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Disaggregating the influence of maturity status on training, anthropometric, performance, skeletal periphery, and hormonal factors in athletic boys

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ABSTRACT

Maturity offset (i.e., age from peak height velocity [PHV]) is widely used to assess maturational status among youth athletes, but details on the skeletal periphery, hormones and training factors are lacking. More precision is also needed to explicate the timing, tempo, and sequence of growth-related events. These gaps were addressed in a cross-sectional study. One hundred and two athletic boys (aged 14.1 ± 0.5 years) were evaluated for training details, salivary testosterone and cortisol, height, body mass, body mass index, body fat, fat-free mass (FFM), hand and carpal bone area, bone mineral content (BMC) and density (BMD), and countermovement jump performance. Participants were assigned to circa-PHV ($N = 56$) and post-PHV ($N = 46$) groups for comparisons, before data pooling and disaggregation using generalized additive and linear regression models. The older post-PHV group had a larger body size, more testosterone, and better performance and skeletal outcomes, whilst weekly training and school-based exercise favored the younger circa-PHV group (all $p < 0.001$). Smoother plots verified these differences via linear, or weakly non-linear, associations. Maturity offset was predicted ($R^2 = 0.848$) by the linear combination of FFM (42.0 % relative contribution), hand BMD (31.5 %), chronological age (16.0 %), testosterone (6.7 %), and training hours (3.8 %). In conclusion, athletic boys who presented at different stages of maturity (-0.98 to 2.84 years from PHV) also differed on many developmental features. Most variables increased at constant, or near-constant, tempo with a higher maturity offset, with FFM and hand BMD emerging as the strongest linear predictors of maturational status.

1. Introduction

Somatic maturity, often defined by age at peak height velocity (PHV), is a major inflection point in life where the maximal growth spurt occurs during adolescence [1]. Since the processes of somatic growth and maturation occur concurrently, and are related, many growth indicators like height, body mass, and fat-free mass (FFM) also correlate with maturity offset and physical performance [1–4]. Crucially, the body dimensions and functional capacity of young athletes mature on different time courses. This means that two individuals at the same chronological age might differ in their maturity offset or age from PHV. It is becoming increasingly important to accommodate for these differences to enhance the selection, assessment, avoidance of injury, and training of young athletes in sport [1,5,6].

In cross-sectional studies, maturity status is typically determined by predicting age at, or from, PHV [5]. Few reports have considered peripheral measurements of bone mineral density (BMD) and content (BMC), as direct measures of somatic maturity. Research indicates that age-related increases in hand BMD and BMC, when measured by dual-energy X-ray absorptiometry (DXA), parallel changes in total or subtotal body BMD and BMC across childhood and adolescence, and these outcomes strongly covary ($r = 0.81–0.96$) [7]. Hand BMD is also related, strongly and positively, to common indicators of maturity status (i.e., physical performance, maturity offset, lean body mass [LBM]) in children [7,8]. Moreover, BMC and BMD from the skeletal periphery (e.g., arms, forearms) can differentiate mechanical loads imposed by different sports, and between sporting and non-sporting groups [9,10], likely adding to its discriminate potential in youth sport.

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Information on sex hormones (e.g., testosterone, dehydroepiandrosterone, estradiol) is also lacking in sports literature, despite playing a pivotal role in the growth and maintenance of skeletal muscle tissue, and general physical development [1,4,11,12]. Testosterone and it's active metabolite dihydrotestosterone also work with cortisol to regulate muscle protein turnover [13,14], which can affect bone matrix via strain arising from muscle tissue accretion. Moreover, testosterone and cortisol exert pleiotropic actions on the neuromuscular system affecting energy metabolism, muscle contractions, and human movement [13], thereby supporting other functions that contribute to bone and muscle remodeling. Habitual physical activity, which includes sports training, has a significant independent influence on LBM accrual during adolescence, even when controlling for biological maturity and stature [15]. Hence, additional testing of skeletal periphery, hormonal, and training factors could help discern the causes and consequences of maturity status in young athletes.

A common research methodology involves comparing athletic boys at different maturational stages (e.g., pre-PHV, circa-PHV, post-PHV) [1,5]. Post-PHV boys tend to be older and possess a larger body size with superior physical qualities [2,16,17], whereas pre-PHV or circa-PHV boys are younger and smaller, but with greater potential for performance gains over time [18,19]. Categorical comparisons are, however, less precise for detecting the timing, tempo, and sequencing of growth-related events. Two complementary approaches, each focusing on maturity offset as a continuous variable, could address this gap. The first is use of bivariate smoother plots to depict the timing and tempo of a selected event (e.g., pubertal surge in testosterone) [20]. The second involves an equivalent regression model to affirm assumptions on physical growth and biological maturation, whilst overcoming bias with fitting linear models to non-linear maturational processes [20].

