Competitions and matches were usually held on weekends, where athletes represented their local club (football players played with their club in the national league). In addition to the normal academy activities, training camps abroad were organised, and international football teams were invited regularly to take part in mini-tournaments (two visiting teams and one Aspire team). The U16 through U18 football squads also functioned as national teams, with the same staff and players preparing for international U17 and U19 qualification and tournament campaigns (Asian Football Confederation Championships). During the summer break (June through August), players were not regularly monitored. In athletics, some athletes participated in training camps and competed during the summer; these were monitored in the same way as during the normal academy season.

Study samples

Detailed inclusion criteria for each study are described in the data management section. *Paper I* was a retrospective analysis of injury data for the U16, U17 and U18 football squads (excluding U13, U14 and U15). In total, 211 full-time or part-time players contributed to 406 player-seasons (one player for one season) from 2012/13 through 2016/17 (five seasons).

Papers II and *IV* included athletes in the general programme (non-specialised) and specialised event groups (endurance, sprints, jumps and throws). Only full-time athletes who completed a full season were included, while part-time athletes and trialists were excluded. *Paper II* included 179 athletes (391 athlete-seasons) from 2014/15 through 2018/19 (five seasons). Of these, *Paper IV* included 74 athletes (117 athlete-seasons) in the non-specialised group with complete growth and maturation data from 2014/15 through 2017/18 (four seasons).

Papers III and *V* included full-time and part-time U13 through U18 age group players. Only players that regularly attended Aspire sessions (including U17 national team players) and were monitored by the academy staff were included, while trialists and players who only participated in U19 national team sessions were excluded. Players joining or leaving the programme during the season were included but censored for the period they were not regularly monitored by academy staff. In *Paper III*, 301 players (591 player-seasons) from 2016/17 through 2019/20 (four seasons) were included. Of these, 103 players (145 player-seasons) with complete growth and maturation data from 2016/17 through 2018/19 (three seasons) were included in *Paper V*.

Ethics

Written informed consent to use routinely collected data for research purposes was obtained from the athlete's guardians. An application process was completed through the Aspire Research Committee in October 2017, confirming that the data used for this thesis were within the scope of a larger ongoing study on growth, maturation and athletic development (Appendix I). Ethics approval for this study was granted from the Anti-Doping Lab Qatar Institutional Review Board (IRB Application #E20140000012) (Appendix II).

Football injury surveillance (Papers I, III and V)

Data from the Aspire Academy Football Injury Surveillance Programme were analysed for *Papers I*, *III* and *V*. Injuries were recorded prospectively by team physiotherapists who were present at all team sessions, following the consensus procedures outlined by Fuller et al.[25] The physiotherapists updated injury records continuously in a spreadsheet database; supervised and revised on a monthly basis by a senior physiotherapist until 2018 and after that by a researcher.

A broad medical-attention injury definition was applied in *Paper I* and a recordable event was defined as *"any musculoskeletal complaint sustained by a player that resulted in a clinical examination by a member of the academy medical staff, regardless of time loss"*. As a direct consequence of the findings in *Paper I*, the injury definition was amended for *Papers III* and *V* to only include time-loss injuries, defined as *"any physical complaint leading to the medical staff partially or fully restricting participation in future team football activities"*.

Injury diagnoses were classified by the team physiotherapist using the Sports Medicine Diagnostic Coding System (SMDCS)[173] and confirmed by a physician. The date of injury, session type, contact type and specific mechanism were recorded for each injury. A player was considered injured until the date he returned to full participation in team training and was available for match selection,[25] determined by the medical staff. If a player left the academy before returning to full participation or if an injury was still ongoing at the end of a season, the treating clinician estimated the return date.[25] This was the case for 30 injuries (2.7% of all injuries) in *Paper III*.

Football exposure data were not available for *Paper I*. For *Papers III* and *V*, daily individual training and match exposure data were recorded by the team sports scientist in a spreadsheet database. The actual duration of each session was reported, in addition to information about the session type and any deviations from the main team activity by the individual player (e.g. rehabilitation session, illness or absence). Club strength & conditioning coaches reported the duration of club activities and following the completion of the data collection, individual match duration was corrected retrospectively against official federation match reports to identify missing entries and errors.

Injury data included in *Papers III* and *V* were cross-checked against the exposure database to identify missing entries and verify injury start and end dates. If a potentially missing injury or missing injury details were identified, the player's electronic medical record (Millennium Power Chart, Cerner, North Kansas City, MO, USA) was audited for additional information. Injuries occurring outside football activities were removed and exposure accumulated while a player was injured (e.g. rehabilitation or individual fitness sessions) was excluded.

Athletics injury surveillance (Papers II and IV)

Data from the Aspire Athletics Injury Surveillance Programme were analysed for *Papers II* and *IV*. Injuries were recorded by the squad physiotherapist, who was present at all squad sessions, following the consensus procedures outlined by Timpka et al.[29] Injuries were continuously updated and entered into an electronic athlete management system (Smartabase, Fusion Sport, Milton, QLD, Australia), supervised by the same senior physiotherapist for the whole observation period.

A recordable injury was defined as *"any recorded medical attention sustained during training or competition that results in an athlete being unable to participate in athletics activities, as planned by the coaching staff, for ≥1 day"*. Injuries diagnoses were classified using the SMDCS,[173] verified by a medical doctor. Classification of injury location and injury type followed the consensus recommendations for athletics (here, pelvis/sacrum is considered as part of the head/trunk),[29] with the addition of "non-specific pain" as a separate category. Tissue type was classified in five main groups, based on the SMDCS diagnosis: bone, muscle, joint/ligament, tendon and miscellaneous (other). The date of injury, session type and mode of onset were recorded by the physiotherapist. An athlete was considered fully recovered from an injury when able to complete the planned session with minimal or no limitations.

Exposure was reported for each individual athlete-season as the number of athlete exposures (AE) based on the attendance recorded by the squad coaches. This was revised and verified at the individual athlete level by the senior physiotherapist. One AE represented one attended training (TE) or competition (CE) session, where the athlete was able to complete the normal training or trained with only minimal limitations. Athletes did not accumulate AE when injured or training alternatively (e.g. combined rehabilitation/fitness sessions) with the medical staff.

Assessments of growth and maturation (Papers IV & V)

Assessments of growth and maturation followed the same procedures for athletes participating in athletics (*Paper IV*) and football (*Paper V*).

Anthropometric measurements

Anthropometric measurements were done by trained academy staff at regular intervals throughout the seasons. The data collection followed the ISAK-recommended procedures outlined by Stewart et al.[114] for standing height (stature), trunk height (sitting height) and body mass. To reduce the impact of diurnal variation, measures were taken in the morning, prior to activities.[114,115] Standing height was measured to the nearest 0.1 cm using a wall-mounted stadiometer (Holtain Limited, Crymych, UK) using the stretch stature method and the head placed in the Frankfort plane. Sitting height was measured with a stadiometer and the athlete seated on a purpose-built platform (Holtain Limited, Crymych, UK), using the same stretch stature method. Athletes were instructed not to contract the gluteal muscles or push with the legs. Leg length was calculated as the difference between height and sitting height. Body mass was measured to the nearest 0.1 kg using digital scales (Athletics: ADE Electronic Column Scales, Hamburg, Germany; Football: Adam Equipment, Milton Keynes, UK).

Test-retest reliability assessments were performed in the football group (unpublished data from measurements of 17 players), demonstrating a standard error of the measurement (SEM) of 0.34 cm (95% confidence interval (CI): 0.25 to 0.52) for standing height and 0.20 cm (0.15 to 0.30) for sitting height. This corresponded to a minimal detectable change (MDC) of approximately 1 cm for both measures. The potential for inter-rater variations was minimized by using trained staff members. For ISAK Level 2 accredited technicians, the technical error of measurement (TEM) for length measures must be below 2% compared to a criterion technician and intra-rater TEM must be below 1%.

Assessment of skeletal maturation

The assessment of skeletal maturation was performed annually using x-ray images of the athlete's left hand/wrist complex (including the distal radius and ulna), taken by the Radiology Department at Aspetar Orthopaedic and Sports Medicine Hospital. To avoid unnecessary exposure to radiation, assessments were normally not continued for athletes who had previously been classified as skeletally mature. The upper limit for a typical effective radiation dose of a hand x-ray has been reported at 0.00017 mSv;[174] this was described as "almost negligible" in the IOC consensus statement on age determination in high-level youth athletes[13] and was considered equivalent to 1 hour of background radiation in major cities in the UK.[13]

Images were interpreted by a single experienced assessor and entered into a spreadsheet database. Skeletal age in *Papers IV* and *V* was determined using the Fels method, described by Roche et al.[136] and based on a reference sample from the Fels Longitudinal Study.[108] For this method, skeletal age for a given chronological age is converted from maturity indicators including grading of shapes of carpal bones and epiphyses, and diaphyses of the radius, ulna, metacarpals and phalanges (1st, 3rd and 5th digits). Grades are assigned to each indicator by matching the image to specified criteria, and linear measurements of the epiphyseal and metaphyseal widths are used to calculate ratios that are also included in the calculation of skeletal age (the indicators included and individual contribution differ depending on chronological age).[108] The standard error for skeletal age using the Fels method has been reported as 0.27 to 0.49 for football players aged 13 to 14 years and 0.28 to 0.72 for players aged 15 to 17 years.[175] Intra-rater reliability has previously been reported with an intraclass correlation coefficient (ICC) of 0.998 (95% CI: 0.996 to 0.999).[90] In *Paper IV*, a prediction of mature height was included, based on the TW3 method.[139] This uses the athlete's current height, chronological age and TW3 maturity score (max. 1000 points/16.5 years), a score based on the stages of maturation for the radius, ulna, carpals, metacarpals and phalanges (1st, 3rd and 5th digits).[108] Unpublished reliability data from this academy demonstrated an ICC of 0.95 (0.92 to 0.97) for the TW3 RUS (radius, ulna and short bones) overall score.

Data management and statistical analyses

Paper I

The aim of *Paper I* was to explore the effect on the number of reported injuries when team recorders or supervisors in the same surveillance programme were involved in research projects relying on the collected data. With this in mind, we compared three settings: 1) the injury recorder relied on the collected data for a specific research project ("invested recorder"), 2) the injury recorder was not invested in research but was under close supervision by a senior physiotherapist who relied on the data for research purposes ("invested supervisor") or 3) injuries were recorded without the recorder nor supervisor relying on the data for specific research projects ("non-invested"). Exposure data were not available and injuries were therefore grouped by squad-month (one month for one squad) to account for differences in season duration and confounding variables with a greater level of detail. Squad-months were included based on the criteria outlined in Table 9.

Table 9. Inclusion and exclusion criteria for squad-months.

Inclusion criteria	Exclusion criteria
✓ U16, U17 or U18 squad ✓ Could confidently assign recording setting: o Invested recorder o Invested supervisor o Non-invested ✓ <1/3 of the month was in the off-season ✓ Could confidently assign month type (co-factor): o National team preparation month o Normal academy month	✓ U13, U14 or U15 squad ✓ Unclear recording setting ✓ >1/3 of the month was in the off-season ✓ Unclear month type (co-factor)

Injuries were classified as either non-time loss or time loss based on the number of days lost from training sessions and matches, as reported by the injury recorder. Time-loss injuries were further classified to severity categories: minimal (1 to 3 days), mild (4 to 7 days), moderate (8 to 28 days) or severe (>28 days).[25] The diagnosis and injury location were used to classify injuries into four body regions: head/neck, upper limb, trunk or lower limb.[25] For this study, injuries that occurred outside of football activities were included (3.6% of the total), as these could be considered more or less relevant to record by different medical staff.

Two co-factors were considered: age group and national team preparations. Age group was included as the rate of injuries differed with age in previous football academy studies (described earlier). The specific organisation of this academy, where squads functioned as national teams for certain periods, also had to be taken into account as the training environment in the months leading up to tournaments differed from the rest of the academy season. Typically, academy physiotherapists were involved and had more contact time with players during training camps; therefore, players could be thought to have more opportunities, and a lower threshold, for seeking medical attention. A national team preparation month was only added as a co-factor when the academy team physiotherapist (injury recorder) was also the national team physiotherapist for the corresponding age group.

Statistical analyses

The main outcome of the study was the number of injuries per squad-month for each injury category, relative to the number of players in the squad (player-months). Player-months were standardised to the actual number of days in each month to represent the number of injuries per player for a 31-day month. A Poisson regression model was used to explore differences in incidence between recording settings, reported with 95% CI after adjusting for co-factors. Pairwise comparisons between the estimated marginal means were conducted applying a Bonferroni post hoc correction and *P*-values <0.05 indicated significant differences.

Paper II

The aim of *Paper II* was to describe the extent of injuries in elite male youth athletics and identify the injuries with the greatest impact, overall and per event group. Athletes were classified based on their respective training group for a given season (non-specialised, endurance, sprints, jumps or throws). Injuries were classified as index (first recorded event), exacerbation (worsening in the state of an existing index injury) or recurrent (a repeat episode of a fully recovered index injury).[29] Exacerbation episodes were not included in the calculation of incidence; instead, the day loss was added to the index injury. Injury severity was based on the number of days lost: minimal (1 to 3 days), minor (4 to 7 days), moderate (8 to 28 days), serious (29 days to 6 months) or long term (>6 months).

Statistical analyses

Descriptive statistics and cumulative season prevalence were presented as percentages and means with standard deviation (SD).[34] Incidence was calculated as the number of injuries per 1000 AE and burden as the number of days lost per 1000 AE, with 95% CI using Byar's approximation of exact limits.[176] Severity of was presented as the median number of days lost with 25th to 75th percentiles.[34]

Paper III

The aim of *Paper III* was to examine the most common and burdensome injuries in elite male youth football, overall and per age group. Players were grouped according to their age group for a given season (U13 through U18). Following the completion of data collection, injuries were reclassified from the initial SMDCS diagnosis to match the updated SMDCS[177] and IOC consensus statement[34] categories for diagnosis, region, body part, tissue type and pathology type. Onset was classified retrospectively based on the reported mechanism and diagnosis. Two definitions of recurrent injuries were applied: using the full four-season observation period ("overall recurrent injury") and injuries only within the same season ("same-season recurrent injury"). Both definitions considered recurrent injuries as time-loss injuries to the same location with the same pathology type as a previously recorded injury, following return to full participation from the previous event.[34]

Statistical analyses

Descriptive statistics, cumulative season prevalence and average player availability were reported as percentages and means with SD.[34] Incidence was calculated as the number of injuries per 1000 h and burden as the number of time-loss days per 1000 h. Uncertainty for the point incidence and burden was presented as 95% CI assuming a Poisson distribution.[178] Severity was presented as the median number of days lost with 25th to 75th percentiles.[34]

Paper IV

The aim of *Paper IV* was to examine growth rates, maturity status and maturity tempo as risk factors for injury in elite male youth athletics. Growth rate was defined as the change in an anthropometric variable from the start to the end of a season, maturity status as the skeletal age and percentage of predicted mature height at the start of a season and maturity tempo as the change in skeletal age from the start of a season to the start of the next. For descriptive purposes, athletes were classified as mature (skeletal age 18.0 years), early maturing (skeletal age ≥1 year in advance of chronological age), on time (skeletal age within 1 year of chronological age) or late maturing (skeletal age ≥1 year delayed compared to chronological age).[175]

Only non-specialised athletes were included in this study for two reasons: 1) this ensured similar training demands and injury patterns within the sample and 2) the majority of specialised athletes had reached or were near skeletal maturity. Not all athletes had complete growth and maturation measures for the start and/or end of the season. Separate sub-samples were therefore used for each indicator (Figure 4). The injury outcomes included in the analyses were overall, sudden onset, gradual onset, bone tissue and growth plate injuries.

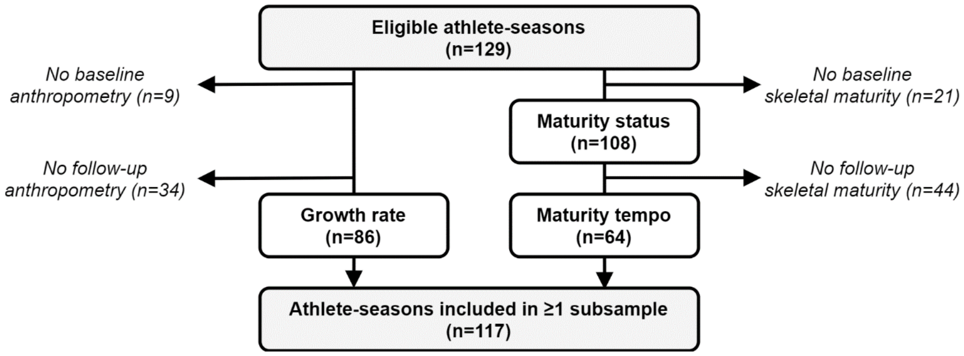

Figure 4. Exclusion and inclusion of athlete-seasons from the non-specialised group.

Statistical analyses

Absolute skeletal age and percentage of predicted mature height were used as indicators of maturity status. Absolute changes in anthropometric measures and skeletal age were calculated as the difference between follow-up and baseline measures. Relative change (percentage change per year) was computed based on the absolute change and the number of days between assessments, for anthropometric measures (growth rate) and skeletal age (maturity tempo). Z-scores were then calculated so that changes were relative to the sample distribution and one unit represented a change of one SD.

Generalized estimating equations were used to examine associations between growth/maturity variables and injuries, in SPSS v.21 (IBM, Armonk, NY, USA). The frequency of injuries was entered as the dependent variable and Z-scores for growth rate, maturity status or maturity tempo as independent factors, adjusting for chronological age at the start of the season. The log-transformed number of AE was entered as the offset variable, allowing exchangeable correlation for repeated athlete-seasons. The incidence rate ratio (IRR) with 95% CI was derived using Poisson and negative binominal regression separately, and Quasi-likelihood under independence model criterion (QIC) values were used to select the model with the best fit. The negative binominal regression demonstrated the lowest QIC values and the output from these analyses was therefore reported with *P*-values <0.05 indicating significant associations.

Paper V

The aim of *Paper V* was to explore the main and combined effects of growth rates, skeletal maturity status and chronological age on injury risk in elite male youth football players. Growth rates were calculated for player-seasons (one player participating in one season) with at least two complete anthropometry assessments (height, leg length and body mass), given that the assessments were within 91 days from the start and end of the season and were at least 60 days apart. For player-seasons with three or more assessments available, we defined two separate growth periods. The absolute change (cm or kg) was divided by the number of days between measurements to account for different durations of growth periods and converted to expressions equivalent to cm/year and kg/year, respectively.[79,179] For a growth period to be included in the analyses, a skeletal maturity assessment had to be available, taken within 91 days of the start of the season. Player exclusion and inclusion is shown in Figure 5. The same classification of relative maturity status as used in *Paper IV* (mature, early, on time or late) was used for descriptive purposes. Only index injuries were considered (the first recorded injury of a location-type combination), with overall, gradual onset, sudden onset, muscle, joint sprain, fracture and physis injuries as the outcome categories of interest.

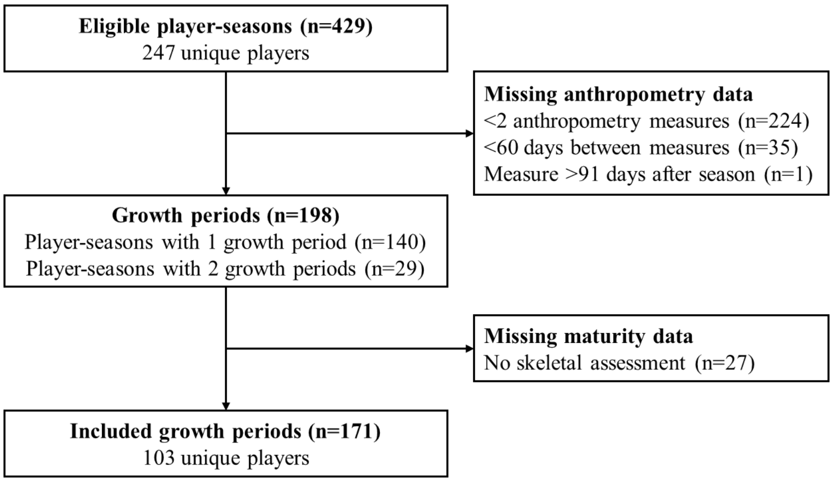

Figure 5. Exclusion and inclusion of player-seasons and growth periods.

Statistical analyses

Descriptive statistics are presented as means with SD. Separate mixed-effects logistic regression models, using the *xtmelogit* command in Stata (StataMP v14.0; StataCorp LP, College Station, TX, USA), estimated associations for the effects of growth rates on the occurrence of an injury in a given category. Growth rates were specified as distinct growth-related predictor variables (fixed effects). Models were adjusted for skeletal age or chronological age and growth × age interaction, with player specified as random effect plus a random intercept. Load, defined as the average weekly training and match exposure during the growth period or until an event occurred, was included as a covariate. An example of the data structure is presented in Table 10.

Table 10. Example of the model data structure. The occurrence of a specified injury type in the growth period (event yes/no), growth rate for height, leg length or body mass for the growth period, chronological age at the start of the growth period, Fels skeletal age at the start of the season and the load (average h/week) during the period (prior to the event for injured players).

ID	**Period no.**	**Event**	**Δ Height (cm/yr)**	**Δ Leg length (cm/yr)**	**Δ Body mass (kg/yr)**	**CA (yrs)**	**SA (yrs)**	**Load (h/week)**
1	1	Y	1.4	0.3	8.3	15.8	16.1	4.0
2	1	Y	4.2	3.4	4.3	14.8	14.7	5.5
2	2	N	3.1	5.9	7.3	15.5	15.7	6.2
3	1	Y	5.8	5.1	4.3	13.3	15.1	6.6
3	2	Y	4.3	4.8	0.0	14.3	17.7	7.4

ID: Player identification. CA: Chronological age. SA: Skeletal age.

The relative quality of each model, within the set of candidates for an injury category, was assessed using the Akaike Information Criterion (AIC). The Akaike difference (ΔAIC) from the estimated best model (i.e. the model with the lowest AIC value: ΔAIC = 0) was evaluated using the following scale: 0–2 (essentially equivalent), >2–7 (plausible alternative), >7–14 (weak support) and >14 (no empirical support).[180] Akaike weights (w_i) provided a scaled interpretation about the relative quality of each competing model as the probability that a given model is the best in the set of six candidate models per injury category. Outcomes are reported as point estimates and 95% CI for estimated odds ratios (OR) with *P*-values <0.05 indicating statistically significant associations. Thresholds for the adjusted ORs of 0.9, 0.7, 0.5, 0.3, and 0.1 and their reciprocals 1.11, 1.43, 2.0, 3.3, and 10 defined small, moderate, large, very large, and extremely large beneficial and harmful effects, respectively.[181] Since there are no established anchors for a practically relevant association between growth rates and injuries, we considered OR=0.90 or OR=1.11 to define substantially beneficial and harmful effects, respectively.[181]

Results and discussion

Involving research-invested clinicians in the data collection affects injury incidence in elite youth football (Paper I)

In this methodological study we compared the injury incidence between different recording settings, based on the level of research investment from the primary recorder or direct supervisor. A total of 137 squad-months were included in the analysis after excluding 31 (11 with unclear recording setting, 18 were considered as off-season, 2 with unclear month-type). During these months, 211 players (mean 1.8 seasons per player, SD 0.9) participated, and contributed to 3615 player-months. The “invested recorder” setting included 51 squad-months (1462 player-months), the “invested supervisor” setting included 68 squad-months (1703 player-months) and the “non-invested” setting included 18 squad-months (450 player-months).

The final sample consisted of 1167 injuries (0.32 injuries per player-month, 95% CI: 0.30 to 0.34), of which 698 were time-loss injuries (0.19, 0.18 to 0.21; 60% of injuries) and 469 were non-time loss injuries (0.13, 0.12 to 0.14; 40%). In terms of severity, 21% of all injuries were minimal, 11% mild, 16% moderate and 12% severe. The majority of injuries were to the lower limb (84%); fewer were to the upper limb (7%), trunk (6%) and head/neck (2%). Injuries were mainly sustained during academy sessions (46%), while 28% were reported from club sessions, 22% from national team sessions and 4% from other contexts.

Injury incidence depends on the level of investment in the programme

Previous studies on injury surveillance methodology have compared outcomes based on different definitions and recording methodology, yet variations within the same surveillance system are not well documented and represent a research gap. In this study, where injury recorders were instructed to follow the same definitions and procedures, we observed differences in the number of recorded injuries depending on the level of investment in the programme. The overall incidence was significantly greater ($P<0.001$) for “invested recorder” (0.60, 0.55 to 0.65) compared to both “invested supervisor” (0.32, 0.29 to 0.36) and “non-invested” (0.27, 0.22 to 0.34). These differences were clearest for non-time-loss injuries (Figure 6), where the incidence for "invested recorder" (0.35, 0.31 to 0.39) was 3.5 times greater (*P*<0.001) than "invested supervisor" (0.10, 0.08 to 0.12) and 8.8 times greater (*P*<0.001) than "non-invested" (0.04, 0.02 to 0.07). Furthermore, the incidence of minimal severity injuries was 2.5 times greater (*P*<0.001) for "invested recorder" (0.10, 0.09 to 0.13) and 2.0 times greater (*P*<0.01) for "invested supervisor" (0.08, 0.06 to 0.10) compared to "non-invested" (0.04, 0.02 to 0.07). In contrast, the incidence for time-loss injuries overall was similar between settings ("invested recorder" 0.24, 0.21 to 0.28; "invested supervisor" 0.21, 0.18 to 0.24; "non-invested" 0.20, 0.15 to 0.25).

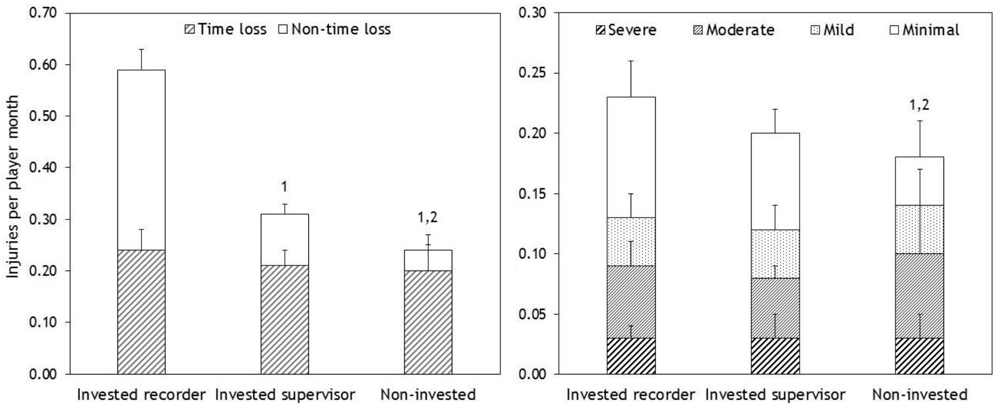

Figure 6. Comparison of adjusted incidence with 95% CI for time-loss and non-time-loss injuries (left) and for severity categories (right). 1: Significantly lower than "Invested recorder". 2: Significantly lower than "Invested supervisor".

These findings support the concerns raised by Orchard & Hoskins,[40] who suggested that medical-attention definitions are particularly prone to differences between recorders, in terms of interpretation of recordable injuries and adherence to protocols. The differences in incidence observed for non-time-loss and minimal injuries can also be seen in light of the findings by Bjørneboe et al.,[50] Flørenes et al.,[49] and Møller et al.,[56] who indicated that less severe injuries are the most challenging for medical staff to accurately record. In contrast, Nilstad et al.[51] emphasized that underreporting by medical staff was a general finding in their study, not just related to a few recorders and also apparent for severe injuries. It therefore seems clear that medical staff recording itself is a method associated with limitations, which are exaggerated when a broad medical-attention definition is applied. The underlying reasons for the differences were not examined in our study, but anecdotally, the large administrative burden, unclear guidelines and a lack of understanding relating to the usefulness of the collected data may have contributed to lower adherence among some recorders. The inability to cross-check non-time-loss injuries against training and match participation records also limited the data quality process as supervisors could not easily identify missed injuries.

Underreporting may be location- and session-specific

Comparisons for body region and session context is presented in Table 11, showing a greater incidence of upper limb injuries in the "invested recorder" compared to the "invested supervisor" setting. This could be related to different perceptions between recorders of which events they consider relevant to report and may be a sport-specific finding. Walden et al.[41] discuss how the same injury can affect participation differently depending on the sport; it could therefore be suggested that upper limb injuries are more often neglected by busy medical staff recorders in football. On the other hand, this was not the case for trunk or head/neck injuries and the differences between recording settings were only consistent for lower limb injuries. Differences were also identified for session type, especially for national team sessions. Although national team preparation months were included as a co-factor, this could reflect an overrepresentation of the "invested recorder" setting in national teams and it is difficult to extrapolate these findings beyond this specific academy context.

Table 11. Adjusted incidence (injuries per player-month) for body region and session context with pairwise comparisons for the three recording settings. 1: Invested recorder, 2: Invested supervisor, 3: Non-invested.

	Invested recorder Incidence (95% CI)	**Invested supervisor Incidence (95% CI)**	**Non-invested Incidence (95% CI)**	**1 vs. 2 *P*-value**	**1 vs. 3 *P*-value**	**2 vs. 3 *P*-value**
Body region						
Head/neck	0.02 (0.01-0.03)	0.01 (0.00-0.02)	0.00 (0.00-0.03)	.31	.08	1.0
Upper limb	0.04 (0.03-0.06)	0.02 (0.01-0.03)	0.03 (0.02-0.06)	*<.001*	.74	.52
Trunk	0.03 (0.02-0.04)	0.02 (0.01-0.03)	0.02 (0.01-0.04)	.51	.72	1.0
Lower limb	0.51 (0.46-0.56)	0.27 (0.24-0.31)	0.21 (0.17-0.27)	*<.001*	*<.001*	.14
Session context						
Academy	0.23 (0.20-0.26)	0.09 (0.07-0.11)	0.10 (0.07-0.14)	*<.001*	*<.001*	1.0
Club	0.07 (0.05-0.09)	0.06 (0.04-0.08)	0.04 (0.02-0.06)	.49	*<.01*	.07
National team	0.17 (0.14-0.20)	0.08 (0.07-0.10)	0.01 (0.00-0.05)	*<.001*	*<.001*	*<.001*
Other	0.01 (0.00-0.02)	0.02 (0.01-0.03)	0.02 (0.01-0.04)	.71	1.0	1.0

P-values in italic indicate significant associations.

Practical implications: We should only report time-loss injuries when multiple recorders are involved

Our findings demonstrated that the level of investment in an injury surveillance programme affects the reported incidence for non-time-loss injuries and injuries with minimal day loss (1-3 days), while time-loss injuries as a whole are unaffected. In a practical setting, assuming a squad of 25 players and using the average injury incidence, around 135 injuries would be recorded over a season in the most invested setting compared to only 61 in the least invested setting. For non-time-loss injuries the effect would be even larger, with approximately 79 and 9 injuries for these two settings, respectively. With variations of this magnitude, direct comparisons between teams and seasons are essentially meaningless as it is not possible to differentiate true changes in injury occurrence from bias relating to recorder investment. It is also impossible to directly compare different contexts (e.g. academies, tournaments or countries) if the recording setting is not clearly described.

As time-loss incidence was not affected by research-investment, this is recommended when multiple medical staff recorders are involved in the data collection. Although this reduces the bias associated with the recording method, it is important to recognize that important details may be missed. Overuse and mild conditions may not be recorded, the time staff spend treating players will not be well reflected and incidence will depend to a larger degree on training and match schedules.[36,44] If a broad definition is considered necessary to capture the injuries of interest, it is vital that guidelines are clear and that staff are sufficiently trained to reduce differences in interpretation. Raising motivation among recorders by involving them in the process and explaining how the data will be used, implementing recording tools that minimise administrative time and allow for regular feedback (e.g. monthly reports) may also increase the overall motivation to record timely and accurately.[34]

Injury epidemiology of elite male youth athletics (Paper II)

In this prospective cohort study, we aimed to improve our understanding of the most common and burdensome injuries in elite male youth athletics, also examining specific event groups. During the five-season observation period, 237 full-time athletes participated in the athletics programme, of which 59 did not complete a full season and were excluded. The final sample therefore consisted of 179 athletes (63 for one season, 51 for two, 39 for three, 21 for four and 5 for five), contributing to

391 athlete-seasons. Initially, 354 time-loss injuries were recorded and after excluding 64 injuries that occurred outside training or competition, 290 were included for analysis. The total accumulated exposure was 72 086 AE (69 326 TE and 2760 CE).

