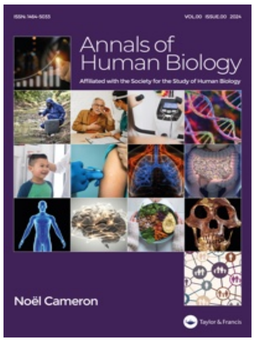

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Ultrasound-derived skeletal maturity estimates of boys and girls selected to football and athletics development programmes: an exploratory study of 716 South African and German adolescents

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ABSTRACT

Background: Differences in maturity status between athletes may affect selection to development programmes. Data supporting this are limited for low- and middle-income countries.
Aim: This exploratory study aimed to describe the maturity by country, sport and position/event, using data from a convenience sample of South African and German adolescents selected to competitive football (soccer) and athletics (track and field) programmes, and school learners from the same geographical area.
Subjects and methods: We included skeletal age estimates from BAUSport ultrasound assessments of 233 girls (age 10–15 years) and 483 boys (age 10–17 years).
Results: South African boys in the athletics group were advanced in maturity compared to football players, who were advanced compared to school learners. Similar patterns could be seen for South African girls (data only available for athletics vs. school learners). German female football players were less mature than the athletics and school samples, with no apparent differences between German male groups. South African boys and girls were delayed in maturity compared to German participants.
Conclusion: Our observations may inspire future research aiming to understand the maturity of athletes in development pathways in South Africa using more robust study designs. Such studies should include a suitable control group.

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Introduction

Adolescence is characterised by rapid changes in biological systems, as children move towards adulthood. Individuals will grow (i.e. change in size) and mature (i.e. tissues and organs progress towards a mature state), but at different times (maturity timing) and with different rates (maturity tempo) (Malina et al., 2004). In sports, it is important to consider individuals' maturity status, as this has implications for performance and health (Parry et al., 2024; Lloyd & Oliver, 2012). For example, earlier maturing boys will typically be taller, heavier and stronger than later maturing athletes of the same chronological age, whilst more advanced maturity in girls is associated with greater size and relatively higher accrual of fat mass (Malina et al., 2004). Depending on a given sport's demands, this may place individuals at an advantage or disadvantage when compared to their chronologically age-matched peers

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(Beunen & Malina, 2007; Malina, 2011; Kozieł et al., 2024). Certain injuries are also more likely to occur at different stages of growth and maturition (Parry et al., 2024; Wik, 2022; Brukner & Khan, 2012). An understanding of these processes is therefore important to promote fair selection to competitive development programmes (e.g. academies, scholarships), and to design safe and appropriate training and competition environments suited to an individual's maturity status.

Whilst differences between individuals and sexes are often considered in the literature, researchers have also observed variations in maturity timing when comparing geographical locations and ethnicities (Malina et al., 2004; Malina, 2011; Beunen et al., 2006; Rogol et al., 2000). For example, Malina highlights that youth from Japan and China tend to be advanced in skeletal maturity, with variations observed between regions in China (Malina, 2011). Further, differences between white and black boys and girls—and adolescents with different ancestry (e.g. Mexican, Asian, African)—are presented from samples within the USA (Malina, 2011). Differences in skeletal maturity, size and body composition between children of different ethnicities are also highlighted by Rogol et al. (2000). In South African adolescents, a longitudinal study found that black boys matured later than white boys, but no differences were observed in girls (Cole et al., 2015). Growth and maturity are largely determined by genetic factors; however, environmental factors also play a role. Socio-economic status, nutrition, exposure to disease, climate and altitude have all been mentioned as potential and inter-related contributing factors (Rogol et al., 2000; Beunen et al., 2006; Cole et al., 2015; Govender & Goodier, 2018). Some researchers suggest that these factors are the primary driver of the differences observed between populations, and that factors such as race, ethnicity or geographic ancestry/origin should not be considered when assessing maturity (Hochberg, 2016; Schmeling et al., 2000). It has also been emphasised that geographical and ethnic variations are not as pronounced as the between-individual variations within each group (Beunen et al., 2006).

Environmental, socio-economic and nutritional factors may not be as important to consider in highly-resourced countries and sports settings, where most adolescents have the opportunity to mature according to their genetic potential, but they are certainly relevant in low- and middle-income countries (LMICs) and lesser-resourced communities where adequate nutrition and access to affordable healthcare are a concern. Athletes who grow up in adverse conditions may therefore not be matched in terms of maturity status, even if they train and compete in the same chronological age bands (e.g. "U13", "U14"). This may have implications for talent identification (e.g. selection to development programmes), as certain maturity profiles have been observed between and within sports. For example, male football (soccer) players selected to academy programmes tend to be relatively earlier maturing (Johnson et al., 2017; Curnyn et al., 2025), whilst female athletes in endurance and aesthetic sports appear to be relatively later maturing (Beunen & Malina, 2007). Different profiles have also been reported for football positions (Towlson et al., 2017; Sweeney et al. 2023; Curnyn et al., 2025) and athletics (track and field) events (Eisenmann & Malina, 2002; Malina et al., 1986). Documenting such maturity patterns is an important starting point for discussions on potential biases in talent development programmes. It helps promote awareness among coaches and other stakeholders of athletes that are potentially not accommodated in their current system (e.g. exclusion of later maturing boys) and informs studies that are specifically designed to examine the existence of, and underlying reasons for, selection biases. This can eventually inform initiatives aimed at creating more inclusive and equitable selection practices (Hill et al., 2023). Yet, data to base these discussions and initiatives on are scarce for girls and athletes from LMICs; this lack of representation has been raised as a general problem in sports and exercise medicine research (Mkumbuzi et al., 2021).