To address gaps in the literature, a cross-sectional study on athletic boys was conducted to disaggregate the influence of maturity offset on selected anthropometric, performance, skeletal periphery, training, and hormonal factors. The boys were initially assigned into two groups (i.e., circa-PHV and post-PHV) for comparisons. After pooling the dataset, these relationships were further illuminated via bivariate smoother plots versus maturity offset, and multiple regression (linear and non-linear) models with stepwise selections to yield a subset of variables that best discriminates maturational status. Two broad hypotheses were generated; (1) post-PHV boys would be older and achieve better results on all outcomes versus circa-PHV boys; (2) smoothing plots on continuous measurements would confirm the categorical results. No firm hypothesis was made regarding the regression models, due to their exploratory nature and the iterative selection of predictors.

2. Material and methods

2.1. Participants

One hundred and six athletic boys (aged 12.3 to 15.2 years) of Polish nationality were recruited from different schools in Warsaw and screened for any injuries, medical conditions, and health status. Four boys presented with a pre-PHV status and thus, were excluded from the final analyses to remove extreme outliers and ensure balanced groups. Therefore, the final sample consisted of 102 boys. The participants reported training regularly for different sports (e.g., football, skateboarding, volleyball, swimming, biathlon, handball). On average (±SD), they reported a training history of 4.8 ± 1.7 years, weekly sports training of 9.1 ± 3.8 h, and school-based physical exercise of 3.6 ± 0.9 h a week. All participants were informed about the study aims, benefits, and risks, before giving written informed consent. Additional consent was obtained from a parent or guardian. This study was approved by the ethics committee at the Institute of Sport – National Research Institute, Poland.

2.2. Study design

A cross-sectional design was used to address the study aims and hypotheses. The participants visited the laboratory on a single day to complete a battery of tests. This visit began with completion of study forms, reporting of basic training information (i.e., training history, sports training each week, school-based exercise each week) and self-collection of a saliva sample for hormone determination. Next, anthropometric dimensions were evaluated, including height, body mass (BM), a BM index (BMI), body fat, and FFM. In the same room, DXA quantification of area, BMC, and BMD of the hand (i.e., metacarpals and phalanges) and carpals or wrist bones was performed. Finally, countermovement jump (CMJ) performance was assessed in a separate biomechanical laboratory. All examinations began at a similar time of day (0930 – 1100 h) to control for circadian shifts in hormone concentrations and maximal exercise (e.g., speed, power, strength) performance [13,21]. Each test outlined was implemented by the same investigator/s to remove any experimenter bias and, where possible, in the same sequence above to eliminate any ordering effect.

2.3. Maturational status

Maturity offset was computed by subtracting chronological age (i.e., date of birth to date of testing) from predicted age at PHV [15,19]. Age at PHV was estimated using the Mirwald et al., equation [22], which is based on the ratio of sitting height to length. Mean differences between predicted and actual age at PHV are stable in Polish boys 13–15 years of age [23]. The participants were assigned into a circa-PHV ($N = 56$) or post-PHV ($N = 46$) group based on established thresholds [2,18,19], where the former group represents a maturity offset band of ±1 year (actual range -0.98 to 1.00) and the latter an offset value >1 year (actual range 1.02 to 2.84). Maturity offset was treated as a continuous variable in subsequent analyses.

2.4. Anthropometry

Standing and sitting height was assessed to the nearest 1 cm with a stadiometer (Siber-Hegner, Switzerland) and BM to the nearest 0.1 kg using digital scales (Tanita, Japan). A BMI was computed by dividing BM by height (in m^2). Body fat percentage was estimated from a published formula [24], based on two skinfold measurements (i.e., triceps, subscapular) taken using body fat calipers (Siber-Hegner, Switzerland). Relative repeatability error for the skinfold measurements ranged from 1.6 % to 3.0 %. As a more precise measurement of metabolically-active tissue, FFM (in kg) was estimated by subtracting body fat (converted to kg from % values) from BM [20]. For all anthropometric measurements, subjects wore only shorts without shoes and socks.