The extent of injuries in elite male youth athletics

Academy settings with daily monitoring, controlled training and full-time medical staff are very rare in youth athletics. Epidemiological data specific to elite male youth athletics are therefore limited and characterised by different recording methods, absence of burden measures and lack of details relating to injury types to specific body parts. This has limited our ability to determine the extent of the injury problem and identify the injuries that have the greatest impact in this population. The cumulative season prevalence (58%) and average number of injuries per athlete per season (0.7, SD 0.2) in our study was lower than what was reported by Carragher et al.[101] (76%, 1.7 per athlete per season). This is likely due to their application of a broader any-complaint athlete-reported approach, which could detect more injury problems. While Jacobsson et al.[103] also used athletes to record injuries, their definition was closer to a time-loss definition, which may explain why their season prevalence (64%) was more similar to ours.

The overall incidence in our study was 4.0 injuries per 1000 AE (95% CI: 3.6 to 4.5), with 3.8 times greater competition incidence (13.8 per 1000 CE, 9.7 to 18.9) compared to training (3.6 per 1000 TE, 3.2 to 4.1). We do not know the actual duration of sessions and when different denominators are used it is difficult to compare incidence to previous studies; however, if we assume a session duration of roughly one hour, our results are comparable to the overall incidence reported by Jacobsson et al.[103] (3.9 per 1000 h) and Rejeb et al.[104] (~6 per 1000 h). This is the first study specifically reporting median duration of injuries and burden in this population, with 6 days lost per injury (25th to 75th percentile: 3 to 12) and an overall burden of 79 days lost per 1000 AE (95% CI: 77 to 81). Using the average number of sessions per season (184), this equates to athletes losing roughly two weeks of training to injuries every season.

Around half the injuries (54%) lasted ≤7 days (1 to 3 days: 35%, 4 to 7 days: 19%), which was similar Carragher et al.[101] (53%), who reported slightly more moderate injuries (33% vs. 23% in our study) and fewer lasting more than 28 days (14% vs. 23% in our study). The distribution in

Jacobsson et al.[103] was more skewed towards severe injuries (47% lasting ≥21 days) with only 23% lasting ≤7 days. Although speculative, these comparisons may indicate a relatively good ability to capture injuries of minor severity in our context and could perhaps be attributed to the use of on-site physiotherapists as recorders in a well-controlled setting.

Which injuries have the greatest impact?

Previous studies identified the lower extremity as the most common injury site,[101,103] which was also the case in our study (72% lower extremity, 19% head/trunk, 8% upper extremity). The most commonly injured body parts were the thigh (19%; 0.8 per 1000 AE) and knee (15%; 0.6 per 1000 AE), followed by the lower leg and foot/toe (both 12%; 0.5 per 1000 AE). The most common types were muscle strains/ruptures (18%; 0.7 per 1000 AE), followed by other bone injuries (these were all bone stress injuries) and growth plate disturbances/avulsions (both 12%; 0.5 per 1000 AE). These findings are consistent with previous research, although bone injuries appear to represent a larger proportion of injuries in our setting. Indeed, bone was the most common tissue type, representing 36% of injuries (1.4 per 1000 AE), followed by muscle (23%; 0.9 per 1000 AE) and miscellaneous (20%; 0.8 per 1000 AE).

Presenting injury frequencies and proportions alone limits our understanding of the injury problem; burden better represents the impact injuries have on training and competition participation. In this study, the most burdensome tissue types were bone (46 days lost per 1000 AE) and muscle (16 days per 1000 AE), while the most burdensome injury types were stress fractures (18 days per 1000 AE), muscle strains/ruptures (16 per 1000 AE), bone stress injuries (10 days per 1000 AE) and growth plate disturbances/avulsions (10 days per 1000 AE). These results highlight that although muscle injuries were the most common, stress fractures should receive more attention in injury prevention programmes to reduce the overall time lost from training and competition.

As discussed earlier, reporting injuries per body part and location separately limits our ability to report the most relevant injuries in sufficient detail to guide preventative efforts. Reducing the occurrence of hamstring muscle strains will, for example, require other interventions than quadriceps muscle contusions and lower leg stress fractures will be targeted with different measures than lower leg muscle strains. In our study, the most common location-specific types were thigh muscle strains/ruptures (14%; 0.6 per 1000 AE), lower leg bone stress injuries (10%; 0.4 per 1000 AE), ankle sprains (7%; 0.3 per 1000 AE), pelvis/sacrum growth plate injuries (6%; 0.2 per 1000 AE), lumbar spine bone stress injuries (5%; 0.2 per 1000 AE) and lumbar spine non-specific pain (5%; 0.2 per 1000 AE). The most burdensome were thigh muscle strains/ruptures (15 days per 1000 AE), followed by lumbar spine stress fractures (12 days per 1000 AE), lower leg bone stress injuries (7 days per 1000 AE), pelvis/sacrum growth plate disturbances/avulsions (5 days per 1000 AE) and knee growth plate disturbances/avulsions (4 days per 1000 AE).

Bone injuries are common and burdensome in elite male youth athletics

In agreement with the observations by Carragher et al.[101] and Jacobsson et al.,[103] muscle injuries were common and injuries to the thigh (hamstring strains in particular) were a major source of time loss from training and competition. Bone injuries were, however, the main concern in this population, especially bone stress injuries to the lumbar spine (spondylolysis) and lower leg (medial tibial stress syndrome grade 1-3), and growth plate injuries to the pelvis (AIIS and ASIS apophysitis) and knee (Osgood-Schlatter disease). The extent of these injuries have not been well described in earlier studies, where other bone injuries represented only 8% of all injuries in the study by Carragher et al.[101] and stress fractures 2% in Jacobsson et al.[103] (6% in our study). The use of proportions (which appear low) may have led to an underestimation of their real impact. The consequences may even be further underestimated in the current study due to the application of a time-loss definition. Bone-stress injuries and stress fractures can be viewed as injuries on the same continuum[95] and although not examined in this study, scheduling of training load, previous fractures, low BMI and energy imbalance have been highlighted as risk factors.[8,182-184] Bone and growth plate injuries may also be related to rapid growth and skeletal immaturity, which are investigated as risk factors in *Paper IV*.

Reporting injuries per event group is important

A challenging aspect of reporting injuries in athletics is that injury characteristics may differ depending on the event groups represented in the sample. This will not only limit our ability to compare results, but also the practical relevance of the findings. An endurance coach may, for example, not be interested in reading about injury characteristics in a sample of mainly throwers. As our sample was relatively large compared to previous studies, we were able to go into detail and report injury characteristics relative to event group (Table 12 and Figure 7). The non-specialised athletes were the youngest, while specialised throwers, jumpers and sprinters on average were older than endurance athletes. Overall, the greatest cumulative season prevalence was observed in endurance athletes and the lowest in throwers. Jumpers had the highest incidence and burden, while sprinters had the lowest incidence and non-specialised athletes the lowest burden. Endurance athletes sustained proportionally more gradual onset injuries and throwers relatively more injuries to the upper extremities, trunk and head.

Table 12. Descriptive demographic, exposure and injury data per event group.

	Non-specialised	Endurance	Sprints	Jumps	Throws
Athlete-seasons	185	66	51	55	34
Mean age (SD)	13.5 (1.0)	15.3 (1.6)	16.7 (1.0)	16.5 (1.1)	16.4 (1.3)
Accumulated AE	30 328	15 429	10 318	8787	7224
Time-loss injuries	130	57	35	43	25
Season prevalence (%)	60.2	70.5	53.1	57.7	50.0
Injury incidence (95% CI)	4.3 (3.5-5.0)	3.7 (2.8-4.8)	3.4 (2.4-4.7)	4.9 (3.6-6.5)	3.5 (2.3-5.0)
Injury burden (95% CI)	71 (67-73)	85 (80-89)	82 (77-88)	101 (95-109)	72 (66-78)
% Acute/gradual onset	51/49	16/84	63/37	58/42	56/44
% Upper extremity	11.5	1.8	2.8	4.6	20.0
% Head & trunk	18.5	17.5	14.3	23.3	28.0
% Lower extremity	70.0	80.7	82.9	72.1	52.0

AE: Athlete exposures.

The mean number of injuries per athlete per season for endurance athletes in our study (0.9) was lower than reported for distance runners by von Rosen et al.[102] (1.4 any-complaint injuries) and Martínez-Silván et al.[100] (4.4 medical-attention injuries), who both applied broader injury definitions. The proportion of gradual onset injuries (84%) was, on the other hand, somewhat higher than the 68% reported for endurance athletes by Carragher et al.[101] and the 76% reported by Martínez-Silván et al.[100] The proportion of lower extremity injuries was also lower than observed by Carragher et al. and von Rosen et al. (both 96%). While contextual factors and differences in recording methods could explain the discrepancies, our study included a larger sample and covered several seasons. Earlier studies may therefore be subject to a greater degree of season and athlete variation.

The majority of injuries to the trunk (n=10) in the endurance group were related to non-specific low back pain (n=5) and spondylolysis (n=3), which may be more of a concern than has been previously reported. The most burdensome injury types in endurance athletes were bone stress injuries (5 days per 1000 AE), stress fractures (5 days per 1000 AE) and growth plate injuries (3 days per 1000 AE), with lower leg bone stress injuries (medial tibial stress syndrome grade 1-3), knee growth plate injuries (Osgood-Schlatter disease) and lumbar spine stress fractures (spondylolysis) as the most burdensome location-specific types. These injury patterns likely reflect the repetitive impact loading athletes are subject to, which suggests that load management may be a fruitful avenue to reduce the occurrence and severity of injuries in endurance athletes.

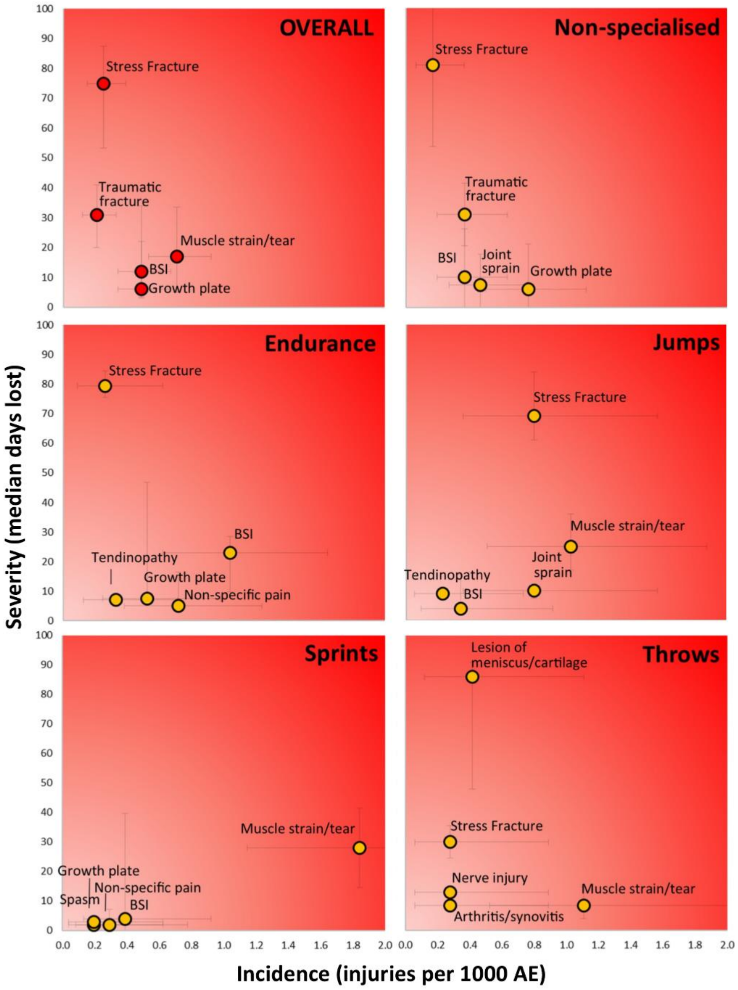

Figure 7. Risk matrices for the most relevant injury types overall and per event group. The horizontal error bars represent 95% CIs for incidence and the vertical error bars represent the 25th and 75th percentiles for severity.

Prospective epidemiology data on youth elite sprinters, jumpers and throwers are limited. In our study, the most burdensome injury type for sprinters was muscle strains/ruptures (9 days per 1000 AE), with hamstring strains responsible for 77% of all days lost. Jumpers were mainly restricted by stress fractures (7 days per 1000 AE) and muscle strains/ruptures (3 days per 1000 AE), with lumbar spine stress fractures (spondylolysis) and thigh muscle strain/ruptures (hamstring strains) as the most burdensome location-specific types. Unlike other event groups, the injuries with the greatest burden for throwers were lesions of meniscus/cartilage (knee and hip; 3 days per 1000 AE), acute fractures (ankle; 1 day per 1000 AE) and muscle strains/ruptures (1 day per 1000 AE). Although this may seem counterintuitive in a sport characterized by upper extremity actions, the power generation through the lower limbs and rotational component of many throwing disciplines may explain why the knee and hip joints are especially vulnerable. This group also had the fewest athletes and lowest number of injuries, and estimates should therefore be interpreted with care.

The injury types with the greatest burden for non-specialised athletes were growth plate injuries (6 days per 1000 AE), stress fractures (5 days per 1000 AE) and acute fractures (5 days per 1000 AE), and the most burdensome location-type combinations were growth plate injuries to the pelvis (mainly AIIS apophysitis), lumbar spine stress fractures (spondylolysis) and "other" injuries to the foot/toe (one case of a calcaneal cyst). The dominance of growth plate injuries in this group may reflect the lower age and expected lower skeletal maturity.

Practical implications: Injury reduction efforts should focus on bone and muscle injuries, but event-specific patterns must be considered

This study revealed that male athletes participating in a high-demand academy athletics programme can expect to sustain around one injury and lose two weeks of training to injuries every season. Bone and muscle injuries were the main concern and location-specific analyses identified thigh muscle strains/ruptures, lumbar spine stress fractures and lower leg bone stress injuries as the most burdensome. This information can be used to guide injury reduction programmes and further research into risk factors. When doing so, our results highlight the importance of considering the event group in the athletics context. Endurance athletes mainly lose time to lower leg bone stress injuries, sprinters to thigh muscle strains, jumpers to lumbar spine stress fractures and throwers to knee lesions of meniscus/cartilage.

Injury epidemiology of elite male youth football (Paper III)

The methodological issues discussed in the background section (i.e. inconsistent methodology, injury location and type reported separately, burden rarely used) make it difficult to understand exactly which injuries have the greatest impact on participation in elite male youth football and if these are the same across age groups. The purpose of this prospective cohort study was therefore to gain a more detailed understanding of the most common and burdensome injuries and to examine age group patterns. A total of 724 player-seasons were screened for eligibility over the four-season observation period, excluding 133 (58 were not full-time or part-time players, 53 did not regularly attend academy sessions, 17 joined after the observation period and 5 did not participate in a full season due to a previous injury). This left 591 player-seasons from 301 players for analysis (133 participating in one season, 83 in two, 48 in three, 37 in four), with a mean age of 14.6 years (SD 1.6) at the start of the season. In total, 1111 time-loss injuries were included (12% overall recurrent, 8% same-season recurrent) after excluding 61 that were sustained outside of football activities. The accumulated exposure was 92 827 h (78 069 training h and 14 758 match h).

The extent of injuries in elite male youth football

The mean number of injuries per player per season in our study was 1.9 (SD 1.8), which is within the range reported in studies using time-loss definitions and medical staff as recorders (0.4 to 2.5).[64,65,68-71,73-76] The cumulative season prevalence has not been included in many of these studies, but was higher in our study (79%) compared with data reported by Hall et al.[65] (40%) and Cezarino et al.[64] (65%). Hall et al. did, however, use a stricter 48-hour time-loss cut-off, which may explain the lower proportion; our findings are closer to those of Kemper et al. (75%) who used a >1-day medical-attention definition. Player availability, considered an easy measure for coaches to relate to,[34] has only been reported by Le Gall et al.[69] with similar results (89% vs. 86% in our study). We were able to expand on these findings by also reporting session-specific availability, which was greater for matches (90%) than for training sessions (85%).

A study by Materne et al.[185] (published after the literature search for this thesis was completed) presented injury data from this football academy, describing injury patterns using the four seasons prior to this study (2012/13 through 2015/16). They did, however, not consider exposure (time spent at risk) which limited their ability to determine injury risk. In our study, the overall incidence was 12.0 injuries per 1000 h (95% CI: 11.3 to 12.7). This is in the higher end compared to other studies that have used similar recording methods and exposure recording at the individual level (2.7 to 12.1 per 1000 h; median 7.5).[73,81,82,84,85,87] The underlying reasons are unclear, but may be related to the high training frequency (two training sessions per day meant small problems were also associated with time loss) and the presence of on-site recorders (minor injuries are more easily captured and the threshold for reporting problems may have been lower). Furthermore, our study included injuries that only led to partial restrictions, where other studies may have only included injuries that led players to fully miss sessions. Match injury incidence (32.0 per 1000 h, 29.2 to 35.0) was 3.9 times greater than training injury incidence (8.2 per 1000 h, 7.6 to 8.8). This is a consistent trend in all studies in this population and confirms that matches carry a relatively higher risk of sustaining time-loss injuries compared to training sessions.

Using the median days lost for reporting injury severity is recommended due to the commonly skewed distribution;[34] however, only three previous studies have done so. The median severity in our study (8 days, 25th to 75th percentile: 2 to 21) was similar to Bult et al.[76] (7 days), but lower than Cezarino et al.[64] (13 days) and Sieland et al.[84] (31 days). This could be seen in conjunction with the higher incidence in our study and may reflect a greater capture rate of less severe injuries. Burden has only been included in two other studies, where Raya-Gonzales et al.[87] (38 days per 1000 h) and Bult et al.[76] (58 days per 1000 h) both reported a lower overall burden than what we have found (255 days per 1000 h, 95% CI: 252 to 259). These differences can likely be attributed to the greater number of injuries recorded in our study, but could also result from some severe injuries (e.g. we recorded four ACL injuries with a median duration close to two years). Our calculated burden equates to roughly three weeks of lost time per player per season and we extend these findings by also reporting the burden of match (717 days per 1000 h) and training (168 days per 1000 h) injuries. The proportion between match and training injury burden (4.3 times greater for match injuries) was similar to the proportion reported for incidence; this indicates that although match injuries were more common, the severity was typically similar (training: 8 days, 2 to 20; match: 9 days, 3 to 22).

Identifying the most common and burdensome injuries

The majority of studies on elite male youth football players fail to report injury types specific to locations and do not consider the burden of injuries. Consistent with previous studies, we recorded mainly injuries to the lower limbs (83%, upper limbs 9%, trunk 6%, head/neck 2%) and the thigh (25%, 3.0 injuries per 1000 h), hip/groin (14%, 1.7 per 1000 h), ankle (14%, 1.7 per 1000 h) and knee (13%, 1.6 per 1000 h) were the most commonly injured body parts. Muscle strains/spasms (22%, 2.6 per 1000 h), contusions (17%, 2.1 per 1000 h) and joint sprains (13%, 1.6 per 1000 h) were also the most common pathology types, meaning the overall injury picture in our sample represents the typical pattern seen in other youth[17] and senior[186] contexts and reflects the nature of the game with high intense actions and duels. The application of the most updated consensus categories for pathology type will enable future studies to directly compare their findings to ours.

To improve our understanding of the injuries with the greatest impact, we examined injury burden for specific tissue and pathology types. For tissue type, the greatest incidence was seen for muscle/tendon (27%, 3.2 per 1000 h), followed by bone (23%, 2.8 per 1000 h) and superficial tissues/skin (18%, 2.2 per 1000 h), while the greatest burden was observed for bone (87 days per 1000 h), ligament/joint capsule (78 days per 1000 h) and muscle/tendon (42 days per 1000 h). This has not previously been reported and highlights the impact of bone injuries in youth football. For pathology types, the most burdensome categories were joint sprains (77 days per 1000 h), muscle strains/spasms (36 days per 1000 h), bone stress injuries (33 days per 1000 h), fractures (33 days per 1000 h) and physis injuries (19 days per 1000 h). These findings further emphasize the impact of bone-related pathology types, an observation that would have been lost using typical count, proportion or incidence measures.

The most frequent location-type combinations were thigh muscle strains/spasms (16%, 1.9 per 1000 h), ankle sprains (8%, 0.9 per 1000 h), hip/groin physis injuries (6%, 0.8 per 1000 h), ankle contusions (4%, 0.5 per 1000 h) and non-specific thigh injuries (4%, 0.5 per 1000 h), with the most common diagnoses being hamstring strains/spasms (8%, 1.0 per 1000 h), ankle sprains not involving the syndesmosis (7%, 0.8 per 1000 h) and adductor strains/spasms (5%, 0.6 per 1000 h). The proportion of hamstring strains was relatively similar to that reported by Renshaw et al.[74] (13%), Hall et al.[65] (12%), Deehan et al.[70] (11%), Cezarino et al.[64] (11%, 0.3 per 1000 h) and Read et al.[75]

(6%), suggesting that these account for approximately every tenth injury. The proportion of ankles sprains was lower than what Cezarino et al.[64] found (16%) although the incidence was greater compared to their study (0.3 per 1000 h). Similarly, the proportion of adductor strains was lower than reported by Deehan et al.[70] and Cezarino et al.[64] (both 8%), but with a greater incidence than in the latter (0.2 per 1000 h). These discrepancies emphasize the importance of reporting injuries relative to exposure to enable direct comparisons between studies.

The most burdensome combinations in our study were knee sprains (46 days per 1000 h), thigh muscle strains/spasms (29 days per 1000 h), ankle sprains (27 days per 1000 h), lumbosacral bone stress injuries (13 days per 1000 h) and hip/groin physis injuries (11 days per 1000 h). The most burdensome diagnoses were complete tears of the ACL (28 days per 1000 h), ankle sprains without syndesmosis injury (18 days per 1000 h), hamstring strains/spasms (15 days per 1000 h), spondylolysis/spondylolisthesis (10 days per 1000 h) and syndesmotic ankle sprains (10 days per 1000 h). This level of detail has not previously been considered and we can speculate that the lack of youth-specific injury categories and exclusion of burden measures has underestimated the impact of bone stress injuries to the lower back and growth plate injuries to the hip in previous studies. In light of our findings, we suggest that measures for preventing these injuries are targeted to a larger degree in general prevention programmes for youth football.

Age-related injury patterns

Detailed injury patterns across age groups in elite male youth football players have not been described in earlier studies, and with our relatively large sample we aimed to identify trends for the most common and burdensome injuries. Descriptive demographic, exposure and injury data for each age group is presented in Table 13 and a risk matrix for overall injuries is shown in Figure 8. Our results reveal a clear tendency of greater incidence with age, which is similar to other studies where exposure is considered.[64,74,77,84] The underlying reasons were not examined, but greater injury risk in older players has previously been attributed to higher training volume and intensity, stronger players and a more aggressive playing style with increased competitiveness.[68,75,187] In light of the greater proportion of recurrent injuries with age in our study, a risk factor for successive injuries in youth football,[188] we can also speculate that a more extensive injury history leaves older players more vulnerable to sustaining subsequent time-loss injuries.

Table 13. Descriptive demographic, exposure and injury data for age groups.

	U13	U14	U15	U16	U17	U18
Player-seasons	102	106	117	102	92	72
Mean age (SD)	12.3 (0.3)	13.3 (0.3)	14.3 (0.3)	15.3 (0.3)	16.3 (0.3)	17.3 (0.3)
Total training hours	15 094	16 726	14 803	12 903	11 203	7340
Total match hours	1978	2519	3062	2816	2535	1848
Time-loss injuries	133	164	194	215	234	171
Overall incidence (95% CI)	7.8 (6.5-9.2)	8.5 (7.3-9.9)	10.9 (9.4-12.5)	13.7 (11.9-15.6)	17.0 (14.9-19.4)	18.6 (15.9-21.6)
Training incidence (95% CI)	6.0 (4.9-7.4)	6.3 (5.1-7.6)	7.4 (6.0-8.9)	8.8 (7.3-10.6)	11.0 (9.1-13.1)	13.2 (10.7-16.1)
Match incidence (95% CI)	21.2 (15.3-28.7)	23.4 (17.8-30.2)	27.8 (22.2-34.3)	35.9 (29.2-43.6)	43.8 (36.0-52.7)	40.0 (31.4-50.3)
Burden (95% CI)	129 (123-134)	207 (200-213)	207 (200-213)	425 (415-435)	316 (307-326)	308 (297-319)
Season prevalence (%)	65.7	75.5	76.1	92.2	82.6	80.6
Overall recurrence (%)	6.0	9.8	10.8	11.2	16.2	15.2
Same-season recurrence (%)	6.0	7.3	5.7	6.5	9.0	9.9
Player availability (%)	90.6	88.6	87.9	78.3	82.7	86.1

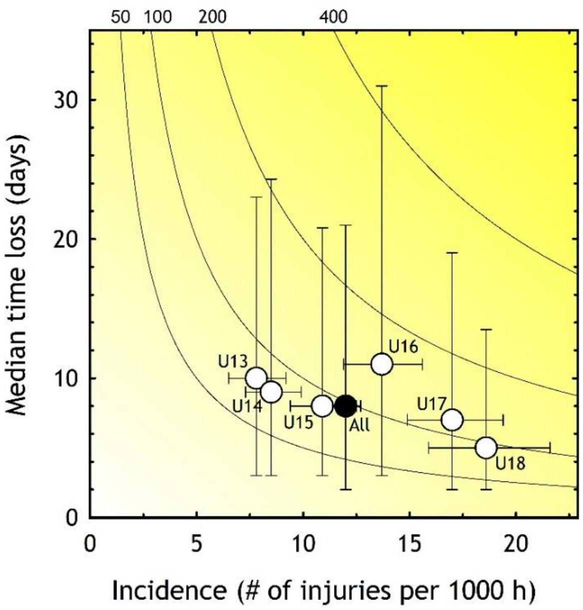

Figure 8. Risk matrix for overall injury incidence and severity. The horizontal error bars represent 95% CIs for incidence and vertical error bars represent the 25th to 75th percentiles for severity. The isobars represent equal burden lines and a darker shade of yellow (further towards the top right corner) indicates a greater burden.

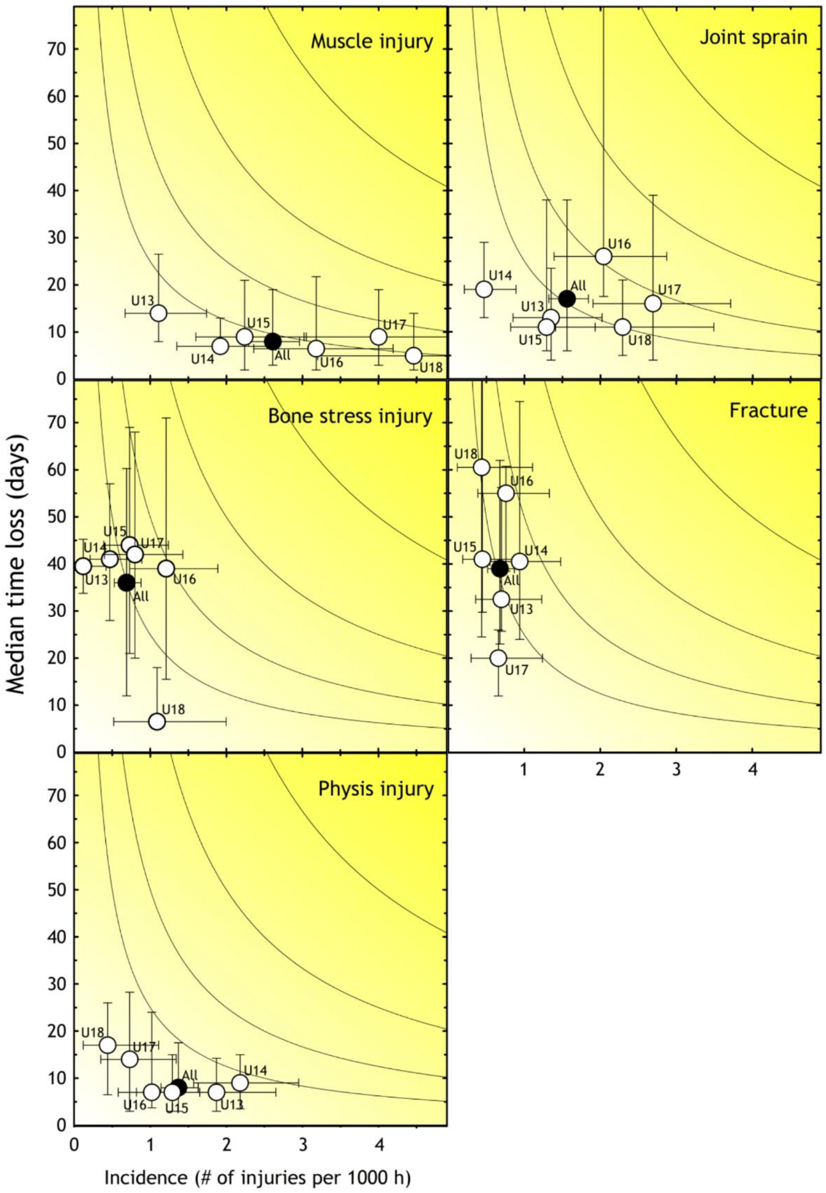

Figure 9. Risk matrices for the five most burdensome pathology types. The horizontal error bars represent 95% CIs for incidence and vertical error bars represent the 25th to 75th percentile for severity. The isobars represent equal burden lines and a darker shade of yellow (further towards the top right corner) indicates a greater burden.

A peak in incidence[76,83] and burden[76,83,87] has been observed for U14 to U16 players elsewhere and others have noted a greater proportion of severe injuries in these age groups.[65,75] This was apparent for burden and player availability in our study (highest burden and lowest availability for U16 players), reflecting a greater severity per injury. The vulnerability of these players has been explained by players experiencing or adjusting to rapid changes in height and weight,[65,75,76,87] and risk may be thought to be further compounded by increasing performance capacity and match demands.[97,98] Injury characteristics across age groups have been explored by Read et al.[75] and Hall et al.,[65] who were limited by their lack of exposure measures, and by Le Gall et al.[69] in a relatively narrow age group range (U14 to U16). Their collective findings indicated that growth-related conditions were dominant in U9 to U14 players, while muscle injuries were more common in older players. We extend on these findings by reporting injury incidence and severity for the five most burdensome pathology types in Figure 9.

Our results demonstrate a greater incidence and burden of muscle injuries and lower incidence and burden of physis injuries with age. Bone stress injuries and joint sprains were more common in the three oldest age groups (U16, U17 and U18), with the greatest burden in U16 players. No clear age-related trends could be seen for fractures. The greater impact of muscle injuries in older players may again be related to greater sprinting speeds and match sprint demands. In support of this, we also found a greater proportion of sprint-related injuries in older players (U13: 4%, U14: 6%, U15: 6%, U16: 9%, U17: 16%, U18: 15%). The impact of physis injuries in younger players is likely related to skeletal immaturity and a greater proportion going through their growth spurt, which is expected in these age groups.[118,171] The transition from more physis injuries to more muscle injuries with age is also in line with the theoretical concept that different structures represent the weak point during maturation,[95] supported by the studies of maturity and injuries by Le Gall et al.[71] and Monasterio et al.[166] We explore the main and combined effects of these factors on injury risk in *Paper V*.

