

Growth, Maturation and Health Profiles of Youth Triathletes; Associations with Training Load, Injury and Illness

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Purpose: To examine the health history, growth and maturation profiles, and current health status of youth triathletes prior to entry into a National Institute Network (NIN); and determine associations between growth, training load, and health problem severity to inform developmental training strategies.

Methods: Youth triathletes (ages 12–18) were monitored over one year. Data was collected on athletic health history, growth (height, weight, arm span) and maturation (bone age (BA); peak height velocity (PHV), predicted adult height (PAH), PAH%). Over 10 weeks the Oslo Sports Trauma Research Centre questionnaire (OSTRC-H2 questionnaire), training load and rate of perceived exertion (RPE) were recorded across triathlon disciplines.

Results: Estimated PHV occurred later than population norms (Female 12.5 ± 0.7 ; Male 13.3 ± 0.6). Estimated BA exceeded chronological age (CA) in both sexes. Males showed higher height tempo ($B = 0.09$, $PD = 0.85$), and arm span tempo than females ($B = 0.20$, $PD = 0.96$). Higher maturity offset was associated with greater total health problem severity ($B = 0.23$, $PD = 0.98$), reflecting a 25% increase per 1-year in maturity offset, and males typically had higher total severity ($B = 0.52$, $PD = 0.90$). Illnesses ($n = 22$) exceeded injuries ($n = 14$) and resulted in more total time-loss (3 vs 2 weeks). Swimming had the highest training volume, 24% higher than the bike ($B = -0.28$, $PD = 0.99$) and 44% higher than the running ($B = -0.58$, $PD = 1.00$), although more lower limb injuries were reported.

Conclusion: Sex-based maturation differences in youth triathletes require tailored training; high illness and injury prevalence identify the need for growth monitoring and balanced training to support long term athlete performance progression.

Keywords: endurance sport, youth athletes, health problems, anthropometrics, maturity offset, training load

Introduction

Triathlon is a dynamic and demanding endurance sport that combines swimming, cycling, and running into a single race. It is competed over varying distances, from short course races such as the Olympic distance event, consisting of a 1500m swim, 40km bike, 10km run, to long course events, including the ironman distance of 3.8km swim, 180km bike and 42.2km run.^{1,2} The 2020 Tokyo Olympics introduced a new event for triathlon, the mixed team relay. This event features teams of four athletes, two men and two women, with each competitor completing a super sprint triathlon of approximately 300m swim, a 6–7 km bike ride, and a 1–2 km run before tagging their teammate.³ This relay format adds a heightened level of intensity and a fast-paced element in comparison to the traditional Olympic distance event.

Performance in short course triathlon requires both high -volume and high-intensity training loads to achieve peak physical and mental conditioning.⁴ Training loads (defined as the physical stress an athlete experiences during their training over a set period of time)⁵ of more than 20 hours per week⁶ have been reported for short course triathletes. Training load is influenced by a variety of factors; duration, intensity, and frequency of these exercise modalities and can be quantified as externally (eg, power produced on the bike in watts) or internally (eg, heart rate or an athletes subjective

response to load).⁷ Coaches may monitor this physical stress' using a subjective rating scale (eg, rate of perceived exertion: RPE) on a scale from 1–10. Ongoing fatigue with high training loads can compromise the immune system and increase illness risk⁴ and also lead to a reduction in performance,⁸ put athletes at risk of injury and lead to time missed from training and competing.^{7,9}

Each triathlon discipline places unique physiological and biomechanical demands on the body, leading to sport-specific patterns of fatigue and injury risk. Swimming primarily stresses the upper body and cardiorespiratory system, with primary injury risk to the shoulders and neck with the swim to bike transition adding additional metabolic load.^{10,11} Cycling emphasizes lower limb muscular endurance and spikes in power with the risk of overuse injuries to the back, neck and lower limbs and also the risk of acute injuries from falls or crashes.^{12–14} Running imposes high impact loads on the musculoskeletal system with additional neuromuscular fatigue following the cycle to run transition with lower body overuse injuries common.^{15–17}

Research focusing specifically on youth triathletes regarding injury and illness risk is limited; however, adolescents aged 12–19 years have been shown to experience higher rates of overuse injury compared to adult triathletes.⁹ Additionally, psychological factors such as stress and perfectionistic tendencies in youth triathletes have also been linked to increased vulnerability to injury.¹⁸ Recently, Crunkhorn et al¹⁹ reported two-thirds of injuries resulted in time loss to training and competition in a cohort of elite Australian triathletes over a 4-year period, with bone stress injuries (BSI) having the highest burden (31.38 days of time loss/365 days). Interventions to mitigate these risks of injury and illness should be prioritised for triathletes for sustained health, wellbeing and optimal performances.⁹

Within the Australian National Institute network (NIN), short course triathletes are supported by a team of professionals who monitor performance health through targeted services (such as Periodic Health Evaluations (PHE) to facilitate early detection and implementation of prevention strategies). Performance health reflects the ability of athletes to maintain their optimal physical, mental and social well-being, and to consistently complete all training sessions to optimize their chance of performance success.²⁰

Youth Australian triathletes, aged 12 to under 19 years, are part of the national development pathway program but are not yet integrated into the NIN. These athletes have access to quality coaching, training camps, skills development, and athlete education outside their regular training environments but are not part of routine national health problem surveillance. While their performances are partially visible through national competitions, there is limited understanding of their health status and health history prior to entering the NIN, representing a critical gap in knowledge for early intervention and long-term athlete development.

Addressing this gap in health knowledge among these athletes is needed for optimising their performance health. Moreover, it may aid in the early identification of risk factors during their growth and maturation, a period recognised in the literature as one of heightened vulnerability to physical and psychological challenges in youth athletes.^{21,22}

Growth refers to the physical increase in body size, typically observed through changes in height, weight, arm span and limb length, whereas maturation encompasses the progression toward full biological and sexual maturity, including skeletal and reproductive development.²³ These processes are non-linear and highly individualized, influenced by genetic, environmental and nutritional factors.^{24,25}

Monitoring growth and maturation is important for high-performance youth athletes due to differences that can occur between chronological age (CA) and biological age, significantly affecting their training load tolerance and injury and illness risk.²² Periods of rapid growth are associated with increased susceptibility to injury due to factors of rapid bone remodelling, soft tissues imbalances and a transient reduction in motor control and spatial awareness.^{26,27}

Accurate and ongoing monitoring of growth and maturation is essential for informing individualized training prescription and recovery strategies. Common measures include skeletal maturity (expressed as bone age (BA)), sexual maturity (Tanner scale; age at first menarche) and age at peak height velocity (PHV).²⁵ Age at PHV (APHV) can be predicted via equations based on CA and anthropometric measurements, as proposed by Mirwald et al.²⁸

Describe the relationship between health history, growth and maturation, training loads and health problems in youth triathletes is paramount to support safe athletic progression. Therefore, this study aims to 1) understand health history, growth and maturation profiles and current health status of youth triathletes prior to entry into the NIN; 2) examine the

associations between growth and maturation, training load, and health problem severity in youth triathletes with the goal of informing long-term appropriate training strategies for optimizing performance health outcomes.

Methods

Participants and Study Design

A total of 53 triathletes (30 males, 23 females) from the state pathway programs volunteered to participate in this study during the 2023–2024 triathlon season. Participants were between 12 and 18 years old (inclusive), and part of the state and academy programs who were able to travel nationally for training camps and competitions. Participant characteristics are reported in Table 1.

The study employed a prospective observational design conducted over a 12-month period from January 2023 to January 2024. Growth and maturation measures were collected at three time points across both competition and training phases. Over a 10-week period, athletes completed four questionnaires: an initial athletic health history, followed by weekly reports on health problems, training load, and sessional RPE. The 10-week monitoring period was aligned with the collection of growth and maturation measures at weeks 1 and 10 (Figure 1).