2.5. Salivary hormones

An unstimulated saliva sample (~0.5 mL), collected at a similar time for all subjects, was taken by passive drool into a 5-mL sterile container and stored at -80 °C within two hours of collection. After thawing and centrifugation (3000 rpm × 15 min), the samples were tested for testosterone (in pg/mL) and cortisol (in ng/mL) concentrations using commercial enzyme-linked immunoassay kits (IBL, Germany). Inter-assay coefficients of variation (CV) on low and high controls on each plate were less than 11 % for both hormones. To prevent sample contamination, instructions were given to avoid eating or drinking (except water) 60 min before sampling began.

2.6. Physical performance

Physical performance was assessed from two CMJ variants that were executed on a force plate (type PJS-4P60k, "JBA" Zb. Staniak, Poland). In the first variation, the hands were held akimbo (ACMJ) on the hips,

followed by a standard CMJ where arm swing was permitted. Three trials were completed per exercise, each interspersed with passive recovery (~1 min), and the best trial was chosen for analysis. Absolute and relative peak power output, as well as maximum vertical displacement of the body's center of mass, were computed from ground reaction force data (measured with an accuracy of <1 Newton and sampled at 1000 Hz) using customized software [25]. Strong reliability coefficients have been reported for CMJ power (CV = 3.4 %) and height (CV = 3.0 %) derived from these procedures in young male athletes [26].

2.7. Skeletal periphery

Peripheral measurements of hand and carpal area (cm^2), BMC (g), and BMD (g/cm^2) were taken using a DXA scanner (Lunar Prodigy Pro-DXA machine, GE Healthcare, USA). The participant's hand was laid palm down and flat on the scanner bed. Each scan focused on the hand / wrist area of the non-dominant hand, using a starting point of two finger widths below the radiocarpal articulation. All scans and in-software analyses were completed by the same researcher using GE Encore (version 16) software. Operator reliability statistics for the hand and wrist measurements of area, BMC, and BMD are typically ≤1.1 % [7,27]. The DXA machine was calibrated daily, prior to examination, with a quality assurance calibration block. Exposure to ionizing radiation during this examination was minimal (<1 min), equating to an absorbed radiation dose of ~2.0 milligray.

2.8. Statistical analyses

The study data were analyzed in R (version 4.3.2) [28] using several packages (i.e., sjPlot, easystats, readxl, xlsx, ggplot2, psych, ggpubr, dplyr, autoReg, relaimpo, mgcv, car) and bespoke R functions. Initial data inspection revealed some missing hormonal (4.9 %), bone (1 %), and performance (5.8 %) values, due to one or more unforeseen factors (e.g., insufficient / poor samples, technical problems, poor adherence). To retain maximum information and prevent listwise deletion in subsequent models, we used multivariate imputation chained equations to predict the missing values from all features contained in the dataset [29]. Our analytical procedures, as described below, were performed on the new dataset with partially-imputed values unless stated otherwise.

To broadly evaluate the influence of maturity status on each study variable, we compared data across the circa-PHV and post-PHV groups using unpaired T-tests. As an effect size statistic, standardized Cohen differences were calculated with a 95 % confidence interval (CI). Differences were interpreted qualitatively, as small (0.2 to <0.5), medium (0.5 to <0.8), large (0.8 to < 1.2) or very large (≥ 1.2) effects. To better understand the bivariate association between maturity offset and each variable, we constructed a series of smoothing plots using a generalized additive model (GAM) [30]. Each smoother was generated with a cubic regression spline [20] to maintain data integrity without modifying the underlying growth patterns [15]. The shape of these associations can be determined from the effective degrees of freedom (EDF) statistic, as follows: linear (EDF = 1.0), weakly non-linear (EDF > 1 to 2) or highly non-linear (EDF > 2).

To select the best predictors of maturity offset, a model-building procedure was applied. First, Pearson correlations were used to identify strong bivariate relationships indicating collinearity and thus, assist variable removal. We set an *r* threshold of 0.70 or -0.70 for this purpose [2]. This process left 11 (of 25) variables available for model selection: chronological age, FFM, body fat, physical exercise, training hours and years, testosterone, cortisol, ACMJ height, hand BMD, and carpal area. Next, these terms were entered simultaneously into a multiple linear regression model and further triaged using a backwards stepwise elimination procedure. This process was repeated as a GAM to test whether any predictor is better represented as a non-linear function. Finally, we computed the relative (%) importance of each predictor, adjusted to the model R^2. Coefficients from the linear regression model and relative importance values are given with a bootstrapped 95 % CI (N = 10,000 iterations). The GAM does not generate coefficients for continuous variables, due to spline implementation with a k basis to construct a smoother (i.e., EDF) function [30]. Significance for all analyses was set at an alpha level of $p < 0.05$.