Our primary aim with this exploratory study was to provide initial insights into the skeletal maturity of South African adolescents selected to football academies and an athletics development programme, and compare these to a sample of school learners from the same geographical area (considered as "non-selected"). A secondary aim was to explore how participants from South Africa, a LMIC, might differ to adolescents from Germany, a high-income country (HIC). Finally, we aimed to describe maturity status for football positions and athletics event groups. This study cannot provide any definite conclusions, as it is exploratory and based on a convenience sample from a LMIC and HIC. It can also not address underlying reasons for any observed differences between countries, sports or positions/events. This is still an important first step towards informing the design of future research studies aiming to understand the maturity of athletes in developmental pathways in South Africa.

Materials and methods

Study design

This study followed a cross-sectional exploratory design including skeletal age assessments in a convenience sample of South African and German adolescents. Data were collected in 2023 and 2024 for applied and research purposes, recruiting from three settings within each country (football academy, athletics programme, and school). The study was motivated by informal conversations with several coaches within South Africa, who perceived their players as smaller and less mature than players from other countries, and the unexpectedly low number of early maturing football academy players observed when using a novel ultrasound device to estimate skeletal age. In accordance with supporting literature suggesting delayed maturity among South African adolescents (Cole et al., 2015; Hawley et al., 2012; Hawley et al., 2009), we considered it important to conduct a more systematic exploration of this phenomenon.

The manuscript preparation was inspired by the guidelines provided by Ditroilo et al. (2025) for exploratory research in sport science. As an exploratory study, we did not perform an *a priori* size estimation (Ditroilo et al. 2025). Logistical challenges associated with data collection within South Africa meant that the data included in this article represent the maximal number of participants we could reach during 2023 and 2024 with a small research team, limited resources and challenges in reaching parents for signing of consent forms. With the South African sample in mind, we attempted to match the nature of participants (i.e. setting and sex) in the German sample as best as possible.

Ethical approval

In South Africa, ethical approval was granted by Stellenbosch University Health Research Ethics Committee for recruitment, data collection and data storage as part of a larger research database project ("South African Adolescent Athlete Database" ref.no. B22/02/001) with an additional approval for extracting and analysing data relevant to this sub-study (ref.no. N24/02/020_Sub Study B22/02/001). Signed parental consent and child assent forms were obtained for all participants included. Additional approval was obtained by the Western Cape Education Department (ref.no. 20220609-2981). In Germany, ethical approval was granted by the ethics committee of the Faculty of Human and Business Sciences at Saarland University (ref.no. 24-10). Parents and children provided consent and assent, respectively. Inclusion criteria for this sub-study were: 1) age 10 to 17 (boys) or 10 to 15 years (girls), 2) documented participant consent or child assent and parent consent, 3) for football and athletics: having gone through a selection process for a development programme, and 4) at least one maturity assessment conducted in 2023 or 2024.

Study setting and participants

South African learners were recruited from one public school in the Western Cape province. The school was categorised in Quintile 2 (i.e. second poorest quintile, non-fee school) on the national quintile system which is based on poverty rankings of the school's surrounding community and infrastructure (Western Cape Education Department, 2013). Football players were recruited from the academies of three clubs in the Western Cape who participated in a high-performance league organised for the top academies in the Cape Town area. Two academies formed part of clubs with senior teams in the Premier Soccer League (PSL; highest national level) and one belonged to a club with a third-tier senior team. Academies fielded boys' teams based on two-year chronological age groups (i.e. U12, U14, U16 and U18) with roughly 18 players per team who were primarily recruited from the surrounding communities. Academies were highly competitive and players represent a selected group that were provided with specialised coaching, mentoring and development opportunities. Across academies and age groups, players typically participated in three weekly training sessions and one competitive match with their teams. One athletics bursary programme in the Western Cape took part. The programme scouted athletes from the whole province, with selected individuals being offered a high-school bursary combined with professional coaching. Athletes typically participated in five organised training sessions or competitions per week. We included athletes who were already part of this programme in 2023, or were selected to take part in the final on-site camp prior to admission for 2024.

In Germany, learners were recruited from one secondary school (i.e. public high school) in the federal state of Baden-Württemberg. Football players were recruited from a single academy competing at the highest German level in their respective age groups for boys and girls, with senior teams competing at the highest national level. Boys' teams were organised based on one-year chronological age groups (U12, U13, U14, U15, U16, and U17), whilst girls competed in U13, U14, U15, and U17 age groups. Players in the younger age groups typically participated in three training sessions and one match per week, while older age groups trained up to five times per week in addition to a match. Athletics participants were selected based on their competitive performance in their respective disciplines and age groups within the federal state of Baden-Württemberg, representing a cohort of regionally scouted and identified youth talents. No information on their typical training week was available to the researchers.