Table 1 Health History Questionnaire Summary

	Female (n = 12)	Male (n = 15)
Age (years)	15.5 ± 1.4 (12.4–16.9)	15.0 ± 1.5 (11.9–17.3)
Training years (years)	3.1 ± 3.3 (0.25–12)	4.9 ± 3.2 (1–11)
Training load per week (hours)		
Swim	5.5 ± 3.1 (0.5–12)	4.4 ± 1.6 (2–7.5)
Bike	2.5 ± 1.3 (0–4.5)	4.4 ± 2.2 (2–9)
Run	2.8 ± 1.4 (0.75–4.5)	2.4 ± 1.3 (0–4)
Strength & Conditioning [n (%)]	7 (58)	11 (73)
1 session / week [n (%)]	0 (0)	5 (33)
2 sessions / week [n (%)]	5 (42)	3 (20)
3 sessions / week [n (%)]	2 (17)	3 (20)
Current health problems [n (%)]	3 (25)	4 (27)
Previous health problems [n (%)]	9 (75)	10 (67)
Growth injuries [n (%)]	6 (50)	7 (47)
Bone injuries [n (%)]	7 (54)	11 (73)
Other [n (%)]	5 (38)	5 (36)
Female athlete health		
Started menstruation [n (%)]	9 (70)	
Age at menarche (years)	13.7 ± 1.5 (11.42–16.58)	
Current other Sports [n (%)]	6 (50)	10 (67)
Hr/week	(0.75–5)	(1–5)
Previous Sports [n (%)]	11 (92)	13 (87)
Years	3.7 ± 2.2 (1.5–10)	5.39 ± 2.66 (1–11)

Notes: Data are reported as mean ± standard deviation (range), number of athletes (percent total athletes) [n(%)].

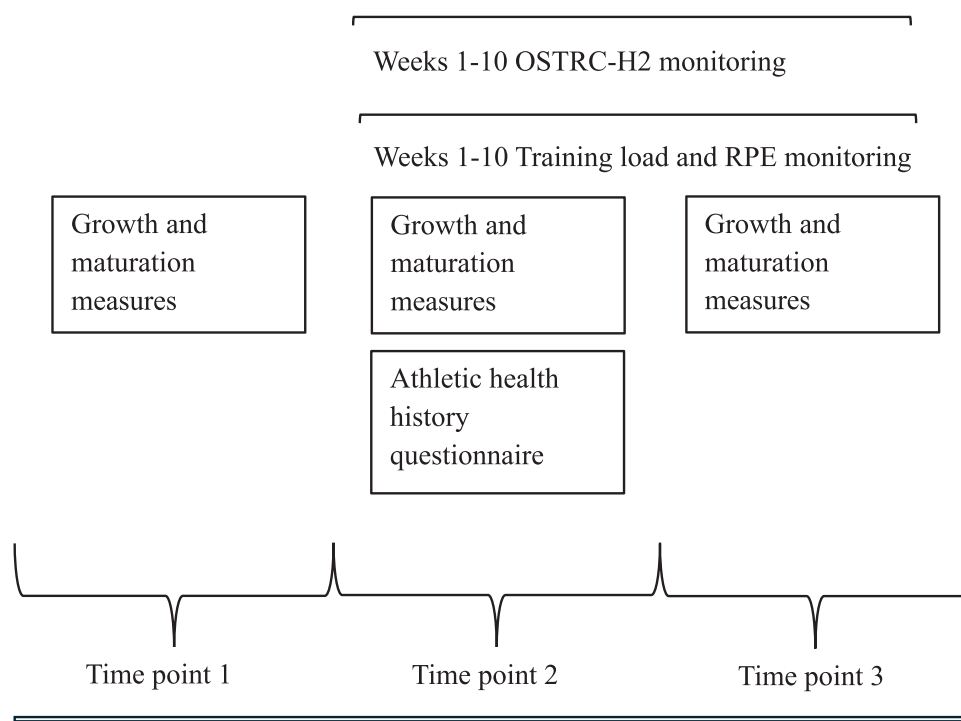


Figure 1 Overview of data collection, timeline and measures.

Abbreviations: OSTRC-H2, Oslo Sports Trauma Research Centre Questionnaire on health problems. RPE, Rate of perceived exertion.

The study's results were reported using the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for observational studies.²⁹ Ethical approval for the study was obtained from the University of Canberra Human Research Ethics Committee (Approval #202312112). For all athletes under 18 years of age, informed consent was provided from parents or guardians and assent was obtained from the athletes. Athletes aged 18 years, provided their own informed consent. The study complies with the Declaration of Helsinki.

Athletic History Questionnaire

An online Athletic History questionnaire was sent to participants or their parent/guardian via Email in week 1 of the 10-week data capture period. The questionnaire was conducted using the Qualtrics survey platform (Qualtrics Survey Software, 2023, www.qualtrics.com). The questionnaire recorded their background in sport, training load history, and previous health problems. Five questions related to female athlete health were included for female athletes. The athletic history questionnaire was developed in collaboration with industry allied health professionals and adapted from the clinical physiotherapy components of the PHE currently used in AusTriathlon ([Supplementary File Figure 1](#)).

Growth and Maturation Assessment

Anthropometric and growth measurements were collected at three time points; January 2023 (Time point 1), September 2023 (Time point 2), and January 2024 (Time point 3) ([Figure 1](#)). These corresponded, respectively, to the early competitive season (summer), start of season training (spring), and the subsequent competitive season (summer). All assessments were conducted at race venues and training camps representative of the athletes' normal sporting environments.

All measurements were performed by the Chief Investigator AF, an International Society for the Advancement of Kinanthropometry (ISAK)³⁰ accredited anthropometrist and a Sports and Exercise Physiotherapist with more than 20 years of clinical experience. Standardised ISAK anthropometric protocols were followed throughout and athletes received a familiarization session explaining the measurement procedures and expected duration at each time point.

Body mass (kg) was assessed using the A&D UC-321 digital series scale (A&D Ltd., Tokyo, Japan), while stretch stature (cm) and sitting stature (cm) were measured using the Seca 213 portable stadiometer (Seca GmbH & Co., Hamburg,

Germany). Athletes were measured in light clothing without footwear. The stadiometer was positioned on a level surface and each measurement was taken twice, and the reported values reflect the average of these repeated measurements. The digital scale was calibrated prior to data collection. Growth tempo was evaluated by calculating the average monthly changes in height and arm span between Time point 1 to Time point 2, and Time point 2 to Time point 3.

To account for variations in biological development that extend beyond chronological age, additional assessments of skeletal and somatic maturation were included in the study. Estimated BA was calculated at all three time points using a validated prediction model equation (Cabral et al)³¹ that incorporates stretch stature (m), arm girth (cm), triceps skinfold (mm), humerus diameter (cm), and femur diameter (cm), CA, and sex. (Equation 1).³¹ These measurements were taken by the Chief Investigator AF, using Harpenden skinfold calipers and the Holtain bone anthropometer. Bone age offset was calculated as estimated BA minus CA.

$$\text{Estimated bone age} = -11.620 + 7.004(\text{Stature}) + 1.226(\text{Dsex}) + 0.749(\text{age}) \\ -0.068(\text{Tr}) + 0.214(\text{ACP}) - 0.588(\text{HD}) + 0.388(\text{FD})$$

Equation 1. Prediction model equation to estimate bone age using measures of arm girth, triceps skinfolds, humerus diameter, femur diameter, age, and sex, as described in Cabral et al (2013). Male sex: Dsex = 0; female sex: Dsex = 1, Stature = (standing height in m). Age (years), Tr = tricipital skinfold (mm), ACP = arm corrected perimeter (arm perimeter-tricipital skinfold, cm), HD = humeral diameter (cm), FD = femoral diameter (cm).

Somatic maturation was assessed using a spreadsheet developed by Towlsen et al,³² which applies sex-specific equations from Mirwald et al²⁸ to estimate APHV and maturity offset (CA minus APHV). These calculations incorporate standing height, sitting height, weight and estimated leg length. Predicted adult height (PAH) was also calculated using the same spreadsheet,³² and the Khamis and Roche method³³ which incorporates anthropometric data with mid-parental height. Data entry and calculations were performed by AF.

Health Problems

Participants were asked to complete the Oslo Sports Trauma Research Centre Questionnaire on health problems (OSTRC-H2)³⁴ once per week for ten consecutive weeks. The questionnaire was conducted on the Qualtrics survey platform (Qualtrics Survey Software, 2023, www.qualtrics.com) and consisted of four questions that assessed any health problems the participants had encountered in the previous seven days. It covered aspects such as training participation, modified training or competition, performance, and the presence of health problem symptoms (Supplementary File Figure 2). Participants had the option to report multiple health problems if applicable. They were also required to provide details about the location, type of the health problem, and whether any modifications to their training or time away from training were necessary. Participants could also include additional details in a comment section and were asked whether they had consulted a healthcare professional regarding their health problem.

The severity of the injuries and illnesses reported using the OSTRC-H2 questionnaire was calculated according to previously documented methods in youth athletes.³⁵ For each reported health problem, a severity score is given from 0 to 100 and is based on four key questions: 1) Limitation in sports participation, 2) Reduction in training volume, 3) Impact on sports performance, and 4) Presence and intensity of symptoms. Each question was scored from 0 to 25 and the total severity score was the sum of all 4 questions. Weekly reminders were sent to participants on Sunday afternoons via text message or email, and a follow-up reminder was sent on Monday if the questionnaire had not been completed. No additional reminders were provided after these. The data from the 10-week collection period was reviewed only after completion to prevent any bias in the interpretation of the results. Thirty-four (15 females, 19 males) participants completed at least one week of the questionnaire, with participants completing at least six weeks of the questionnaire on average (SD = 3.4, range = 1–10).