3. Results

There was no difference in the number of participants in each group (χ^2 $p = 0.322$) and a visual inspection of plotted pairwise differences did not reveal any major deviations from normality. The post-PHV boys were significantly ($p < 0.001$) older, both in chronological age and age at PHV, with a higher maturity offset than the circa-PHV group (see Table 1). Effect size differences on these outcomes were large to very large (see Fig. 1). The post-PHV boys also presented a larger body size (i.e., height, BM, BMI, FFM), a higher testosterone concentration, superior ACMJ and CMJ performance, and higher bone values than the circa-PHV group ($p < 0.001$), with group differences ranging from moderate to very large effects. Only weekly physical exercise and training hours were significantly higher (both moderate effects) in the circa-PHV versus post-PHV group. Between-group comparisons of body fat, training years, and cortisol concentration were non-significant ($p > 0.500$).

The smoother plots are illustrated in Fig. 2. When aligning data by individual differences in maturity status, positive and linear or weakly non-linear trajectories were seen for chronological age, age at PHV, height, BM, BMI, FFM, testosterone, all ACMJ and CMJ variables, along with hand and carpal area, BMC, and BMD. Linear, but negative, associations emerged for weekly physical exercise and sport training hours.

Table 1
Descriptive means (SD) for all variables in the pooled sample of athletic boys and in the circa-PHV (N = 56) and post-PHV (N = 46) groups.

Variables	Pooled		Circa-PHV		Post-PHV		
	Mean	SD	Mean	SD	Mean	SD	*p* values
Maturity offset (years)	0.88	0.93	0.19	0.56	1.72	0.48	<0.001
Age (years)	14.1	0.50	13.8	0.47	14.3	0.38	<0.001
Age at PHV (years)	14.9	1.29	14.0	0.83	16.1	0.74	<0.001
Height (m)	1.76	0.11	1.69	0.08	1.85	0.07	<0.001
BM (kg)	60.7	11.0	53.7	8.17	69.2	7.43	<0.001
BMI (kg/m^2)	19.3	1.97	18.6	1.84	20.2	1.79	<0.001
Body fat (%)	15.9	3.65	15.9	4.20	15.9	2.90	0.990
FFM (kg)	50.9	8.95	45.0	6.17	58.1	6.05	<0.001
Physical exercise (hours)	3.57	0.87	3.84	0.89	3.24	0.74	<0.001
Training (hours)	9.21	3.84	10.41	3.70	7.75	3.52	<0.001
Training (years)	4.83	1.67	4.73	1.62	4.96	1.73	0.501
Testosterone (pg/mL)	49.2	25.1	40.3	22.1	60.0	24.6	<0.001
Cortisol (ng/mL)	1.67	1.07	1.71	1.19	1.62	0.91	0.658
ACMJ height (m)	0.36	0.05	0.34	0.04	0.39	0.05	<0.001
ACMJ pp (W)	1424	446	1166	300	1738	390	<0.001
ACMJ relative pp (W/kg)	23.4	4.72	21.9	4.63	25.3	4.18	<0.001
CMJ height (m)	0.42	0.06	0.39	0.05	0.45	0.06	<0.001
CMJ pp (W)	1900	659	1520	396	2364	620	<0.001
CMJ relative pp (W/kg)	31.2	6.96	28.6	6.06	34.4	6.70	<0.001
Hand area (cm^2)	79.1	9.42	73.8	7.59	85.6	7.11	<0.001
Hand BMC (g)	23.5	5.79	19.6	4.05	28.2	3.71	<0.001
Hand BMD (g/cm^2)	0.29	0.05	0.26	0.04	0.33	0.03	<0.001
Carpal area (cm^2)	13.3	1.77	12.5	1.49	14.3	1.56	<0.001
Carpal BMC (g)	5.15	1.45	4.26	1.13	6.23	1.00	<0.001
Carpal BMD (g/cm^2)	0.38	0.07	0.33	0.06	0.43	0.05	<0.001

Key: PHV = peak height velocity, BM = body mass, BMI = BM index, FFM = fat-free mass, ACMJ = akimbo countermovement jump, pp = peak power, CMJ = countermovement jump, BMC = bone mineral content, BMD = bone mineral density.