Anthropometric and skeletal age assessments

Measures of height and body mass were standardised as far as possible across sites, following the guidelines outlined by the International Society for the Advancement of Kinanthropometry (ISAK) (Stewart et al., 2011) and taken by trained research personnel. Standing height was measured with a Seca 213 portable stadiometer (Seca GmbH, Hamburg, Germany) to the nearest 0.1 cm and body mass with a Seca 813 (Seca GmbH, Hamburg, Germany) electronic scale to the nearest 0.1 kg. Two measures were taken (average value used), with a third measure taken if the difference was >0.4 cm for height or >0.4 kg for body mass (in these cases, the median value was used) (Mirwald et al., 2002). Participants wore light clothing (e.g. shorts/skirts and t-shirts) and socks were permitted. Assessments varied slightly in timing, as they could not be organised outside of school hours or training sessions/competitions, but were always conducted prior to their planned physical activity. School assessments were conducted in the morning, whilst football testing was conducted prior to training sessions and matches (the majority in the afternoon, with some morning assessments prior to weekend matches). Participants from the athletics programme were assessed mid-day. This procedure was comparable between South Africa and Germany.

Skeletal age *via* ultrasound was assessed using separate BAUSport devices (SonicBone Medical, Tel-Aviv, Israel) (Rachmiel et al., 2017) in South Africa and Germany by researchers trained by the manufacturer. The device assesses three sites of the left hand-wrist (radius and ulna, third phalanx and metacarpals) by identifying landmarks and positioning the participants' arm and hand in standardised fixed positions after entering their sex, date of birth, height and body mass. Skeletal age is estimated for each site and for the average of all sites, the latter being used in this study. The algorithm used to estimate skeletal age is protected and there is no confirmed upper limit (personal communication, 2024). Skeletal age estimates using the device have shown to be comparable to skeletal age estimated by the Fels method from hand-wrist radiographs, supporting its validity in adolescent athletic populations (Cumming et al., 2024). Test-retest assessments (separate height, body mass and skeletal age assessments within 15 days) of 18 participants (mean chronological age 13.3 years, standard deviation (SD) 2.3, range 10.7 to 17.9) in the South African sample demonstrated an Intraclass Correlation Coefficient (ICC) of 0.992 (95% CI: 0.978–997) and Standard Error of Measurement (SEM) of 0.19 years (indicating a minimum difference needed to be considered "real" (Weir, 2005) of 0.55 years) for the skeletal age estimate. Test-retest values from 17 athletes (SEM: 0.13 years) have previously been published for the German site (Ruf et al., 2023).

Data management

Data were extracted for boys aged 10.0–17.0 years and girls aged 10.0–15.0 years. The lower age limit was restricted by the inclusion criteria for the larger South African research project. This also matched the lowest age of players in the South African football academies. The upper age limit for boys matched the age range that the BAUSport device has been validated for (i.e. 9 to 17 years) (Rachmiel et al., 2017; Cumming et al., 2024). For girls, a decision was made within the research team to set the upper chronological age limit at two years younger than boys to match the typical difference in maturity timing. These cut-offs would increase our confidence that participants of both sexes could be classified as either "late" (skeletal age >1 year delayed of chronological age), "on time" (skeletal age within 1 year of chronological age) or "early" (i.e. skeletal age >1 year in advance of chronological age) maturing (Malina, 2011). Data were used at face value (i.e. no adjustments of estimates or removal of data points by the research team) to reflect the use of this device in a practical setting. For participants with multiple assessments in 2023 and 2024, only the first measure was included. A new variable, "SA-CA difference," was created by subtracting chronological age (CA) from skeletal age (SA) (Malina et al., 2000).

Football positions were determined using a player's main position for the season, including goalkeepers, wide defenders, central defenders, wide midfielders, central midfielders and forwards/strikers. The same level of granularity in positions was not available for the German female footballers, who were categorised as goalkeepers, defenders, midfielders or forwards/strikers. Athletics event groups (distance athlete or sprinter/jumper) were determined based on athletes' training group and primary event. Non-specialised athletes and throwers (low number of athletes) were not described specifically, but were included in the calculations for athletics overall.