Training Load

Participants were asked to report on any training sessions and/or competitions they had completed in the previous seven days starting at Time point 2 (September 2023) once per week for ten consecutive weeks (Figure 1). This data was captured using the same online form used to capture health problems, as described above and this data capture period coincided with the start of the triathlon season training camps and finishing with competitions. Participants were asked to

report on the type of session (swim, bike, run, or other), the duration of the session (in minutes), and their RPE for the session ([Supplementary File Figure 2](#)). Training load (au) was calculated as the product of duration (minutes) and RPE.³⁶

Statistical Analysis

All analyses were conducted using R (version 4.4.2) in RStudio (version, 2024.12.1+563, Posit PBC, posit.co). Results from the Athletic History questionnaire, growth and maturation assessments, health problems and training load questionnaire are reported using descriptive statistics ([Tables 1–3](#)). A Bayesian framework was employed for statistical analysis and modelling of relationships between growth and maturation, health problems, and training load.

The relationship between CA (centred) and BA offset, height tempo, and arm span tempo were each modelled using a gaussian mixed model with a random intercept for each participant, and an interaction term for CA (centred) and sex. To model the relationship between maturity offset and total severity (illness severity + injury severity), a hurdle lognormal mixed model was used. The hurdle component modelled the logit of whether a participant has 0 severity, or greater than 0 severity, and the lognormal component models the relationship between maturity offset and the natural logarithm of total severity.

A lognormal mixed model was used to model weekly training load according to participation, sport type (swim, bike, run, other), CA (centred) and sex. A random intercept was included for each participant and an interaction term was included for participation and sport type. Bayesian modelling was conducted using the *brms* R package.³⁷ The posterior distributions of the model coefficients are presented as the median and 95% highest density credible intervals (HDI), and the probability of direction (PD, ie, the probability of a positive or negative effect).³⁸

The sample size was based on convenience sampling from a finite population of eligible athletes who were accessible during the study period. As the total number of potential participants was limited, we aimed to include as many eligible and willing participants as possible. While the sample size was not determined by a formal power calculation, the Bayesian approach allowed us to quantify uncertainty in parameter estimates and assess the strength of evidence for our hypotheses given the available data.

Table 2 Growth and Maturation Characteristics Across the Three Data Collection Timepoints

Time Point	Female			Male		
	1 (n = 6)	2 (n = 23)	3 (n = 10)	1 (n = 9)	2 (n = 30)	3 (n = 12)
Age (years)	15.4 ± 1.6 (12.4–16.9)	15.3 ± 1.9 (11.8–18.6)	15.4 ± 1.9 (12.9–18.9)	14.8 ± 1.4 (13.1–17.3)	14.8 ± 1.6 (11.9–18.0)	15.3 ± 1.0 (13.9–16.8)
Mass (kg)	55.7 ± 4.0 (50.6–59.5)	56.8 ± 8.0 (42.6–73.3)	53.6 ± 7.4 (42.6–65.0)	55.1 ± 12.6 (32.7–69.0)	56.5 ± 12.0 (35.5–74.9)	55.7 ± 10.7 (36.4–74.3)
Stretch Stature Height (cm)	167.4 ± 5.6 (161.5–176.5)	165.4 ± 5.4 (156.5–176.8)	165.8 ± 5.9 (158.1–177.1)	170.0 ± 12.03 (149.6–180.3)	170.0 ± 11.9 (145.0–185.4)	170.2 ± 9.6 (154.5–184.5)
Arm Span (cm)	169.7 ± 6.1 (163.5–178.5)	166.8 ± 7.0 (157.0–180.0)	167.1 ± 7.5 (157.5–179.9)	171.6 ± 10.9 (155.5–183.0)	173.1 ± 13.3 (148.0–193.0)	172.2 ± 10.6 (154.0–187.0)
Estimated Bone Age (years)	16.9 ± 1.5 (14.2–18.4)	16.9 ± 1.9 (13.1–20.1)	17.00 ± 2.01 (14.0–20.4)	15.77 ± 2.27 (12.0–18.9)	15.8 ± 2.4 (11.8–19.5)	16.34 ± 1.85 (13.3–18.8)
Predicted Adult Height (cm)*	167.0 ± 1.8 (165.7–168.2)	169.4 ± 5.0 (160.8–176.6)	169.4 ± 5.5 (161.5–176.9)	183.7 ± 0 (183.7–183.7)	182.9 ± 4.5 (175.8–194.2)	180.1 ± 5.4 (172.2–187.1)
Predicted Adult Height (%)*	99.0 ± 0.5 (98.6–99.3)	98.5 ± 1.3 (95.7–100.1)	98.7 ± 1.0 (97.7–100.1)	89.40 ± 0 (89.4–89.4)	95.6 ± 4.9 (84.0–100.5)	95.8 ± 3.4 (89.7–99.1)
Age at Peak Height Velocity (years)	12.6 ± 0.8 (11.4–13.6)	12.5 ± 0.7 (11.3–14.1)	12.5 ± 0.7 (11.4–14.2)	14.0 ± 0.8 (12.9–15.5)	13.3 ± 0.6 (11.9–14.3)	13.6 ± 0.5 (12.4–14.3)

Notes: Data are reported as mean ± standard deviation (range). *Calculations taken from n=2, n=10, and n=5 females; and n=1, n=15, and n=8 males across Points 1, 2 and 3, respectively, due to missing information from participants. Predicted Adult Height = estimated final height at full maturation. Predicted adult height percentage (%) = percent of final adult height already attained. Peak Height Velocity (PHV) = fastest rate of growth in height during adolescence.

Table 3 Training Load Statistics Swim, Bike, Run and Other

Discipline	Training totals	Female			Male		
		Senior (>17yrs) (n = 3)	Intermediate (15–17yrs) (n = 5)	Junior (<15yrs) (n = 7)	Senior (>17yrs) (n = 2)	Intermediate (15–17yrs) (n = 9)	Junior (<15yrs) (n = 8)
Swim	Total Weekly Load (au)	1817.9 ± 1685.3 (240.0–4680.0)	958.5 ± 860.0 (144.0–3840.0)	1382.5 ± 1148.0 (120.0–4085.0)	1039.0 ± 663.3 (570.0–1508.0)	996.1 ± 519.5 (282.0–2400.0)	1424.9 ± 1031.5 (320.0–5520.0)
	Total Weekly Duration (min)	315.1 ± 272.1 (60.0–720.0)	168.3 ± 139.2 (19.0–480.0)	215.8 ± 143.7 (30.0–575.0)	241.0 ± 192.3 (105.0–377.0)	188.7 ± 85.7 (70.0–390.0)	207.4 ± 118.3 (60.0–645.0)
Bike	Total Weekly Load (au)	637.5 ± 454.3 (120.0–1560.0)	814.7 ± 583.8 (165.0–1905.0)	1088.5 ± 900.6 (200.0–3455.0)	1186.0 ± 1083.3 (420.0–1952.0)	860.1 ± 604.9 (240.0–2790.0)	983.6 ± 761.5 (240.0–3220.0)
	Total Weekly Duration (min)	122.5 ± 88.1 (30.0–300.0)	149.1 ± 107.4 (40.0–330.0)	158.1 ± 107.6 (30.0–470.0)	171.5 ± 157.7 (60.0–283.0)	165.4 ± 101.4 (49.0–473.0)	167.9 ± 115.5 (40.0–490.0)
Run	Total Weekly Load (au)	502.5 ± 310.0 (120.0–1180.0)	663.8 ± 921.2 (40.0–4519.0)	615.0 ± 395.3 (120.0–1410.0)	853.5 ± 270.8 (662.0–1045.0)	798.0 ± 428.3 (68.0–1740.0)	729.1 ± 498.9 (16.0–2210.0)
	Total Weekly Duration (min)	113.8 ± 66.1 (30.0–250.0)	86.3 ± 100.5 (20.0–503.0)	99.5 ± 59.0 (30.0–240.0)	132.5 ± 10.6 (125.0–140.0)	122.9 ± 57.8 (28.0–264.0)	113.5 ± 62.0 (16.0–260.0)
Other	Total Weekly Load (au)	549.0 ± 342.7 (90.0–1080.0)	1050.4 ± 913.8 (150.0–2980.0)	758.0 ± 659.5 (90.0–2055.0)	225.5 ± 106.8 (150.0–301.0)	608.4 ± 511.3 (47.0–2327.0)	1286.5 ± 1164.1 (135.0–4560.0)
	Total Weekly Duration (min)	105.0 ± 49.5 (30.0–180.0)	166.9 ± 161.2 (30.0–560.0)	114.3 ± 73.3 (30.0–253.0)	36.5 ± 9.2 (30.0–43.0)	87.8 ± 53.4 (30.0–266.0)	173.9 ± 139.8 (30.0–510.0)

Notes: Arbitrary units (au)= training load (minutes) × RPE; minutes (min); RPE (rate of perceived exertion, scale 1–10). Data reported as mean ± standard deviation (range). Other = race simulation sessions, competitions and other sport training.