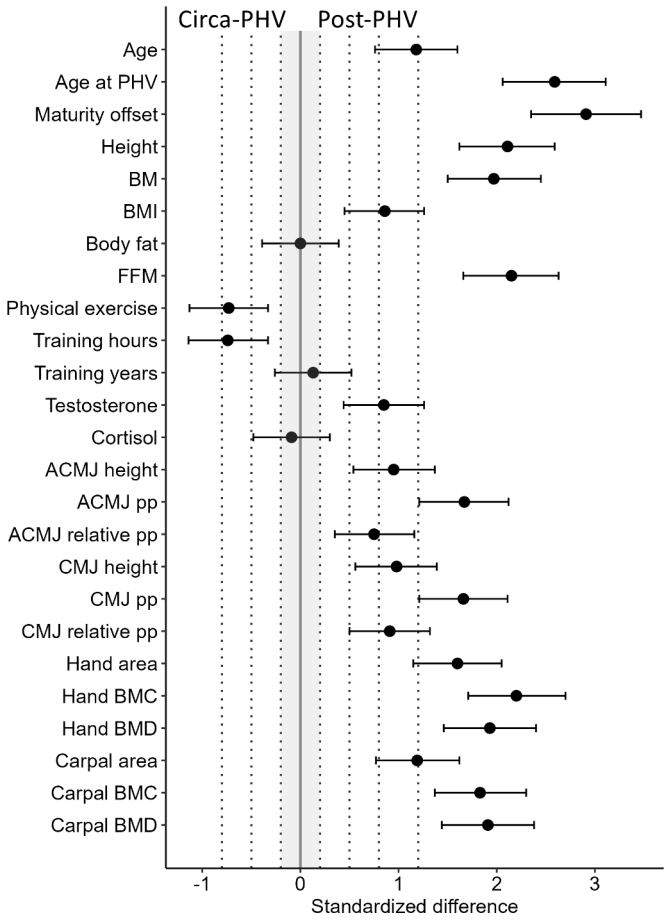

Fig. 1. Standardized difference (95 % CI) for all study variables between the circa-PHV and post-PHV groups. The broken vertical lines represent the thresholds for small, medium, large, and very large effects. Key: PHV = peak height velocity, BM = body mass, BMI = BM index, FFM = fat-free mass, ACMJ = akimbo countermovement jump, pp = peak power, CMJ = countermovement jump, BMC = bone mineral content, BMD = bone mineral density.

Flatter trajectories (linear or weakly non-linear) were seen for body fat, training years, and cortisol, indicating no meaningful association between these variables and individual differences in maturity offset. These observations are consistent with group comparisons in Table 1 and Fig. 1.

The stepwise procedure identified five linear predictors of maturity offset (see Table 2). Each variable was a significant contributor to this model, apart from testosterone, and each predictor had a positive coefficient, except for weekly sports training. Collectively, these variables explained ~84.8 % (adjusted R^2) of the individual variation in maturity offset (model $p < 0.001$). Plots of model residuals approximated normality and the variance inflation factor, as a collinearity check among predictors, was acceptable with no values exceeding 3.3. Two metrics confirmed that the model generated was not overfitted; a moderate ratio of observations to predictors (~20:1), and similar adjusted R^2 (0.848) and predicted R^2 (0.833) values. Post-hoc power analyses for multiple linear regression was performed using G*Power (version 3.1.9.7) [31]. The final model was adequately powered for detecting a medium effect size ($f^2 = 0.15$) at 85 % power with an alpha level of 0.05.

The equivalent GAM also revealed a linear effect of all five variables (EDFs = 1) on maturity offset and obtained p values that replicated multiple linear regression (see Table 2). The observed fit of the GAM (adjusted $R^2 = 0.848$) was again identical to linear regression, likewise the goodness of fit for both models (i.e., Akaike Information Criterion = 89.63). In terms of relative importance (Fig. 3), FFM (42.0 %) and hand BMD (31.5 %) were the strongest contributors to the linear regression model. Participant age was the next strongest variable (16.0 %), followed by testosterone (6.7 %) and training hours (3.8 %). Inspection of the pairwise CI differences confirmed a significant graded effect, whereby FFM and hand BMD > chronological age > testosterone and training hours.

4. Discussion

This study sought to disaggregate the impact of maturity status on a broad array of developmental indicators in young male athletes. Three main findings emerged; (1) post-PHV boys were older and showed greater development in body size, testosterone concentration, physical performance, and skeletal periphery than circa-PHV boys, whereas training hours and physical exercise favored the latter group; (2) the same differentiating variables were related to maturity offset in a linear, or weakly non-linear, way; (3) a linear combination of five variables (i.e., FFM, hand BMD, chronological age, testosterone, training hours) strongly predicted maturity offset, but with different model contributions.