Statistical analyses

Descriptive statistics are presented using counts, percentages and means with standard deviation (SD). Comparisons of group averages between settings (football vs. athletics vs. school), countries (South Africa vs. Germany), and football positions/athletics event groups were completed using Analysis of Covariance (ANCOVA) with chronological age as covariate. ANCOVA models were fitted using the lm() function in RStudio (v2023.06.2 + 561), with Type III sum of squares analysis conducted through the car package (v3.1.3). To address potential heteroscedasticity robust standard errors were computed using the HC3 estimator using the sandwich (v3.1.1) and lmtest packages (v0.9.40). To assess model fit and compare the null model (without the covariate) and the full models (including chronological age as covariate) the Akaike Information Criterion (AIC) was used. For comparisons involving three groups or more, a visual inspection of residuals and a Breusch-Pagan test was completed to assess heteroscedasticity. Tukey post-hoc tests were then performed using the emmeans package (v1.11.1) to control for multiple comparisons. Sensitivity analyses were conducted for comparisons between the two research sites (i.e. South Africa vs. Germany). For this, we used data from the validation study by Cumming et al. (2024) which compared BAUSport skeletal age against Fels skeletal age as the reference method (Cumming et al., 2024). Their study indicated upper and lower limits of agreement of 1.05 and −1.50, respectively. On this basis, we included a measurement error of 0.46 (calculated from the SD of 0.65) to estimate confidence intervals (CI) from 2000 simulations with the same ANCOVA model as described above. Statistical significance was set at alpha = 0.05 for all analyses. Visualisations were made using Matplotlib (v3.5.1) and Seaborn (v0.11.2) in Python (v3.8.13).

Results

Participants

Data from 716 adolescents were included (South Africa: $n = 314$; Germany: $n = 402$). The average chronological age of girls ($n = 233$) was 13.0 (SD 1.2) years, whilst for boys ($n = 483$) it was 13.9 (SD 1.7) years old.

Skeletal maturity between countries and settings

Results are presented by country, setting and football position/athletics event group in Table 1 (boys) and Table 2 (girls), with individual participant data for SA-CA difference shown in Figure 1 (boys) and Figure 2 (girls). Within South Africa, boys in the football and athletics groups were significantly more mature compared to school learners (football vs. school: 1.0 year higher, $p < 0.001$; athletics vs. school: 1.8 years higher, $p < 0.001$, athletics vs. football: 0.8 years higher, $p < 0.001$). Girls in the athletics programme were on average more mature than school learners, but differences were not significant (0.8 years

Table 1. Assessments of height, body mass and skeletal age from 235 South African and 248 German adolescent males, grouped by country, setting and football position/athletics event group.

	n	Height (cm, SD)	Body mass (kg, SD)	Chronological age (yr, SD)	Skeletal age (yr, SD)	SA-CA (yr, SD)	Early (n, %)	On time (n, %)	Late (n, %)
South Africa									
School	43	147.1 (9.2)	38.8 (9.0)	12.3 (1.5)	11.1 (1.5)	−1.3 (1.2)	1 (2.3%)	20 (46.5%)	22 (51.2%)
Football	154	161.9 (13.8)	52.3 (13.4)	14.1 (2.0)	13.7 (2.3)	−0.3 (1.1)	11 (7.1%)	100 (64.9%)	43 (27.9%)
Goalkeeper	22	167.6 (14.9)	59.5 (16.8)	14.0 (2.1)	14.5 (2.4)	0.5 (0.9)	4 (18.2%)	17 (77.3%)	1 (4.5%)
Central defender	24	168.1 (12.8)	59.5 (13.3)	14.4 (1.9)	14.5 (2.0)	0.1 (0.8)	2 (8.3%)	18 (75.0%)	4 (16.7%)
Wide defender	18	163.1 (11.6)	50.9 (10.0)	13.8 (1.7)	14.0 (2.0)	0.3 (0.8)	3 (16.7%)	13 (72.2%)	2 (11.1%)
Central midfielder	37	156.2 (13.9)	47.2 (11.4)	13.9 (2.1)	12.9 (2.4)	−1.0 (1.2)	1 (2.7%)	17 (45.9%)	19 (51.4%)
Wide midfielder	21	159.9 (12.3)	50.2 (12.1)	14.7 (1.8)	13.7 (2.1)	−1.0 (1.0)	0 (0.0%)	11 (52.4%)	10 (47.6%)
Forward/ striker	30	160.9 (13.6)	50.2 (12.2)	13.9 (2.1)	13.6 (2.3)	−0.3 (0.9)	1 (3.3%)	24 (80.0%)	5 (16.7%)
Athletics	38	168.7 (8.8)	57.6 (9.3)	14.7 (1.2)	15.1 (1.2)	0.4 (1.0)	8 (21.1%)	26 (68.4%)	4 (10.5%)
Distance	14	167.1 (11.2)	52.9 (8.6)	15.1 (1.0)	14.9 (1.5)	−0.2 (0.9)	1 (7.1%)	10 (71.4%)	3 (21.4%)
Sprint/jump	21	169.7 (7.6)	58.6 (7.4)	14.6 (1.3)	15.3 (1.2)	0.7 (0.8)	5 (23.8%)	15 (71.4%)	1 (4.8%)
Germany									
School	54	168.6 (9.4)	57.9 (13.4)	14.3 (0.9)	15.1 (1.5)	0.8 (1.3)	21 (38.9%)	28 (51.9%)	5 (9.3%)
Football	117	166.7 (13.2)	55.0 (13.8)	13.9 (1.8)	14.5 (2.1)	0.6 (1.0)	38 (32.5%)	70 (59.8%)	9 (7.7%)
Goalkeeper	14	174.4 (14.3)	60.7 (15.2)	14.2 (1.8)	15.4 (1.9)	1.2 (0.8)	8 (57.1%)	6 (42.9%)	0 (0.0%)
Central defender	18	170.9 (13.2)	59.8 (15.3)	13.8 (1.9)	15.0 (2.0)	1.2 (0.7)	9 (50.0%)	9 (50.0%)	0 (0.0%)
Wide defender	19	164.8 (12.4)	53.9 (12.8)	14.0 (1.6)	14.3 (2.0)	0.4 (0.9)	5 (26.3%)	13 (68.4%)	1 (5.3%)
Central midfielder	37	163.7 (11.6)	50.8 (11.5)	13.9 (1.9)	14.0 (1.9)	0.2 (1.1)	7 (18.9%)	24 (64.9%)	6 (16.2%)
Wide midfielder	11	169.5 (10.4)	58.5 (11.8)	14.6 (1.5)	15.0 (1.8)	0.4 (1.0)	3 (27.3%)	8 (72.7%)	0 (0.0%)
Forward/ striker	18	162.9 (15.3)	53.6 (15.6)	13.2 (1.8)	14.0 (2.5)	0.7 (1.2)	6 (33.3%)	10 (55.6%)	2 (11.1%)
Athletics	77	164.6 (12.1)	51.3 (12.8)	13.7 (1.3)	14.1 (1.8)	0.5 (1.1)	22 (28.6%)	48 (62.3%)	7 (9.1%)
Distance	15	170.1 (7.4)	51.1 (7.0)	14.7 (0.8)	15.0 (1.2)	0.4 (1.0)	4 (26.7%)	10 (66.7%)	1 (6.7%)
Sprint/jump	22	176.4 (7.4)	66.2 (8.0)	14.7 (1.0)	15.9 (1.0)	1.2 (0.9)	11 (50.0%)	11 (50.0%)	0 (0.0%)