Results

Athletic Health History Questionnaire

Twenty-seven participants (male = 15, female = 12) completed the health history questionnaire (Table 1). Participants ranged from school years 7 to 12, with seven engaged in casual employment and two in part-time roles. All participants competed in super sprint to sprint distance events with some (n = 18) incorporating strength and conditioning training, either independently, through personal trainers, or school programs. In addition to their triathlon training and competition, 16 participants (males = 10, females = 6) were involved in a range of other sports. The five most common additional sports were swimming competitions, surf lifesaving, soccer, athletic events, and Australian Rules Football (AFL). During childhood 24 athletes (males = 13, females = 11) reported broad multisport participation, often concurrently. Soccer, surf lifesaving and athletics the most common for both male and females alike. AFL was popular amongst male participants. Three female athletes had previously been accepted into youth high-performance academy programs; soccer, kayaking, AFL and gymnastics.

Both past and current health problems reported that had the most significant impact on training and competition included two female participants reporting ongoing current injuries from prior cycling accidents (shoulder rotator cuff and knees, hip and hand injuries). Additionally, a notable number of participants (n = 13; males = 7, females = 6) reported a history of growth-related injuries, with Severs the most common (n = 8). Other time loss health problems included appendicitis with complications (over 12 months), foot bone oedema (2 months) and a hamstring tear (3 months). Previous bone injuries included fractures (n = 18) and bone oedema (n = 2). Medical history intervention included surgical (adenoid/tonsil removal n = 6, appendectomy n = 1, hernia repair n = 1), orthopaedic evaluations for upper limb fractures n = 4, and hospital admissions (for cycling trauma n = 2, concussion n = 2, and stitches n = 3).

Among female participants (n = 9), the average age at menarche was 13.7 years ± 1.5, with an average cycle length of 28 days. However, eight participants reported menstrual irregularities, and one participant reported amenorrhea lasting

approximately three months on two separate occasions. The menstrual symptoms most common were tiredness ($n = 7$), others were pain ($n = 4$), nausea ($n = 4$) and cramping ($n = 4$).

Growth and Maturation

Table 2 shows descriptive statistics for growth and maturation measures across Time points 1, 2 and 3. Figure 2A and B provide a descriptive visualization of maturity offset and the estimated APHV of the participant cohort, respectively. Additional data are provided in Supplementary File Table 1.

For females at the mean CA, estimated BA was 1.58 ($B_{\text{intercept (mean age, female)}} = 95\% \text{ HDI} = [1.22, 1.87]$) years greater than CA, and this tended to remain consistent with an increase in age ($B_{\text{age, female}} = 0.06$, $95\% \text{ CI} = [-0.10, 0.21]$, $\text{PD} = 0.79$)

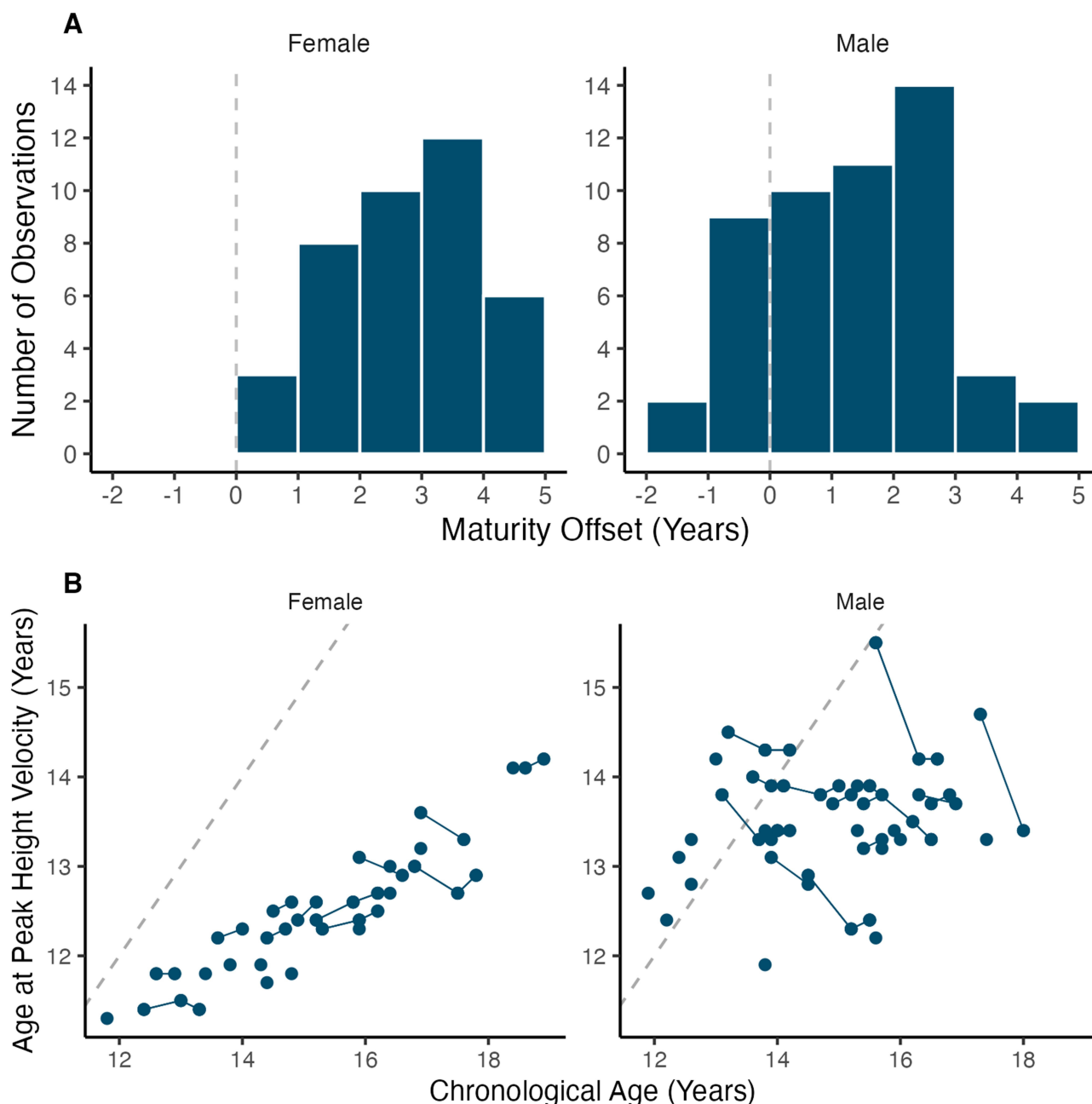


Figure 2 (A) Distribution of maturity offset (CA minus APHV) among the participant cohort. **(B)** Relationship between chronological age (CA) and age at peak height velocity (APHV). Navy points represent observed values for participants with repeated measures across timepoints joined by a navy line. The grey dashed line shows 1:1 CA: APHV reference line.

(Figure 3A). On the other hand, for males at the mean CA, estimated BA was 1.23 ($B_{\text{intercept (mean age, female)}} + B_{\text{male}} = 1.24$, 95% HDI = [0.93, 1.51], PD = 1.00) years greater than CA and this increased by 0.45 ($B_{\text{age, female}} + B_{\text{age} \times \text{male}} = 95\% \text{ HDI} = [0.30, 0.59]$, PD = 1.00) years with every additional year of CA (Figure 3A). The relationship between CA and BA offset depended on sex ($B_{\text{age} \times \text{male}} = 0.38$, 95% HDI = [0.16, 0.58], PD = 0.99) (Figure 3B).