In line with our first hypothesis, the older post-PHV group displayed a larger body size, a higher testosterone concentration, better ACMJ and CMJ performance, and enhanced skeletal maturity (i.e., area, BMC, BMD) compared to younger circa-PHV boys. These results are congruent with studies on adolescent athletes [2,16-19,32,33] and children [4,15]. Conversely, the circa-PHV boys declared more training hours per week; a finding contrary to expectations and empirical evidence [15]. As part explanation, sports training often becomes more specialized during early adolescence [34], including more intensive training that necessitates longer recovery, and at the exclusion of other sports, thereby lowering overall training hours each week. An alternative explanation lies in the uneven distribution of sports after group assignment, especially individual sports (e.g., swimming, gymnastics) where weekly training hours might be double that of team-sport (e.g., handball) athletes [35]. The variation in school-based exercise, which also favored the circa-PHV group, is more difficult to explain. Possible causes include different school curricula regarding physical education classes and individual preferences for exercise during unstructured play time.

As hypothesized, the smoother plots corroborated all significant between-group differences. Whilst most variables increased or decreased linearly with a higher maturity offset, others (i.e., height, testosterone, ACMJ height and relative power, CMJ height, hand and carpal area and BMD) increased in a non-linear manner. Nevertheless, no clear deflection points were visible in any smoothed variable when plotted against maturity offset, because trajectory divergence from linearity was still relatively minor (EDFs 1.2–1.5) in each case. Conflicting results come from athletic boys aged 8–19 years [20]. In this study, distinctly non-linear trajectories emerged when mapping body composition (EDFs up to 4.2), physical performance (up to 4.2), and hormonal (up to 3.7) measures onto chronological age [20]. We ascribe our lower EDF values to a narrow age range (~3 years) and, accordingly, maturity offset range (~3.8 years). Participant testing slightly before, and after, age at PHV is another consideration, given that many bodily and biological features are acquired at a similar rate at this time [4,15,20,27,36,37]. This also means that linear models (e.g., Pearson correlations, least squares regression) can be applied to examine growth and maturational processes, at least when certain sampling conditions are met.

Regression analyses revealed that a linear combination of FFM, hand BMD, age, testosterone, and training hours explained ~84.8 % of individual differences in maturity offset. These selections are not unexpected, because they represent the major physiological (i.e., muscular, skeletal, endocrine) systems that define the transitioning period from childhood to adulthood [4,15,27,37,38], exposure to sport-related stressors (e.g., training, competition) that engage and/or shape these