Table 2. Assessments of height, body mass and skeletal age from 79 South African and 154 German adolescent females, grouped by country, setting and football position/athletics event group.

	n	Height (cm, SD)	Body mass (kg, SD)	Chronological age (yr, SD)	Skeletal age (yr, SD)	SA-CA (yr, SD)	Early (n, %)	On time (n, %)	Late (n, %)
South Africa									
School	58	149.2 (7.9)	41.4 (9.1)	11.9 (0.9)	11.5 (1.5)	−0.4 (1.3)	7 (12.1%)	33 (56.9%)	18 (31.0%)
Athletics	21	158.0 (5.4)	48.7 (10.0)	13.8 (0.6)	14.0 (1.2)	0.2 (1.2)	5 (23.8%)	12 (57.1%)	4 (19.0%)
Distance	9	156.9 (4.4)	45.8 (5.8)	14.1 (0.7)	13.6 (1.1)	−0.5 (0.9)	0 (0.0%)	6 (66.7%)	3 (33.3%)
Sprint/jump	11	158.2 (5.9)	48.2 (7.8)	13.5 (0.5)	14.0 (0.9)	0.5 (1.1)	4 (36.4%)	6 (54.5%)	1 (9.1%)
Germany									
School	38	164.4 (5.4)	54.8 (7.1)	13.9 (0.4)	15.4 (1.0)	1.5 (1.1)	27 (71.1%)	11 (28.9%)	0 (0.0%)
Football	64	154.0 (9.5)	45.0 (10.4)	12.7 (1.3)	13.0 (1.9)	0.3 (1.3)	17 (26.6%)	38 (59.4%)	9 (14.1%)
Goalkeeper	4	156.1 (10.1)	42.7 (12.3)	12.6 (1.0)	12.9 (1.9)	0.3 (1.8)	1 (25.0%)	2 (50.0%)	1 (25.0%)
Defender	16	155.9 (9.3)	48.8 (11.5)	12.7 (1.4)	13.6 (1.8)	0.8 (1.1)	7 (43.8%)	8 (50.0%)	1 (6.2%)
Midfielder	27	153.9 (9.9)	44.0 (10.4)	12.8 (1.4)	12.8 (2.2)	0.1 (1.3)	7 (25.9%)	15 (55.6%)	5 (18.5%)
Forward/striker	17	152.0 (9.2)	43.5 (8.7)	12.6 (1.4)	12.7 (1.7)	0.0 (1.2)	2 (11.8%)	13 (76.5%)	2 (11.8%)
Athletics	52	164.6 (6.4)	51.6 (7.8)	13.5 (0.9)	14.6 (1.4)	1.2 (0.9)	25 (48.1%)	27 (51.9%)	0 (0.0%)
Distance	4	164.9 (6.8)	53.6 (4.0)	14.1 (0.6)	15.1 (0.9)	1.1 (1.0)	1 (25.0%)	3 (75.0%)	0 (0.0%)
Sprint/jump	27	167.8 (4.7)	54.8 (6.7)	14.1 (0.4)	15.4 (1.0)	1.3 (1.0)	14 (51.9%)	13 (48.1%)	0 (0.0%)

higher, $p = 0.06$). Within Germany, there were no apparent or significant differences in skeletal age between boys in different groups (football vs. school: 0.2 years lower, $p = 0.52$; athletics vs. school: 0.3 years lower, $p = 0.20$; athletics vs. football: 0.1 years lower, $p = 0.65$). For girls, football players were significantly less mature than school learners and athletics participants (football vs. school: 1.2 years lower, $p < 0.001$; athletics vs. school: 0.3 years lower, $p = 0.37$; athletics vs. football: 0.9 years higher, $p < 0.001$).