The association between CA and height is presented in Figure 4A. The relationship between CA and height tempo did not vary by sex ($B_{\text{age} \times \text{male}} = 0.00$, 95% HDI = [-0.13, 0.11], PD = 0.55) (Figure 4B). However, there was some evidence that height tempo was higher (by 0.09 cm per month) for males than females ($B_{\text{male}} = 0.09$, 95% HDI = [-0.09, 0.27], PD = 0.85). Estimated height tempo at the mean CA was 0.30 cm per month for females ($B_{\text{intercept (mean age, female)}} = 0.30$, 95% HDI = [0.15, 0.43] and 0.39 cm per month for males ($B_{\text{intercept (mean age, female)}} + B_{\text{male}} = 0.39$, 95% HDI = [0.27, 0.50]). Further, height tempo was lower for older athletes compared to younger athletes (by 0.09 cm per month for each year older) ($B_{\text{age}} = -0.09$ [-0.17, -0.02], PD = 0.99).

The association of CA and arm span is presented in Figure 5A. Similar to height tempo, the relationship between CA and arm span tempo did not vary by sex ($B_{\text{age} \times \text{male}} = -0.03$, 95% HDI = [-0.18, 0.11], PD = 0.68) (Figure 5B). Arm span tempo was higher (by 0.20 cm per month) for males than females ($B_{\text{male}} = 0.20$, 95% HDI = [-0.01, 0.42], PD = 0.96). Estimated arm span tempo at the mean CA was 0.23 cm per month for females ($B_{\text{intercept (mean age, female)}} = 0.23$, 95% HDI = [0.07, 0.39] and 0.43 cm per month for males ($B_{\text{intercept (mean age, female)}} + B_{\text{male}} = 0.43$, 95% HDI = [0.29, 0.57]). Unlike height tempo,

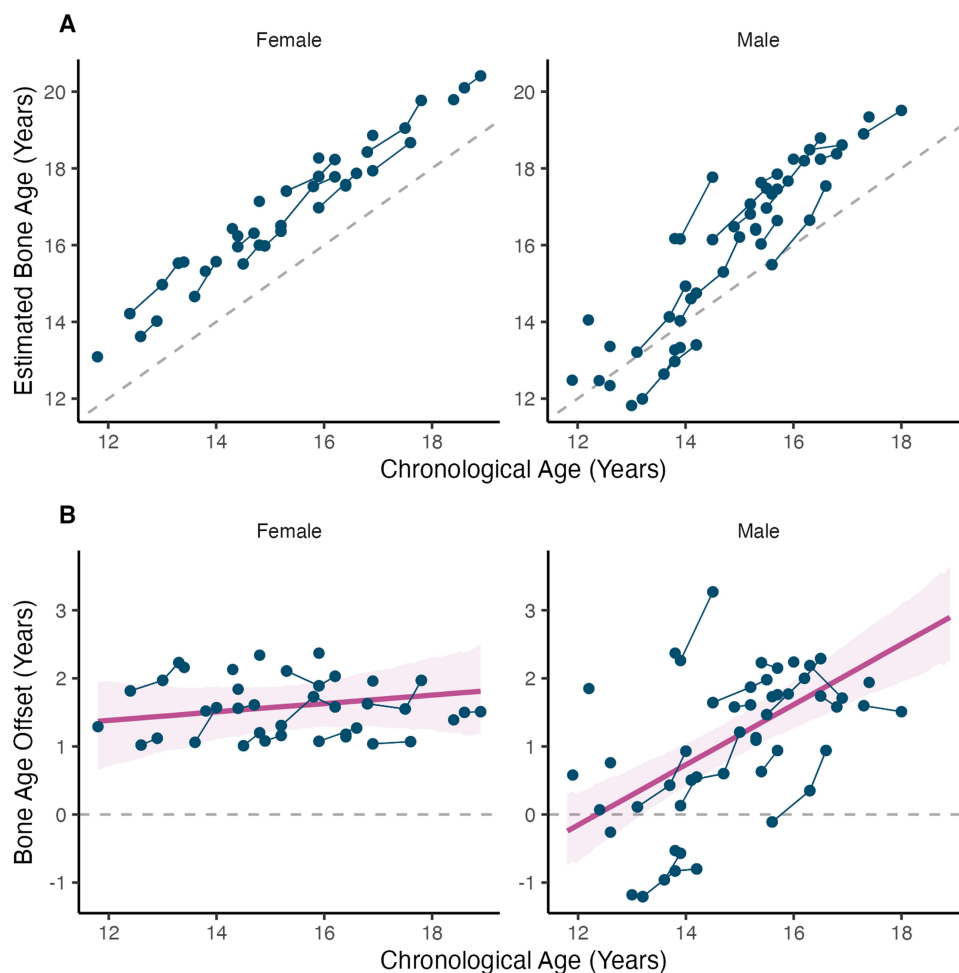


Figure 3 (A) Relationship between chronological age (CA) and bone age (BA). **(B)** Relationship between CA and BA offset (BA minus CA). Navy points represent observed values for participants with repeated measures across timepoints joined by a navy line. The pink line and ribbon show estimated marginal means and 95% credible intervals for BA offset. The grey dashed line shows 1:1 CA:BA reference line.

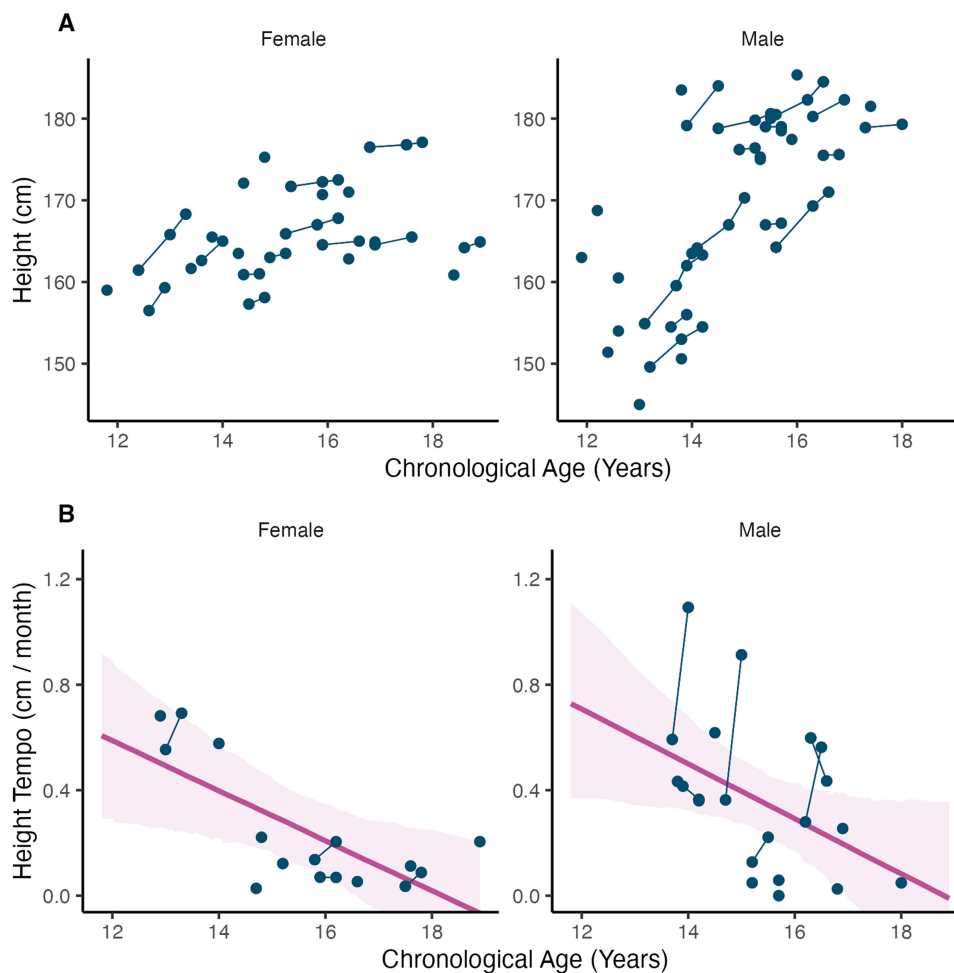


Figure 4 (A) Relationship between chronological age (CA) and height. **(B)** Relationship between CA and height tempo (cm per month). Navy points represent observed values for participants with repeated measures across timepoints joined by a navy line. The pink line and ribbon show estimated marginal means and 95% credible intervals for height tempo.

there was relatively weak evidence to suggest that arm span tempo was lower for older athletes compared to younger athletes ($B_{\text{age}} = -0.02 [-0.11, 0.06]$, PD = 0.69).