Practical implications: Injury reduction programmes should target the main football injuries, but can potentially be tailored to age groups

An elite male youth football player in our context would, on average, sustain two injuries and lose three weeks of valuable training and match participation every season. Coaches could expect to only have 85% of their squad (four injured players in a typical 25-player group) available for training sessions and every tenth player would be unavailable for match selection. We found a clear trend of greater injury incidence with age; this was, however, dependent on the pathology type. Muscle injuries were more common in older age groups and physis injuries in younger age groups. Players in the U16 age group lost the most time to injury and had the lowest availability. This age group also had the highest burden of joint sprains and bone stress injuries.

The patterns identified in this study may be useful for implementing targeted injury reduction programmes for specific age groups. Knee sprains, thigh muscle injuries and ankle sprains had the greatest impact on participation overall, which suggests that general multimodal injury prevention programmes aimed at typical "football injuries" (e.g. FIFA 11+[189]) should still remain central. Our analyses did, however, reveal a high impact of bone injuries, especially to the lumbosacral spine and hip/groin. These have received less attention in earlier epidemiological studies and should be further investigated in terms of risk factors and potential preventative measures. Managing training load (ensuring variation in movement patterns, safe progression and sufficient recovery) is a general recommendation for youth athletes[7] that should be investigated more closely in future studies.

Growth rate and maturation are related to bone and growth plate injuries in elite male youth athletics (Paper IV)

No study has examined growth rates, absolute maturity status or maturity tempo as injury risk factors in a sample of single-sport athletes from athletics. The purpose of this risk factor study was therefore to investigate these relationships in a group of non-specialised athletes participating in a structured academy programme, including 74 athletes (117 athlete-seasons). The chronological age at the start of the season was 13.4 years (SD 1.0) and based on passport nationality, 91.5% of the athlete-seasons represented Western-Asian countries with the remaining 8.5% from Northern-Africa. For the athlete-seasons with a skeletal maturity assessment, 5.6% were mature, 68.5% early maturing, 23.1% on time and 2.8% late maturing. A total of 87 time-loss injuries were recorded (18 287 AE; 4.8 injuries per 1000 AE). Consistent with the findings reported in *Paper II,* injuries to bone tissue were the most common (45%) and growth plate injuries represented the most common bone-related injury type (24% of all injuries). Baseline values, absolute change and relative change in growth and maturity indicators are described in Table 14.

Table 14. Baseline characteristics, absolute and relative change for the growth rate (n=86), maturity status (n=108) and maturity tempo (n=64) samples. Absolute change represents the actual change from baseline to follow-up, while relative change represents the annual percentage change.

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

SA: Skeletal age. CA: Chronological age.

Rapid growth in height and leg length were associated with injury

The risk of injury associated with relative changes in height, body mass, BMI, leg length and trunk height are presented in Table 15. Athletes with greater increases in height and leg length over a season sustained more bone and growth plate injuries and a larger increase in leg length was also associated with higher overall injury risk. In this study, a one-unit change represented an increase of one SD above the sample mean and for height this equated to approximately 8.9 cm/year or 0.7 cm/month, which is typical for PHV (averages range from 8 to 10 cm/year).[108] Growth rates in height exceeding 0.6 cm/month were associated with greater risk of injury in the study by Kemper et al.[63] in Dutch football players, while Rommers et al.[79] found that greater increases in height were associated with lower risk of acute injuries in Belgian footballers (U13 through U15). The latter finding appears counterintuitive; however, their analyses did not seem to account for age as a potential confounder. It can therefore be speculated that the players in these age groups who grew the most were also the youngest, reflecting a greater risk of acute injuries with older age rather than a direct effect of lower growth rates. They did, however, report an increased risk of overuse injuries in younger players (U10 through U12) with greater change in leg length, which was similar to our findings.

Table 15. Associations between relative change in anthropometric variables and injury risk.

	IRR (95% CI)	***P*-value**
Overall injuries (n=73)		
Δ Height	1.10 (0.86-1.40)	.46
Δ Body mass	1.04 (0.69-1.57)	.86
Δ Body mass index	1.01 (0.67-1.52)	.96
Δ Trunk height	0.87 (0.59-1.27)	.46
Δ Leg length	1.30 (1.01-1.67)	*.039*
Gradual onset injuries (n=46)		
Δ Height	1.25 (0.97-1.61)	.08
Δ Body mass	1.11 (0.77-1.62)	.57
Δ Body mass index	1.01 (0.66-1.54)	.97
Δ Trunk height	1.04 (0.79-1.37)	.77
Δ Leg length	1.29 (0.99-1.68)	.06
Sudden onset injuries (n=27)		
Δ Height	0.80 (0.50-1.30)	.37
Δ Body mass	0.81 (0.41-1.61)	.55
Δ Body mass index	0.89 (0.51-1.54)	.68
Δ Trunk height	0.64 (0.30-1.38)	.25
Δ Leg length	1.26 (0.76-2.10)	.37
Bone injuries (n=36)		
Δ Height	1.47 (1.11-1.94)	*.007*
Δ Body mass	1.13 (0.75-1.71)	.55
Δ Body mass index	1.03 (0.65-1.65)	.89
Δ Trunk height	1.16 (0.85-1.57)	.36
Δ Leg length	1.41 (1.04-1.92)	*.029*
Growth plate injuries (n=19)		
Δ Height	2.14 (1.46-3.13)	*<.001*
Δ Body mass	1.23 (0.68-2.26)	.49
Δ Body mass index	1.02 (0.47-2.24)	.96
Δ Trunk height	1.31 (0.91-1.88)	.15
Δ Leg length	2.06 (1.43-2.97)	*<.001*

IRR: Incidence rate ratio. *P*-values in italic indicate significant associations.

No significant associations were apparent for changes in body mass, BMI or trunk height. This contrasts the findings by Kemper et al.,[63] where positive changes in BMI (>0.3 kg/m² per month; $P<0.05$) were associated with greater injury risk. We can speculate that these discrepancies can be attributed to sport-specific injury aetiologies (body mass changes may perhaps play a larger role in injury occurrence in contact sports) or differing training and competition demands in individual sports. Still, our findings indicate that measuring whole body mass and trunk height is of less importance in terms of injury risk in elite male youth athletics. It cannot be ruled out that related, but more specific, measures (e.g. changes in fat percentage, lean body mass or limb mass) are needed to better understand these relationships.

Increased risk of injury with lower skeletal age and greater maturity tempo

An athlete's point in the maturation process is suggested to affect the overall injury risk or of certain injury types. Skeletal age is considered the best indicator of maturity status and, on average, athletes in our study were almost two years advanced of their chronological age. As expected, the variation and range in skeletal age was larger than for chronological age. The advanced maturity could indicate a selection bias towards early maturing athletes who have a particularly large advantage in athletics since performance in many events is closely linked to speed and power.[129] Older skeletal age and greater percentage of predicted adult height was associated with a lower rate of growth plate injuries, with no differences observed for other injury categories (Table 16). This finding seems intuitive, as a greater skeletal maturity status, in general, implies fewer open growth plates and more mature bone. It can also be assumed that athletes with a greater skeletal age were more likely to have passed their period of most rapid growth, which we already identified as a risk factor for growth plate injuries. A potential interaction effect of growth rate and maturity on injury risk may therefore be present, which we explored for football players in *Paper V*.

No study has explored maturity tempo as an injury risk factor in elite youth athletes, most likely because it is difficult to track athletes longitudinally over many years. We defined maturity tempo as the change in skeletal age from one year to the next and observed variations in skeletal age advancement between athletes (0 to 3 years change over one calendar year). A change equal to one SD above the sample mean (2 years as opposed to 1 year) was associated with a 1.5 times greater rate of bone injuries (Table 16). The underlying reasons are not clear, but it can be suggested that baseline skeletal age plays a role. An athlete with a skeletal age of 14 years would, for example, have more potential for skeletal age advancement than an athlete with a skeletal age of 17 years and a younger skeletal age has already been shown to influence the rate of growth plate injuries. It may also be possible that greater skeletal age advancement is related to rapid growth in height and leg length. Explorations of our data did, however, not support this idea (low correlations between maturity tempo and growth rates for height or leg length for athlete-seasons with both measures) and they appear to represent different aspects of growth and maturation. Investigations including other maturational and developmental markers (e.g. of behaviour) would provide a more in-depth understanding of these relationships but were not examined in this study.

Table 16. Associations between absolute maturity status, relative change in skeletal age and injury risk.

	Injuries	IRR (95% CI)	*P*-value
Overall injuries			
Skeletal age	76	0.99 (0.85-1.15)	.89
% Predicted mature height	76	0.99 (0.94-1.05)	.82
Δ Skeletal age	48	0.99 (0.70-1.39)	.94
Gradual onset injuries			
Skeletal age	44	1.03 (0.84-1.28)	.77
% Predicted mature height	44	1.00 (0.93-1.07)	.92
Δ Skeletal age	31	1.13 (0.77-1.65)	.53
Sudden onset injuries			
Skeletal age	32	0.95 (0.78-1.16)	.61
% Predicted mature height	32	1.00 (0.93-1.08)	.99
Δ Skeletal age	17	0.78 (0.51-1.19)	.25
Bone injuries			
Skeletal age	34	0.88 (0.70-1.11)	.29
% Predicted mature height	34	0.95 (0.87-1.03)	.22
Δ Skeletal age	20	1.54 (1.03-2.29)	*.035*
Growth plate injuries			
Skeletal age	18	0.64 (0.48-0.85)	*.002*
% Predicted mature height	18	0.83 (0.73-0.96)	*.009*
Δ Skeletal age	12	1.12 (0.74-1.69)	.60

IRR: Incidence rate ratio. *P*-values in italic indicate significant associations.

Practical implications: Monitoring height, leg length and skeletal age may be warranted in youth athletics

Bone and growth plate injuries are common in youth athletics and in this study, younger skeletal age at the start of the season and greater change in height, leg length and skeletal age over a season were associated with a greater incidence of these. Our findings may be used to develop and implement potential preventative measures. Growth and maturation represent non-modifiable intrinsic factors and it is not possible (or at least reasonable) to influence these processes in otherwise healthy and well-nourished individuals.[108,190] The first step could therefore be to increase the awareness of risk factors among coaches, athletes, parents and medical staff. Subsequently, monitoring athletes may help identify the athletes that are the most vulnerable and regular assessments of height, leg length and skeletal age appear the most relevant based on our findings. Finally, this information can be used to adjust training content or training groups accordingly. The effects of such interventions are currently not well researched, although general training principles such as load management (progression, variation and recovery) appear important to reduce the impact of injuries in the immature and growing athlete.[7]

Main and combined effects of growth rates and maturity status on injury risk in elite male youth football (Paper V)

Studies of growth, maturation and injury risk in elite male youth football players have used broad outcome measures, rarely accounted for confounding factors and have not explored interaction effects in a robust statistical model that takes repeated athlete observations into account. The purpose of this risk factor study was therefore to explore the main and combined effects of growth rates, maturity status and chronological age on the risk of specific injury types. We included 103 players, contributing to 171 growth periods (mean duration 119 days, SD 58). The chronological age at the start of a growth period was 14.8 years (SD 1.5) and the mean skeletal age at the start of the season was 15.8 years (SD 1.9). The mean growth rate was 4.8 cm/year (SD 4.2) for height, 2.6 cm/year (SD 2.8) for leg length and 5.7 kg/year (SD 5.1) for body mass. The majority of player-seasons were classified as early maturing (40%) or on time (39%); fewer were considered mature (19%) or late maturing (2%). Relative to chronological age, players were 1.1. years (SD 1.1) advanced in skeletal age on average. Within the included growth periods, 182 index injuries and 15 929 exposure hours were recorded (11.4 injuries per 1000 h).

Growth rates over short time intervals were not associated with injury risk

Studies in elite youth football have found greater overall injury risk with monthly change in height and BMI,[63] greater risk of overuse injuries with greater change in leg length over a season for U10 through U12 players and lower risk of acute injuries with greater change in height for U13 through U15 players.[79] The period around PHV has also been associated with greater risk of overall,[76] traumatic[92] and non-contact injuries.[83] While these indicate a potential link between growth rates and injury risk, the underlying rationale for an association appears more applicable to specific injury types rather than broad injury categories. We compared six separate models (growth rates for height, leg length or body mass, adjusted for chronological or skeletal age) for seven injury categories, and did not observe any consistent combination of predictor variables (Table 17). The components for models considered to best explain injury risk for each category are presented in Figure 10. No practically relevant main effects for growth rates were observed, suggesting no effect of growth rates on injury risk. This has also been the result for some growth measures and injury categories in other football studies.[63,79]

Table 17. Relative model quality for the six combinations within each injury category.

Model	AIC	Δ AIC	w_i	*Inference*	Model	AIC	Δ AIC	w_i	*Inference*
Overall (113 events)									
Δ Body mass & Skeletal age	222.3	0.0	0.33	*Best*					
Δ Leg length & Skeletal age	223.2	0.9	0.21	*Essentially equivalent*					
Δ Height & Skeletal age	223.2	0.9	0.21	*Essentially equivalent*					
Δ Body mass & Chronological age	224.6	2.3	0.11	*Plausible alternative*					
Δ Leg length & Chronological age	225.0	2.7	0.09	*Plausible alternative*					
Δ Height & Chronological age	225.7	3.4	0.06	*Plausible alternative*					
Sudden onset (96 events)					Gradual onset (39 events)				
Δ Leg length & Skeletal age	234.8	0.0	0.41	*Best*	Δ Body mass & Chronological age	190.8	0.0	0.44	*Best*
Δ Body mass & Skeletal age	236.2	1.4	0.20	*Essentially equivalent*	Δ Body mass & Skeletal age	192.2	1.5	0.21	*Essentially equivalent*
Δ Height & Skeletal age	236.4	1.7	0.18	*Essentially equivalent*	Δ Leg length & Skeletal age	193.2	2.5	0.13	*Plausible alternative*
Δ Leg length & Chronological age	236.7	2.0	0.15	*Plausible alternative*	Δ Leg length & Chronological age	194.0	3.3	0.09	*Plausible alternative*
Δ Body mass & Chronological age	239.6	4.9	0.04	*Plausible alternative*	Δ Height & Chronological age	194.3	3.5	0.08	*Plausible alternative*
Δ Height & Chronological age	239.9	5.1	0.03	*Plausible alternative*	Δ Height & Skeletal age	194.7	3.9	0.06	*Plausible alternative*
Muscle injury (34 events)					Joint sprain (18 events)				
Δ Leg length & Chronological age	173.8	0.0	0.40	*Best*	Δ Body mass & Skeletal age	111.8	0.0	0.41	*Best*
Δ Height & Skeletal age	174.7	0.9	0.26	*Essentially equivalent*	Δ Height & Skeletal age	112.3	0.5	0.32	*Essentially equivalent*
Δ Leg length & Skeletal age	175.4	1.6	0.18	*Essentially equivalent*	Δ Leg length & Skeletal age	114.0	2.2	0.14	*Plausible alternative*
Δ Height & Chronological age	177.1	3.2	0.08	*Plausible alternative*	Δ Height & Chronological age	114.5	2.7	0.11	*Plausible alternative*
Δ Body mass & Skeletal age	177.3	3.4	0.07	*Plausible alternative*	Δ Body mass & Chronological age	118.7	6.9	0.01	*Plausible alternative*
Δ Body mass & Chronological age	180.5	6.7	0.01	*Plausible alternative*	Δ Leg length & Chronological age	121.5	9.7	0.00	*Weak support*
Fracture (13 events)					Physis injury (17 events)				
Δ Body mass & Chronological age	95.9	0.0	0.46	*Best*	Δ Body mass & Chronological age	114.8	0.0	0.46	*Best*
Δ Body mass & Skeletal age	97.9	2.0	0.17	*Plausible alternative*	Δ Leg length & Chronological age	117.3	2.5	0.13	*Plausible alternative*
Δ Height & Chronological age	98.7	2.7	0.12	*Plausible alternative*	Δ Height & Chronological age	117.5	2.6	0.12	*Plausible alternative*
Δ Leg length & Chronological age	98.7	2.8	0.11	*Plausible alternative*	Δ Leg length & Skeletal age	117.7	2.9	0.11	*Plausible alternative*
Δ Leg length & Skeletal age	99.5	3.6	0.07	*Plausible alternative*	Δ Body mass & Skeletal age	117.9	3.1	0.10	*Plausible alternative*
Δ Height & Skeletal age	99.6	3.7	0.07	*Plausible alternative*	Δ Height & Skeletal age	118.4	3.5	0.08	*Plausible alternative*

AIC: Akaike Information Criterion. ΔAIC: Akaike difference. w_i: Akaike weight.

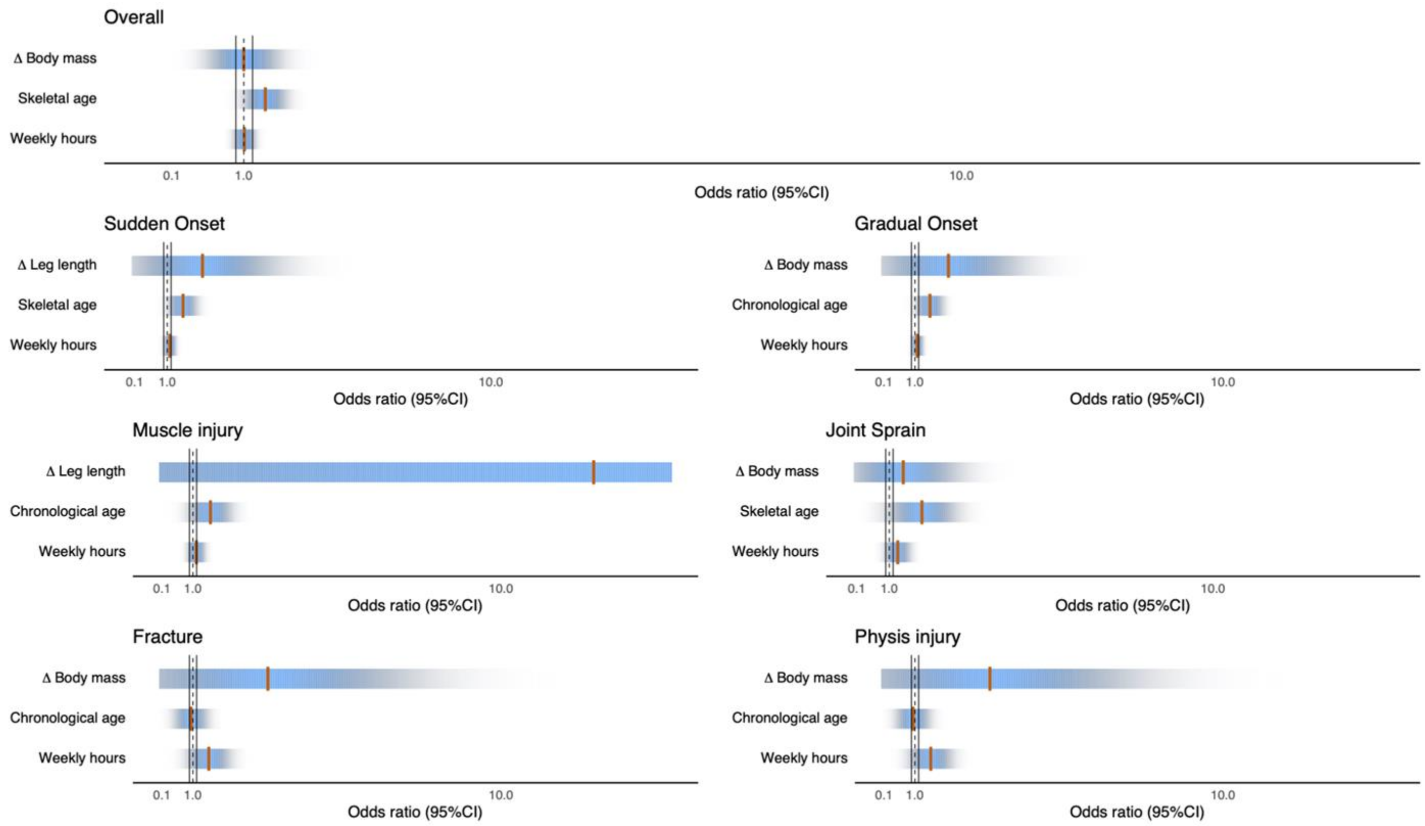

Figure 10. Model components for the best models by injury category. Density strips illustrate parameter uncertainty and vertical tick marks indicate the point estimate for the estimated odds ratio.[191]

No practically relevant associations between maturity status and injury risk

Similar to the findings in *Paper IV* for the athletics programme, we observed a dominance of early maturing or mature players (almost 60% combined) and very few late maturing players (only 2%). This bias towards selecting early maturing players is not uncommon in football academies.[171] Skeletal maturity status has been examined as an injury risk factor in two studies of elite youth football, with no difference in overall injury risk between early, on time or late maturing players.[71,90] In the study by Le Gall et al.,[71] differences were, however, observed for specific injury types. A similar injury type-specific trend was also seen in the study by Monasterio et al.,[166] where percentage of adult height was used. Along these lines, we observed main effects for skeletal age suggesting that more skeletally mature players are at greater risk of sustaining injuries. For overall injuries this was seen in the model with leg length (OR: 1.31, 95% CI: 1.01 to 1.69, P=0.038) and body mass (OR: 1.27, 1.00 to 1.62, P=0.047), for sudden onset injuries with leg length (OR: 1.44, 1.06 to 1.95, P=0.019) and body mass (OR: 1.35, 1.04 to 1.77, P=0.026), for muscle injuries with height (OR: 1.67, 1.03 to 2.69, P=0.037) and leg length (OR: 1.46, 1.00 to 2.12, P=0.049), and for joint sprains with body mass (OR: 1.91, 1.09 to 3.33, P=0.023). Although these associations were statistically significant, they were not considered practically relevant given our predefined thresholds (95% CI for OR <0.9 or >1.1). There were no significant or practically relevant effects for load or growth × age interaction.

Practical implications: Growth rates over short intervals were not related to injury risk and studies may need to consider the full growth and maturity process

This study is more rigorous than earlier studies, as it considers potentially confounding variables and applies a robust statistical approach. When age (skeletal or chronological) and load were taken into account, no main effects for growth rates on injury risk were found and no interaction effects were observed. Despite significant main effects for skeletal age, suggesting that more mature players were at greater risk of overall, sudden onset, muscle and joint sprain injuries, these were not considered practically relevant. To better understand the relationship between growth, maturation and injury risk, future studies should establish and maintain long-term surveillance programmes that cover the full growth and maturity process, including measures of anthropometric variables, maturity indicators, injuries and football exposure.

Methodological considerations

Participants and academy context

The participants were all student athletes at the Aspire Academy, participating in sports programmes targeting boys. Although this ensured a homogeneous sample, we cannot directly apply our findings to elite female youth athletes. On average, girls experience an earlier and less intense growth spurt, gain relatively more weight from fat mass during adolescence and reach maturational landmarks at an earlier age compared to boys,[108] and the effect on injury risk remains unknown. Athletes were heterogenous in terms of geographical origin, but with the majority of students from Western Asian countries. While this may reduce the generalisability of our findings to other ethnicities, the injury epidemiology of elite youth athletes in this area is not as extensively investigated as for European countries. We provide data using consensus-recommended injury categories, accounting for training and competition exposure, which can be used as a basis for studies aiming to compare injury trends within or between geographical regions.

The academy set-up should be considered when interpreting our findings, functioning as a national institute with close links to federations and national teams. Athletes were granted access to top-class facilities and a wide range of support staff already from a young age. A designated academy clinic and easy access to medical imaging and specific expertise at a specialised sports medicine hospital further differentiated this context from most elite youth settings. The single-centre nature of the studies ultimately reduced the external validity of our findings.

Study design and data analysis

Paper I aimed to investigate variations between recorders in the same injury surveillance programme. Researchers have previously indicated that adherence to definitions and different interpretations of recordable events would affect the outcomes,[40] and we used the level of research-investment as an indicator of motivation to keep records complete and adhere to a time-consuming medical-attention definition. Further investigations of extrinsic and intrinsic motivation would be beneficial and qualitative data on attitudes and beliefs among recorders would improve our understanding of underlying mechanisms. A major limitation was the lack of exposure data; therefore, to minimise the bias associated with different session duration and frequency, we had to analyse injuries per month, adjusted for age group and national team preparations. Although a best attempt was made to separate recording settings and exclude unclear months, some overlap should be expected. This was expected to appear at random and therefore apply to all recording settings. Despite the limitations, the incidence of time-loss injuries was not different between recording settings, suggesting that the overall injury picture was similar. This strengthens our confidence in our main message: the incidence of non-time loss injuries can vary greatly and depends heavily on the injury recorder.

Papers II and *III* aimed to describe injury patterns in athletics and football, respectively. Due to the applied nature of the data collection, athletes were included for different durations and some joined or left during an academic year. In athletics, this was handled by only including athletes with a complete season of surveillance data. In football, more granular exposure data were available and we could censor players during the time they were not monitored. This ensured accurate incidence and burden estimates, although the calculation of injuries per player per season and cumulative season prevalence may be slightly underestimated due to the inclusion of players with a shorter season. Repeated season observations of athletes should be considered; an athlete in the athletics programme could progress from the non-specialised group to a specialised group the subsequent season and football players naturally progressed in terms of age group. Group outcomes are therefore not independent and may be influenced by the inclusion of recurrent injuries. Still, these transitions are common in applied settings and the findings reflect the clinical reality of the academy staff. Reporting incidence, severity and burden for injury categories or groups with few events led to uncertain estimates with large CIs and should therefore be interpreted with care.

Papers IV and *V* aimed to examine the associations between growth, maturation and injuries. These were larger than most previous studies, included the best indicator for maturity status (skeletal age), considered confounding variables (age and exposure) and applied robust statistical models that could take repeated athlete observations into account. Growth and maturity data were collected primarily for applied and clinical purposes, which meant a substantial amount of assessments were missed by athletes or were not complete (presumably at random and not related to injury occurrence). This limited our sample size and ability to detect associations, especially for injury categories with few events,[48] and precluded any formal a priori sample size estimations.[192] The growth periods were determined by the availability of assessments and do not reflect the exact phases of the most rapid growth for each individual. Similarly, we were restricted to annual measures of skeletal age to calculate maturity tempo in *Paper IV*, which meant that the surveillance period (September to June) did not perfectly match the period for maturity tempo (September to September). In *Paper IV*, we could only measure growth rates over a full season, which may not account for non-linear growth patterns.[124] We addressed this in *Paper V*; however, using shorter time intervals also introduces greater variability in the calculated growth rates.[109] Sports injuries are also considered to be the result of multiple interacting risk factors (most of which we did not consider, e.g. previous injury), and there is an element of chance involved in the occurrence or non-occurrence of an event for a given period.[193] This could be a greater problem when growth, maturity and injuries are analysed for short isolated periods. To accurately identify periods of accelerated growth and maturation, long-term monitoring over the full growth and maturity process is required.[116,194]

Injury surveillance

The impact of the injury definition has been discussed extensively in the background section, and in the discussion for *Paper I*. As a direct consequence of the findings in this study, we applied time-loss definitions in subsequent investigations to ensure reliable and valid injury data in a context where multiple injury recorders were involved. The narrowing of definition came at a cost of not being able to accurately describe the extent of injuries that do not affect participation directly (especially overuse and long-standing problems), which has been demonstrated in multiple studies.[46,58,195,196]

The strengths and limitations of using medical staff as injury recorders have also been discussed in detail in previous sections. We were fortunate to have on-site physiotherapists employed for each squad and did not have to consider inequalities in medical coverage or associated logistical challenges. While it appears clear that medical staff cannot detect and record all injury problems,[49-51] we argue that the close and daily access to physiotherapists in our studies represent a best-case scenario for medical staff recording in youth sports. The verification against exposure records and electronic medical records further improved our ability to detect injuries. This is a time-consuming exercise, but one that is very important to ensure accurate injury data. Recording by physiotherapists and confirmation of diagnoses by sports medicine physicians improved diagnostic validity. The use of athlete-reported measures was not considered feasible in our specific context, but should be considered elsewhere and could potentially reveal greater or different injury problems.

Our definition of injury severity was based on return to full participation. The verification against exposure records improved accuracy, although some end dates had to be estimated. This introduced uncertainty, especially for long-term injuries (e.g. ACL tears) and the associated burden measures, although it can be argued that the estimates represent best-case scenarios assuming no exacerbations or complications prior to the return to full participation. Basing injury severity on participation, as opposed to tissue healing, also meant that two similar injuries could differ in duration and burden.[197] This approach does not take the athlete's return to prior performance level into consideration (underestimating the impact on athlete and team) and it can be difficult to determine exact return dates for injuries with mild or fluctuating symptoms.[34] This is an area where athlete-reported recording tools may be superior, since a cumulative severity score can be calculated.

Injury classification was facilitated by using an established coding system[173] and consensus categories,[29,34] although discrepancies can be expected in terms of specific diagnoses.[198,199] This may have been a particular issue in our studies as staff members came from a variety of cultural and educational backgrounds. The classification systems are not comprehensive and, although improved in the updated 2020 version,[177] the inclusion of more locations for physeal fractures (e.g. the forearm and tibia) and differentiation between apophysitis and apophyseal avulsions would be beneficial. At the moment, a sudden onset avulsion fracture and gradual onset apophysitis have the same diagnosis code, meaning that both would be classified as "acute - sudden onset" injuries. In *Papers III* and *V*, we recorded football injuries according to the original code and converted to the new classification; some granularity was therefore lost. This was, for example, the case for proximal adductor injuries, which were originally not differentiated from other adductor injuries and classified as thigh injuries. In the new SMDCS version, proximal injuries would have been classified as hip/groin injuries but it was not possible for us to retrospectively assign these accurately. In *Papers II* and *IV*, a new category was included to account for non-specific pain (i.e. where a diagnosis was not clear). This limits the comparability with other studies, where these would likely have been included in the category for other injuries. In our context, medical imaging was available, and this allowed us to differentiate different grades of muscle and bone stress injuries in the athletics studies with more precision.

The differentiation between injuries that are the result of repetitive mechanisms or specific events is not always clear and we used a dichotomous approach (acute/sudden or gradual onset). The classification of onset in *Papers III* and *V* was done retrospectively based on the specific mechanism and diagnosis and should be interpreted with this in mind. Although the IOC consensus statement recommends three categories, including one for "repetitive - sudden onset" injuries (e.g. some stress fractures),[34] we could not retrospectively allocate these. In *Papers II-V*, recurrent injuries were defined as an injury to the same location of the same type as a previous injury. We did, however, not have the athletes' full injury history available prior to joining the surveillance programme and the true proportion of reinjuries was therefore likely underestimated.

In *Papers II* and *IV*, the number of sessions (AE) was used to account for the exposure to training and competition. This is primarily because accurate duration of sessions was not available for all event groups, and the risk of sustaining an injury per hour is therefore not known. It can, however, be argued that there are advantages to comparing event groups relative to the number of sessions since the content and duration of actual training varies. An endurance session may consist of a relatively longer time in activity, while sessions in explosive events may only include a few bouts of high-intense actions separated by long rest periods. In this sense, using hours of exposure does not necessarily represent a better alternative without more detailed information about training content. In *Papers III* and *V*, the session duration was accurately recorded and since the activities were more homogenous among football players (except goalkeepers), this can be considered the best approach. A limitation for all studies is the inability to account for training intensity and load accumulated outside of the academy, which may have an impact on especially the gradual onset injuries.

Growth and maturity assessments

The use of anthropometric measures primarily collected for applied and clinical purposes meant that multiple assessors were used for the data analysed for *Papers IV* and *V*. Inter-observer variation may have created noise in the dataset (although presumably unrelated to subsequent injury status), which could have reduced our ability to detect associations. This was, however, not considered an issue based on our test-retest data from the football group, and all assessors were properly trained to minimise variations. Our measures were general; measuring specific segment lengths and relating these to injuries in the surrounding structures would have been interesting. Measuring the source of body mass changes (e.g. gain in lean body mass) could also have led to other findings. A greater frequency of measures would have enabled time-to-event analyses using the nearest anthropometric measure to an injury rather than defined growth periods. The magnitude of change over shorter periods of time may, however, not have been greater than the MDC (approximately 1 cm) and more specific and frequent measures would also have been time- and resource-demanding. It can be argued that the measurement frequency and growth periods we used represent realistic scenarios in practical settings and improve the generalisability of our findings.