When comparing countries and controlling for chronological age, South African boys were significantly less mature than German boys in the school (2.7 years lower skeletal age, $p < 0.001$) and football (0.9 years

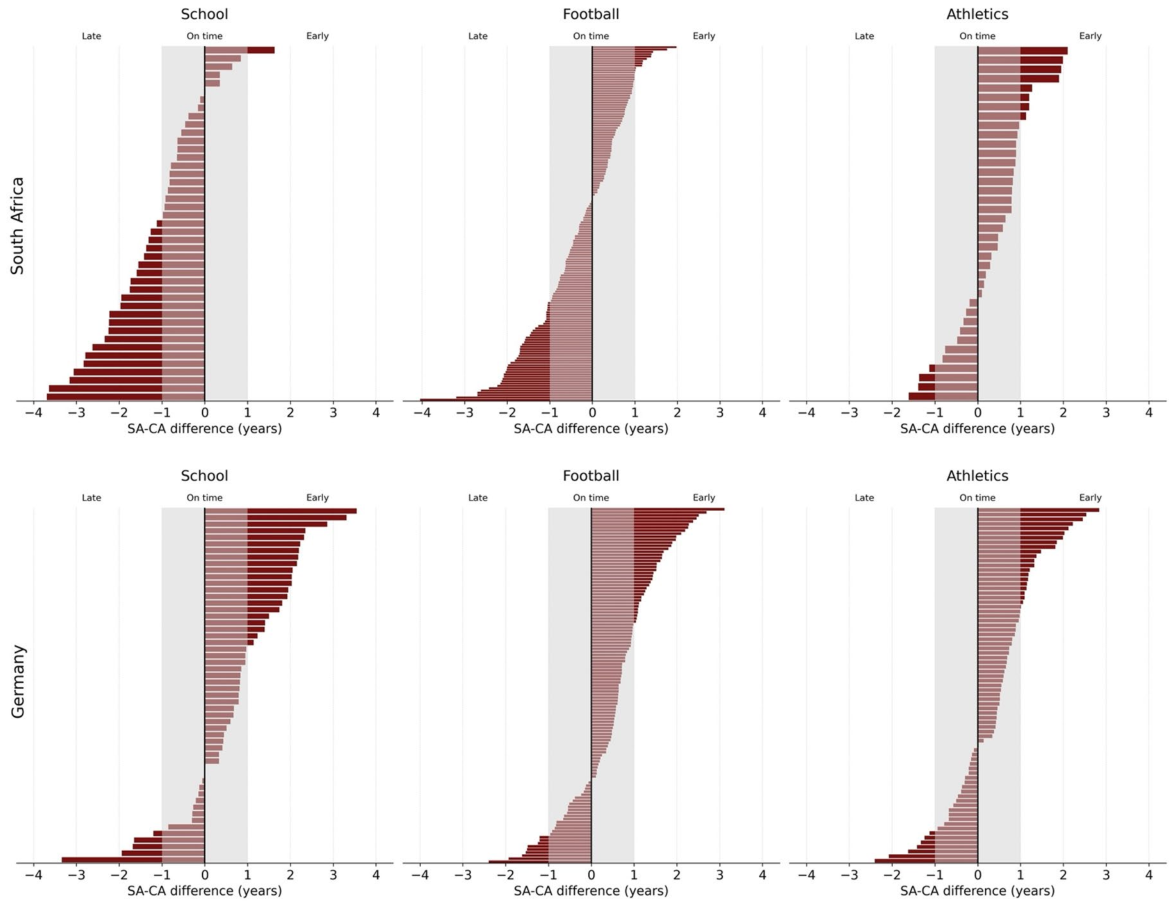

Figure 1. Individual data for the difference between skeletal age and chronological age (SA-CA difference) in 483 adolescent males by country and setting. Late = Skeletal age >1 year in delay of chronological age. On-time = Skeletal within 1 year of chronological age. Early = Skeletal age >1 year in advance of chronological age. Estimates should be interpreted with caution, as validation studies have only been conducted in limited samples and it was not possible to compare reliability between the South African and German assessors/devices.

lower, $p < 0.001$) groups, but not in athletics (0.1 years lower, $p = 0.72$). For girls, significantly lower skeletal ages were observed for the South African school (2.2 years lower, $p < 0.001$) and athletics (1.0 years lower, $p < 0.01$) groups compared to the German sample. Sensitivity analyses indicated that these outcomes would hold when considering plausible measurement error (95% CI: −2.9 to −2.5 for male school, −1.1 to −0.8 for male football, −0.3 to 0.1 for male athletics, −2.5 to −1.9 for female school, and −1.2 to −0.8 for female athletics). Supplementary Figures 1–3 illustrate how hypothetical one-year chronological age groups in football and athletics would compare in terms of skeletal age, height, and body mass.