Health Problems

During the 10-week data capture period for the health problems questionnaire, there were a total of 36 unique health problems reported from 20 athletes (7 out of 15 females, 13 out of 19 males). The reported health problems consisted of 22 illnesses (from 16 athletes: 6 females and 10 males) and 14 injuries (from 11 athletes: 4 females and 7 males). Out of the 20 athletes that reported any health problem, 7 athletes (3 females and 4 males) reported both an injury and an illness (at least 1 of each). Reported illnesses consisted of respiratory (16 total, 7 females, 9 males), gastrointestinal (3 total, all males), stress or external factors (2 total, 1 female, 1 male), and menstrual (1 total). Reported injuries consisted of pain in the lower and upper leg (2 total, both from males), stress reaction (1 male), stress fracture (1 male), strain (lower back 1 male, upper arm 1 females), trauma in the upper leg (1 female). Further, there were 7 injuries reported (3 females and 4 males) where the location and type were not reported and have been listed as “unknown”.

The time-loss of illness and injuries are presented in Figure 6A and B respectively. Overall, illnesses contributed to 3 weeks of total time-loss, 21 weeks of modified time-loss, and 7 weeks of non-time-loss. Injuries contributed to 2 weeks of total time-loss, 23 weeks of modified time-loss, and 5 weeks of non-time-loss.

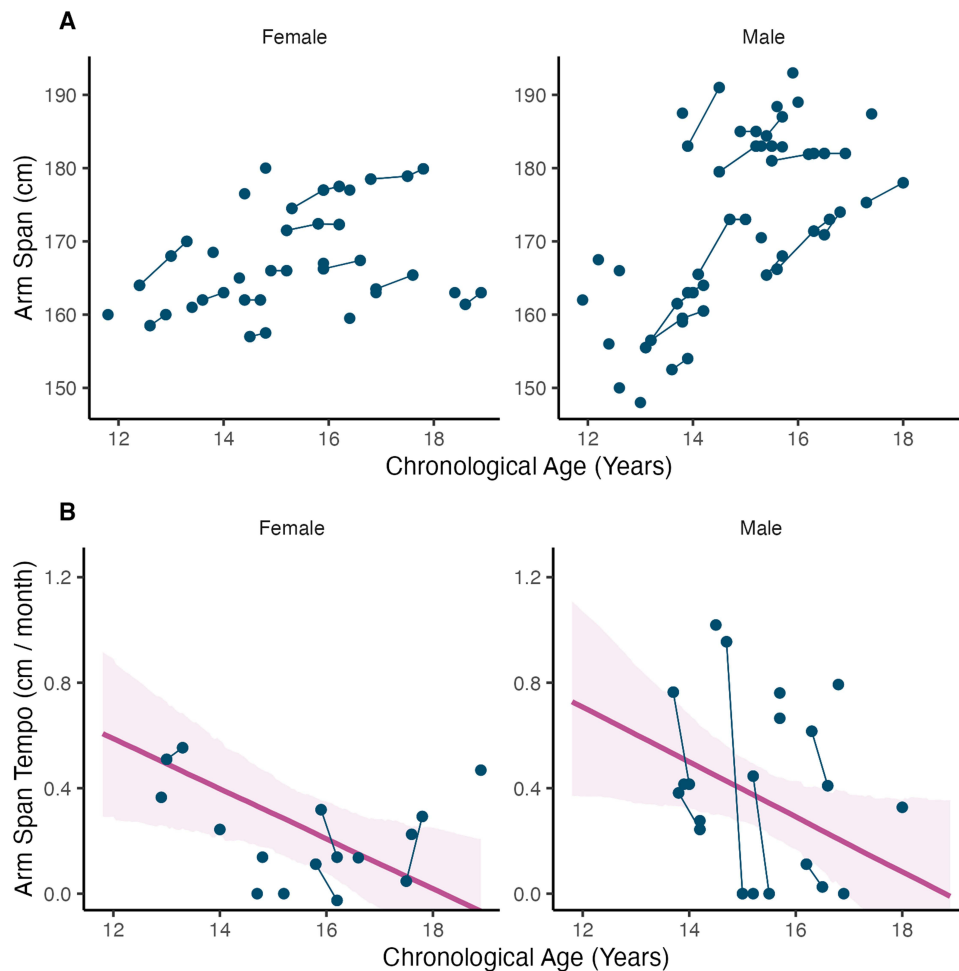


Figure 5 (A) Relationship between chronological age (CA) and arm span. (B) Relationship between CA and arm span tempo (cm per month). Navy points represent observed values for participants with repeated measures across timepoints joined by a navy line. The pink line and ribbon show estimated marginal means and 95% credible intervals for arm span tempo.

There was evidence of a relationship between maturity offset and total health problem severity ($B_{\text{maturity offset (log)}} = 0.23$, [95% HDI = 0.01, 0.46], PD = 0.98), whereby estimated severity increased by 25% ($e^{0.23}-1$) for every 1-year increase in maturity offset. Further, there was evidence that males typically had higher total severity compared to females ($B_{\text{male (log)}} = 0.52$, [95% HDI = -0.33, 1.28], PD = 0.90) by 68% ($e^{0.52}-1$) (Figure 7).

Training Load

Descriptive statistics for training load can be found in Table 3. Additional data are provided in Supplementary File Table 2.

When athletes were fully participating in training without health problems, reported weekly training load for the swim was 24% higher than the bike ($B_{\text{bike (log)}} = -0.28$, 95% HDI = [-0.46, -0.10], PD = 0.99), 44% higher than the run ($B_{\text{run (log)}} = -0.58$, 95% HDI = [-0.76, -0.40], PD = 1.00), and 38% higher than “other” disciplines ($B_{\text{other (log)}} = -0.49$, 95% HDI = [-0.69, -0.30], PD = 1.00) (Figure 8). There was evidence that training load was lower among older athletes compared to younger athletes (by 9% per year) ($B_{\text{age (log)}} = -0.09$, 95% HDI = [-0.69, -0.30], PD = 1.00). There was weak evidence that training load declined when athletes reported “reduced participation due to a health problem” ($B_{\text{reduced participation (log)}} = -0.09$, 95% HDI = [-0.38, 0.21], PD = 0.73), with the exception of the run ($B_{\text{reduced participation} \times \text{run (log)}} = -0.57$, 95% HDI = [-0.98, -0.15], PD = 0.99), which was reduced by 48%. There was no evidence of a difference in training load between females and males ($B_{\text{male (log)}} = -0.07$, 95% HDI = [-0.40, 0.24], PD = 0.67).

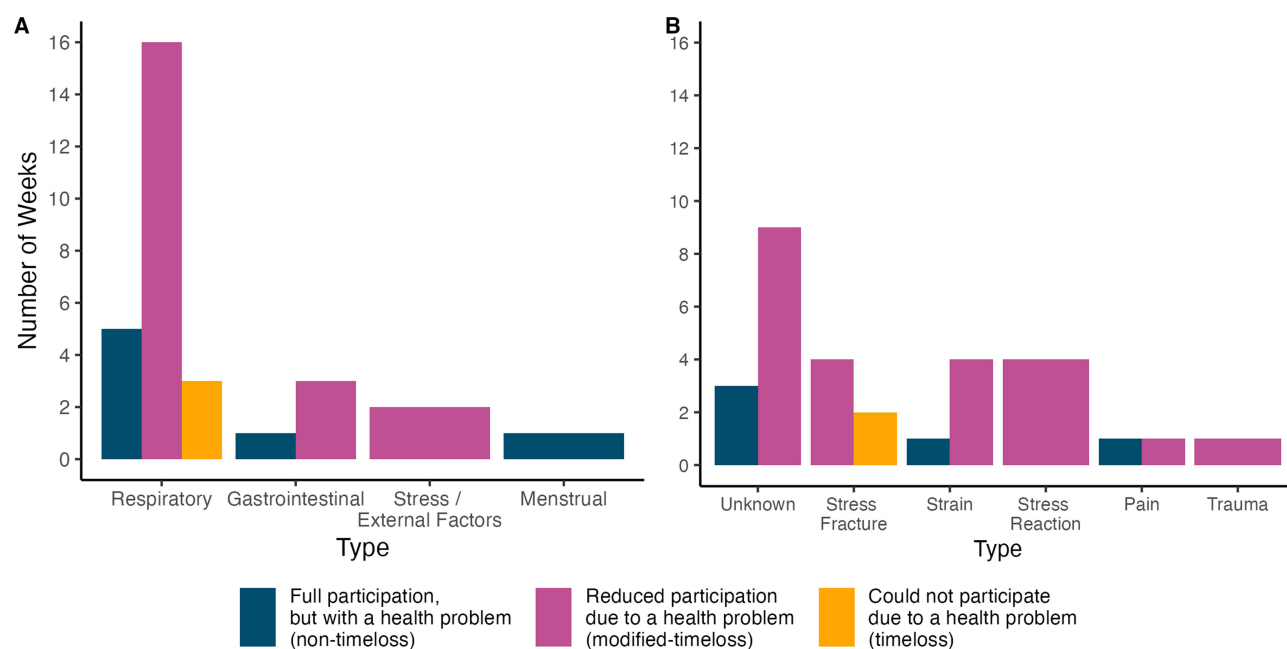


Figure 6 Health problems by type and the number of weeks of time-loss (**A**) Illnesses and (**B**) Injuries.