Skeletal maturity

A major strength of *Papers IV* and *V* is the use of skeletal age; still, this marker is associated with some limitations. First, it involves low dose radiation, which limited frequency to maximum one measure per year. We therefore had to assume that an athlete's maturity status at the start of a season was representative for the whole season, which may not be the case given the range in change (0 to 3 skeletal age years over a calendar year) presented in *Paper IV*. Second, only the hand/wrist complex is considered in the determination of skeletal age, which may not be representative of all growth areas. For example, the pubic apophyseal plate typically closes around the age of 21 years.[150] While not feasible, measuring the skeletal maturity of bones in different body parts and relating them to injuries in the same area (e.g. ossification of the tibial tubercle in relation to Osgood-Schlatter disease) would have been desirable to better understand these associations. Third, the differences and variations in geographical origin and ethnicity between the study samples and reference sample should be considered. Between-athlete variations may have had an impact in our context with athletes from different backgrounds, although it is unlikely that this was systematically biased towards injured or not-injured athletes. Finally, the assessment of skeletal age is costly, technician dependent and not always considered appropriate for sports studies, limiting the application and comparison of our findings to other academy contexts.

Conclusions

1. A significant bias was demonstrated within an injury surveillance programme, with a greater incidence of non-time-loss and minimal (1-3 days lost) injuries when the recorder or supervisor was more invested in the data collection. Time-loss incidence was not affected and this definition should be applied whenever multiple medical staff recorders are involved.

2. Bone (stress fractures, bone stress injuries and growth plate injuries) and muscle (muscle strains/ruptures) injuries were the most burdensome in elite male youth athletics and should be considered for injury reduction programmes and risk factor studies. Event group is an important factor to consider, as the most common and burdensome injury types differ.

3. Knee and ankle sprains, thigh muscle strains/spasms, lumbosacral bone stress injuries and hip/groin physis injuries were the most burdensome in elite male youth football. The incidence and burden of muscle injuries was greater in older players, while the incidence of physis injuries was lower. General football injury reduction programmes can be recommended, although tailoring to age group may be possible.

4. Greater changes in height and leg length were related to bone and growth plate injuries in athletics; changes in trunk height, body mass and BMI were not. Younger skeletal age was associated with more growth plate injuries and greater maturity tempo with bone injuries. Awareness about these non-modifiable risk factors, regular monitoring and considerations to adjust training content for vulnerable athletes can be suggested to reduce injury risk, although the effects of such interventions are not yet explored.

5. When accounting for age (skeletal or chronological) and load, no main effects of growth rates (height, leg length or body mass) on injury risk were observed in football. More skeletally mature players had a significantly greater risk of sustaining overall, sudden onset, muscle and joint sprain injuries, although the effects were not considered practically relevant. Studies observing the full growth and maturity process may be required to better understand the role of growth and maturation on injury risk in football.

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Paper I

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ORIGINAL ARTICLE

WILEY

Involving research-invested clinicians in data collection affects injury incidence in youth football

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It is well established that differences in injury definition and recording methodology restrict comparisons between injury surveillance programmes. There is, however, little documentation of the variation that can exist between data recorders. The aim of this study was, therefore, to explore the effect on reported injuries when team recorders or supervisors are involved in research. Injury data collected prospectively over five seasons for the U16, U17, and U18 age groups in a youth football (soccer) academy were used to compare different recording settings based on the research involvement of the clinicians. A research-invested team physiotherapist reported an 8.8 times greater incidence ($P < 0.001$) of non-time-loss injuries and a 2.5 times greater incidence ($P < 0.001$) of minimal injuries (1-3 days lost) compared to a setting where neither the team physiotherapists nor the supervisor relied on the collected data for research purposes. When team physiotherapists were not invested in research themselves but were supervised by a researcher, the incidence of non-time-loss injuries and minimal injuries was 2.5 times ($P < 0.001$) and 2.0 times greater ($P < 0.01$) than in the non-invested setting, respectively. However, there were no differences between recording settings for overall incidence of time-loss injuries. The results from this study demonstrate that involving clinicians that are relying on the collected data for research purposes can significantly affect the reported rates of non-time-loss and minimal injuries. Time-loss injuries overall were not affected by research investment, and should therefore be preferred for comparisons between teams and seasons.

KEYWORDS
adolescent, athletes, documentation, epidemiology, injury prevention, male, medical staff, soccer

1 | INTRODUCTION

Robust epidemiological data are essential in the process of preventing injuries and maximizing performance,[1-3] and guidelines for injury surveillance have therefore been established.[4] Yet, differences in injury definitions and recording methods continue to restrict comparisons between contexts, teams, and seasons.[5-7] The consensus-recommended injury definitions "any physical complaint," "medical attention," and "time loss" operate on a spectre from broad to narrow, and as a consequence, injury rates differ based on the chosen definition.[5,8,9] Similarly, outcomes are affected by the method used for capturing injuries and those responsible for documenting them in sporting populations.[10-18]

When a broad injury definition is applied with multiple recorders there is going to be differences in interpretation.[5,8] An incident could be considered insignificant and simply a normal response to training by one clinician, while another could meticulously note down every single contact with a player. This could be related to the motivation of the recorder,[8] and when clinicians are involved as recorders, their personal interest in the study outcomes, role in a research project or intensity of the supervision could be thought to lead to variations in the collected data.

Previous studies have assessed the strengths and limitations of different injury definitions, and in general, narrow definitions (eg "missed match" or "time loss") are considered superior in terms of reliability and cost efficiency, while broad definitions (eg "medical attention" or "any physical complaint") are more appropriate for capturing overuse and mild conditions.[5,8,9,19] Comparisons have also been made between different recording methods, such as reporting by technical delegates, parents, coaches, medical staff or players themselves, and collectively their findings indicate that different methods capture different conditions and therefore provide contrasting results.[10-18] There is, however, little documentation of discrepancies within the same injury surveillance programme, where the definition and method is designed to be consistent.

Variation between data recorders has widely been acknowledged as a limitation in previous epidemiological research. The aim of this study was, therefore, to explore the effect on reported injuries when team recorders or supervisors in the same injury surveillance programme are involved in research relying on the collected data.

2 | METHODS

2.1 | Study population

This study used injury data collected prospectively over five seasons in an elite youth football (soccer) academy in the Middle East. The participants in the injury surveillance programme were full-time and part-time players registered with the U16, U17, and U18 squads for the 2012/13 through the 2016/17 seasons (Table 1). Ethical approval was obtained from the Anti-Doping Lab Qatar Institutional Review Board (IRB Application #E20140000012), and written informed consent was obtained from all players and their guardians.

Full-time players (student athletes) participated in 8-11 weekly academy sessions (6-8 football sessions and 2-3 strength & conditioning sessions) while part-time players (not registered students with the academy's school) participated in 6-7 academy sessions (5 football sessions and 1-2 strength & conditioning sessions). In addition, both full-time and part-time players participated in local club games on a weekly basis and 1-2 academy matches against international clubs every third week. A player was assumed to have participated with the same squad throughout the season, and although possible, training and playing matches with other age groups was a rare exception. In these cases, injuries were still reported for the age group the player was registered with for the season.

TABLE 1 Summary of months, players, and injuries included in the final analyses (FT, full-time players; PT, part-time players)

	Months	No. of players (FT/PT)	No. of injuries (FT/PT)
U16			
2012-2013	9	28 (15/13)	49 (31/18)
2013-2014	10	28 (26/2)	165 (160/5)
2014-2015	8	26 (24/2)	65 (60/5)
2015-2016	11	24 (15/9)	113 (89/24)
2016-2017	8	22 (11/11)	42 (19/23)
U17			
2012-2013	10	27 (17/10)	53 (41/12)
2013-2014	11	26 (12/14)	48 (30/18)
2014-2015	10	30 (28/2)	190 (188/2)
2015-2016	9	25 (23/2)	84 (80/4)
2016-2017	5	25 (16/9)	16 (14/2)
U18			
2012-2013	10	33 (19/14)	68 (48/20)
2013-2014	10	23 (18/5)	46 (37/9)
2014-2015	10	28 (13/15)	50 (34/16)
2015-2016	11	28 (21/7)	150 (139/11)
2016-2017	5	33 (18/15)	28 (20/8)
Total	137	406 (276/130)	1167 (990/177)

2.2 | Injury surveillance

The injury definition was adopted from the football consensus statement,[4] and a recordable incident was defined as any musculoskeletal complaint sustained by a player that resulted in a clinical examination by a member of the academy medical staff, regardless of time loss. Every academy age group had their own physiotherapist and access to medical doctors at all times. All injuries were diagnosed by a medical doctor and entered continuously in a team injury database (Microsoft Excel®) throughout the season by the designated team physiotherapist based on a standardized injury report form. The form contained information on player demographics (age group and status with the academy), as well as the injury characteristics and circumstances (date of injury, discharge date, number of days lost, session type, final diagnosis, and injury site).

2.3 | Data extraction and classification

Entries from the team injury databases for the seasons and squads of interest were matched with the player's squad assignment and status (full time vs part time) as registered in the central academy database. Duplicates and multiple entries from the same incident were removed, along with illnesses and entries from players who were not full-time or part-time players (trial players and national team players that were not associated with the academy). Injuries were classified as either time loss or non-time loss based on the actual number of days lost from training sessions and matches, as reported by the physiotherapist. In cases where this was not reported, the number of days lost was calculated using the date of injury and date of return to full participation. The same approach was used to categorize severity of time-loss injuries (minimal: 1-3 days, mild: 4-7 days, moderate: 8-28 days, severe: >28 days).[4] If a case was not resolved at the time of data extraction, the treating clinician provided an estimate for the date of return to full participation in order to calculate the number of days lost.[4]

The final diagnosis and injury site were used to categorize every injury based on body region (head/neck, upper limb, trunk, lower limb).[4] The injury context was based on the session in which the injury was reported to occur (academy, club, national team, other). Other injuries, which were related to participation in activities outside of football or were non-sport injuries, were included as they made up a considerable number of complaints seen by the academy staff.

2.4 | Comparison of injury recording settings

Accurate training exposure data were not available for all five seasons, and injuries were therefore analyzed by squad month according to the season (2012/13 to 2016/17), age group (U16, U17 or U18) and month of injury (Figure 1) to account for different season durations.

Three recording settings were identified, based on the level of research investment in the injury surveillance programme. The first setting was when the injury recorder (one of the team physiotherapists) relied on the collected data for a specific research project ("Invested clinical recorder"). The second setting was when injuries were recorded by the other non-research-invested team physiotherapists under close supervision by the senior physiotherapist who relied on the collected data for research purposes ("Invested supervisor"). The third setting was when injuries were recorded without involvement of a physiotherapist or supervisor relying on the data for specific research projects ("No research-invested supervision").

		JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
2012-2013	U16			REC	2	2	2	2	2	2	2	2	2	INC
	U17		INC	2	2	2	2	2	2	2	2	2	2	INC
	U18		INC	1	1	1	1	1	1	1	1	1	1	INC
2013-2014	U16		INC	1-N	1-N	1	1	1	1	1	1	1	1	
	U17		2	2	2	2	2	2	2	2	2	2	2	INC
	U18		2-N	2-N	2-N	MON	2	2	2	2	2	2	2	INC
2014-2015	U16	REC	REC	REC	REC	2	2	2	2	2	2	2	2	INC
	U17	INC	1-N	1-N	MON	1	1	1	1	1	1	1	1	INC
	U18			1	1	1	1	1	1	1	1	1	1	INC
2015-2016	U16		2-N	2-N	2-N	2	2	2	2	2	2	2	2	INC
	U17			INC	2	2	2	2	2	2	2	2	2	INC
	U18		1-N	1-N	1-N	1	1	1	1	1	1	1	1	
2016-2017	U16				INC	3	3	3	3	3	3	3	3	
	U17				INC	3	3	3	3	3	REC	REC	REC	
	U18				INC	3	3	3	3	3	REC	REC	REC	

FIGURE 1 Overview of all squad months that were evaluated for inclusion in the final analyses, by season and age group. Grey fill represents excluded months and reason for exclusion is provided (REC = Unclear recording setting, INC = Incomplete month, with more than 1/3 of the days outside of season, MON = Unclear month type, where less than 2/3 of the days were either national team preparation or standard academy). Numbers indicate the allocated injury recording setting for the included months (1: Research-invested clinical recorder, 2: Research-invested supervisor, 3: No research-invested supervision). "N" indicates that the squad was preparing for an upcoming Asian Football Confederation (AFC) qualification or championship with the national team, which was added as a co-factor in the statistical model

Age group was included as a co-factor when comparing recording settings to account for potential differences in injury characteristics, which previously have been observed in football academies in Europe and the Middle East.[20-22] National team tournament preparation was added as a co-factor given the unique organization of this specific football academy and national football association. The academy teams were commonly organized based on upcoming international target tournaments; the AFC (Asian Football Confederation) qualifications and championships, involving the U17 and U19 national teams. In the months leading up to these tournaments football activity revolved around the national team, with a different training environment compared with the rest of the academic year. Typically, both players and medical staff from the academy squads were involved in the national teams. Physiotherapists had more contact time with players during these training camps, and players could potentially have had easier access to and a lower threshold for seeking medical attention. National team preparation month was only added as a co-factor if the academy team physiotherapist was also the national team physiotherapist for the corresponding age group.

Any month with a registered training session for the given season and squad was considered eligible for inclusion, and exclusion was performed stepwise based on three criteria (Figure 1). To start with, months for which we could not confidently assign a single recording setting were excluded. Subsequently, we excluded months where the off-season period represented more than 1/3 of the days, using the first (for the start of the season) or last (for the end of the season) training session of the season as the cut-off dates. Finally, months with unclear co-factors were removed. This concerned only the month type ("national team preparation month" or "academy month"), and a 2/3 definition was applied. For this calculation, the dates of the first national team session and last tournament match were used. The choice of cut-off for these exclusion criteria was agreed upon following discussions with the involved medical staff.

2.5 | Statistical analysis

Injury counts for each outcome category were used to compare injury recording settings. To calculate incidence, the nominator consisted of injury counts for the given category and/or recording setting, while the denominator (exposure) consisted of the number of player months for the corresponding squads. Player months were standardized so that the incidence represents the number of injuries per player for a 31-day month. Incidence is presented with 95% confidence intervals (CI). A Poisson regression model was used to examine the effect of different recording settings, adjusting for potential co-factors (age group and month type). Odds ratios for the co-factors age group and month type were generated in the regression model, and are presented for overall injuries in order to inform on the impact they had on the statistical comparisons. Pairwise comparisons between recording settings were made between the estimated marginal means applying a Bonferroni post hoc correction, where P-values < 0.05 were considered significant.

3 | RESULTS

3.1 | Squad months, players and exposure

Figure 1 gives an overview of squad months. A total of 168 months were identified for potential inclusion for the seasons and age groups of interest. Of these, 31 were excluded (11 with unclear injury recording setting, 18 with > 1/3 of days outside of season, 2 with < 2/3 of days as either national team preparation or academy), resulting in 137 squad months included in the final analyses.

A total of 374 player seasons (267 full time, 107 part time) were identified in the database. After reviewing the original squad lists with the associated medical staff, 32 missing player seasons (9 full time, 23 part time) were included. This resulted in a total of 406 player seasons (211 unique players; mean 1.8 ± 0.9 seasons per player) in the final analyses (Table 1).

The exposure for the five seasons was 3615.2 player months overall (one player month equals one player participating for one normalized 31-day month), where full-time and part-time players contributed with 2473.1 and 1142.0 player months, respectively. The overall exposure was 1462.4 player months for the research-invested clinical recorder setting (n = 51 squad months), 1702.8 for research-invested supervisor (n = 68 squad months) and 450.0 for No research-invested supervision (n = 18 squad months).

3.2 | Injuries

The initial extraction from team injury databases resulted in a total of 1357 incidents recorded by the academy physiotherapists. Of these, 53 entries were excluded (3 duplicates, 6 multiple entries for the same incident, 1 illness, 38 entries for players who were not full-time or part-time students, 4 entries with date of injury outside the study period, 1 blank entry), leaving 1304 entries in the final data set. In 40 cases, actual day loss was not reported by the clinician, and the dates of injury and return to full participation were used to calculate the number of days lost. There was one case where the player had not returned to play at the time of data extraction, and context was missing for one injury.

The final sample consisted of 1167 injury entries for the included months (Table 1). Frequency, distribution and incidence for each injury category are described in Table 2 for all players combined, full-time players and part-time players.

TABLE 2 Frequency, distribution, and incidence (injuries per player month) by category for all players combined, full-time players (FT) and part-time players (PT) (Minimal: 1-3 d, Mild: 4-7 d, Moderate: 8-28 d, Severe: >28 d)

	No. of injuries			Distribution (%)			Injuries per player month (95% CI)		
	All	FT	PT	All	FT	PT	All	FT	PT
Overall									
All injuries	1167	990	177				0.32 (0.30-0.34)	0.40 (0.38-0.43)	0.15 (0.13-0.18)
Time loss									
Time loss	698	570	128	59.8	57.6	72.3	0.19 (0.18-0.21)	0.23 (0.21-0.25)	0.11 (0.09-0.13)
Non-time loss	469	420	49	40.2	42.4	27.7	0.13 (0.12-0.14)	0.17 (0.15-0.19)	0.04 (0.03-0.06)
Severity of time loss									
Minimal	244	205	39	20.9	20.7	22.0	0.07 (0.06-0.08)	0.08 (0.07-0.10)	0.03 (0.02-0.05)
Mild	126	101	25	10.8	10.2	14.1	0.03 (0.03-0.04)	0.04 (0.03-0.05)	0.02 (0.01-0.03)
Moderate	186	150	36	15.9	15.2	20.3	0.05 (0.04-0.06)	0.06 (0.05-0.07)	0.03 (0.02-0.04)
Severe	142	114	28	12.2	11.5	15.8	0.04 (0.03-0.05)	0.05 (0.04-0.06)	0.02 (0.02-0.04)
Body region									
Head/neck	28	25	3	2.4	2.5	1.7	0.01 (0.01-0.01)	0.01 (0.01-0.01)	0.00 (0.00-0.01)
Upper limb	85	74	11	7.3	7.5	6.2	0.02 (0.02-0.03)	0.03 (0.02-0.04)	0.01 (0.00-0.02)
Trunk	73	63	10	6.3	6.4	5.6	0.02 (0.02-0.03)	0.03 (0.02-0.03)	0.01 (0.00-0.02)
Lower limb	981	828	153	84.1	83.6	86.4	0.27 (0.25-0.29)	0.33 (0.31-0.36)	0.13 (0.11-0.16)
Context									
Academy	539	451	88	46.2	45.6	49.7	0.15 (0.14-0.16)	0.18 (0.17-0.20)	0.08 (0.06-0.09)
Club	326	269	57	27.9	27.2	32.2	0.09 (0.08-0.10)	0.11 (0.10-0.12)	0.05 (0.04-0.06)
National team	259	239	20	22.2	24.1	11.3	0.07 (0.06-0.08)	0.10 (0.08-0.11)	0.02 (0.01-0.03)
Other	42	30	12	3.6	3.0	6.8	0.01 (0.01-0.02)	0.01 (0.01-0.02)	0.01 (0.01-0.02)

3.3 | Age group and month type as co-factors

Both co-factors (age group and month type) contributed significantly to the statistical model for overall injuries ($P < 0.001$). The overall incidence for the U16, U17, and U18 age groups was 0.38 (0.34 to 0.41), 0.33 (0.30 to 0.36) and 0.27 (0.24 to 0.30) injuries per player month, respectively. Using the U18 age group as the reference, the odds ratio was 1.7 (1.4 to 2.0) for U17 players and 1.9 (1.6 to 2.2) for U16 players. The overall incidence for academy months was 0.28 (0.27 to 0.30) injuries per player month, while the incidence for national team preparation months was 0.70 (0.61 to 0.79). When standard academy month was set as the reference, the odds ratio was 2.1 (1.8 to 2.5) for a national team preparation month.

3.4 | Injury recording setting

Overall, the adjusted incidence for the research-invested clinical recorder setting was 0.60 (0.55 to 0.65; n = 623 injuries) injuries per player month, which was significantly greater ($P < 0.001$) than both the research-invested supervisor and No research-invested supervision settings, where the incidence was 0.32 (0.29 to 0.36; n = 458) and 0.27 (0.22 to 0.34; n = 86), respectively.

The incidence of time-loss injuries was not significantly different between any recording settings (Invested recorder 0.24, 0.21 to 0.28; Invested supervisor 0.21, 0.18 to 0.24; Non-invested 0.20, 0.15 to 0.25) (Figure 2). For non-time-loss injuries, the incidence for the research-invested clinical recorder setting (0.35, 0.31 to 0.39) was 3.5 times greater than the research-invested supervisor setting (0.10, 0.08 to 0.12; $P < 0.001$) and 8.8 times greater than the No research-invested supervision setting (0.04, 0.02 to 0.07; $P < 0.001$). Non-time-loss incidence was 2.5 times greater for the research-invested supervisor setting compared to the No research-invested supervision setting ($P < 0.001$).

For severity categories of time-loss injuries, only minimal injuries showed differences between recording settings (Figure 3). Compared to the No research-invested supervision setting (0.04, 0.02 to 0.07), the Research-invested supervision setting (0.08, 0.06 to 0.10) resulted in 2.0 times greater adjusted incidence ($P < 0.01$) while the research-invested clinical recorder setting (0.10, 0.09 to 0.13) resulted in 2.5 times more minimal injuries per player month ($P < 0.001$).

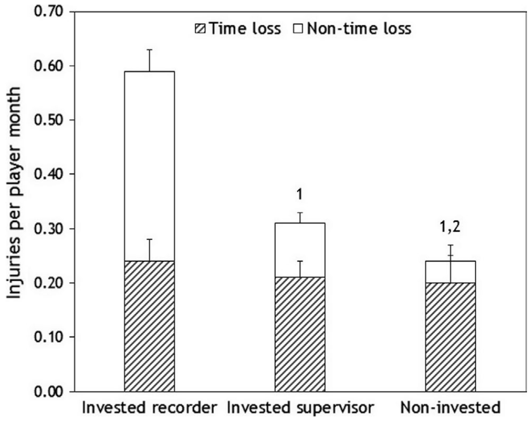

FIGURE 2 Comparison of adjusted incidence (95% CI) for time-loss and non-time-loss injuries between the three injury recording settings. 1: Significantly lower than Research-invested clinical recorder, 2: Significantly lower than Research-invested supervisor

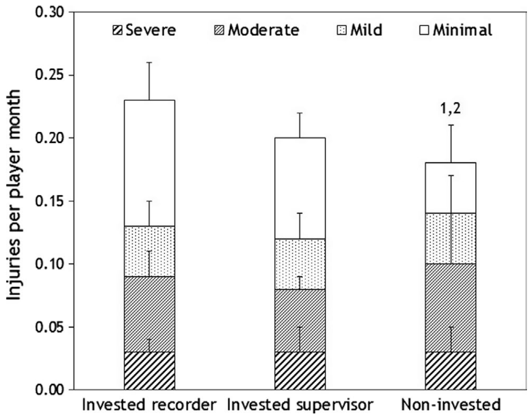

FIGURE 3 Comparison of adjusted incidence (95% CI) for time-loss severity categories between the three injury recording settings. Severity categories are based on the number of days lost (Minimal: 1-3 d, Mild: 4-7 d, Moderate: 8-28 d, Severe: >28 d). 1: Significantly lower than Research-invested clinical recorder, 2: Significantly lower than Research-invested supervisor

Comparisons of incidence between the recording settings for body region and injury context are presented in Table 3.

4 | DISCUSSION

This is the first study to examine the variations in injury incidence between medical staff recorders with different levels of research-investment within the same surveillance program. Based on 1167 injuries from 406 academy player seasons, the results demonstrated that the incidence of non-time-loss injuries and injuries with short day loss (1-3 days) was significantly greater when research-invested clinicians were involved in the data collection. The incidence of time-loss injuries overall was, in contrast, similar between clinicians, irrespective of research investment.

4.1 | Injury incidence depends on the level of research investment

Orchard & Hoskins[8] suggested that methodological limitations are responsible for discrepancies in injury incidence between studies applying medical attention definitions. They argue that data recorders will respond to less serious incidents differently, either due to adherence with the injury definition or a pragmatic approach to what is considered a real injury. As a consequence, the reliability of the surveillance system will suffer. This argument is supported by the findings in the current study, where the incidence of less severe injuries (non-time loss and minimal) was significantly greater with increasing involvement of research-invested clinicians, while the incidence of time-loss injuries was the same, independent of the recording setting.

Non-time-loss incidence was especially sensitive to different recording settings, and a research-invested clinical recorder reported almost nine times greater incidence compared to the setting where research-invested clinicians were not involved as data recorders or as a supervisor. In practical terms, the adjusted injury rates from the most invested setting imply that an academy squad with 25 players could expect around 135 injuries overall during a 9-month season, where approximately 54 injuries would result in time loss from training sessions and/or matches and 79 would not. In comparison, the adjusted injury rates from the more common setting, where team physiotherapists are not invested in the research project or supervised by a researcher, suggest that the squad could expect around 61 overall injuries, where approximately 45 would lead to time loss and only 9 would not. The large variations in overall and non-time-loss injuries essentially render comparisons between teams and seasons meaningless, as it is nearly impossible to tell whether the variation was a result of real differences in injury rate, for example as a result of a new training regime and/or prevention programme, or was simply due to the rigor of recording by the assigned team physiotherapist.

4.2 | Upper limb injuries may be more often neglected

As discussed above, the variations in the number of recorded injuries could be caused by clinicians considering certain injuries more or less relevant to record. In support of this, a greater incidence of upper limb injuries was revealed for the

TABLE 3 Adjusted incidence (injuries per player month) for body region and context with pairwise comparisons of the three different injury recording settings (1: Research-invested clinical recorder, 2: Research-invested supervisor, 3: No research-invested supervision)

	Invested recorder	Invested supervisor	Non-invested	Pairwise comparisons		
	Adjusted incidence (95% CI)	Adjusted incidence (95% CI)	Adjusted incidence (95% CI)	*P* (1-2)	*P* (1-3)	*P* (2-3)
Body region						
Head/neck	0.02 (0.01-0.03)	0.01 (0.00-0.02)	0.00 (0.00-0.03)	0.31	0.08	1.00
Upper limb	0.04 (0.03-0.06)	0.02 (0.01-0.03)	0.03 (0.02-0.06)	<0.001	0.74	0.52
Trunk	0.03 (0.02-0.04)	0.02 (0.01-0.03)	0.02 (0.01-0.04)	0.51	0.72	1.00
Lower limb	0.51 (0.46-0.56)	0.27 (0.24-0.31)	0.21 (0.17-0.27)	<0.001	<0.001	0.14
Context						
Academy	0.23 (0.20-0.26)	0.09 (0.07-0.11)	0.10 (0.07-0.14)	<0.001	<0.001	1.00
Club	0.07 (0.05-0.09)	0.06 (0.04-0.08)	0.04 (0.02-0.06)	0.49	<0.01	0.07
National team	0.17 (0.14-0.20)	0.08 (0.07-0.10)	0.01 (0.00-0.05)	<0.001	<0.001	<0.001
Other	0.01 (0.00-0.02)	0.02 (0.01-0.03)	0.02 (0.01-0.04)	0.71	1.00	1.00

most research-invested setting (invested clinical recorder) compared with the setting where physiotherapists were supervised by a clinical researcher but were not invested in research themselves. Injuries to the upper limb may not be considered crucial to football participation, and it could therefore be suggested that these are more likely to be neglected when reporting injuries. This sports-specific aspect has been emphasized previously as a limitation for time-loss definitions,[23] as some injuries would allow a player to fully train and compete while still undergoing treatment or rehabilitation. At the same time, there were no differences for head/neck and trunk injuries, and a consistent trend for unequal reporting was only observed for injuries to the lower limb.

The differences between recording settings in terms of injury context were especially apparent for national teams, with 17 times greater overall incidence in the most invested compared to the least invested setting. Although important for understanding the current dataset, it should be interpreted with caution given the very specific and complex interplay between academy teams and national teams in this setting. As mentioned previously, medical staff, and players frequently crossed over between the two, and even though national team tournament preparation months were controlled for, it was not possible to accurately control for national team activity for the remainder of the season. It is also possible that invested physiotherapists were more likely to be recruited for national team duty.

4.3 | Should only time-loss incidence be used for comparisons?

The overall incidence for players in this specific football academy can be translated to approximately 2.9 injuries per player over a typical 9-month academy season from September to May. As mentioned in the introduction, one of the main issues with injury surveillance studies is the inability to confidently compare results to similar programmes and assess whether or not these numbers are normal for academy players. Given the stability across recording settings that was demonstrated in the current study, using time-loss injuries alone for comparisons would be considered the most appropriate. In this football academy the incidence of time-loss injuries equated to approximately 1.7 per player/season, which can be considered normal based on the injury incidence of 1.35 (U16) and 2.14 (U18) reported in English youth academies.[22]

The incidence of non-time-loss injuries (approximately 1.2 per player/season) suggests that these were less frequent than time-loss injuries and accounted for around 40% of the injuries seen by the academy staff. As was highlighted in the present study, this could vary significantly depending on the setting of the injury recording and should therefore not be assumed to accurately represent the real situation. The proportion of non-time-loss injuries in this academy was also higher than what was reported for an English football academy, where only 12% of the injuries did not result in days lost.[24] Following the points made previously, these comparisons provide little value, as we do not know how invested the data recorders were, even though the injury definition and recording methodology were the same.

If non-time-loss injuries are neglected in epidemiological studies due to questionable reliability, it is important to understand the consequences of narrowing the definition. Even though a time-loss definition is arguably the most reliable, it is vulnerable to differences in training and match schedules and season phase and does not capture situations where players participate with pain or use painkillers in order to play.[5,8] It is also less suited for individual sports, where athletes compete less frequently and can modify their training on a more individual basis.[5,8] The time-loss definition captures what many consider the most relevant injuries affecting sporting participation, but will not capture the full extent of mild and overuse issues that athletes face.[19] Applying a medical attention definition is suggested to provide a better indication of the true burden of injuries,[5,9] and in the current injury surveillance programme a broad medical attention definition was considered the most appropriate, given the high proportion of overuse injuries in academy athletes in the Middle East.[20,25] This definition also provides a better representation of the staff workload than a time-loss definition alone would,[5] which could be valuable in the process of allocating staff and justifying jobs.

4.4 | Methodological considerations

This study included a large dataset from several teams, with very few missing data points. A consistent methodology was applied over all five seasons, and the broad coverage ensured equal treatment opportunities with experienced physiotherapists as data collectors. Even so, there are some important methodological limitations to take into account when interpreting the results.

First, the specific context and cultural considerations can limit the applicability of the findings to other football academies and surveillance programmes. The reader is therefore encouraged to compare this setting with their own practice and evaluate the similarities and differences. Second, retrospective examination of injury databases and squad lists has limitations even though the data were recorded prospectively by the physiotherapists and academy staff. It is not certain that the squad lists for a season were accurate for each month and accurate training exposure data could not be obtained. Even though the best effort was made to separate injury recording settings, injury cases could be handled by multiple clinicians, and physiotherapists exceptionally covered training sessions and matches for other teams than their own. Third, the analyses were based on assumptions that there were no systematic differences in the training regime or injury prevention programmes that would affect one recording setting more than another. There was only one season with non-invested supervision; however, the similarity in time-loss incidence suggests that the injury pattern was not very different between seasons. Finally, there was no examination of underlying factors for the level of research-investment (eg intrinsic and extrinsic motivation, academic qualifications), and this classification is solely based on whether or not the clinician was involved in research projects using the collected data.

4.5 | Perspectives

This study demonstrates that the incidence of overall and non-time-loss injuries can increase substantially if recorders or supervisors are invested in research relying on the collected data. Time-loss injuries were not affected by research involvement, and should therefore be preferred for comparisons between teams and seasons.

Although no injury surveillance system will capture all injuries, estimating the direction and extent of bias by underreporting is important.[26] The findings from this study are therefore relevant for all practitioners and researchers involved in injury surveillance programmes using multiple data recorders, and should be taken into account when interpreting results from epidemiological studies. Over several seasons with inevitable staff turnover in clinical settings, variation between data recorders has the potential to compromise the outcomes of any otherwise well-designed surveillance programme. If medical staff is recording injuries, using a broad injury definition, it is important to ensure that recorders receive sufficient training, and that there is a clear consensus about what constitutes a recordable injury.