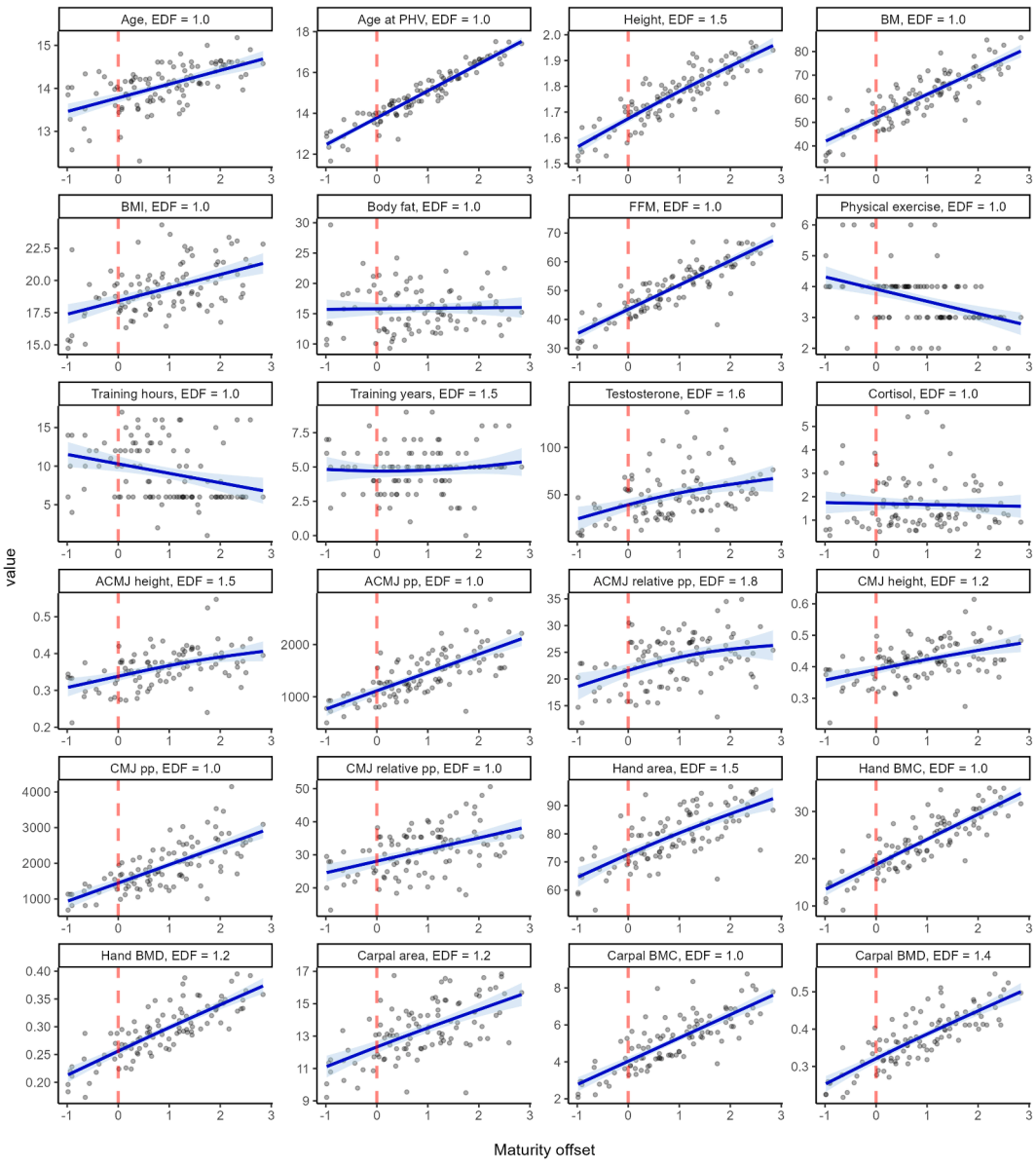

Fig. 2. GAM smoother plots for each study variable plotted against maturity offset. The predicted trends (solid blue lines) are shown with a 95 % CI (blue shaded regions). The vertical line represents a maturity offset of zero. Key: EDF = effective degrees of freedom, PHV = peak height velocity, BM = body mass, BMI = BM index, FFM = fat-free mass, ACMJ = akimbo countermovement jump, pp = peak power, CMJ = countermovement jump, BMC = bone mineral content, BMD = bone mineral density.

Table 2
Prediction of maturity offset using multiple linear regression and a generalized additive model (GAM). Predictors were selected using an iterative stepwise elimination procedure.

	Multiple linear regression			GAM		
Predictors	Est.	95 % CI[1]	*p* value	Predictors	EDF	*p* value[2]
Age	0.426	0.249, 0.613	<0.001	s(Age)	1.0	<0.001
FFM	0.059	0.043, 0.075	<0.001	s(FFM)	1.0	<0.001
Training	-0.023	-0.044, -0.003	0.018	s(Training)	1.0	0.018
Testosterone	0.002	-0.001, 0.005	0.130	s(Testosterone)	1.0	0.130
Hand BMD	3.960	1.210, 6.757	0.005	s(Hand BMD)	1.0	0.005
Observations	102			Observations	102	
Dev explained	85.6 %			Dev explained	85.6 %	
Adj-R^2	0.848			Adj-R^2	0.848	

Key: FFM = fat-free mass, BMD = bone mineral density. [1]Model estimates are shown with a 95 % bootstrapped CI. [2]Significance values are approximated.

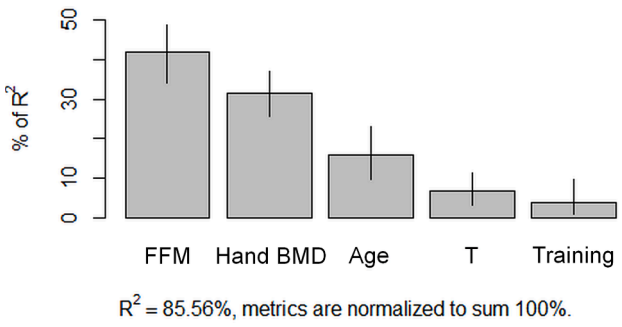

Fig. 3. Relative importance of predictor variables in explaining individual variability in maturity offset. Each variable is presented with a 95 % bootstrapped CI. Key: FFM = fat-free mass, BMD = bone mineral density, *T* = testosterone.