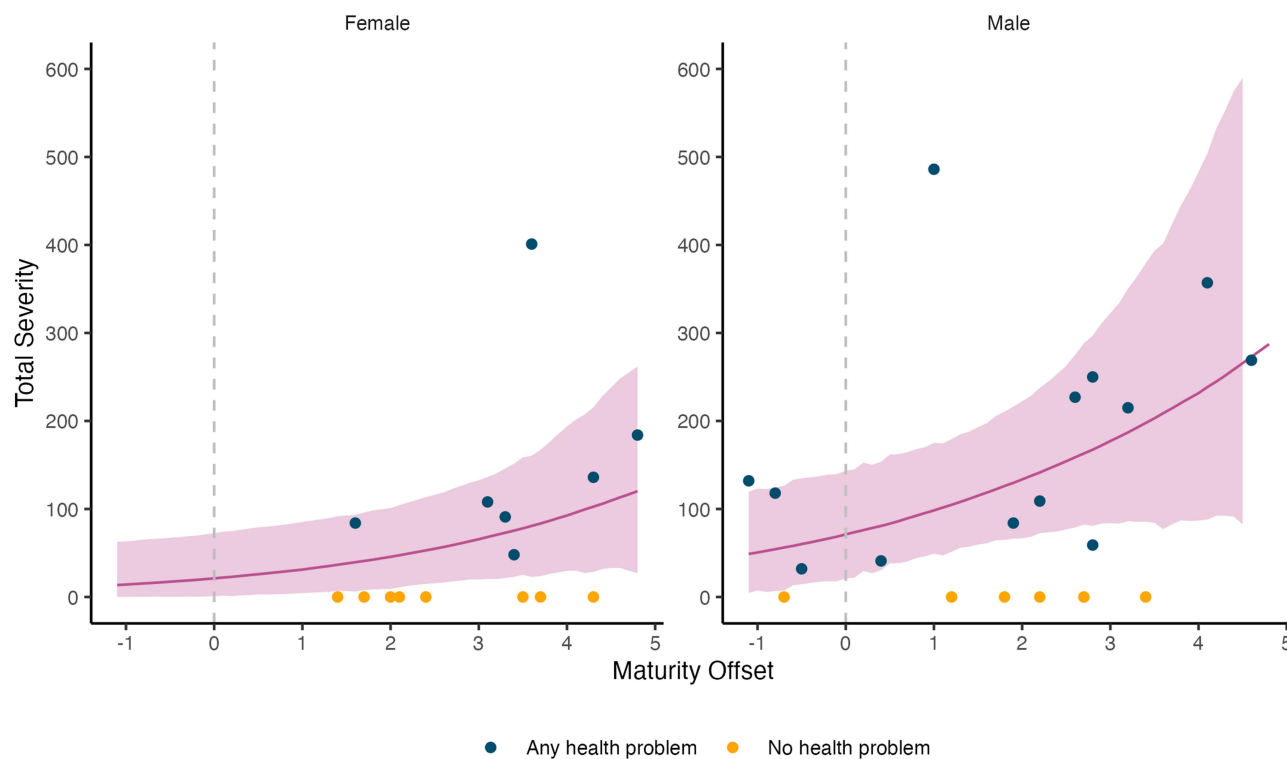


Figure 7 Relationship between maturity offset (CA minus APHV) and total severity of health problems. Navy and yellow points represent observed values for individual participants. The pink line and ribbon show estimated marginal means and 95% credible intervals for total severity.

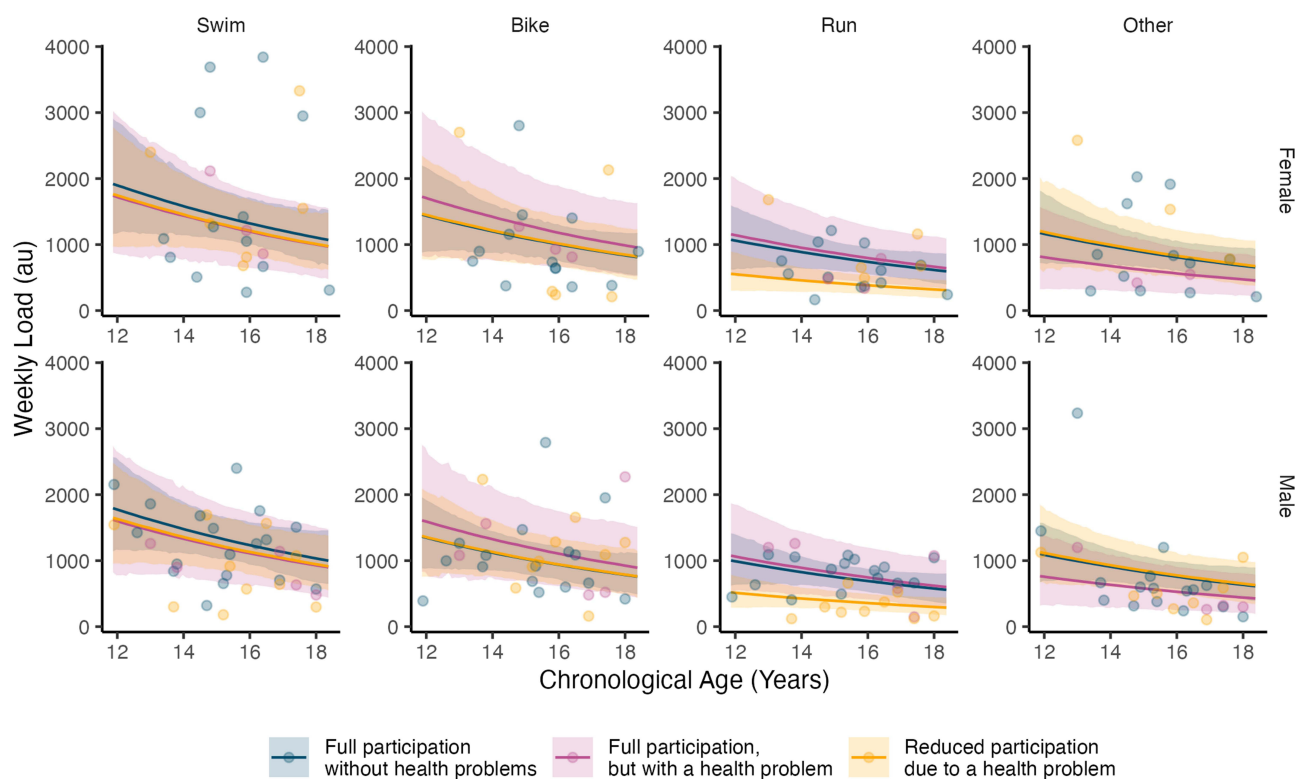


Figure 8 Relationship between chronological age (CA) and weekly training load according to discipline (swim, bike, run, other) and participation. Points represent observed participant mean values, and lines and ribbons represent estimated marginal means and 95% credible intervals. Other includes race simulation sessions, competitions, and other sport training.

Discussion

This study aimed to explore the athletic health history, growth and maturation and current health status of youth triathletes prior to entry into the NIN, and to examine the associations between growth, training load and health problem severity. Key findings across the three focus areas revealed slightly later PHV in both sexes compared to population norms and other sports, with males demonstrating accelerated arm span growth over females ahead of height stature increases. Health problems were frequently reported, with illness having greater total time-loss than injury, and severity increased in athletes beyond PHV (particularly males). Additionally, training load imbalances occurred across the three disciplines relative to race distances and injury profiles.