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Paper II

Injury characteristics in male youth athletics: a five-season prospective study in a full-time sports academy

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ABSTRACT

Objectives To describe the injury characteristics of male youth athletes exposed to year-round athletics programmes.

Methods Injury surveillance data were prospectively collected by medical staff in a cohort of youth athletics athletes participating in a full-time sports academy from 2014–2015 to 2018–2019. Time-loss injuries (>1 day) were recorded following consensus procedures for athletics. Athletes were clustered into five event groups (sprints, jumps, endurance, throws and non-specialised) and the number of completed training and competition sessions (athletics exposures (AE)) were calculated for each athlete per completed season (one athlete season). Injury characteristics were reported overall and by event groups as injury incidence (injuries per 1000 AE) and injury burden (days lost per 1000 AE).

Results One-hundred and seventy-eight boys (14.9±1.8 years old) completed 391 athlete seasons, sustaining 290 injuries. The overall incidence was 4.0 injuries per 1000 AE and the overall burden was 79.1 days lost per 1000 AE. The thigh was the most common injury location (19%). Muscle strains (0.7 injuries per 1000 AE) and bone stress injuries (0.5 injuries per 1000 AE) presented the highest incidence and stress fractures the highest burden (17.6 days lost per 1000 AE). The most burdensome injury types by event group were: bone stress injuries for endurance, hamstring strains for sprints, stress fractures for jumps, lesion of meniscus/cartilage for throws and growth plate injuries for non-specialised athletes.

Conclusion Acute muscle strains, stress fractures and bone stress injuries were identified as the main injury concerns in this cohort of young male athletics athletes. The injury characteristics differed between event groups.

INTRODUCTION

Athletics is one of the most universal sports at the youth level, with athletes from more than 170 countries participating in the last Youth Olympic Games.[1] Early sports specialisation and intensive training may expose young athletes to a greater risk of injuries,[2–6] and injury surveillance reveals essential for determining injury risks and prevention strategies.[7] However, youth athletes are a difficult population to study due to the autonomous nature of athletics and the lack of structured sports medicine and science programmes for youth categories. As a consequence, youth athletics studies are scarce and most of them rely on self-reported questionnaires[6 8–12] or are included in multiple sport studies,[13–15] while most studies in adult athletes arise from major athletics competitions.[16–18] Although the aetiology of injuries in youth athletes may differ to that of their senior counterparts due to the substantial biological changes happening during adolescence, a causal relationship between growth and injuries remains unclear.[19–22]

Injury definitions and data collection methods vary substantially across youth athletics studies, making comparisons and interpretation of results difficult. Both non time-loss[11 12 15] and time-loss injury definitions have been used, with time-loss cut-offs varying from 1 day[10 13 14 23] to 1 week[8 24] and 3 weeks.[6 9] Many studies rely on retrospective data[6 8 9] and studies applying the recommended prospective design often report athletics injuries for one season or less[10–12 25] or as part of multiple-sports cohorts.[13–15] However, the heterogeneity in samples is probably one of the most important limitations for interpreting results, since athletes from different age groups, training contexts and athletics disciplines are frequently grouped together without considering potential confounding factors.

Large homogeneous cohorts with systems that monitor training exposure (TE) and injury incidence are warranted in youth athletics. While other sports are organised in full-time youth sports academies[26 27] athletics is rarely part of such structured full-time programmes. Most of the injury surveillance data from youth academies is collected in football[28–30] or multiple sports combined,[21 31] therefore, the injury characteristics of youth athletes participating in full-time athletics programmes is unknown. For this reason, a prospective injury surveillance system was implemented in a youth athletics academy as per the athletics consensus[32] to describe the extent and characteristics of injuries of adolescent athletics athletes exposed to year-round training programmes.

METHODS

Study design

A prospective cohort design covering five consecutive seasons (2014–2015 through 2018–2019) of the athletics programme in a youth sports academy based in the Middle East was used for this study. The athletes had direct access to the medical staff both in training and at the onsite medical facilities. A team of five physiotherapists and one Sports Medicine physician working full-time within the academy worked with athletics during the study period and were trained on injury data collection procedures.

Study population

The athletics programme included adolescent athletes ranging from 12 to 18 years recruited through a talent identification programme. Athletes followed comprehensive year-round training plans, typically consisting of eight sessions per week alongside a full-time educational curriculum. Only full-time athletes completing at least one entire season (from September to June, with some extending the season for summer competitions) were included in the study. The time between the beginning of the academic year and the end of season was considered as 'one athlete-season'. Written informed consent for the storage and analysis of data for research purposes was obtained from the athletes' guardians at the start of each season, but the patients did not participate in the study design or interpretation.

Injury and athletic exposure data collection

An injury was defined as 'any recorded medical attention sustained during training or competition that results in an athlete being unable to participate in athletics activities, as planned by coaching staff, for ≥1 day'. A diagnosis based on the Sports Medicine Diagnostic Coding System (SMDCS)[33] was provided by the physician, who had direct access to a fully equipped Sports Medicine Hospital within the same facility. A standardised template was designed following the criteria from the consensus statement for injury data collection in athletics,[32] including information about the date of injury and return to full participation, injury type (an additional category was created for 'non-specific pain'), injured body part, activity during which the complaint was reported (training, competition or non-sport) and mode of onset (acute if the onset could be clearly identified or gradual if the onset could not be identified). Five main tissue types were defined based on the SMDCS[33]: bone, muscle, joint/ligament, tendon and miscellaneous (other). Although labelled as different injury types in this study, bone stress injuries (BSI, categorised under 'other bone injuries') and stress fractures are considered just different stages of the bone stress continuum[34] (BSI=grades 1–3 in MRI[35]; stress fractures=grade 4) and may be referred as 'overuse bone injuries'.

All injury details were subsequently entered into a password-protected electronic athlete management system (Smartabase, Fusion Sport, Australia) that was updated daily by the team physiotherapists. Entries to the database were coded according to the consensus definitions[32] as either an index injury (first recordable episode of a physical complaint sustained by an athlete requiring medical attention), exacerbation (worsening in the state of an existent index injury) or reinjury (a repeat episode of a fully recovered index injury). The athlete was considered fully recovered from an injury when able to complete the planned session with minimal or no limitations. Injury severity was determined based on days lost as minimal (1–3 days lost), minor (4–7 days), moderate (8–28 days), serious (29 days to 6 months) or long term (>6 months).[32] The number of days lost for all exacerbation episodes linked to an index injury were summed; for example, an Achilles tendinopathy with 7 days lost and one exacerbation episode with 10 days lost would be accounted as one injury with 17 days lost.

Athletes were clustered into their respective training groups for each given season; Endurance, Sprints, Jumps, Throws and Non-specialised (athletes following a generic athletic development programme). Athletics exposures (AE) were computed by summing the total number of training sessions and competitions attended during the season for each athlete, based on the attendance recorded by their coaches and further divided into training

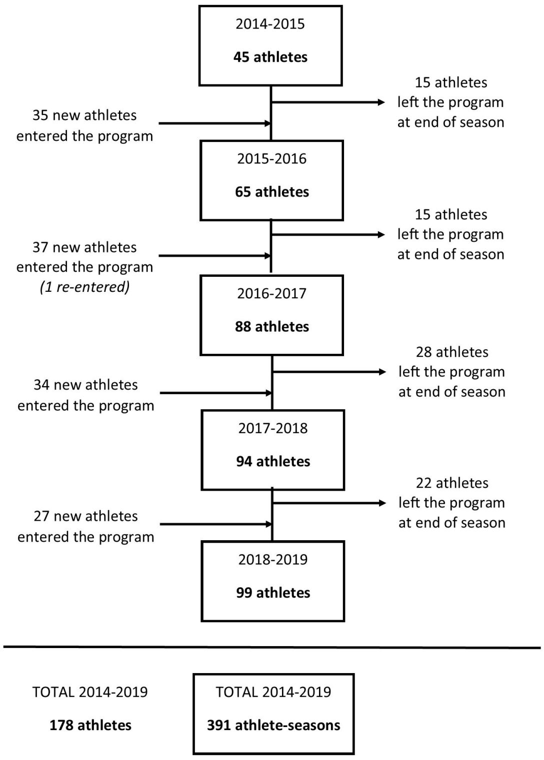

Figure 1 Chart flow of athletes participating in the study for each season.

exposure (TE) and competition exposure (CE). A session was considered 'attended' when the athlete was able to complete normal training or with minimal limitations and AE were not accumulated while injured until back to regular training.

Statistical analysis

Descriptive statistics included season prevalence, percentage distributions, incidence rate, injury burden,[36] median days lost and injury occurrence by date for the five-season period combined and for each subcategory. Season prevalence was expressed as the proportion of athletes sustaining at least one time-loss injury during a given season. Injury incidence was calculated as the number of injuries per 1000 AE and injury burden as the number of days lost per 1000 AE, both with a 95% CI using Byar's approximation of the exact limits as described by Rothman.[37] The median number of days lost is presented with the 25– 75th percentile.

RESULTS

Two-hundred and thirty-seven male athletes participated in the athletics programme across the five seasons. Fifty-nine athletes did not complete a whole season for non-medical reasons and were excluded from the analyses. A total of 178 athletes were followed for 1–5 seasons (one season: n=63; two seasons: n=51; three seasons: n=39; four seasons: n=20; five seasons: n=5) contributing to 391 athlete seasons (mean age ±SD: 14.9±1.8 years old at season start), (figure 1). In terms of geographical representation (based on United nations area codes as per athlete

Table 1 Athlete distribution, athletic exposure and injury characteristics overall and by event group

	Non-specialised	Endurance	Sprints	Jumps	Throws	Overall
Athlete seasons	185	66	51	55	34	**391**
Mean age (±SD)	13.5 (±1.0)	15.3 (±1.6)	16.7 (±1.0)	16.5 (±1.1)	16.4 (±1.3)	**14.9 (±1.8)**
Athletic exposure						
Total AE	30 328	15 429	10 318	8787	7224	**72086**
Training/competition exposures	29301/1027	14870/559	9886/432	8385/402	6884/340	**69326/2760**
Mean AE per athlete season (±SD)	164 (±43)	234 (±74)	202 (±70)	160 (±57)	213 (±71)	**184 (±64)**
Injury occurrence						
N injuries (training/competition)	130 (117/13)	57 (54/3)	35 (23/12)	43 (33/10)	25 (25/0)	**290 (252/38)**
N acute/N gradual onset	64/66	9/48	22/13	25/18	14/11	**134/156**
Mean season prevalence % (±SD)	60.2 (±16.5)	70.5 (±16.1)	53.1 (±9.4)	57.7 (±6.8)	50.0 (±10.2)	**58.1 (±11.5)**
% 1st/2nd/3rd/4th trimester	49/27/21/3	46/19/30/5	31/40/20/9	46/26/23/5	48/32/16/4	**46/27/22/5**
Injury incidence						
Injuries per 1000 AE (95% CI)	4.3 (3.5 to 5.0)	3.7 (2.8 to 4.8)	3.4 (2.4 to 4.7)	4.9 (3.6 to 6.5)	3.5 (2.3 to 5.0)	**4.0 (3.6 to 4.5)**
Training/competition	3.9/12.7	3.6/5.4	2.4/27.8	4.1/24.9	3.6/0.0	**3.6/13.8**
Injury burden						
Days lost per 1000 AE (95% CI)	70.8 (67 to 73)	84.5 (80 to 89)	81.5 (77 to 88)	101.3 (95 to 109)	72.0 (66 to 78)	**79.1 (77 to 81)**
Acute/gradual onset	32.2/38.5	9.6/74.9	65.9/15.6	34.6/66.7	43.9/28.1	**33.7/45.4**
Body region						
Upper extremities (%)	15 (11.5)	1 (1.8)	1 (2.8)	2 (4.6)	5 (20.0)	**24 (8.3)**
Head and trunk (%)	24 (18.5)	10 (17.5)	5 (14.3)	10 (23.3)	7 (28.0)	**56 (19.3)**
Lower extremities (%)	91 (70.0)	46 (80.7)	29 (82.9)	31 (72.1)	13 (52.0)	**210 (72.4)**

Bold: overall values.
AE, athletic exposures.

nationality)[38] 70% originated from Western Asia and 30% from Africa (18% from Eastern Africa; 9% from Northern Africa and 3% from Western Africa). Overall, 72 086 AE were recorded, where 96% corresponded to training and 4% to competitions (table 1). A total of 354 time-loss injuries were recorded and of these, 64 injuries (18%) originated from activities outside of the training programme and were excluded. Therefore, 290 injuries related to participation in athletics were included in the analyses.

Overall injury characteristics

Athletes sustained 0.7±0.2 injuries per season, equating to a season prevalence of 58%±11.5. Only 10% were recurrent injuries and 23% of athletes sustained two or more injuries within the same season. Almost half of all injuries (46%) were recorded during the first trimester of the season (September to November).

A summary of the overall injury characteristics is described in table 1. Most injuries were sustained in the lower extremities (72%). The thigh was the most common location (19%), followed by the knee (14.8%) (online supplemental file). The overall incidence was 4.0 injuries per 1000 AE and the overall burden 79 days lost per 1000 AE. Competition incidence was 3.8 times greater compared with training incidence.

The median time loss per injury was 6 days (25–75th percentile: 3–12). Most injuries (35%) were of minimal severity, 19% were minor, 23% moderate and 23% serious. Most serious injuries were bone fractures (stress or traumatic) (37%), most of the moderate injuries were muscle strains (27%) while contusions, muscle spasm and non-specific pain were the most common types among the minor and minimal ones.

Injury types, tissue type and common diagnoses

Muscle strains, BSI, stress fractures and growth plate injuries were the most common injury types, accounting for 48% of all injuries. The most burdensome injury types were stress fractures (17.6 days lost per 1000 AE), followed by muscle strains (15.8 days lost per 1000 AE) and BSI (10.0 days lost per 1000 AE). A risk matrix combining the incidence and severity for the most relevant injury types overall and by event group is presented in figure 2.

Bone was the most affected tissue type, and most bone injuries (85%) had a gradual onset. The most common diagnoses were spondylolysis and medial tibial stress syndrome (MTSS), with severity depending on the bone stress grade (table 2). Apophysitis of the iliac spine (37%) and tibial tuberosity (Osgood-Schlatter disease; 29%) were the most frequent growth plate injuries. A high variability of time lost according to injury location and the athlete's age at injury was observed for growth plate injuries: calcaneal apophysitis (Sever disease) was diagnosed at a younger age compared with Osgood-Schlatter disease and anterior inferior iliac spine apophysitis (table 2).

For muscle injuries, the thigh was the most common location and hamstring strains the most burdensome diagnosis, accounting for 61% of all muscle strains. Almost half of all hamstring injuries (45%) were sustained during competitions, the majority of them (86%) moderate or serious, although the number of days lost was dependent on injury grade diagnosed by MRI (table 2).

Event group analyses

A complete analysis of injuries for each event group is displayed in tables 1 and 3. Jumps presented the highest incidence and injury burden and sprints the highest incidence of injuries in competition. For most groups, almost half of the injuries occurred during the first trimester of the season, except for sprints in which most injuries occurred in the second trimester.

Endurance athletes accumulated the most AE per athlete season and presented a higher burden of gradual onset injuries. BSI were the most common injury type in endurance, and MTSS the most frequent injury diagnosis (1.0 injuries per 1000 AE). Most injuries in sprinters were acute. Hamstring strains in the sprint group were the diagnosis with the highest incidence and

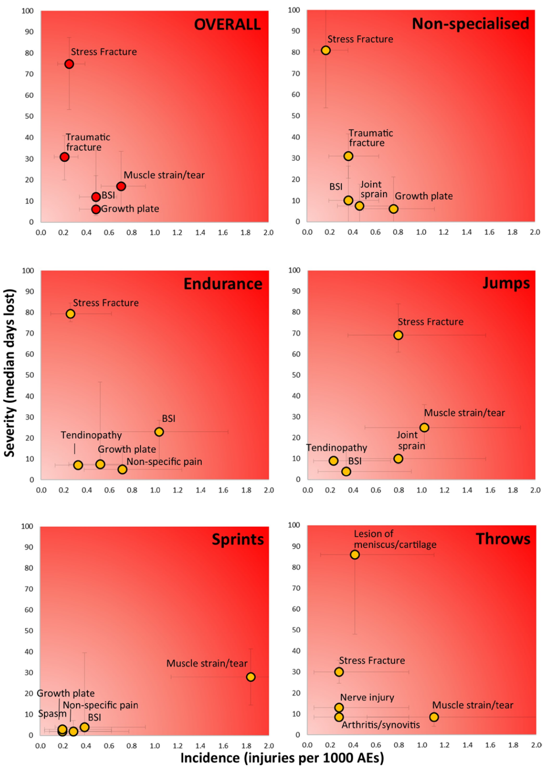

Figure 2 Risk matrix illustrating the burden of different types of injuries overall and for each event group. Incidence is expressed as number of injuries per 1000 AE with a 95% CI and severity as median days lost with a 25th to 75th percentile. AE, athletics exposure; BSI, bone stress injuries.

burden (1.8 injuries per 1000 AE; 62 days lost per 1000 AE) across all event groups. Jumps presented a high incidence of stress fractures, muscle strains and joint sprains, with hamstring strains and lateral ankle sprains as the most common diagnoses, and spondylolysis as the most burdensome (45 days lost per 1000 AE). Throws displayed the highest proportion of trunk and upper extremities injuries (48%), muscle strains being the most common type of injury and lesions of meniscus/cartilage the most burdensome. Most growth plate injuries (89%) occurred in endurance and non-specialised groups, who also had the youngest athletes. A risk matrix with the five most burdensome injury types by event group is presented in figure 2.

DISCUSSION

This is the first prospective study describing the injury characteristics of highly trained youth athletes in a full-time athletics academy following the athletics consensus recommendations.[32] The main findings were the high incidence of overuse bone injuries in such a young cohort and the clear difference observed in injury characteristics across event groups.

Injury impact of highly trained youth athletes

The incidence of injuries in this group (4.0 injuries per 1000 AE) was high compared with the most similar studies in youth athletics in terms of methodology,[10 13 14 23] in which incidence rates were reported between 0.6 and 2.1 injuries per 1000 AE. Minimal time-loss injuries had a high impact on the overall incidence (1.4 injuries per 1000 AE) although their impact on health and performance is dubious (3 days lost per 1000 AE). This would support the use of injury burden instead of incidence to report the actual impact of injuries in sport, as recommended by Bahr *et al*.[36] It is likely that the proximity to medical staff and the involvement of research-invested clinicians in the data collection contributed to a greater number of minimal time-loss injuries being reported.[39] This would partly explain the higher incidence rates in this study compared with those previously reported in youth athletics.

BSIs, stress fractures and acute muscle strains were the most burdensome injury types overall. Although the majority of injuries were associated with training as in previous cohorts[8 10 14 15 23], injury incidence was 3.8 greater in competitions and hamstring strains were the most common diagnosis as already showed in major athletics events.[17 18]

Identifying differences between event groups

Athletics is composed of several disciplines with differing movement patterns and physical demands that may expose athletes to different injury risks. Whether this requires a high degree of specialisation or not is unknown, but the injury characteristics described in this cohort of youth athletes are similar to what has been observed in other athletics studies.[8 10 11 15 16 23 24] Although muscle strains were identified as the most frequent type of injury in this cohort, event group analyses showed they were more common in explosive events such as sprints, jumps and throws but almost negligible in endurance and non-specialised athletes. Conversely, overuse bone injuries were frequent in events requiring repetitive impacts like jumps and endurance while growth plate injuries were frequent in groups with younger athletes (non-specialised and endurance).

The most relevant differences with other studies were: (1) the predominance of overuse bone injuries in endurance in our cohort in contrast to lower leg muscle strains, foot injuries and knee tendinopathy, previously described for distance runners[9 10 15 18 23 24]; (2) the high burden of stress fractures in jumpers; (3) growth plate injuries, under-reported in previous surveillance studies, were described in this cohort; (4) the different pattern for injury occurrence in sprinters, who got most injuries during the second trimester in contrast to the rest of the groups and previous studies in which most injuries happened at the beginning of the season[8 10 11 24 40] and (5) the high burden of meniscus/cartilage injuries in throws.

The main concern: overuse bone injuries

Bone was the most frequently injured tissue type (36%) as opposed to other studies in athletics in which muscle had been reported as the most common.[9 12 18 23] Only two studies had reported higher incidence of bone injuries, but both with retrospective self-report designs and injury definitions of 1 week[41] and 3 weeks[6] lost.

Stress fractures, reported to represent between 0% and 2.3% of all injuries in youth athletics[10 12 13 23 42] accounted for 6.2% in our study and their incidence was 3 to 17 times greater than similar cohorts of youth athletes.[10 23 43] The incidence of MTSS was also 19 times higher than what Pierpoint *et al*[23] reported. This may be due to a more accurate diagnosis thanks to the availability of MRI in our study, but many other factors could also explain this finding. (1) Although female athletes are known to be at higher risk of BSIs,[41 44–47] relative energy deficiency in

Table 2 Injury distribution by location for the most common injury types and diagnoses

Body Part / Injury type / *Diagnosi*	Injuries Count	Incidence Inj. per 1000 AE (95% CI)		Median time loss Days (25–75th percentile)		Burden Days lost per 1000 AE (95% CI)		Age at injury Mean (95% CI)	
Upper extremity	**24**	**0.3**	**0.2 to 0.5**	**4**	**3 to 10**	**3.4**	**3.0 to 3.8**	**15.0**	**14.0 to 16.0**
Traumatic fracture	6	0.1	0.0 to 0.2	15	6 to 34	1.9	1.6 to 2.2	13.7	12.2 to 15.2
Muscle strain/tear	4	0.1	0.0 to 0.1	4	3 to 8	0.4	0.3 to 0.6	17.6	14.3 to 20.9
Head and trunk	**56**	**0.8**	**0.6 to 1.0**	**9**	**3 to 41**	**20.2**	**19.2 to 21.3**	**15.4**	**15.0 to 15.7**
Stress fracture	13	0.2	0.1 to 0.3	69	53 to 83	12.2	11.4 to 13.1	15.5	14.7 to 16.2
Spondylolysis	12	0.2	0.1 to 0.3	72	54 to 85	11.6	10.8 to 12.4	15.6	14.8 to 16.4
Growth plate	17	0.2	0.1 to 0.4	6	3 to 24	5.0	4.5 to 5.6	14.9	14.4 to 15.4
AIIS apophysitis	7	0.1	0.0 to 0.2	12	5 to 39	3.7	3.3 to 4.2	14.6	13.6 to 15.5
ASIS apophysitis	6	0.1	0.0 to 0.2	5	3 to 8	0.7	0.5 to 0.9	15.3	14.3 to 16.3
Non-specific pain	15	0.2	0.1 to 0.3	3	3 to 5	1.0	0.7 to 1.2	15.7	14.7 to 16.7
Hip and groin	**8**	**0.1**	**0.0 to 0.2**	**24**	**6 to 49**	**3.6**	**3.2 to 4.1**	**16.0**	**14.4 to 17.5**
Thigh	**55**	**0.8**	**0.6 to 1.0**	**13**	**3 to 32**	**15.8**	**14.9 to 16.8**	**16.0**	**15.5 to 16.5**
Muscle strain/tear	41	0.6	0.4 to 0.8	20	7 to 38	14.6	13.7 to 15.5	16.6	16.1 to 17.1
Hamstring strain grade 0–1	19	0.3	0.2 to 0.4	13	5 to 23	4.4	4.0 to 5.0	16.7	16.0 to 17.4
Hamstring strain grade 2–3	12	0.2	0.1 to 0.3	41	37 to 66	8.4	7.7 to 9.1	17.3	16.5 to 18.1
Quadriceps strain	6	0.1	0.0 to 0.2	7	6 to 15	0.9	0.7 to 1.2	14.5	13.8 to 15.3
Adductor strain	4	0.1	0.0 to 0.1	17	11 to 21	0.8	0.6 to 1.1	16.8	14.3 to 19.3
Spasm/cramp	11	0.2	0.1 to 0.3	2	2 to 3	0.3	0.2 to 0.5	14.2	13.2 to 15.2
Knee	**43**	**0.6**	**0.4 to 0.8**	**5**	**2 to 12**	**9.6**	**8.9 to 10.4**	**15.3**	**14.8 to 15.8**
Growth plate—*Osgood-Schlatter*	10	0.1	0.1 to 0.3	7	2 to 40	3.9	3.5 to 4.4	14.3	13.7 to 14.9
Tendinopathy	9	0.1	0.1 to 0.2	6	1 to 12	2.1	1.7 to 2.4	15.6	14.7 to 16.5
Lower leg and Achilles tendon	**40**	**0.6**	**0.4 to 0.8**	**9**	**3 to 29**	**11.7**	**10.9 to 12.5**	**15.3**	**14.8 to 15.9**
Other bone injury	28	0.4	0.3 to 0.6	11	3 to 29	7.4	6.8 to 8.1	15.6	14.9 to 16.2
MTSS grade 1	8	0.1	0.0 to 0.2	3	2 to 7	0.5	0.4 to 0.7	15.2	13.5 to 16.8
MTSS grade 2	11	0.2	0.1 to 0.3	10	4 to 28	2.5	2.1 to 2.9	16.5	15.7 to 17.4
MTSS grade 3	8	0.1	0.0 to 0.2	43	27 to 50	4.4	3.9 to 4.9	14.8	13.9 to 15.7
Stress fracture—*MTSS grade 4*	3	<0.1	0.0 to 0.1	89	84 to 90	3.6	3.1 to 4.0	15.7	12.9 to 18.6
Ankle	**28**	**0.4**	**0.3 to 0.6**	**10**	**5 to 15**	**6.1**	**5.5 to 6.7**	**14.7**	**14.0 to 15.5**
Ligament/joint sprain	20	0.3	0.2 to 0.4	9	3 to 11	3.4	3.0 to 3.9	14.8	14.0 to 15.7
Traumatic fracture	3	<0.1	0.0 to 0.1	31	29 to 59	2.0	1.7 to 2.4	14.3	6.6 to 21.9
Foot/toe	**36**	**0.5**	**0.3 to 0.7**	**4**	**2 to 18**	**8.7**	**8.0 to 9.4**	**14.9**	**14.2 to 15.5**
Traumatic fracture	4	0.1	0.0 to 0.1	37	31 to 43	2.0	1.7 to 2.4	14.0	11.3 to 16.7
Stress fracture	2	<0.1	0.0 to 0.1	65	56 to 73	1.8	1.5 to 2.1	15.4	5.9 to 25.0
Growth plate—*Sever disease*	5	0.1	0.0 to 0.2	2	2 to 5	0.2	0.1 to 0.4	13.1	12.2 to 14.1

Bold: overall values by body part.

AE, athletics exposure; AIIS, anterior inferior iliac spine; ASIS, antero-superior iliac spine; MTSS, medial tibial stress syndrome.

sport[48] has been proposed as a major bone injury risk factor in male athletes; (2) early specialised athletes and long distance runners are known to be at higher risk when exposed to high training loads[11 49]; (3) rapid growth in stature and leg length may also represent a risk for bone injuries in male youth athletics[19]; (4) various specific genetic markers have also been associated with a greater risk of fracture, although not in a West Asian population[50]; (5) other contextual and cultural factors like over-scheduling,[51] chronic sleep deprivation[52] and low vitamin D and calcium intake[53 54] may be critical in highly trained athletes.

Growth plate injuries are a unique entity in skeletally immature athletes that often lead to several weeks of rest or activity modification.[55 56] Although they were among the most frequent injury types in this study, a time-loss injury definition may under-estimate their real impact. Interestingly, there was an age-related pattern for different growth plate injuries, with distal growth plates provoking symptoms at an earlier age compared with proximal ones, which seems to resemble a distal to proximal apophyseal ossification pattern.[57] An event group analysis is probably not valid for growth apophysitis, as younger athletes are at higher risk regardless of their event specialisation.

METHODOLOGICAL CONSIDERATIONS

One of the strengths of this study is the homogeneity in data collection methods and contextual factors throughout five seasons, as opposed to most athletics studies with shorter surveillance periods and heterogeneous samples. Our unique setting allowed medical staff to work with athletes in a controlled training environment, making it possible to quantify and analyse injuries of youth athletes exposed to intensive year-round training programmes. However, in athletics, it is not easy to define athlete training availability on a daily basis in the same manner as team sports,[58] so we were not able to describe training sessions based on whether the athlete was in full training, modified training or rehabilitation. The main limitation of the study is our inability to monitor training load and volume, important aspects of athlete exposures that have helped identify injury risk

Table 3 Injury distribution and injury burden for different types of injuries by event group

Tissue type / Type of injury	Non-specialised n (%)	Non-specialised Days lost/1000 AE (95% CI)	Endurance n (%)	Endurance Days lost/1000 AE (95% CI)	Sprints n (%)	Sprints Days lost/1000 AE (95% CI)	Jumps n (%)	Jumps Days lost/1000 AE (95% CI)	Throws n (%)	Throws Days lost/1000 AE (95% CI)
Bone										
Fracture (traumatic)	11 (8)	10.8 (9.7 to 12.1)	2 (4)	4.5 (3.5 to 5.6)	0 (0)	0 (NA)	1 (2)	0.2 (0.0 to 0.7)	1 (4)	12.0 (9.7 to 14.8)
Stress fracture	5 (4)	12.1 (10.9 to 13.4)	4 (7)	20.9 (18.7 to 23.2)	0 (0)	0 (NA)	7 (16)	58.8 (53.9 to 64.1)	2 (8)	8.3 (6.4 to 10.6)
Other bone injury	11 (8)	8.8 (7.8 to 9.9)	16 (28)	23.5 (21.1 to 26.0)	4 (11)	5.6 (4.3 to 7.2)	3 (7)	3.9 (2.7 to 5.3)	1 (4)	0.4 (0.1 to 1.1)
Growth plate	23 (18)	14.3 (13.0 to 15.7)	8 (14)	15.9 (14.0 to 18.0)	2 (6)	0.6 (0.2 to 1.2)	1 (2)	0.3 (0.1 to 0.9)	1 (4)	0.1 (0.0 to 0.6)
Muscle										
Strain/rupture/tear	14 (11)	5.1 (4.4 to 6.0)	1 (2)	0.5 (0.2 to 0.9)	19 (54)	65.4 (60.6 to 70.5)	9 (21)	24.7 (21.6 to 28.1)	8 (32)	11.4 (9.1 to 14.0)
Spasm/cramp	12 (9)	0.8 (0.5 to 1.2)	1 (2)	0.1 (0.0 to 0.3)	2 (6)	0.4 (0.1 to 0.9)	1 (2)	0.1 (0.0 to 0.5)	0 (0)	0 (NA)
Joint/ligament										
Sprain	14 (11)	6.1 (5.3 to 7.0)	2 (4)	0.3 (0.1 to 0.6)	0 (0)	0 (NA)	7 (16)	7.3 (5.7 to 9.2)	1 (4)	5.7 (4.1 to 7.6)
Arthritis/synovitis/bursitis	1 (1)	0.2 (0.1 to 0.4)	2 (4)	0.5 (0.2 to 0.9)	2 (6)	0.3 (0.1 to 0.8)	2 (5)	0.6 (0.2 to 1.2)	2 (8)	2.4 (1.4 to 3.7)
Tendon										
Tendinopathy	8 (6)	2.0 (1.5 to 2.5)	5 (9)	4.1 (3.2 to 5.3)	1 (3)	7 (5.5 to 8.7)	2 (5)	2.0 (1.3 to 3.2)	1 (4)	0.1 (0.0 to 0.6)
Miscellaneous										
Contusion	16 (12)	1.7 (1.3 to 2.3)	2 (4)	0.5 (0.2 to 1.0)	1 (3)	0.2 (0.0 to 0.6)	4 (9)	0.9 (0.4 to 1.7)	0 (0)	0 (NA)
Non-specific pain	13 (10)	1.5 (1.1 to 1.9)	11 (19)	9.5 (8.1 to 11.2)	3 (9)	0.8 (0.4 to 1.5)	3 (7)	1.6 (0.9 to 2.6)	1 (4)	0.4 (0.1 to 1.1)
Meniscus/cartilage lesion	0 (0)	0 (NA)	0 (0)	0 (NA)	0 (0)	0 (NA)	0 (0)	0 (NA)	3 (12)	26.6 (23.0 to 30.5)
Other injury	2 (2)	7.3 (6.4 to 8.3)	3 (5)	4.3 (3.3 to 5.4)	1 (3)	1.3 (0.7 to 2.1)	3 (7)	0.8 (0.4 to 1.6)	4 (16)	4.6 (3.2 to 6.3)
Total	**130 (100)**	**70.8 (67.8 to 73.8)**	**57 (100)**	**84.5 (80.0 to 89.1)**	**35 (100)**	**81.5 (76.1 to 87.2)**	**43 (100)**	**101.3 (94.8 to 108)**	**25 (100)**	**72.0 (66.0 to 78.4)**

AE, athletics exposure; NA, not avilable.

in other populations. For this reason, the findings of our study have limited external validity as we cannot compare the training demands in this population to other heterogeneous groups with varying TEs.