and other bodily systems [13,39], and unobserved factors relating to the ageing process (e.g., muscle architecture, motivated behaviours). When ranked on relative importance, FFM and hand BMD exceeded all other variables in predicting maturity offset, both individually (31.5–42.0 % vs. 3.8–16.0 %) and collectively (73.5 % vs. 26.5 %), when controlling for chronological age, testosterone, and training hours. The prognostic value of FFM and hand BMD is reinforced by a strong explanatory model (79.8 % shared variation) when entered, as the solitary predictors, into a linear regression model.

In the current context, the predictive utility of FFM is likely based on its approximation of LBM in boys [7,15] and LBM accrual as a major hallmark of pubertal growth and maturation [1,15]. Similarly, DXA measures of hand BMD correlate strongly with, or closely parallel, total or subtotal BMD changes during childhood and adolescence [7,27] and thus, offers a ubiquitous measure of whole-body growth. Assessment of the dominant hand can help explain the strong BMD link to maturity offset. Evidence shows greater BMD and/or LBM in the dominant (vs. non-dominant) arm of children [36] and sport-related differences in the arm or forearm BMD [9,10]. It is attractive to speculate that peripheral measurements of BMD reflect both normal growth patterns and additional interactions with sporting demands, allowing for better characterization of maturity status among young developing athletes. Our predictions could also be a function of targeting circa-PHV and post-PHV boys during study recruitment. That is, a large proportion of both bone and lean tissue accumulates in boys approximately ±2 years from the age of PHV [15,33,37,40]; an epoch that captures 85.3 % of subjects in the present study.

On a practical level, the present study offers new knowledge to enhance the bio-banding of youth athletes [6]. One example being the matching of athletic boys on FFM and hand BMD to better equalise competitive games or prescribe suitable training loads, rather than approaches based on chronological age [5]. In fact, individual loads can be adjusted to better suit biological maturity where performance is similar and accompanying training are being undertaken homogeneously. Similarly, these indicators could ensure that appropriate goals are set, and standards achieved, when young athletes enter a structured training environment, potentially lowering injury risk. As proxies of lean muscle and skeletal development, both measures could also help identify and develop natural talent in sport, over and above performance benchmarking. More generally, hand BMD offers an alternative approach to assessing somatic maturity in young athletes and overcomes bias with indirect measures (i.e., estimated age at PHV). Further opportunities exist for analytical advancements in this area. Specifically, explicit testing of linearity (e.g., using GAM smoothers) during bivariate and multivariate analyses, as per this study, is encouraged to affirm growth and/or maturational assumptions, identify non-linear effects that could be obscured by linear models, and improve model fit for better data translation [20].

The current findings do come with important caveats. For instance, our results only infer causation, due to the cross-sectional design, and we did not cross-validate the regression models constructed. Furthermore, it was not possible to test all predictor combinations because of computational issues with 25 predictors and relatively few observations. The narrow maturity offset range should also be interpreted carefully, especially when attempting to define a true population model, and notwithstanding any estimation errors when predicting age at, and from, PHV [23,41]. As a delimitation, our results may not translate well to ethnically diverse (i.e., non-white European) athletic boys or to specific sporting groups, especially those with a propensity to be early or late maturers (e.g., gymnastics). Adding to this, we recruited boys partaking in both osteogenic (e.g., soccer) and low-osteogenic (e.g. swimming) sports that can differentially affect BMC and BMD during maturation [42]. These gaps will be tackled in a forthcoming national growth project, involving study replication on a large (1000′s) cohort of early-, circa-, and late-maturing boys.

5. Conclusions

This cross-sectional study supports the central idea that athletic boys presenting at different stages of maturity also differ in chronological age and many developmental or maturational indicators. Most variables increased at a constant (linear) or near-constant (weakly non-linear) tempo with a higher maturity offset. Fat-free mass and hand BMD emerged as the strongest linear predictors of maturity status and thus, can inform evidence-based decisions regarding the selection, assessment and training of athletic boys.

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CRediT authorship contribution statement

Blair T Crewther: Writing – review & editing, Writing – original draft, Visualization, Software, Funding acquisition, Formal analysis, Data curation. **Anna Pastuszak:** Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Christian J Cook:** Writing – review & editing, Writing – original draft. **Zbigniew Staniak:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

The authors do not have permission to share data.

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