Football positions and athletics event groups

Individual participant data by football position is presented in Figure 3 (outcomes from post-hoc tests are included in Supplementary Table 1). When combining data for males in South Africa and Germany, goalkeepers were significantly advanced in maturity compared to central midfielders (1.2 years higher skeletal age, $p < 0.001$) and wide midfielders (1.2 years higher, $p < 0.001$). Central defenders were also significantly more mature than central midfielders (1.0 years higher, $p < 0.001$) and wide midfielders (1.0 years higher, $p < 0.01$). Wide defenders were significantly more mature than central midfielders (0.8 years higher, $p < 0.01$) and wide midfielders (0.8 years higher, $p = 0.03$). For female football players (Germany only), no significant differences were observed between positions, although defenders appeared more advanced in maturity. Individual data by athletics event are shown in Figure 4. The combined data from South Africa and Germany indicated that sprinters/jumpers were significantly more mature compared to distance athletes for both males (0.8 years higher skeletal age, $p < 0.001$) and females (1.1 years higher, $p < 0.01$).

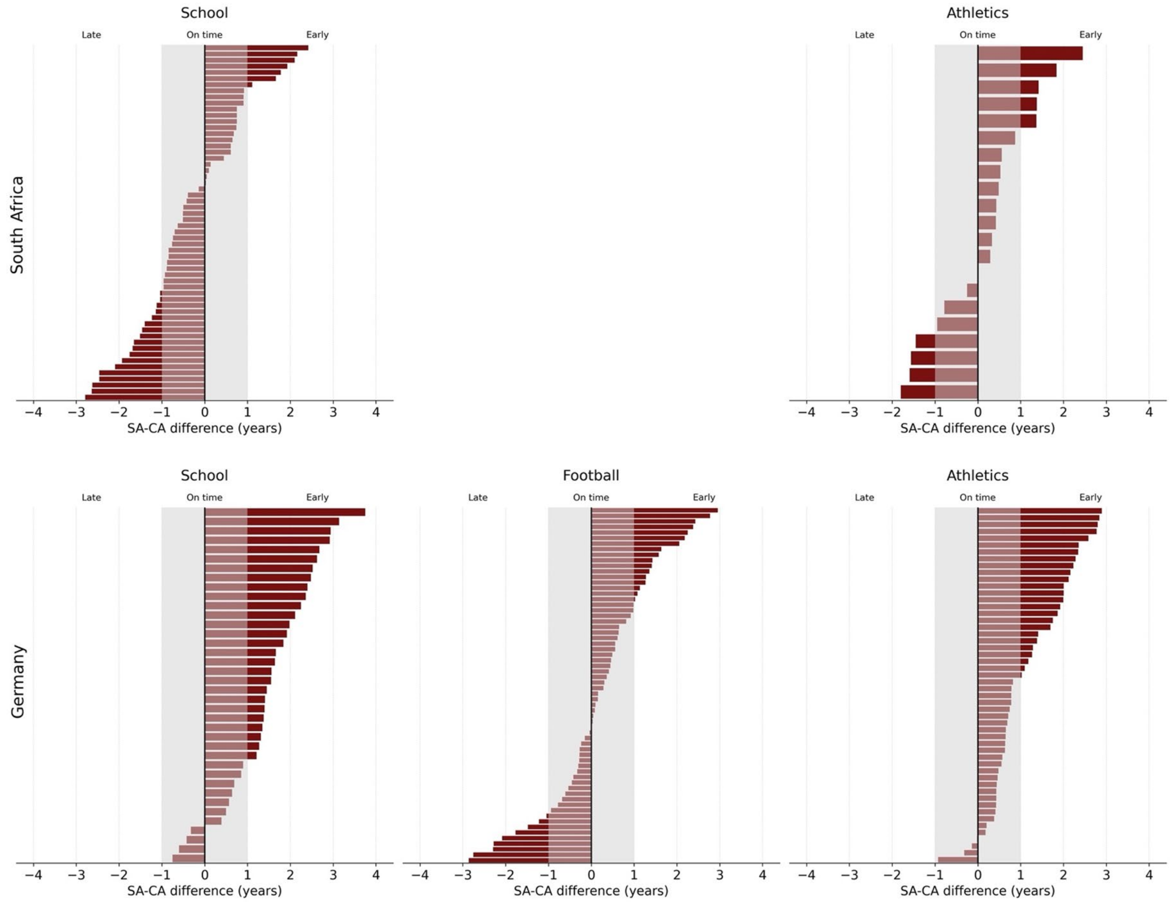

Figure 2. Individual data for the difference between skeletal age and chronological age (SA-CA difference) 233 adolescent females by country and setting. Late = Skeletal age >1 year in delay of chronological age. On-time = Skeletal within 1 year of chronological age. Early = Skeletal age >1 year in advance of chronological age. Estimates should be interpreted with caution, as validation studies have only been conducted in limited samples and it was not possible to compare reliability between the South African and German assessors/devices.