CONCLUSIONS

This study highlights the most relevant injury characteristics of youth athletics athletes in a full-time sports academy. This may help addressing specific risk factors in future research studies, as well as targeted prevention measures for different athletics disciplines.

Key messages

What are the findings?

- Youth male athletes engaged in a full-time athletics programme present high injury rates especially for overuse bone injuries and muscle strains.
- Stress fractures and bone stress injuries are common in endurance and jumps, while muscle strains are common in explosive events and during competitions (especially in sprints).
- The most burdensome injury types were bone stress for endurance, hamstring strains for sprints, stress fractures for jumps, lesion of meniscus or cartilage for throws and growth plate injuries for non-specialised athletes.

How might it impact on clinical practice in the future

- Consistent methodologies for injury definition and data collection may help comparing with other cohorts of youth athletics.
- Practitioners should be especially aware of overuse bone injuries in jumps and endurance and muscle strains in explosive events in youth athletes following intensive training programmes.
- Identifying injury characteristics for each event group may help addressing specific risk factors for future investigations and implementation of injury prevention programmes.

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Supplementary file. Distribution of injuries according to mode of onset for each body part and event-group.

Main body part Subcategory	Overall n	(%)	Acute/ Overuse	General program n	(%)	Acute/ Overuse	Endurance n	(%)	Acute/ Overuse	Sprints n	(%)	Acute/ Overuse	Jumps n	(%)	Acute/ Overuse	Throws n	(%)	Acute/ Overuse
Upper extremity																		
Shoulder/clavicle	**10**	**(3.4)**	**6/4**	4	(3)	3/1	1	(2)	0/1	0	(0)	0/0	1	(2)	0/1	4	(16)	3/1
Elbow	**3**	**(1)**	**3/0**	3	(2)	3/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Forearm	**2**	**(0.7)**	**1/1**	1	(1)	1/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	1	(4)	0/1
Wrist	**5**	**(1.7)**	**4/1**	4	(3)	3/1	0	(0)	0/0	1	(3)	1/0	0	(0)	0/0	0	(0)	0/0
Hand	**3**	**(1)**	**3/0**	3	(2)	3/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Finger	**1**	**(0.3)**	**1/0**	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	1	(2)	1/0	0	(0)	0/0
Head and trunk																		
Face	**0**	**(0)**	**0/0**	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Head	**1**	**(0.3)**	**1/0**	1	(1)	1/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Neck/cervical spine	**1**	**(0.3)**	**1/0**	1	(1)	1/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Thoracic spine/upper back	**2**	**(0.7)**	**0/2**	1	(1)	0/1	0	(0)	0/0	1	(3)	0/1	0	(0)	0/0	0	(0)	0/0
Lumbar spine/lower back	**32**	**(11)**	**6/26**	8	(6)	2/6	8	(14)	1/7	2	(6)	0/2	8	(19)	1/7	6	(24)	2/4
Abdomen	**2**	**(0.7)**	**2/0**	2	(2)	2/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Pelvis/sacrum/buttock	**18**	**(6.2)**	**1/17**	11	(8)	1/10	2	(4)	0/2	2	(6)	0/2	2	(5)	0/2	1	(4)	0/1
Lower extremity																		
Hip	**2**	**(0.7)**	**2/0**	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0	1	(2)	1/0	1	(4)	1/0
Groin	**6**	**(2.1)**	**1/5**	2	(2)	0/2	3	(5)	0/3	0	(0)	0/0	1	(2)	1/0	0	(0)	0/0
Thigh	**55**	**(19)**	**44/11**	22	(17)	12/10	1	(2)	1/0	21	(60)	20/1	8	(19)	8/0	3	(12)	3/0
Knee	**43**	**(14.8)**	**12/31**	18	(14)	6/12	15	(26)	3/12	2	(6)	0/2	3	(7)	2/1	5	(20)	1/4
Lower leg	**36**	**(12.4)**	**3/33**	11	(8)	2/9	16	(28)	0/16	4	(11)	0/4	4	(9)	0/4	1	(4)	1/0
Achilles tendon	**4**	**(1.4)**	**1/3**	2	(2)	1/1	2	(4)	0/2	0	(0)	0/0	0	(0)	0/0	0	(0)	0/0
Ankle	**28**	**(9.7)**	**25/3**	17	(13)	14/3	2	(4)	2/0	0	(0)	0/0	6	(14)	6/0	3	(12)	3/0
Foot/toe	**36**	**(12.4)**	**17/19**	19	(15)	9/10	7	(12)	2/5	2	(6)	1/1	8	(19)	5/3	0	(0)	0/0
Total	**290**	**(100)**	**134/156**	**130**	**(100)**	**64/66**	**57**	**(100)**	**9/48**	**35**	**(100)**	**22/13**	**43**	**(100)**	**25/18**	**25**	**(100)**	**14/11**

Paper III

Injury patterns differ with age in male youth football: a four-season prospective study of 1111 time-loss injuries in an elite national academy

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ABSTRACT

Objectives To describe age group patterns for injury incidence, severity and burden in elite male youth football.

Methods Prospective cohort study capturing data on individual exposure and time-loss injuries from training and matches over four seasons (2016/2017 through 2019/2020) at a national football academy (U13–U18; age range: 11–18 years). Injury incidence was calculated as the number of injuries per 1000 hours, injury severity as the median number of days lost and injury burden as the number of days lost per 1000 hours.

Results We included 301 players (591 player-seasons) and recorded 1111 time-loss injuries. Overall incidence was 12.0 per 1000 hours (95% CI 11.3 to 12.7) and burden was 255 days lost per 1000 hours (252 to 259). The mean incidence for overall injuries was higher in the older age groups (7.8 to 18.6 injuries per 1000 hours), while the greatest burden was observed in the U16 age group (425 days; 415 to 435). In older age groups, incidence and burden were higher for muscle injuries and lower for physis injuries. Incidence of joint sprains and bone stress injuries was greatest for players in the U16, U17 and U18 age groups, with the largest burden observed for U16 players. No clear age group trend was observed for fractures.

Conclusion Injury patterns differed with age; tailoring prevention programmes may be possible.

INTRODUCTION

Reducing the impact of football injuries will improve the health status of young players and maximise opportunities for development and, ultimately, performance.[1 2] To achieve this, it is essential to first gain a thorough understanding of the problem.[3 4]

Although the overall injury patterns for elite male youth football players seem to be similar to senior players,[2] specific injury trends throughout the developmental process are not well described. The adolescent elite athlete is exposed to intense training and match programmes while transitioning from child to an adult, a process characterised by immature tissue and periods of rapid growth.[5–9] This may explain the elevated rates of growth-related injuries and greater injury burden observed around the age where height and weight typically change the most.[10–16]

Methodological variations in studies on youth football have led to wide ranges in reported injury outcomes.[2] Different injury definitions and recording methods, inconsistent injury classification, short observation periods and small samples limit the ability to compare contexts and reach meaningful conclusions. Furthermore, studies most often focus only on the rate of injuries, without considering the impact of each injury on participation. While injury incidence accounts for how often injury events occur, understanding injury burden is also important.[17–19] Specifically, taking the severity of each injury into account might enable more clinically precise comparisons of 'rare but severe injuries' (eg, ACL tears and fractures) and 'common but minor injuries' (eg, contusions and spasms).[17–19]

In professional football academies, identifying the injuries which limit participation in training and matches is fundamental to inform the implementation of prevention programmes and optimise player development. The aim of this study was therefore to describe age-related injury patterns for incidence, severity and burden in elite male youth players.

METHODS

Study population

This study used data collected prospectively over four seasons at the Aspire Academy, an elite male national football academy in Qatar. The participants were players aged 11–18 years enrolled in the football programme (U13–U18) for the 2016/2017 through the 2019/2020 seasons. Full-time players typically participated in eight morning or afternoon academy sessions during the school week, in addition to weekend games in the national youth league with their local club. Part-time players typically participated in five afternoon academy sessions in addition to weekend club games. Written informed consent to use regularly collected injury and football exposure data for research purposes was obtained from the athlete's guardians. Participants were not included in the design or interpretation of the study.

Injury surveillance

Injuries were recorded prospectively by each squad's designated sports physiotherapist to a spreadsheet database following the consensus procedures for football outlined by Fuller *et al*.[20] The physiotherapists were present during all team sessions and updated records continuously. The Aspire Academy Football Injury Surveillance Programme was supervised by a senior physiotherapist for the first two seasons and a researcher for the last two seasons, who revised the injury records each month. Only time-loss injuries were included, defined as any physical complaint leading to the medical staff partially or fully restricting participation in future team football activities.

Injuries were classified according to their diagnoses, verified by the team physiotherapist and confirmed by a medical doctor, based on the Sports Medicine Diagnostic Coding System (SMDCS).[21] For each injury, the date of injury, session type, contact type and specific mechanism were reported. A player was considered injured until the date he returned to full participation in team training and was available for match selection as determined by the medical staff.[20] Return dates were estimated by the treating clinician if a player left the academy before returning to full participation and if an injury was still ongoing at the end of the observation period.[20]

Recording of training and match exposure

Daily individual training and match exposure data were recorded in a spreadsheet database by the designated team sports scientist. Exposure was collected for individual player activities, including information about the session type and any deviations from the main team activity (eg, absence, rehabilitation session or illness) as well as the duration of the session in minutes. The duration of club activities was collected from club strength and conditioning staff and individual match duration was corrected retrospectively against official federation match reports.

Data handling and statistical analyses

Following the completion of the data collection, injuries were reclassified by a researcher to match the updated 2020 SMDCS[22] and IOC consensus statement[18] categories for diagnosis, region, body part, tissue type and pathology type. Proximal adductor injuries could not be accurately differentiated from mid/distal injuries and therefore all adductor injuries were considered as thigh injuries as per the original SMDCS code. Onset was classified retrospectively based on the reported mechanism and diagnosis. Mechanisms indicating identifiable events (eg, 'sprinting' or 'change of direction') were considered as sudden onset, while 'gradual onset/overuse' indicated a gradual onset injury. When the specific mechanism was not available, the diagnosis was used to determine the most appropriate category (eg, strains as sudden onset and apophysitis as gradual onset).

Two separate definitions were used to describe the extent of recurrent injuries: the first using the whole observation period for the player as a reference ('overall recurrent injury') and the second using injuries during the same season only ('same-season recurrent injury'). Where the same-season definition likely underestimates the proportion of recurrent injuries, especially for severe pathologies,[23] it is less affected by differences in duration of follow-up between players (multiple injuries are more likely in players with longer observation time).[24] Complete operational definitions used in the study are provided in table 1.

The injury database was controlled against the exposure database to identify missing injuries and to verify the start and return dates for each injury. If a potential injury was identified, the player's electronic medical record (Millennium Power Chart, Cerner, North Kansas City, Missouri, USA) was audited for additional injury entries and missing details. Injuries occurring outside football activities were discarded. Exposure accumulated during periods where a player was not considered fully available due to an injury (eg, for rehabilitation sessions or partial participation in team activities) was excluded and players joining or leaving the academy during a season were censored for the period they were not regularly monitored by academy staff.

Descriptive statistics, season incidence proportion and average player availability are reported as percentages and means with SD.[18] Injury severity is presented as the median number of days lost (duration of restricted participation) with 25th and 75th percentiles.[18] Incidence was calculated as the number of time-loss injuries per 1000 player hours, including recurrent injuries, and burden as the number of time-loss days per 1000 player hours.[18,20,25] Uncertainty for the point incidence and burden is presented as 95% CI assuming a Poisson distribution.[26]

RESULTS

Over the four-season observation period, 724 player-seasons with recorded training or match exposure were screened for eligibility. Of these, 133 were excluded from the analyses as they were not registered full-time or part-time players (n=58), did not regularly attend academy sessions (n=53), joined after the observation period ended (n=17) or did not participate at all during the entire season due to an injury sustained in the previous season (n=5; four ACL tears and one osteochondral lesion). The final sample included 301 unique players (133 players followed for one season, 83 for two seasons, 48 for three seasons and 37 for four seasons) contributing to 591 player-seasons (mean age at the start of the season: 14.6, SD 1.6 years). The flow of players joining and leaving the academy throughout the study is shown in figure 1. The total accumulated exposure was 78 069 training

Table 1 Operational definitions used in the study

Measure	Definition
Player-season	One player participating in one given season.
Training exposure	Team-based and individual physical activities under the control or guidance of the team's coaching or fitness staff that are aimed at maintaining or improving football skills or physical condition.[20]
Match exposure	Play between teams from different clubs, academies or federations.[20]
Time-loss injury	Any physical complaint or manifestation experienced by a player that requires the medical staff to fully or partially restrict participation in a future football team training session or match.[20]
Injury incidence	The number of time-loss injuries per 1000 player hours.[20,25]
Season incidence proportion	The proportion of players with at least one recorded time-loss injury for a given season.[25]
Overall recurrent injury	A time-loss injury to the same location with the same pathology type as a previously recorded injury during the observation period, following return to full participation from the previous event.[18]
Same-season recurrent injury	A time-loss injury to the same location with the same pathology type as a previously recorded injury during the same season, following return to full participation from the previous event.[18]
Injury burden	A measure of the injury impact, taking both incidence (how often) and severity (duration) into account. Calculated as the total days lost per 1000 player hours.[17,18]
Player availability	The proportion of fully available players (not restricted by injury) for training and match entries in the exposure database.[18]

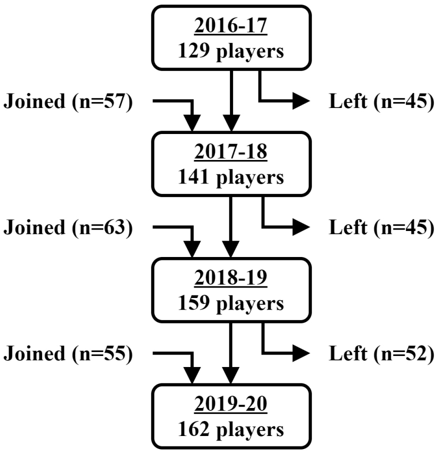

Figure 1 Player flow during the observation period.

hours and 14 758 match hours with a median season duration of 36 weeks (25–75th percentile: 29–38).

Main injury outcomes

A total of 1111 time-loss injuries were included for analysis during the observation period (1.9, SD 1.8 per player-season). A further 61 injuries sustained outside of football activities were excluded. The overall incidence was 12.0 injuries per 1000 hours (95% CI 11.3 to 12.7) and was similar in full-time (11.8, 11.0 to 12.6) and part-time (12.9, 11.1 to 14.8) players. Incidence during match play (32.0 per 1000 hours, 29.2 to 35.0) was 3.9 times greater compared with training (8.2 per 1000 hours, 7.6 to 8.8). The proportion of players sustaining at least one injury during a season (cumulative incidence proportion) was 78.5%. Overall recurrent injuries accounted for 12.0% of the time-loss episodes with same-season recurrent injuries accounting for 7.5%. Overall player availability was 85.8% (85.1% and 89.6% for training sessions and matches, respectively). Injury outcomes by age group are presented in table 2 and seasonal data are available in online supplemental table 1.

The total number of days lost was 23 713, resulting in an overall burden of 255 days lost per 1000 hours (252 to 259). The burden was lower in full-time players (233 days, 229 to 236) compared with part-time (375 days, 365 to 384) players. Return dates were estimated in 30 cases (2.7%). Median severity was 8 days per injury (2 to 21), with similar severity for training injuries (8 days, 2 to 20) and match injuries (9 days, 3 to 22). The burden of match injuries (717 days per 1000 hours, 704 to 731) was 4.3 times greater than for training injuries (168 days per 1000 hours, 165 to 171). A risk matrix displaying the overall incidence and severity for each age group is presented in figure 2.

Onset and mechanism

The majority of injuries were retrospectively classified as sudden onset (75%) with the remaining 25% as gradual onset. The incidence of gradual onset injuries was similar in full-time (3.1, 2.7 to 3.5) and part-time (2.6, 1.8 to 3.6) players. Non-contact injuries represented 60% of the total, with contact mechanisms accounting for 38% (24% direct contact by player, 11% direct contact by ball/object and 4% indirect contact by player; 2% missing). The specific mechanism was missing or reported as 'other/unknown' for 31% of the injuries, while 23% were the result of duels (tackled, tackling or kicked), 18% from gradual onset/overuse, 10% from sprinting and 5% from shooting or passing.

Diagnosis, tissue and pathology type

The lower limbs were most commonly injured (83%), followed by the upper limbs (9%), trunk (6%) and head/neck (2%). The incidence, severity and burden for the most relevant pathology types and diagnoses are presented in table 3.

The tissue types with the greatest incidence were muscle/tendon (3.2 injuries per 1000 hours, 2.9 to 3.6; 27% of all injuries), bone (2.8, 2.4 to 3.1; 23%), superficial tissues/skin (2.2, 1.9 to 2.5; 18%), ligament/joint capsule (1.5, 1.3 to 1.8; 13%) and non-specific (1.4, 1.2 to 1.7; 12%). Bone injuries were the most burdensome (87 days per 1000 hours, 85 to 89; 34% of all days lost), followed by ligament/joint capsule (78, 77 to 80;

Table 2 Demographic, exposure and injury data per age group for the combined four-season observation period

	U13	U14	U15	U16	U17	U18
Player-seasons	102	106	117	102	92	72
Age (years, SD)	12.3 (0.3)	13.3 (0.3)	14.3 (0.3)	15.3 (0.3)	16.3 (0.3)	17.3 (0.3)
Stature (cm, SD)	153.6 (7.5)	160.4 (7.9)	168.6 (6.6)	172.0 (6.4)	174.9 (7.0)	176.2 (7.4)
Body mass (kg, SD)	41.7 (6.4)	48.0 (8.3)	55.7 (7.6)	60.3 (6.8)	65.0 (7.8)	66.8 (8.7)
Total accumulated training exposure (hours)	15 094	16 726	14 803	12 903	11 203	7340
Total accumulated match exposure (hours)	1978	2519	3062	2816	2535	1848
Time-loss injuries (n)	133	164	194	215	234	171
Overall injury incidence (95% CI)	7.8 (6.5 to 9.2)	8.5 (7.3 to 9.9)	10.9 (9.4 to 12.5)	13.7 (11.9 to 15.6)	17.0 (14.9 to 19.4)	18.6 (15.9 to 21.6)
Training injury incidence (95% CI)	6.0 (4.9 to 7.4)	6.3 (5.1 to 7.6)	7.4 (6.0 to 8.9)	8.8 (7.3 to 10.6)	11.0 (9.1 to 13.1)	13.2 (10.7 to 16.1)
Match injury incidence (95% CI)	21.2 (15.3 to 28.7)	23.4 (17.8 to 30.2)	27.8 (22.2 to 34.3)	35.9 (29.2 to 43.6)	43.8 (36.0 to 52.7)	40.0 (31.4 to 50.3)
Season incidence proportion (%)	65.7	75.5	76.1	92.2	82.6	80.6
Overall recurrent injuries (%)	6.0	9.8	10.8	11.2	16.2	15.2
Same-season recurrent injuries (%)	6.0	7.3	5.7	6.5	9.0	9.9
Median days lost per injury (25–75th percentile)	10 (3 to 23)	9 (3 to 24)	8 (3 to 21)	11 (3 to 31)	7 (2 to 19)	5 (2 to 14)
Injury burden (95% CI)	129 (123 to 134)	207 (200 to 213)	207 (200 to 213)	425 (415 to 435)	316 (307 to 326)	308 (297 to 319)
Overall player availability (%)	90.6	88.6	87.9	78.3	82.7	86.1
Player training availability (%)	90.1	88.2	87.0	77.2	82.0	85.4
Player match availability (%)	94.0	90.9	92.6	84.4	86.8	89.1

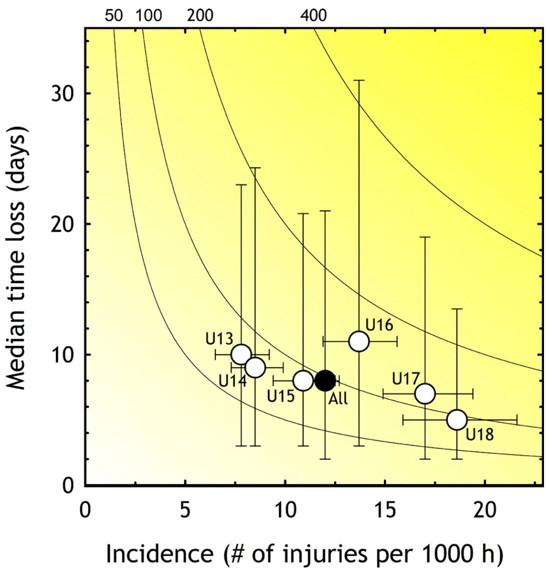

Figure 2 Risk matrix illustrating the incidence (how often) and severity (duration) of time-loss injuries per age group in a national youth football academy. A darker shade represents a greater burden and the isobars indicate equal burden lines. The horizontal error bars represent 95% CIs for incidence and vertical error bars indicate the 25th and 75th percentile for severity.

31%), muscle/tendon (42, 41 to 43; 16%), cartilage/synovium/bursa (19, 18 to 20; 8%) and superficial tissues/skin (14, 13 to 14; 5%).

For pathology types, the greatest incidence was observed for muscle injuries (2.6, 2.3 to 3.0 injuries per 1000 hours; 22% of all injuries), superficial contusions (2.1, 1.8 to 2.4; 17%), joint sprains (1.6, 1.3 to 1.8; 13%), non-specific pathologies (1.4, 1.2 to 1.7; 12%) and physis injuries (1.4, 1.1 to 1.6; 11%). The most burdensome pathology types were joint sprains (77, 75 to 79 days per 1000 hours; 30% of all days lost), followed by muscle injuries (36, 35 to 37; 14%), bone stress injuries (33, 32 to 34; 13%), fractures (33, 32 to 34, 13%) and physis injuries (19, 19 to 20; 8%).

Age group patterns

The proportion of gradual onset injuries was lower in the older age groups (U13: 33%; U14: 37%, U15: 25%, U16: 23%, U17: 21%, U18: 18%) while the proportion of injuries attributed to sprinting was greater (U13: 4%, U14: 6%, U15: 6%, U16: 9%, U17: 16%, U18: 15%). The proportion of non-contact injuries was similar between age groups (U13: 61%, U14: 68%, U15: 57%, U16: 60%, U17: 60%, U18: 56%). The incidence and severity by age group for the five most burdensome pathology types are presented as risk matrices in figure 3. The greatest incidence of joint sprains was observed for U16, U17 and U18 players, with a peak in median severity and burden in the U16 group. Muscle injury incidence and burden were the greatest in the older age groups. Bone stress injuries were more common in the U16, U17 and U18 age groups, with the greatest burden observed for U16 players. Fractures did not display any clear trend for incidence or burden, while the incidence and burden of physis injuries was the greatest in the younger age groups.

DISCUSSION

This study used observational data from four seasons in a national youth football academy (U13–U18), including 591 player-seasons and 1111 time-loss injuries. The large number of injuries and inclusion of injury burden allowed for comparisons between age groups, providing a better understanding of the impact of location-specific pathology types and diagnoses than what has previously been described. We observed age-related differences in injury pattern with higher incidence and burden of muscle injuries and lower incidence and burden of physis injuries in the older age groups. Joint sprains and bone stress injuries were reported more frequently in the three oldest age groups, with a peak burden observed for U16 players. No clear age-related trend was observed for fractures.

Injury characteristics from the same academy programme have recently been described by Materne *et al*,[16] based on data from the four seasons (2012/2013 through 2015/2016) preceding our observation period (2016/2017 through 2019/2020). We extend their work by including data on individual training and match exposure, a fundamental element to accurately describe injury incidence and burden.[18 25] Differences in exposure between age groups represent a confounder which must be taken into account when interpreting data on absolute injury rates (injuries per season/year), as injury occurrence is highly dependent on the time players spend at risk (in football activities).[23] The present data set, which includes exposure, therefore allows for direct comparisons and more nuanced interpretation, unbiased by different season durations, frequency and duration of matches and training sessions, or time lost due to injury, illness or for other reasons.

Overall injury trends

For a typical squad of 25 players, a coach in this academy could expect approximately 50 injuries and 1000 player days of restricted availability over a season, highlighting the impact injuries have on participation in young players and, consequently, on their potential for development. The overall incidence in the current study (12.0 per 1000 hours) was greater than the pooled estimates provided by Jones *et al*[2] in their systematic review of injuries in high-level youth football (5.8 for age groups U9–U21). Although similar injury rates have been reported in single studies from Germany (10.4 for U19),[27] England (12.1 for U18–U21),[28] Turkey (12.1 for U17–U19)[29] and the Netherlands (12.4 for U15 and 10.1 for U17),[14] elite players in the Middle East appear to be at the higher end of the spectrum when it comes to time-loss incidence. The underlying causes for this are not known and differences in methodology have to be taken into consideration when directly comparing results from different surveillance programmes.[18 23 30–32] The high training frequency in this academy (often two sessions per day) meant that even minor problems were likely to cause time loss,[31] and the presence of physiotherapists at every session ensured accurate recording.[31 33] While incidence was similar between full-time and part-time players, burden was lower among full-time players. This could result from closer follow-up of injured full-time players, with the opportunity for two treatment sessions per day, as opposed to one for part-time players.

Knee sprains were the primary cause of restricted participation, with 59% classified as non-contact injuries. A complete tear of the ACL was the most burdensome diagnosis and although these were not common, they led to a substantial amount of time away from football with graft ruptures or contralateral injuries occurring in all four cases prior to full recovery from

Table 3 Data on the most burdensome injuries in a national youth football academy over a four-season observation period

Body part	Injuries	Incidence rate		Median time loss		Burden	
Pathology Diagnosis	n	Injuries per 1000 hours (95% CI)		Days (25–75th percentile)		Time loss days per 1000 hours (95% CI)	
Head and neck	27	0.3	(0.2 to 0.4)	14	(7 to 18)	4	(4 to 5)
Concussion	20	0.2	(0.1 to 0.3)	16	(10 to 18)	3	(3 to 3)
Upper limb	97	1.0	(0.8 to 1.3)	16	(4 to 32)	24	(23 to 25)
Fracture	42	0.5	(0.3 to 0.6)	32	(19 to 56)	17	(17 to 18)
Forearm fracture	20	0.2	(0.1 to 0.3)	32	(22 to 55)	8	(7 to 9)
Hand/finger fracture	18	0.2	(0.1 to 0.3)	27	(17 to 43)	6	(6 to 7)
Joint sprain	20	0.2	(0.1 to 0.3)	14	(4 to 20)	3	(3 to 4)
Contusion (superficial)	33	0.4	(0.2 to 0.5)	3	(1 to 9)	3	(3 to 3)
Trunk	62	0.7	(0.5 to 0.9)	10	(2 to 43)	18	(17 to 19)
Bone stress injury	20	0.2	(0.1 to 0.3)	56	(43 to 78)	13	(13 to 14)
Spondylolysis/-listhesis	13	0.1	(0.1 to 0.2)	69	(44 to 105)	10	(9 to 11)
Pars stress reaction	6	0.1	(0.0 to 0.1)	53	(48 to 57)	3	(3 to 4)
Hip/groin	159	1.7	(1.5 to 2.0)	10	(5 to 20)	28	(27 to 29)
Physis injury	71	0.8	(0.6 to 1.0)	10	(6 to 17)	11	(10 to 11)
AIIS apophysitis	47	0.5	(0.4 to 0.7)	9	(5 to 15)	6	(5 to 6)
ASIS apophysitis	19	0.2	(0.1 to 0.3)	13	(6 to 22)	3	(3 to 4)
Bone stress injury	20	0.2	(0.1 to 0.3)	21	(11 to 37)	7	(7 to 8)
Pubic bone stress/apophysitis	19	0.2	(0.1 to 0.3)	20	(10 to 33)	5	(5 to 6)
Muscle injury	22	0.2	(0.1 to 0.4)	19	(8 to 23)	4	(4 to 5)
Iliopsoas strain/spasm	17	0.2	(0.1 to 0.3)	19	(12 to 22)	3	(3 to 4)
Non-specific pathology	23	0.2	(0.2 to 0.4)	3	(2 to 9)	2	(2 to 3)
Thigh	274	3.0	(2.6 to 3.3)	6	(2 to 16)	38	(36 to 39)
Muscle injury	179	1.9	(1.7 to 2.2)	9	(4 to 21)	29	(28 to 30)
Hamstring strain/spasm	92	1.0	(0.8 to 1.2)	9	(3 to 21)	15	(15 to 16)
Adductor strain/spasm	57	0.6	(0.5 to 0.8)	7	(3 to 15)	7	(6 to 7)
Quadriceps strain/spasm	30	0.3	(0.2 to 0.5)	16	(8 to 31)	7	(6 to 7)
Muscle contusion	40	0.4	(0.3 to 0.6)	3	(2 to 7)	4	(4 to 4)
Quadriceps contusion	37	0.4	(0.3 to 0.5)	3	(2 to 8)	4	(3 to 4)
Physis injury—*Ischial apophysitis*	6	0.1	(0.0 to 0.1)	18	(8 to 26)	1	(1 to 2)
Knee	145	1.6	(1.3 to 1.8)	8	(2 to 25)	71	(70 to 73)
Joint sprain	29	0.3	(0.2 to 0.4)	25	(17 to 167)	46	(45 to 48)
ACL complete tear	4	0.0	(0.0 to 0.1)	644	(551 to 737)	28	(27 to 29)
Patellar dislocation/subluxation	4	0.0	(0.0 to 0.1)	136	(106 to 170)	6	(6 to 7)
MCL sprain	13	0.1	(0.1 to 0.2)	17	(11 to 25)	5	(4 to 5)
Cartilage	7	0.1	(0.0 to 0.2)	47	(23 to 151)	9	(9 to 10)
Meniscal tear	6	0.1	(0.0 to 0.1)	71	(26 to 178)	9	(8 to 9)
Physis injury	34	0.4	(0.3 to 0.5)	4	(1 to 22)	6	(6 to 7)
Osgood-Schlatter's disease	33	0.4	(0.2 to 0.5)	5	(1 to 23)	6	(6 to 7)
Contusion (superficial)	35	0.4	(0.3 to 0.5)	3	(2 to 7)	2	(2 to 3)
Lower leg	100	1.1	(0.9 to 1.3)	4	(2 to 10)	14	(13 to 15)
Bone stress injury	20	0.2	(0.1 to 0.3)	21	(6 to 49)	8	(7 to 8)
Medial tibial stress syndrome	14	0.2	(0.1 to 0.3)	10	(6 to 39)	4	(4 to 5)
Lower leg stress fracture	4	0.0	(0.0 to 0.1)	54	(42 to 80)	3	(3 to 3)
Muscle injury	38	0.4	(0.3 to 0.6)	4	(1 to 9)	3	(2 to 3)
Ankle	158	1.7	(1.4 to 2.0)	11	(3 to 27)	39	(38 to 40)
Joint sprain	88	0.9	(0.8 to 1.2)	16	(5 to 36)	27	(26 to 28)
Ankle sprain (excl. syndesmosis)	78	0.8	(0.7 to 1.0)	15	(4 to 27)	18	(17 to 18)
Ankle sprain (incl. syndesmosis)	10	0.1	(0.1 to 0.2)	80	(48 to 105)	10	(9 to 10)
Synovitis/capsulitis—*Impingement*	17	0.2	(0.1 to 0.3)	21	(10 to 28)	5	(4 to 5)
Contusion (superficial)	45	0.5	(0.4 to 0.6)	3	(1 to 7)	3	(3 to 3)
Foot	89	1.0	(0.8 to 1.2)	6	(2 to 15)	19	(18 to 20)
Fracture	9	0.1	(0.0 to 0.2)	67	(43 to 96)	7	(6 to 7)
Bone stress injury	4	0.0	(0.0 to 0.1)	77	(33 to 158)	5	(4 to 5)
Non-specific pathology	11	0.1	(0.1 to 0.2)	15	(4 to 39)	3	(3 to 4)
Physis injury—*Sever's disease*	16	0.2	(0.1 to 0.3)	4	(3 to 10)	1	(1 to 1)

Injury categories were reported in the table if at least four injuries were recorded, and a total of 200 days were lost (one injury and 50 days lost per season on average). Body parts were collapsed into body regions if they did not meet the criteria, and two relevant diagnoses for youth athletes were arbitrarily included despite not meeting the required cut-off for days lost (Severs' disease and ischial apophysitis).