Growth and Maturation

Female triathletes was estimated as occurring at 12.5–12.6 years, slightly later than the general population (12 years)³⁹ and female athletes involved in team and individual sports (11.8 years).⁴⁰ Male triathletes PHV was estimated at 13.3–14.0 years, compared to 13.1 years in young male athletes,⁴¹ primarily European footballers. Other studies report PHV at 14.4, 12.9 and 12.7 in soccer and tennis players, respectively.^{42–44}

In the present study, male athletes demonstrated an average arm span growth tempo of 0.51 ± 0.35 cm per month from Time point 2 to Time point 3, with individual values reaching up to 1.02 cm per month, suggesting accelerated limb growth during our monitoring period, but prior to stretch stature growth (Figures 4 and 5). This pattern is consistent with existing adolescent growth and maturation literature which describes a distal-to-proximal growth sequence, whereby limbs grow before the trunk.^{45,46}

In the context of triathlon, this is particularly relevant for the swim discipline, where arm span contributes significantly to stroke mechanics and propulsion.⁴⁷ Sudden changes in upper limb length may temporarily disrupt technique or outpace neuromuscular adaptations, potentially impairing performance and increasing the risk of

musculoskeletal strain. Similarly, rapid changes in upper body dimensions can compromise bike fit, reducing handling efficiency and contributing to compensatory movement patterns, particularly in the neck and shoulders. Potentially elevating the risk of overuse injuries or contributing to reduced stability and increased crash risk. Monitoring arm span tempo presents a practical, non-invasive method to inform training modifications, equipment adjustments, and injury prevention strategies during key phases of adolescent triathlon growth and development.

Males showed a greater increase in BA offset (0.45 years) with CA than females, and an overall higher number of illnesses and injuries than females. This suggests the importance of sex- and maturity-specific training, including consideration of discipline type (weight bearing vs non-weight bearing) in terms of less mature tissues on similar training loads.

Female athlete health data indicated a later average age of menarche (13.7 years) in triathletes, aligning with findings from Anjos et al⁴⁸ who reported delayed menarche in athletes participating in sports such as soccer, gymnastics and triathlon (median age triathlon: 13 years). Noting the female participants in our study also had athletic histories of soccer and gymnastics (Table 1). Several athletes in our study also reported ongoing menstrual irregularities, dysmenorrhea, and tiredness, symptoms commonly associated with low energy availability. Low energy availability has been linked to impaired bone mineral accrual, delayed recovery and increased injury risk in endurance sports,^{48,49} thus longer-term monitoring of total weekly training load along with menstrual cycle patterns could help inform timely nutritional and training prescription in young female athletes.

Health Problems

Illness was reported more frequently than injury during the 10-week monitoring period (22 vs 14 cases), with respiratory illnesses comprising the majority of reports. This illness prevalence aligns with previous findings in short course triathletes and other endurance athletes, where high-intensity training has been associated with transient immunosuppression and increased susceptibility to infections.^{9,50} Notably, seven athletes experienced both injury and illness within the same period, suggesting a potential cyclical relationship driven by cumulative fatigue, inadequate recovery, and a combination of external (eg academic demands, family, life commitments) and internal (training load, growth, early season performance anxiety) stressors. This cycle may have been further exacerbated by minimal reductions in training load during health problems, except for running sessions.⁵¹

Health problems were also monitored over a 10-week period starting in Spring (September/October) in Australia corresponding to the start of the triathlon season, when athletes were building training volume and intensity. In addition, the timing of monitoring during Spring may have presented seasonal challenges, such as rising temperatures, humidity, and allergens, potentially contributing to injury and illness risk. These observations highlight the impact of both illness and injury on training consistency and the need for recovery focused strategies, including adequate nutrition, sleep and work-load management supporting athlete health and performance.⁵²

The injury profile observed was predominantly stress-related bone injuries and soft tissue strains, primarily affecting the lower leg. This injury profile is also consistent with other youth endurance sports and studies involving elite triathletes.^{9,19,53} The severity of health problems appeared to increase in triathletes with a higher maturity offset (ie, greater than ~2.5). This observation also agrees with previous research demonstrating a higher injury prevalence following PHV, characterised by greater training time loss.^{22,54} Two male athletes and one female athlete who all had previous growth-related injuries and/or bone injuries (Table 1) reported lower leg, knee, and lumbar pain as well as lower leg bone stress injuries during the 10-week study. Although we do not know the exact time frame (years) from previous injuries (Table 1) to current injuries (Figure 6) it may independently contribute to injury risk (since previous injury is a strong risk factor for a new injury).^{55,56}

Training Load

There were notable differences in training loads across the swim, bike, run, and “other” disciplines among youth triathletes. Interestingly, the swim discipline consistently had the highest total weekly training load, averaging 24% more than the bike, 44% more than the run, and 38% more than “other” activities. These lower training loads in the run discipline may also be a contributing factor to the higher incidence of bone stress injuries observed in the male youth

triathletes.⁵⁷ Research indicates that insufficient loading of developing bones can lead to increased risk of stress fractures and other overuse injuries. Therefore, the combination of lower run training volumes but higher intensity sessions in the run discipline, and “other” may place undue stress on later maturing male triathletes lower limbs and insufficient bone remodelling time.⁵⁸ Similar patterns have been observed in distance running where overuse injuries were common, particularly in the lower extremities, and were often linked to training loads that were either too high or improperly managed.⁵⁹ Thus, the importance of balanced training loads and the earlier implementation of consistent strength and conditioning sessions inclusive of plyometric and proprioceptive exercises may mitigate these bone stress and lower body injury risks on developing athletes.^{59–61}

Additionally, higher swim volume has also been seen as an increased risk of running-related injuries.⁶² The senior female athletes weekly swim load was the highest across the whole cohort, they also had the lowest weekly run load. This could be a potential risk factor for injury or pain due to lack of a protective fitness response, even allowing for their biological advancement in bone age.⁷

Limitations

This study has several limitations that should be acknowledged. First, the use of non-invasive maturity prediction equations such as the Mirwald method,²⁸ while practical for sport and widely used in sport research settings, may be less accurate in individuals who mature significantly earlier or later than average, potentially affecting the interpretation of growth-related findings.⁶³ Similarly, the bone age prediction equation used (Cabral et al)³¹ may have limitations in precision in comparison to imaging techniques. The sample size was relatively small, with varying participation across data points, 53 athletes were included in the study, but 34 athletes completed the health problems questionnaire and training load monitoring, while 27 completed the athletic health questionnaire which may introduce selection and attrition bias and limit the reliability of certain comparisons in growth.

Seven injuries remained unclassified, which may reflect underreporting or limited communication between athletes and coaches, a well-documented challenge in youth sport settings.⁶⁴ Additionally, the 10-week monitoring period for health problems and training load may limit the generalization of these findings to longer term trends and this should be considered when interpreting the results.

Table 4 Key Findings

Key Findings	Potential Risks/Outcomes	Monitoring/ Practical Considerations
Growth tempo differs between upper body vs lower body	Increased vulnerability to injury and illness	Consider monitoring growth and maturation regularly for tracking growth tempo, informing training progression and potential equipment adjustments (eg bike fit)
High incidence of illness and health problem severity post-PHV	Risk of missed training and decreased performance	Within a long-term athlete developmental framework, apply ongoing health problem surveillance and structured recovery protocols across the season; encourage early reporting of symptoms to inform year-to-year athlete management
Imbalance in training load (eg, higher swim vs lower running volume)	Potential musculoskeletal overload/injury risk	As indicated, implement discipline specific programming with strength and conditioning/plyometrics to build resilience over multiple competitive seasons; monitor training balance longitudinally
Female athletes – menstrual cycle changes	Potential early signs of low energy availability	Where required, track menstrual cycles longitudinally; guiding nutrition and fuelling strategies
Sex differences in health problems and growth and maturation	Individual variability in response to training	Review and implement sex and maturity informed training plans; based on observed performance, guide progression/modified training loads through multiple stages of development and across years of athlete growth

Practical Considerations/Summary

These key findings (Table 4) suggest the need for long-term monitoring frameworks that respond to individual growth and maturation patterns rather than chronological age alone. Integrating health surveillance, training load balance, musculoskeletal capacity and sex-specific indicators can help guide safer, more sustainable athlete development across multiple seasons.

Future research should further investigate these sex-specific differences during growth and maturation, including menstrual health, using longer term longitudinal tracking. Developing a more comprehensive understanding of how youth triathletes respond to discipline-specific training loads, recovery and nutritional intake will help strengthen athlete management approaches aimed at supporting musculoskeletal adaptation through growth and maturation while reducing health problem risk. In addition, education for coaches and performance staff will be needed to ensure these insights are effectively translated into practice.

Conclusions

Youth triathletes showed later peak height velocity than population norms and advanced predicted bone age relative to chronological age. Severity of health problems was greater among athletes' post-peak height velocity with males showing higher severity of health problems than females. Illness was reported more frequently than injuries, with greater total time-loss, and several athletes reported both injury and illness concurrently. Most injuries were to the lower limb despite swimming having higher weekly training load volume and running the lowest training load volume. The findings suggest the need for individualized, longitudinal monitoring in youth triathlon pathways, indicating the importance of tracking growth and maturation, alongside balanced discipline and sex-specific training load prescription to support long-term performance progression and transition to the NIN and sustained elite-level competition.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

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