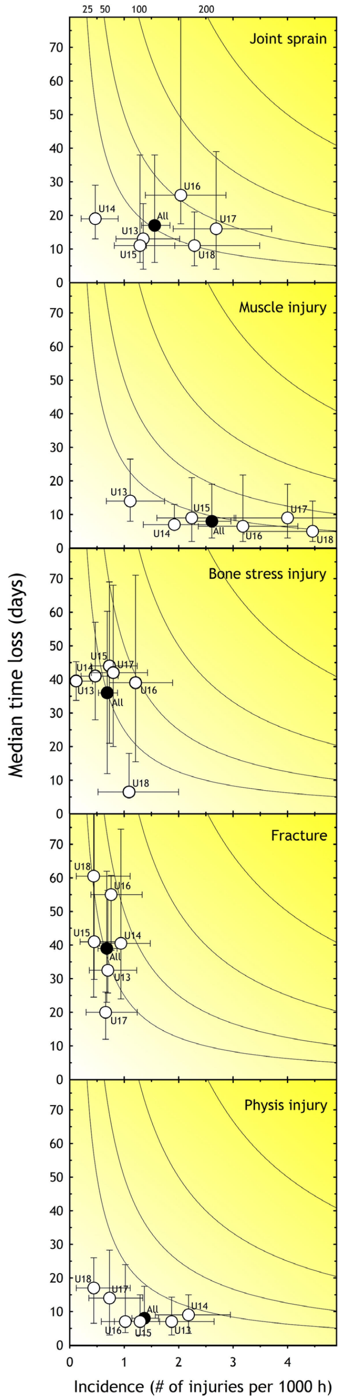

Figure 3 Risk matrices for the most burdensome pathology types in a national youth football academy. A darker shade represents a greater burden and the isobars indicate equal burden lines. The horizontal error bars represent 95% CIs for incidence and vertical error bars indicate the 25th and 75th percentile for severity.

the initial event. ACL injuries and subsequent surgical interventions are challenging in skeletally immature athletes,[34] and reinjuries and long-term health consequences are not unusual, stressing the importance of primary prevention.[35] Thigh muscle injuries and ankle sprains occurred often and were associated with moderate time loss, resulting in a high burden. In this study, 95% of thigh muscle injuries were classified as non-contact, while 58% of ankle sprains resulted from contact mechanisms. A high frequency of muscle strains and ligament sprains is in line with previous research on youth and senior football players[2 36] and reflects the nature of the game with frequent high-intensity actions and duels. Bone was the tissue type associated with the greatest burden, accounting for one third of total time loss. These injuries are especially interesting when dealing with adolescent athletes due to the immature skeletal system and growth spurt. Bone stress injuries were of particular concern in the lumbosacral area (spondylolysis-/listhesis and pars stress reactions) and should be recognised early as they are considered high-risk injuries in youth athletes.[7]

Injury patterns depend on age group

The overall injury incidence was higher in older players and more than doubled from the U13 to the U18 age group (7.8 to 18.6 per 1000 hours). A greater proportion of match versus training exposure with age should be taken into account; however, both training and match incidence were higher. Greater injury rates with age is a trend also observed in previous research, although not consistent across all studies.[2] Suggestions for underlying reasons include greater playing intensity, higher training volume, stronger players, increased competitiveness and a more aggressive playing style.[10 11 37] More advanced age, maturity and body size have indeed been associated with greater maximal aerobic and sprinting speed and match running performance in this academy.[38–40] The higher incidence could also reflect a greater likelihood of having sustained a previous injury, a commonly accepted risk factor for a new injury in youth football.[41] This is supported by a higher proportion of recurrent injuries with age in the present study.

While incidence was the greatest in the two oldest age groups, burden peaked and player availability was the lowest for U16 players. This reflects a greater severity of each injury and emphasises the importance of including burden alongside injury counts and incidence rates in epidemiological studies. Burden is not often presented for age groups, but our results match the findings from Dutch and Spanish elite youth footballers[14 15] and the observation of more severe injuries in the U14–U16 groups elsewhere.[10 13] This has mainly been attributed to players either experiencing or adjusting to rapid changes in height and weight[10 13–15] and may be compounded by the aforementioned increases in performance capacity and match demands.

Age group trends differed for specific pathology types. A higher incidence of muscle injuries in older players could again reflect greater playing demands and increased running speeds, which may also explain the greater proportion of sprint-related injuries with age. A lower incidence of physis injuries could be related to more advanced skeletal maturation status and a greater proportion of players having gone through their growth spurt, which would be expected in the older age groups.[42 43] Apophyses are considered especially sensitive to excessive and repetitive forces, which may increase following periods of rapid skeletal lengthening and muscular strength gains.[44] The observed concomitant lower incidence of physis injuries and greater incidence of muscle injuries also supports the idea that different structures represent the point of failure throughout growth and maturation, and similar mechanisms may manifest as different pathologies depending on a player's maturity status.[8] This is supported by reports of fewer osteochondral injuries and more groin strains in early maturing players and fewer tendinopathies in late maturing players of the same age.[45] Muscle injuries also appear to occur at a greater percentage of adult height compared with growth-related injuries,[46] although the degree of somatic development may not always align with skeletal maturation and the ossification of specific bones.[47 48]

Methodological considerations

A time-loss definition was applied in this study to reduce the potential bias associated with combining injury data collected by multiple physiotherapists under the supervision of different staff members[49] and allow for direct comparison with studies from other settings. Although this definition is considered reliable and captures injuries affecting participation, it likely underestimates the incidence of gradual onset injuries and complaints that only require medical attention.[50] The impact of injuries on performance, considered an important aspect by athletes, coaches and practitioners,[51] is also not well described.[52] Basing severity on participation and availability as opposed to tissue healing may have led to different injury duration and burden for two similar injuries.[53]

Diagnoses were provided by medical staff; yet, some variation should be assumed in terms of the recorded diagnoses and pathology types. Inconsistencies have been demonstrated among sports medical staff presented with similar case descriptions,[54 55] and we therefore grouped diagnoses into larger clusters, such as 'strain/spasm' and 'ankle sprain (excluding syndesmosis)', rather than reporting the specific SMDCS diagnosis. The low number of injuries within each pathology type for some age groups led to uncertain estimates and broad CIs, which should be recognised as a limitation for these comparisons. Furthermore, age groups were not unpaired and some players are represented in multiple age groups. The injury pattern of the 37 players monitored for four full seasons did, however, reflect the overall trends with seasonal variation and greater incidence with age.

The conversion from old to new SMDCS codes impaired accuracy, as some categories were more granular in the updated codes. The onset of injuries was assigned retrospectively and should therefore be interpreted with care. The SMDCS classification was not applied, as this considers physis injuries 'acute—sudden onset', which is not consistent with the mainly gradual onset clinical presentation of the apophyseal injuries recorded in this study. The 'repetitive—sudden onset' classification could also not be used with the information available. The proportion of recurrences may be underestimated, as a complete injury history was not available for all participants; the first recorded injury during the observation period for each player was therefore considered an index injury. The specific mechanism could not be cross-checked using additional data sources. This introduces uncertainty, solely reliant on the judgement of the medical staff either through direct observation on the pitch or the description by the player or coach.

While all academy, club and national team activities were recorded during the season, physical activity outside the organised sessions (eg, leisure time and school activity for part-time players) and training during the summer break were not monitored. This may have an impact on especially the gradual onset type injuries. Finally, we highlight that contextual factors inherent to training philosophies, lifestyle habits and environmental conditions require consideration when generalising the findings of this study.

What are the findings?

- Overall injury incidence was higher in older age groups and the greatest burden and lowest player availability was observed in the U16 age group.
- Injury incidence and burden was higher in older age groups for muscle injuries and in younger age groups for physis injuries. Joint sprains and bone stress injuries were more common in the U16, U17 and U18 age groups, with the greatest burden observed for U16 players. No clear trend was observed for fractures.

How might it impact on clinical practice in the future?

- Identifying the most common and the most burdensome injuries allows practitioners to target the injuries with the greatest impact on player participation. While evidence-based multicomponent programmes aimed at a broad range of injuries (eg, the 11+) are still regarded as best practice, practitioners may consider adapting interventions according to the age-related patterns described in this study.
- Generic and specific injury-type audits are valuable to inform decisions relating to the optimal youth player management in professional academies.

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Supplementary Table 1. Descriptive data for each of the four seasons included in the study.

	2016-17	**2017-18**	**2018-19**	**2019-20**
Player-seasons	129	141	159	162
Median season weeks [25th to 75th pctl]	37 [37 to 38]	36 [34 to 36]	38 [36 to 38]	29 [29 to 31]
Total accumulated training exposure (h)	17 727	18 051	22 291	20 000
Total accumulated match exposure (h)	3 926	3 705	3 949	3 178
Time-loss injuries (n)	211	258	420	222
Overall injury incidence (95% CI)	9.7 (8.5 to 11.2)	11.9 (10.5 to 13.4)	16.0 (14.5 to 17.6)	9.6 (8.4 to 10.9)
Training injury incidence (95% CI)	5.2 (4.2 to 6.4)	8.2 (6.9 to 9.6)	11.9 (10.5 to 13.4)	6.7 (5.6 to 7.9)
Match injury incidence (95% CI)	30.3 (25.1 to 36.3)	29.7 (24.4 to 35.8)	39.2 (33.3 to 45.9)	27.7 (22.2 to 34.1)
Season incidence proportion (%)	79.1	78.0	86.8	70.4
Same-season recurrent injuries (%)	3.8	7.0	9.8	7.2
Median days lost per injury [25th to 75th pctl]	11 [3 to 26]	9 [3 to 21]	6 [2 to 17]	10 [3 to 23]
Injury burden (95% CI)	268 (261 to 275)	282 (275 to 289)	277 (271 to 283)	195 (190 to 201)
Overall player availability (%)	86.6	83.9	84.6	88.3
Player training availability (%)	85.9	82.9	83.8	88.1
Player match availability (%)	90.3	89.3	88.9	89.9

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ORIGINAL ARTICLE

WILEY

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

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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 whether 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: 1.1-1.9) and growth plate injuries (IRR: 2.1; 1.5-3.1). Growth rate for leg length was associated with greater overall injury risk (IRR: 1.3; 1.0-1.7) as well as the risk of bone (IRR: 1.4; 1.0-1.9) and growth plate injuries (IRR: 2.1; 1.4-3.0). Athletes with greater skeletal maturity, expressed as skeletal age (IRR: 0.6 per year; 0.5-0.9) and percentage of predicted mature height (IRR: 0.8 per percent increase; 0.7-1.0), 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; 1.0-2.3). 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

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

1 | 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 among 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 11-12 years in girls and 13-14 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 toward 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 vary 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 with 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.

2 | MATERIAL AND METHODS

2.1 | 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 toward a single event group were considered eligible for inclusion. These athletes followed a general athletics development program and typically participated in eight 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.

2.2 | 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.) and body mass using digital scales with a precision of 0.1 kg (ADE Electronic Column Scales). 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.), 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 with a criterion measurer and intra-rater TEM has to be less than 1% for accreditation.

2.3 | 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, 0.996-0.999)[27] and reliability data from the academy demonstrated an ICC of 0.95 (0.92-0.97) for the TW3 RUS (radius, ulna, and short bones) overall score (unpublished data).

2.4 | 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, six 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) by the coaching staff and reviewed case-by-case by the senior physiotherapist after each season.

2.5 | 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: 1-7 days lost, Moderate: 8-28 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.

2.6 | Statistical analysis

Descriptive statistics for growth and maturation variables are reported as mean ± 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 was used to select the model with best fit. The negative binominal regression demonstrated the lowest QIC values and the output from these analyses is therefore reported with P-values < .05 indicating significant associations. All statistical analyses were performed in SPSS ver. 21 (IBM).

3 | RESULTS

3.1 | 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 1-3) satisfied the inclusion criteria. Maturity status could be analyzed for 108 athlete-seasons from 71 athletes (1.4 ± 0.6; 1-3), where 64 athlete-seasons from 42 athletes (1.4 ± 0.6; 1-3) 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; 1-3). Chronological age at the start of the season was 13.4 ± 1.0 years (11.7-17.2), with a stature of 163 ± 11 cm (137-184) and body mass of 53 ± 16 kg (28-112). Based on nationality, 91.5% of the athlete-seasons represented Western-Asian countries, while the remaining 8.5% represented Northern-African countries.

3.2 | 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.

3.3 | Injuries

A total of 87 time-loss injuries (0.7 ± 0.9; 0-3 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; 0-165 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 Tables 3 and 4.

4 | 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.

4.1 | 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.

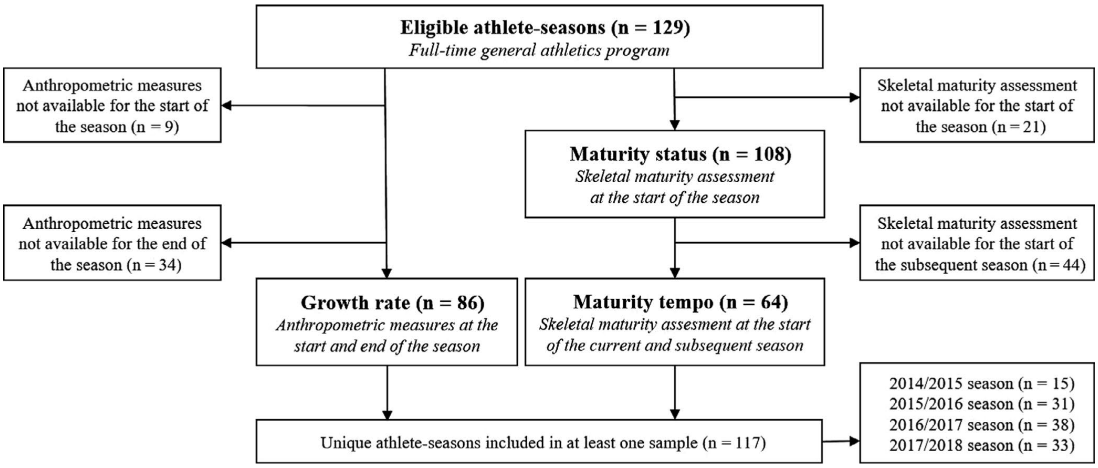

FIGURE 1 Flow diagram describing the inclusion of athlete-seasons from the academy athletics program to the final study samples, with the number of athlete-seasons excluded due to missing anthropometric or skeletal maturity assessments

TABLE 1 Baseline values and seasonal change for the growth and maturation variables included in the analyses

	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/m^2)	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

Note: Absolute changes represent the actual change from baseline to follow-up while relative changes represent the annual percentage change.

In the study of growth rates in Dutch footballers by Kemper et al,[6] a BMI increase exceeding 0.3 kg/m^2 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/m^2 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 with team sports. Assessing specific changes in limb mass and identifying the sources of weight gain (eg, 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.

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 (100.0)	21 (24.1)	5 (5.7)	5 (5.7)	8 (9.2)	11 (12.6)	7 (8.0)	5 (5.7)	25 (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 among adolescent athletics athletes

	IRR (95% CI)	P
Overall injuries (n = 73)		
Δ Stature	1.10 (0.86-1.40)	.46
Δ Body mass	1.04 (0.69-1.57)	.86
Δ Body mass index	1.01 (0.67-1.52)	.96
Δ Trunk height	0.87 (0.59-1.27)	.46
Δ Leg length	1.30 (1.01-1.67)	*.039*
Gradual onset injuries (n = 46)		
Δ Stature	1.25 (0.97-1.61)	.08
Δ Body mass	1.11 (0.77-1.62)	.57
Δ Body mass index	1.01 (0.66-1.54)	.97
Δ Trunk height	1.04 (0.79-1.37)	.77
Δ Leg length	1.29 (0.99-1.68)	.06
Sudden onset injuries (n = 27)		
Δ Stature	0.80 (0.50-1.30)	.37
Δ Body mass	0.81 (0.41-1.61)	.55
Δ Body mass index	0.89 (0.51-1.54)	.68
Δ Trunk height	0.64 (0.30-1.38)	.25
Δ Leg length	1.26 (0.76-2.10)	.37
Bone injuries (n = 36)		
Δ Stature	1.47 (1.11-1.94)	*.007*
Δ Body mass	1.13 (0.75-1.71)	.55
Δ Body mass index	1.03 (0.65-1.65)	.89
Δ Trunk height	1.16 (0.85-1.57)	.36
Δ Leg length	1.41 (1.04-1.92)	*.029*
Growth plate injuries (n = 19)		
Δ Stature	2.14 (1.46-3.13)	*<.001*
Δ Body mass	1.23 (0.68-2.26)	.49
Δ Body mass index	1.02 (0.47-2.24)	.96
Δ Trunk height	1.31 (0.91-1.88)	.15
Δ Leg length	2.06 (1.43-2.97)	*<.001*

Note: P-values in italics indicate significant associations.

4.2 | Fewer growth plate injuries near skeletal maturity

The average skeletal age was 1.8 years advanced compared with 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 (eg U14, U16, and U18)[36] may have further amplified these differences, explaining the skewed distribution.

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 among adolescent athletics athletes

	Total inj.	IRR (95% CI)	P
Overall injuries			
Skeletal age	76	0.99 (0.85-1.15)	.89
% Predicted height	76	0.99 (0.94-1.05)	.82
Δ Skeletal age	48	0.99 (0.70-1.39)	.94
Gradual onset injuries			
Skeletal age	44	1.03 (0.84-1.28)	.77
% Predicted height	44	1.00 (0.93-1.07)	.92
Δ Skeletal age	31	1.13 (0.77-1.65)	.53
Sudden onset injuries			
Skeletal age	32	0.95 (0.78-1.16)	.61
% Predicted height	32	1.00 (0.93-1.08)	.99
Δ Skeletal age	17	0.78 (0.51-1.19)	.25
Bone injuries			
Skeletal age	34	0.88 (0.70-1.11)	.29
% Predicted height	34	0.95 (0.87-1.03)	.22
Δ Skeletal age	20	1.54 (1.03-2.29)	*.035*
Growth plate injuries			
Skeletal age	18	0.64 (0.48-0.85)	*.002*
% Predicted height	18	0.83 (0.73-0.96)	*.009*
Δ Skeletal age	12	1.12 (0.74-1.69)	.60

Note: P-values in italics indicate significant associations.

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 with 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 are responsible for the increased injury rates.

4.3 | 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, for example 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.

4.4 | 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]

5 | 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 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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Paper V

TITLE

Main and combined effects of growth rate and skeletal maturity status on injury risk in elite youth football players

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ABSTRACT

Injuries impact opportunities for participation in football (soccer) activities and may affect the development of youth players. Growth and maturation have been associated with injury risk in earlier studies; however, methods and outcomes are inconsistent and firm conclusions cannot be drawn. The aim of this study was to explore main and combined effects of growth rates (height, leg length and body mass), chronological age and maturity status (Fels skeletal age) on overall, gradual onset, sudden onset, muscle, joint sprain, fracture and physis injury risk in 103 male elite youth football players over three seasons. We compared the relative quality of mixed-effects logistic regression models with growth rates for 171 growth periods (average 119 days, SD 58) included as fixed effects, and adjusted for skeletal age or chronological age plus football load (average weekly hours). Associations were interpreted as practically relevant based on the confidence interval for odds ratios, using thresholds of 0.90 and 1.11 to define small beneficial and harmful effects, respectively. The uncertainty for the estimated odds ratios show no practically relevant main effects for growth rates on injury risk. Likewise, the effects for load and growth × age interaction were not practically relevant. While long-term tracking of growth and maturity status may inform player development strategies, our study findings suggest that their roles for general and type-specific injury risk is limited. Future studies should consider establishing long-term programs monitoring players from childhood through full maturation to explore the potential influence of growth rates on injury risk.

Key words:

Soccer, growth and development, epidemiology, sports medicine

INTRODUCTION

Elite football academies guide players through structured and intensive training programmes to optimise long-term development. Injuries impact these opportunities and identification of risk factors is an important step towards to reducing injury occurrence and severity.[1] In youth football, growth and maturation are considered potential risk factors; still, the existing literature is inconclusive and studies are considered at high risk of bias.[2]

Growth and maturation refer to separate but related biological concepts. Growth represents an increase in the size of the body as a whole or of a specific body part, assessed using anthropometric measures.[3] Puberty represents an accelerated period of growth, with mean growth rates around 8 to 10 cm/year at peak height velocity (PHV) and 8 to 10 kg/year at peak weight velocity (PWV) for boys.[3] In elite youth football, a limited number of studies have indicated that players may be vulnerable to certain injuries during and following PHV[4-7] and within periods of rapid increase in stature, leg length and body mass index.[8,9]

Maturation is more complex, defined as the process of becoming mature (e.g. fully functioning reproductive system or ossified skeleton).[3] The timing and tempo varies greatly between individuals and the maturity status (where an individual is in the process at a given point) of two football players who train and compete in the same age group can therefore be very different.[3] Skeletal age is considered the single best marker of maturity status, as the start (skeleton of cartilage) and end points (skeleton of mature bone) are known and can be followed precisely and reliably throughout the maturation process.[3] This is, however, not considered practical in the applied sports context as it is costly, time consuming and requires expertise,[10] even if radiation dose is almost negligible.[11] Only two studies have related skeletal age to injury risk in male elite youth football players, both indicating no difference in overall incidence.[12,13] Le Gall et al.[12] did, however, report a greater incidence of groin strains and tendinopathies in early maturing players and higher incidence of osteochondral disorders in late maturing players.[12] This is in line with studies reporting different injury patterns depending on chronological age group.[14-17] Since firm conclusions cannot be drawn from the existing literature regarding growth, maturation and injury risk, the aim of this study was to explore the main and combined effects of growth rates, skeletal maturity and chronological age on injury risk in elite male academy players.

MATERIAL AND METHODS

We used injury, training, growth and maturity data collected prospectively over three seasons (2016/17 through 2018/19) at Aspire Academy, an elite national football academy in Qatar. The injury and training data included in this study have been explored in a previous publication, describing the most common and burdensome injuries in addition to age group patterns.[14] Participants were boys aged 11 to 18 years (U13 through U18) and full-time players typically participated in eight morning and/or afternoon sessions during the school week, in addition to games with their local club in the national youth league on weekends. Part-time players participated in five afternoon sessions in addition to weekend club games. Written informed consent to use routinely collected monitoring data for research purposes was obtained from the player's guardians and ethics approval was granted from the Anti-Doping Lab Qatar Institutional Review Board (IRB Application #E20140000012).

Injury and exposure data

Injuries were recorded by the designated team physiotherapist, present at all team sessions. Recording procedures followed the consensus recommendations from Fuller et al.,[18] including only time-loss injuries,[19] i.e. any physical complaint leading to the medical staff partially or fully restricting participation in future football activities. The Aspire Academy Football Injury Surveillance Programme was supervised by two researchers. Physician-verified diagnoses were reported based on the Sports Medicine Diagnostic Coding System (SMDCS),[20] in addition to details about the date of injury and mechanism. A player was considered injured until the date he returned to full participation in team training and was available for match selection, as determined by the medical staff.[18] Individual training and match exposure were recorded by a designated team sports scientist. Information about the session type and deviations from team activity (e.g. rehabilitation session, recovery or illness), along with their duration in minutes, was collected. Club training and match exposure were recorded by the club strength & conditioning staff and match duration was corrected against official match reports.

Following the completion of the data collection, a researcher verified the injury database against the training database to confirm injury dates and identify missing details, for which a player's electronic medical record (Millennium® Power Chart, Cerner Corporation, North Kansas City, MO, USA) was subsequently audited. The same researcher converted injury diagnoses to the updated SMDCS categories for pathology type[21] and retrospectively allocated onset (sudden or gradual) based on the reported mechanism and diagnosis. Only index injuries (first injury during the respective observation period) were considered for this study while recurrent injuries were excluded; these were defined as a time-loss injury to the same location of the same type as a previous injury recorded during the same observation period.[22]

Assessment of growth and maturation

Anthropometric measures, including standing height, sitting height and body mass were obtained at regular intervals (typically at the start, middle and end of the season) by team sports scientists, trained to follow the recommendations outlined by Stewart et al.[23] Measures were taken in the morning, prior to any activities to minimize diurnal variations. Standing height was measured to the nearest 0.1 cm applying the stretch stature method, using a wall-mounted stadiometer (Holtain Ltd, Crymych, UK). Sitting height was measured to the nearest 0.1 cm with the athlete seated on a purpose-built platform with a stadiometer (Holtain Ltd, Crymych, UK) and leg length was calculated as the difference between standing and sitting height. Body mass was measured to the nearest 0.1 kg using digital scales (Adam Equipment™, Milton Keynes, UK). Unpublished test-retest data in a subsample of 17 players from this population revealed a standard error of the measurement (SEM) of 0.34 cm (95% confidence interval (CI): 0.25 to 0.52 cm) and 0.20 cm (0.15 to 0.30 cm) for standing and sitting height, respectively. This corresponds to a minimal detectable change (MDC) of approximately 1 cm for both measures.

Skeletal maturity was assessed at the beginning of the season using x-ray images of the player's left hand/wrist complex taken at Aspetar Orthopaedic and Sports Medicine Hospital. Skeletal age was determined using the Fels method[24] by one trained assessor. Assessments were not continued for players previously identified as skeletally mature (skeletal age 18.0).[25] Intra-rater reliability for this method has previously been reported (intraclass correlation coefficient (ICC): 0.998, 95% CI: 0.996 to 0.999).[13]

Data handling and statistical analyses

For calculation of growth rates, at least two full anthropometric assessments (i.e. including data for height, leg length and body mass) were required during the season, usually at the start and the end to be included. Anthropometric measures were excluded if taken more than 91 days from the start or end of the season, based on the recommendation to measure growth at least twice per year to detect changes.[26] It has been suggested that researchers examine growth over shorter periods of time to better account for non-linear growth patterns,[27] and, if a third, mid-season measurement was available, we split each player-season into two growth periods. An arbitrary cut-off was set to ensure that two measures were minimum 60 days apart to allow for meaningful changes. The absolute change (cm or kg) was divided by number of days between measurements to account for the duration of the growth period and converted to expressions equivalent to cm/year and kg/year, respectively.[9,28] For a growth period to be included in the final analyses, a skeletal assessment for the season also had to be available as a covariate (assessed maximum 91 days within the start of the season).

Descriptive statistics are presented as means with SD. Separate mixed-effects logistic regression models (*xtmelogit* command) estimated associations for the effects of changes in growth on the occurrence of overall, gradual onset, sudden onset, muscle injury, joint sprain, fracture and physis injury as clinical end-points of interest. Growth rates for height, leg length, and body mass were specified as distinct growth-related predictor variables (fixed effects). Models were adjusted for chronological age or skeletal age and growth × age interaction, with player specified as a random effect plus a random intercept. The average weekly training and match load (hours per week) during the period (or until the event, if an injury occurred) was added as a covariate in the model. An example of the data structure is provided in Table 1.

The Akaike Information Criterion (AIC) assessed the relative quality of each mixed-effects logistic regression model in the set of candidate models. The Akaike difference (ΔAIC) from the estimated best model (i.e. the model with the lowest AIC value; ΔAIC = 0) was evaluated according to the following scale: 0–2, essentially equivalent; >2–7, plausible alternative; >7–14, weak support; >14, no empirical support.[29] Akaike weights (w_i) provided a scaled interpretation about the relative quality of each competing model as the probability that a given model is the best in the set of six candidate models per end-point. Thresholds for the adjusted odds ratios (OR) of 0.9, 0.7, 0.5, 0.3, and 0.1 and their reciprocals 1.11, 1.43, 2.0, 3.3, and 10 defined small, moderate, large, very large, and extremely large beneficial and harmful effects, respectively.[30] In the absence of an established anchor defining practically relevant associations between growth rates and injury occurrence, we considered OR=0.90 or OR=1.11 to define substantially beneficial and substantially harmful effects, respectively.[30] Associations were declared practically relevant based on the location of the confidence interval for the estimated ORs to these thresholds. Outcome statistics are reported as point estimates and 95% CI. Statistical analyses were performed using Stata (StataMP v14.0; StataCorp LP, College Station, TX, USA).

RESULTS

The final sample included 171 growth periods from 103 unique players (57 with one growth period, 28 with two, 15 with three, 2 with four and 1 with five periods), with a mean duration of 119 days (SD 58). The inclusion and exclusion of player-seasons and growth periods are shown in Figure 1. The mean age at the start of a growth period was 14.8 years (SD 1.5) while the mean skeletal age at the start of the season was 15.8 years (SD 1.9). The mean growth rate was 4.8 cm/year (SD 4.2) for height, 2.6 cm/year (SD 2.8) for leg length and 5.7 kg/year (SD 5.1) for body mass. Players were considered mature in 19% of the player-seasons included (skeletal age 18 years), early maturing in 40% (skeletal age 1 year in advance of chronological age), on time in 39% (skeletal age within 1 year) and late maturing in 2% (skeletal age 1 year delayed).[31] On average, players were 1.1 years (SD 1.1) advanced in skeletal age relative to chronological age. A total of 182 index injuries and 15 929 training and match hours were recorded within the growth periods included (11.4 injuries per 1000 h).

Main and combined effects of growth rate and maturity status

The relative model quality of the six model combinations within the seven injury categories is presented in Table 2. Growth rate for body mass combined with skeletal age best explained the overall injury risk and that of joint sprains, while rate of change in body mass combined with chronological age best explained the risk of gradual onset injuries, fractures and physis injuries. The model with growth rate for leg length adjusted for skeletal age was the best for sudden onset injuries and leg length growth combined with chronological age for muscle injuries.

The models emerging as the best in the set of candidates per injury category are presented in Figure 2 (Supplementary Table 1 gives a complete overview of the components for all the models). No practically relevant main effects for growth rates were observed. For skeletal age, we observed main effects for overall injuries with leg length (OR: 1.31, 95% CI: 1.01 to 1.69, *P*=0.038) and body mass (OR: 1.27, 1.00 to 1.62, *P*=0.047), for sudden onset injuries with leg length (OR: 1.44, 1.06 to 1.95, *P*=0.019) and body mass (OR: 1.35, 1.04 to 1.77, *P*=0.026), for muscle injuries with height (OR: 1.67, 1.03 to 2.69, *P*=0.037) and leg length (OR: 1.46, 1.00 to 2.12, *P*=0.049) and for joint sprains with body mass (OR: 1.91, 1.09 to 3.33, *P*=0.023). These results suggested a statistically significant greater injury risk with more advanced skeletal age, yet not practically relevant given our predefined thresholds (95% CI for OR <0.9 or >1.1). The effects for load and relevant growth × age interaction were not practically relevant (see Supplementary Table 2 for details).

DISCUSSION

The present study explored the effects of growth rates on injury risk, adjusting for skeletal maturity status, chronological age, and training and match load. Using routinely collected clinical and exposure data from 103 elite youth football players over three seasons, we could not detect any practically relevant main effects for growth rate or any interaction effect with skeletal maturity status on injury risk. From an applied perspective, the outcomes from our model comparison (Table 2) also did not identify a consistent combination of predictor variables to describe the growth-injury risk relationship.

Young athletes have been considered especially vulnerable to overuse injuries during the growth spurt[33] and studies on elite youth football players have associated the time around PHV and periods of increased growth rates to greater overall, overuse, acute and non-contact injury risk.[4-6,8,9] While these findings indicate a potential link between growth rate and injury risk, the underlying rationale for an association appears more plausible if specific injury types are addressed, such as fractures or growth plate injuries. Rapid skeletal growth has been suggested to increase tension on vulnerable apophyses,[34] lead to temporarily decreased bone mineral density[35,36] and reduced neuromuscular control,[37,38] which in turn could be expected to affect the risk of physis injuries, fractures, joint sprains or muscle injuries.

No study has considered individual training/match exposure and maturity status or age as potential confounders in a model taking repeated measures into account. When taking these factors into consideration, we did not observe any practically relevant main effects of growth rate for height, leg length or body mass on injury risk. These findings suggest there is no relationship between growth rates and injuries, which has also been the conclusion for some growth measures and injury outcomes in other football studies.[8,9] While the analysis of short time intervals (average: 119 days) can be considered appropriate to capture periods of rapid growth,[27] long-term longitudinal monitoring is required to place these periods in the context of each player's individual growth process.[39,40] Furthermore, the use of short periods to examine injury risk may not be ideal in a complex sport like football; injuries are considered to be the result of a complex interplay between factors (e.g. previous injury, fitness).[41] Most of these factors were not considered in this study and there will always be an element of chance involved in the occurrence or non-occurrence of an event for a given period.[42] Analysing short predefined growth intervals in isolation may therefore not be the best approach if the goal is to identify players that are vulnerable to injury or to describe the relationship between growth and injury risk.

The role of skeletal maturity status and age on injury risk

In this sample, nearly half of the players were early mature and only 2% were considered late maturing based on the difference between skeletal age and chronological age. These observations are in accordance with a bias observed in football academy programmes, favouring early maturing players.[43] Potential variations in ethnicity and living conditions should, however, be taken into account.[11] The majority of our players originate from Western Asian countries and may not directly compare to the sample of American children and adolescents growing up in the 1930s to 1970s on whom the reference values forming the basis for the Fels method were based on.[11,31]

Maturity status, in absolute or relative terms, has been suggested as a risk factor for injury in elite male youth football,[5,7,12,13,44-46] although largely limited to somatic maturity derived from prediction equations. In the two studies using indicators of skeletal maturity,[12,13] no differences were found for overall incidence, while Le Gall et al.[12] observed differences for specific injury types. Our results include model combinations with significant main effects of skeletal age on overall, sudden onset, muscle and joint sprain injuries. In general, this indicates that skeletally older players were at greater risk of sustaining these types of injuries, although confidence intervals were broad and did not justify labelling these effects as practically relevant. We also point to the predominantly non-significant main effects and urge caution when interpreting results based on a limited number of athletes and events.

Rommers et al.[9] found that acute injuries in the U13 to U15 age groups were related to lower growth rates. This appears counterintuitive and authors discussed the possibility that relatively older players were more likely to have passed their growth spurt, reflecting an increased injury risk with age rather than with lower growth rates *per se*. Explorations of data from our sample of appeared to support this notion, where older and more skeletally mature players displayed lower growth rates for height and leg length, but not body mass. Along the same lines, Johnson et al.[5] did not find any effect of players maturing late, on time or early when their PHV-status (pre-, circa- or post-PHV) was accounted for. The findings from these studies may suggest an interaction between growth rates and age or maturity on injury risk; however, in our study, the effects for growth × chronological/skeletal age interaction were not practically relevant. As discussed for growth rates, this could also reflect limitations associated with analysing injury risk using short time intervals.

Methodological considerations

Although we addressed several limitations from previous studies on growth, maturation and injury risk with our models including skeletal age as a criterion indicator of maturity status, some limitations should be considered when interpreting our results. First, our growth and maturity data were primarily collected for clinical and applied purposes, which led to a substantial amount of missing data points (presumably at random). This limited our sample size and subsequently the number of events included for each injury category. Second, our maturity measures were based on the hand/wrist complex. Although this is considered representative for the skeleton as a whole,[3] it does not necessarily represent the maturity status of bones in other locations.[47] The pubic apophyseal plate, for example, typically closes around the age of 21 years.[48] Third, the exploratory nature of our study, involving a retrospective analysis of routinely collected clinical and exposure data, precluded any formal a priori sample size estimation relevant to a mixed-effects modelling framework.[49] Fourth, by analysing short time intervals in isolation, our growth periods were dependent on the available anthropometric measures and might not truly reflect the exact phases of rapid growth for each individual. Finally, the use of a time-loss definition limited our ability to capture injuries that did not affect participation;[50] this is especially relevant for the gradual onset and physis injury categories.[22]

PERSPECTIVE

In this study, we examined the risk of different injury types in relation to growth rates for height, leg length and body mass, in combination with skeletal age or chronological age, adjusted for individual training and match load. Despite statistically significant main effects for skeletal maturity, suggesting greater risk of certain injury types (overall, sudden onset, muscle and joint sprain injuries) with older skeletal age, these associations were not practically relevant. Our study can be considered an addition to the existing literature; however, we suggest that future research moves away from analyzing short periods of growth and direct resources towards establishing robust long-term surveillance systems that can capture the whole growth and maturity process alongside reliable collection of injury and exposure data.[39,40]

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TABLES

Table 1 Example of the model data structure. The occurrence of a specified injury type in the growth period (event yes/no), growth rate for height, leg length or body mass for the growth period, chronological age at the start of the growth period, Fels skeletal age at the start of the season and the average training and match load (h/week) during the period (prior to the event for injured players).

ID	Period no.	Event	Δ Height (cm/yr)	Δ Leg length (cm/yr)	Δ Body mass (kg/yr)	CA (yrs)	SA (yrs)	Load (h/week)
1	1	Y	1.4	0.3	8.3	15.8	16.1	4.0
2	1	Y	4.2	3.4	4.3	14.8	14.7	5.5
2	2	N	3.1	5.9	7.3	15.5	15.7	6.2
3	1	Y	5.8	5.1	4.3	13.3	15.1	6.6
3	2	Y	4.3	4.8	0.0	14.3	17.7	7.4

ID: Player identification. CA: Chronological age. SA: Skeletal age.

Table 2 Relative model quality for each injury category.

Model	AIC	Δ AIC	w_i	*Inference*
Overall (113 events)				
Δ Body mass & Skeletal age	222.3	0.0	0.33	*Best*
Δ Leg length & Skeletal age	223.2	0.9	0.21	*Essentially equivalent*
Δ Height & Skeletal age	223.2	0.9	0.21	*Essentially equivalent*
Δ Body mass & Chronological age	224.6	2.3	0.11	*Plausible alternative*
Δ Leg length & Chronological age	225.0	2.7	0.09	*Plausible alternative*
Δ Height & Chronological age	225.7	3.4	0.06	*Plausible alternative*
Sudden onset (96 events)				
Δ Leg length & Skeletal age	234.8	0.0	0.41	*Best*
Δ Body mass & Skeletal age	236.2	1.4	0.20	*Essentially equivalent*
Δ Height & Skeletal age	236.4	1.7	0.18	*Essentially equivalent*
Δ Leg length & Chronological age	236.7	2.0	0.15	*Plausible alternative*
Δ Body mass & Chronological age	239.6	4.9	0.04	*Plausible alternative*
Δ Height & Chronological age	239.9	5.1	0.03	*Plausible alternative*
Gradual onset (39 events)				
Δ Body mass & Chronological age	190.8	0.0	0.44	*Best*
Δ Body mass & Skeletal age	192.2	1.5	0.21	*Essentially equivalent*
Δ Leg length & Skeletal age	193.2	2.5	0.13	*Plausible alternative*
Δ Leg length & Chronological age	194.0	3.3	0.09	*Plausible alternative*
Δ Height & Chronological age	194.3	3.5	0.08	*Plausible alternative*
Δ Height & Skeletal age	194.7	3.9	0.06	*Plausible alternative*
Muscle injury (34 events)				
Δ Leg length & Chronological age	173.8	0.0	0.40	*Best*
Δ Height & Skeletal age	174.7	0.9	0.26	*Essentially equivalent*
Δ Leg length & Skeletal age	175.4	1.6	0.18	*Essentially equivalent*
Δ Height & Chronological age	177.1	3.2	0.08	*Plausible alternative*
Δ Body mass & Skeletal age	177.3	3.4	0.07	*Plausible alternative*
Δ Body mass & Chronological age	180.5	6.7	0.01	*Plausible alternative*
Joint sprain (18 events)				
Δ Body mass & Skeletal age	111.8	0.0	0.41	*Best*
Δ Height & Skeletal age	112.3	0.5	0.32	*Essentially equivalent*
Δ Leg length & Skeletal age	114.0	2.2	0.14	*Plausible alternative*
Δ Height & Chronological age	114.5	2.7	0.11	*Plausible alternative*
Δ Body mass & Chronological age	118.7	6.9	0.01	*Plausible alternative*
Δ Leg length & Chronological age	121.5	9.7	0.00	*Weak support*
Fracture (13 events)				
Δ Body mass & Chronological age	95.9	0.0	0.46	*Best*
Δ Body mass & Skeletal age	97.9	2.0	0.17	*Plausible alternative*
Δ Height & Chronological age	98.7	2.7	0.12	*Plausible alternative*
Δ Leg length & Chronological age	98.7	2.8	0.11	*Plausible alternative*
Δ Leg length & Skeletal age	99.5	3.6	0.07	*Plausible alternative*
Δ Height & Skeletal age	99.6	3.7	0.07	*Plausible alternative*
Physis injury (17 events)				
Δ Body mass & Chronological age	114.8	0.0	0.46	*Best*
Δ Leg length & Chronological age	117.3	2.5	0.13	*Plausible alternative*
Δ Height & Chronological age	117.5	2.6	0.12	*Plausible alternative*
Δ Leg length & Skeletal age	117.7	2.9	0.11	*Plausible alternative*
Δ Body mass & Skeletal age	117.9	3.1	0.10	*Plausible alternative*
Δ Height & Skeletal age	118.4	3.5	0.08	*Plausible alternative*

AIC: Akaike Information Criterion, ΔAIC: Akaike difference, w_i: Akaike weight.

FIGURE LEGENDS

Figure 1. Inclusion and exclusion of player-seasons and growth periods.

Figure 2. Outcomes from the best models by injury category. Density strips illustrate parameter uncertainty and vertical tick marks indicate the point estimate for the estimated odds ratio.[32]

FIGURE 1

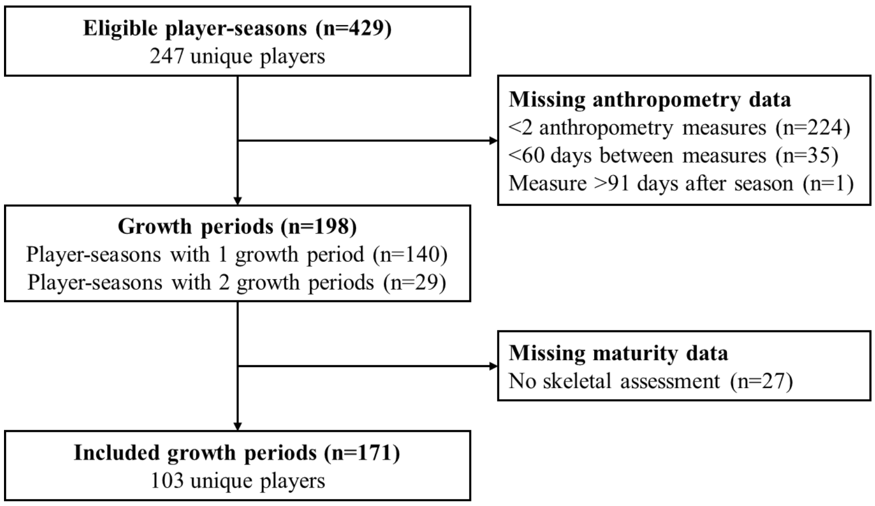
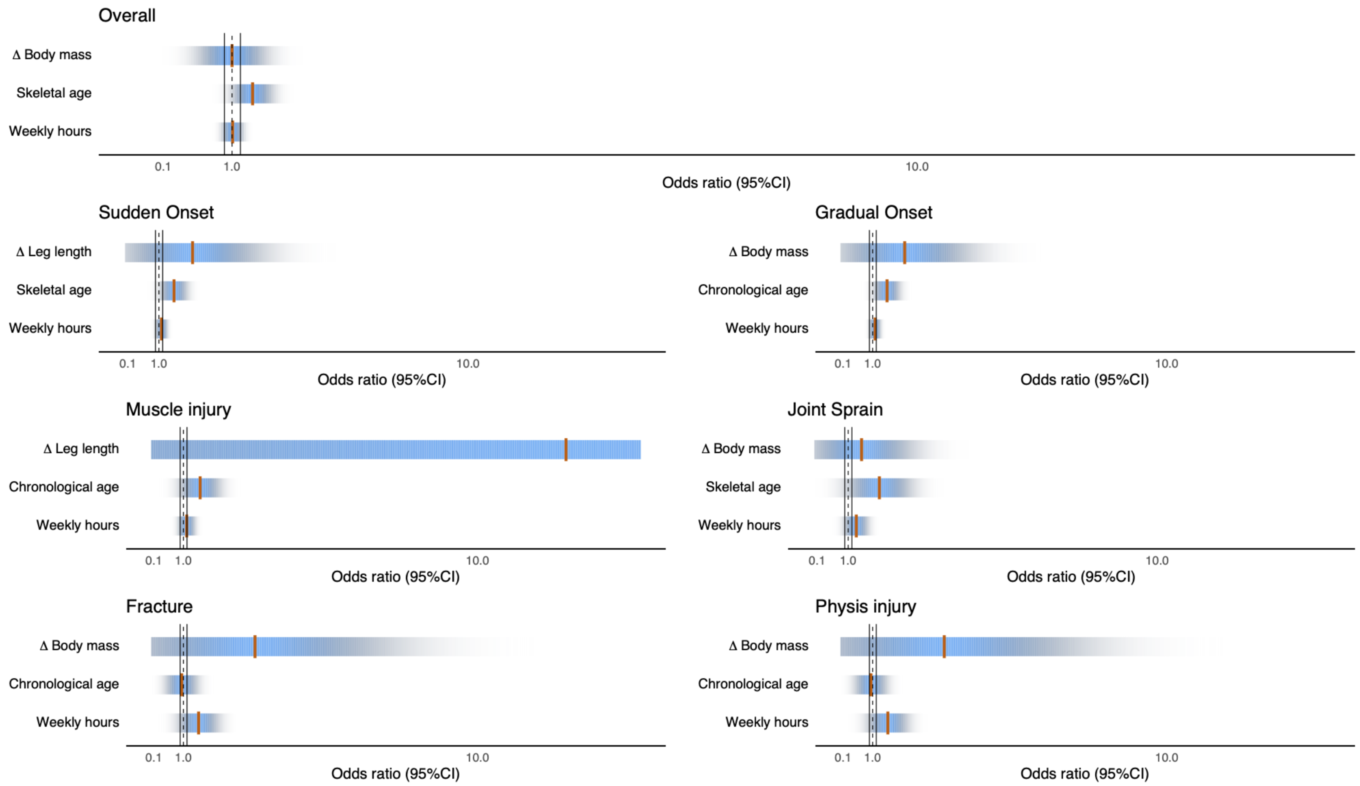

Eligible player-seasons (n=429)
247 unique players
Missing anthropometry data
<2 anthropometry measures (n=224)
<60 days between measures (n=35)
Measure >91 days after season (n=1)
Growth periods (n=198)
Player-seasons with 1 growth period (n=140)
Player-seasons with 2 growth periods (n=29)
Missing maturity data
No skeletal assessment (n=27)
Included growth periods (n=171)
103 unique players

FIGURE 2



Overall
Δ Body mass
Skeletal age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)
Sudden Onset
Δ Leg length
Skeletal age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)
Gradual Onset
Δ Body mass
Chronological age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)
Muscle injury
Δ Leg length
Chronological age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)
Joint Sprain
Δ Body mass
Skeletal age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)
Fracture
Δ Body mass
Chronological age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)
Physis injury
Δ Body mass
Chronological age
Weekly hours
0.1
1.0
10.0
Odds ratio (95%CI)

Supplementary Table 1 Components for all model combinations for all injury categories.

Injury category	Model	Components	Odds ratio (95% CI)	*P*-value
Overall	Δ Stature & Chronological age	Δ Stature (cm/yr)	0.81 (0.33 to 1.97)	.64
		Chronological age (a)	1.13 (0.79 to 1.61)	.50
		Hours per week (h)	1.00 (0.85 to 1.16)	.95
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	1.83 (0.52 to 6.51)	.35
		Chronological age (a)	1.36 (0.99 to 1.87)	.06
		Hours per week (h)	1.02 (0.87 to 1.18)	.85
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	1.16 (0.61 to 2.18)	.66
		Chronological age (a)	1.35 (0.98 to 1.86)	.07
		Hours per week (h)	1.01 (0.87 to 1.18)	.86
	Δ Stature & Skeletal age	Δ Stature (cm/yr)	0.79 (0.38 to 1.67)	.54
		Skeletal age (a)	1.17 (0.88 to 1.54)	.28
		Hours per week (h)	0.99 (0.85 to 1.16)	.95
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	1.31 (0.48 to 3.57)	.59
		Skeletal age (a)	1.31 (1.01 to 1.69)	*.038*
		Hours per week (h)	1.00 (0.86 to 1.17)	.96
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	1.00 (0.60 to 1.67)	1.0
		Skeletal age (a)	1.27 (1.00 to 1.62)	*.047*
		Hours per week (h)	1.01 (0.87 to 1.18)	.91
Sudden onset	Δ Stature & Chronological age	Δ Stature (cm/yr)	0.95 (0.36 to 2.52)	.92
		Chronological age (a)	1.17 (0.79 to 1.72)	.43
		Hours per week (h)	1.07 (0.91 to 1.27)	.42
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	3.40 (0.67 to 17.36)	.14
		Chronological age (a)	1.46 (0.99 to 2.15)	.06
		Hours per week (h)	1.10 (0.91 to 1.33)	.31
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	1.30 (0.67 to 2.52)	.44
		Chronological age (a)	1.35 (0.98 to 1.87)	.07
		Hours per week (h)	1.08 (0.91 to 1.28)	.36
	Δ Stature & Skeletal age	Δ Stature (cm/yr)	0.90 (0.40 to 2.03)	.79
		Skeletal age (a)	1.25 (0.92 to 1.71)	.16
		Hours per week (h)	1.08 (0.91 to 1.27)	.39
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	1.98 (0.61 to 6.41)	.25
		Skeletal age (a)	1.44 (1.06 to 1.95)	*.019*
		Hours per week (h)	1.08 (0.90 to 1.28)	.41
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	1.17 (0.66 to 2.07)	.58
		Skeletal age (a)	1.35 (1.04 to 1.77)	*.026*
		Hours per week (h)	1.08 (0.92 to 1.28)	.35
Gradual onset	Δ Stature & Chronological age	Δ Stature (cm/yr)	0.75 (0.26 to 2.19)	.60
		Chronological age (a)	1.03 (0.69 to 1.56)	.87
		Hours per week (h)	1.02 (0.84 to 1.24)	.87
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	1.15 (0.25 to 5.40)	.86
		Chronological age (a)	1.11 (0.78 to 1.58)	.55
		Hours per week (h)	1.04 (0.85 to 1.26)	.72
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	1.63 (0.76 to 3.52)	.21
		Chronological age (a)	1.31 (0.92 to 1.86)	.14
		Hours per week (h)	1.06 (0.86 to 1.31)	.56

	Δ Stature & Skeletal age	Δ Stature (cm/yr)	0.79 (0.32 to 1.95)	.61
		Skeletal age (a)	0.98 (0.70 to 1.36)	.89
		Hours per week (h)	1.02 (0.84 to 1.24)	.83
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	0.47 (0.13 to 1.72)	.25
		Skeletal age (a)	0.92 (0.69 to 1.23)	.57
		Hours per week (h)	1.03 (0.85 to 1.25)	.78
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	1.33 (0.68 to 2.61)	.40
		Skeletal age (a)	1.16 (0.87 to 1.55)	.31
		Hours per week (h)	1.06 (0.86 to 1.30)	.60
Muscle injury	Δ Stature & Chronological age	Δ Stature (cm/yr)	2.99 (0.82 to 10.95)	.10
		Chronological age (a)	1.63 (0.97 to 2.73)	.06
		Hours per week (h)	1.06 (0.84 to 1.34)	.63
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	12.71 (0.92 to 174.71)	.06
		Chronological age (a)	1.51 (0.95 to 2.40)	.08
		Hours per week (h)	1.10 (0.85 to 1.43)	.47
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	1.14 (0.52 to 2.48)	.75
		Chronological age (a)	1.22 (0.84 to 1.76)	.30
		Hours per week (h)	1.05 (0.84 to 1.31)	.67
	Δ Stature & Skeletal age	Δ Stature (cm/yr)	1.56 (0.57 to 4.27)	.39
		Skeletal age (a)	1.67 (1.03 to 2.69)	*.037*
		Hours per week (h)	1.04 (0.84 to 1.28)	.72
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	2.42 (0.57 to 10.28)	.23
		Skeletal age (a)	1.46 (1.00 to 2.12)	*.049*
		Hours per week (h)	1.04 (0.84 to 1.29)	.74
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	0.98 (0.47 to 2.05)	.96
		Skeletal age (a)	1.28 (0.91 to 1.80)	.15
		Hours per week (h)	1.05 (0.84 to 1.30)	.68
Joint sprain	Δ Stature & Chronological age	Δ Stature (cm/yr)	0.36 (0.03 to 3.73)	.39
		Chronological age (a)	0.87 (0.48 to 1.56)	.63
		Hours per week (h)	1.12 (0.82 to 1.54)	.48
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	0.99 (0.10 to 9.28)	.99
		Chronological age (a)	1.39 (0.80 to 2.40)	.24
		Hours per week (h)	1.17 (0.85 to 1.62)	.33
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	1.28 (0.44 to 3.73)	.65
		Chronological age (a)	1.50 (0.94 to 2.37)	.09
		Hours per week (h)	1.24 (0.88 to 1.73)	.22
	Δ Stature & Skeletal age	Δ Stature (cm/yr)	0.98 (0.13 to 7.14)	.98
		Skeletal age (a)	1.45 (0.78 to 2.69)	.24
		Hours per week (h)	1.16 (0.85 to 1.57)	.35
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	0.68 (0.07 to 7.12)	.75
		Skeletal age (a)	1.67 (0.92 to 3.03)	.09
		Hours per week (h)	1.16 (0.86 to 1.56)	.32
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	1.39 (0.40 to 4.85)	.61
		Skeletal age (a)	1.91 (1.09 to 3.33)	*.023*
		Hours per week (h)	1.24 (0.90 to 1.70)	.19
Fracture	Δ Stature & Chronological age	Δ Stature (cm/yr)	0.73 (0.09 to 5.79)	.77

		Chronological age (a)	0.60 (0.26 to 1.41)	.24
		Hours per week (h)	1.32 (0.87 to 2.01)	.20
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	1.07 (0.07 to 15.40)	.96
		Chronological age (a)	0.73 (0.36 to 1.48)	.39
		Hours per week (h)	1.29 (0.86 to 1.92)	.22
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	3.19 (0.72 to 14.16)	.13
		Chronological age (a)	0.95 (0.53 to 1.70)	.86
		Hours per week (h)	1.46 (0.91 to 2.36)	.12
	Δ Stature & Skeletal age	Δ Stature (cm/yr)	0.67 (0.14 to 3.23)	.62
		Skeletal age (a)	0.73 (0.40 to 1.34)	.31
		Hours per week (h)	1.29 (0.85 to 1.98)	.23
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	0.79 (0.10 to 6.03)	.82
		Skeletal age (a)	0.81 (0.46 to 1.42)	.45
		Hours per week (h)	1.28 (0.84 to 1.94)	.26
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	2.17 (0.63 to 7.44)	.22
		Skeletal age (a)	1.01 (0.61 to 1.68)	.96
		Hours per week (h)	1.42 (0.88 to 2.27)	.15
Physis injury	Δ Stature & Chronological age	Δ Stature (cm/yr)	0.59 (0.14 to 2.57)	.48
		Chronological age (a)	0.66 (0.36 to 1.23)	.19
		Hours per week (h)	1.20 (0.93 to 1.55)	.17
	Δ Leg length & Chronological age	Δ Leg length (cm/yr)	1.08 (0.09 to 12.38)	.95
		Chronological age (a)	0.73 (0.44 to 1.19)	.21
		Hours per week (h)	1.24 (0.95 to 1.62)	.11
	Δ Body mass & Chronological age	Δ Body mass (kg/yr)	2.50 (0.89 to 7.01)	.08
		Chronological age (a)	0.98 (0.63 to 1.52)	.92
		Hours per week (h)	1.28 (0.98 to 1.66)	.07
	Δ Stature & Skeletal age	Δ Stature (cm/yr)	0.73 (0.24 to 2.20)	.57
		Skeletal age (a)	0.80 (0.52 to 1.23)	.32
		Hours per week (h)	1.22 (0.94 to 1.59)	.14
	Δ Leg length & Skeletal age	Δ Leg length (cm/yr)	0.46 (0.09 to 2.29)	.35
		Skeletal age (a)	0.73 (0.50 to 1.07)	.10
		Hours per week (h)	1.22 (0.94 to 1.60)	.14
	Δ Body mass & Skeletal age	Δ Body mass (kg/yr)	1.52 (0.64 to 3.62)	.35
		Skeletal age (a)	0.96 (0.67 to 1.38)	.83
		Hours per week (h)	1.26 (0.96 to 1.65)	.09

P-values in italics indicate significant associations.

Supplementary Table 2 Interaction effects for each model combination.

Model	Odds ratio (95% CI)	*P*-value
Overall		
Δ Height × Chronological age	1.01 (0.95 to 1.08)	.70
Δ Leg length × Chronological age	0.95 (0.87 to 1.04)	.31
Δ Body mass × Chronological age	0.99 (0.95 to 1.03)	.57
Δ Height × Skeletal age	1.01 (0.96 to 1.07)	.58
Δ Leg length × Skeletal age	0.98 (0.92 to 1.05)	.56
Δ Body mass × Skeletal age	1.00 (0.96 to 1.03)	.88
Sudden onset		
Δ Height × Chronological age	1.00 (0.93 to 1.07)	.97
Δ Leg length × Chronological age	0.91 (0.81 to 1.03)	.12
Δ Body mass × Chronological age	0.98 (0.94 to 1.03)	.44
Δ Height × Skeletal age	1.01 (0.95 to 1.06)	.80
Δ Leg length × Skeletal age	0.95 (0.88 to 1.03)	.23
Δ Body mass × Skeletal age	0.99 (0.95 to 1.03)	.58
Gradual onset		
Δ Height × Chronological age	1.02 (0.95 to 1.10)	.61
Δ Leg length × Chronological age	0.99 (0.89 to 1.10)	.80
Δ Body mass × Chronological age	0.96 (0.91 to 1.02)	.17
Δ Height × Skeletal age	1.01 (0.96 to 1.08)	.65
Δ Leg length × Skeletal age	1.05 (0.96 to 1.14)	.29
Δ Body mass × Skeletal age	0.98 (0.94 to 1.02)	.32
Muscle injury		
Δ Height × Chronological age	0.93 (0.84 to 1.02)	.11
Δ Leg length × Chronological age	0.83 (0.68 to 1.00)	.05
Δ Body mass × Chronological age	0.99 (0.94 to 1.04)	.73
Δ Height × Skeletal age	0.98 (0.92 to 1.04)	.50
Δ Leg length × Skeletal age	0.94 (0.86 to 1.03)	.21
Δ Body mass × Skeletal age	1.00 (0.96 to 1.05)	.98
Joint sprain		
Δ Height × Chronological age	1.05 (0.90 to 1.23)	.53
Δ Leg length × Chronological age	1.00 (0.86 to 1.16)	1.0
Δ Body mass × Chronological age	0.98 (0.91 to 1.05)	.54
Δ Height × Skeletal age	0.99 (0.88 to 1.12)	.88
Δ Leg length × Skeletal age	1.03 (0.89 to 1.18)	.71
Δ Body mass × Skeletal age	0.98 (0.91 to 1.05)	.52
Fracture		
Δ Height × Chronological age	1.02 (0.88 to 1.18)	.80
Δ Leg length × Chronological age	1.00 (0.82 to 1.21)	.99
Δ Body mass × Chronological age	0.92 (0.83 to 1.02)	.12
Δ Height × Skeletal age	1.03 (0.92 to 1.14)	.62
Δ Leg length × Skeletal age	1.02 (0.89 to 1.17)	.77
Δ Body mass × Skeletal age	0.95 (0.87 to 1.03)	.21
Physis injury		
Δ Height × Chronological age	1.04 (0.94 to 1.16)	.47
Δ Leg length × Chronological age	0.99 (0.83 to 1.18)	.90
Δ Body mass × Chronological age	0.94 (0.87 to 1.01)	.08
Δ Height × Skeletal age	1.02 (0.95 to 1.11)	.53
Δ Leg length × Skeletal age	1.05 (0.94 to 1.17)	.38
Δ Body mass × Skeletal age	0.97 (0.92 to 1.03)	.34

P-values in italic indicate a significant interaction effect.

Appendix I

Acceptance confirmation: Aspire Research Committee

Eirik Halvorsen Wik

From: Pitre Bourdon
Sent: Thursday, October 26, 2017 11:18 AM
To: Eirik Halvorsen Wik
Subject: Aspire Research Committee Decision - Eirik Wik

Dear Eirik,

To follow is a summary of the ASPIRE Research Committee's decision on the research project you presented at their last meeting:

Proposal Title: "Injury risk in youth academy athletes"

Principal Investigator: Eirik Wik

Research Committee Recommendation: Accepted with no modifications

Comments for your consideration:

- Consider focussing on 1 or 2 sports with larger subject numbers.
- Training load measures will likely be different in different sports – to address this consider focussing purely on football.

If you have any questions about this decision or the process from here please feel free to contact me.

Kind regards,

Pitre

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Appendix II

Approval notice: Anti-Doping Lab Qatar Institutional Review Board

Anti- Doping Lab Qatar Institutional Review Board

Tel: 44132988
Fax: 44132997
Email: ADLQ-RO@adlqatar.com

IRB SCH Registration: SCH-ADL-070
SCH Assurance: SCH-ADL-A-071

APPROVAL NOTICE

Date	2/11/2014
Lead Principal Investigator	**Dr. Pitre Bourdon**
IRB Application #	**E20140000012**
Protocol Title	**Assessment and longitudinal monitoring of routine sport science and medical screenings of ASPIRE Academy Student-Athletes**
Submission Type	**Initial Submission**
Review Type	**Expedited Review**
Approval Period	**2/11/2014- 1/11/2015**

The Anti-Doping Lab Qatar Institutional Review Board has reviewed and approved the above referenced protocol.
As the Principal Investigator of this research project, you are responsible for:

- Ethical Compliance and protection of the rights, safety and welfare of human subjects involved in this research project.
- To follow the policies and procedures as set by ADLQ-IRB in any matters related to the project, following the ADLQ-IRB approval (i.e., with regards to obtaining prior approval of any deviation of protocol, reporting of unanticipated events, and submission of progress reports).
- To inform the ADLQ-RO of the date of commencement of the research*.

Director – ORS/ADLQ (Office of Research Support)
Ms. Noor AlMotawa

مختبر مكافحة المنشطات قطر
Anti Doping Lab Qatar

**For Commencement of Research, Protocol Deviation Reporting, Unanticipated Problem Reporting & Research Progress Annual Report, please contact - Education & Research Office, Anti-Doping Lab Qatar.*

Eirik Halvorsen Wik // Injuries in elite male youth football and athletics