Discussion

We present maturity data based on estimates from an ultrasound device from 523 South African and German adolescents selected to football and athletics programmes, in addition to data from 193 school learners across both countries. South African boys selected to the athletics programme were more advanced in maturity compared to football players, who, in turn, were more advanced than school learners. South African boys in the football and school settings were delayed in maturity compared to German boys. South African girls in the athletics and school settings were less mature than German girls. We also observed apparent differences in maturity between positions in football (predominantly in boys), and between distance athletes and sprinters/jumpers in athletics. The data we present should be interpreted with caution given the exploratory nature of the study and relative novelty of the method used to estimate maturity.

Adolescents in South Africa appear delayed in maturity compared to Germany

We observed an overall pattern of lower maturity status for South African adolescents, compared to German, with the exception of boys in athletics. A delayed maturity status of South African children and adolescents has previously been described in studies based on the "Birth to Twenty" cohort (Richter et al., 2007). For example, Hawley et al. examined the skeletal age of 244 ten-year olds and reported that females, on average, were one year delayed, whilst males were 8 months delayed, relative to their chronological age (Hawley et al., 2012). The authors suggested that this might be explained by factors relating to health and nutrition, which would undermine their genetic potential. We could not examine this

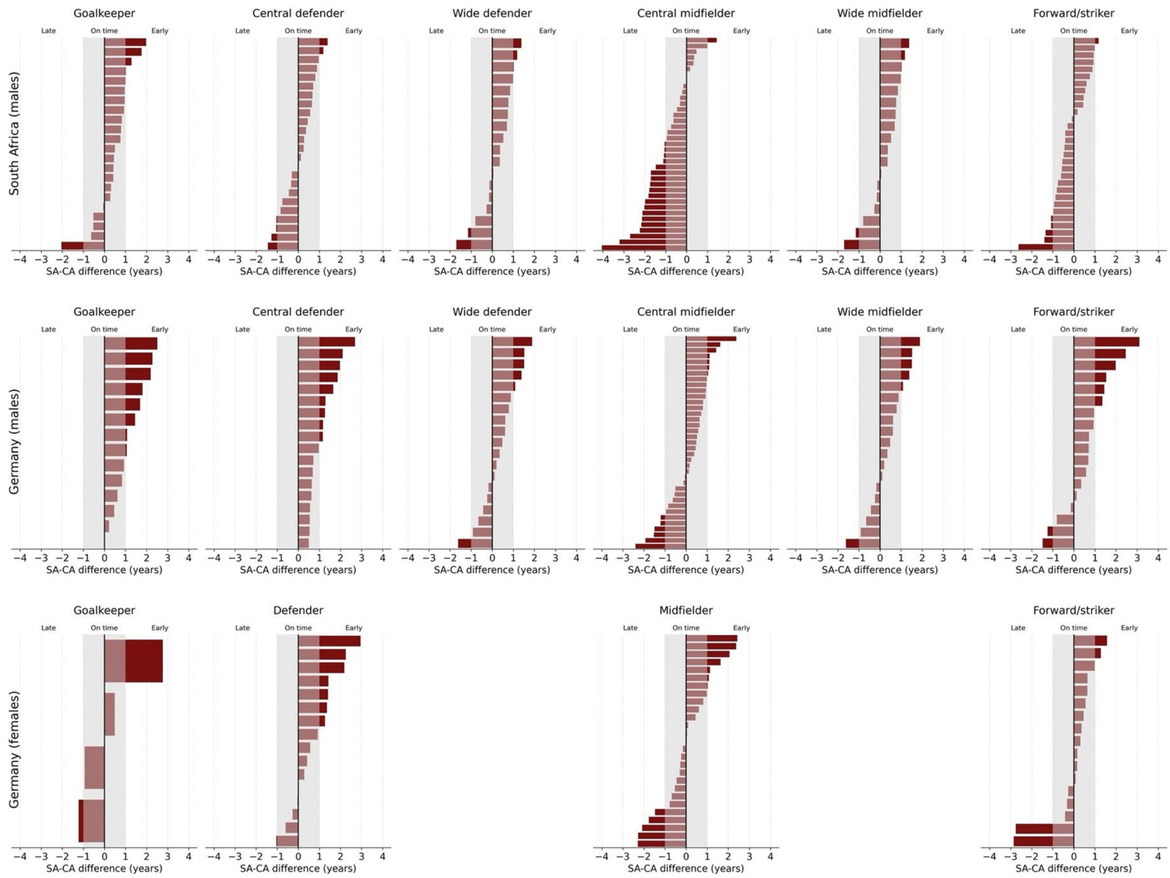

Figure 3. Individual data from male and female football players from South Africa and Germany grouped by position. Late = Skeletal age >1 year in delay of chronological age. On-time = Skeletal within 1 year of chronological age. Early = Skeletal age >1 year in advance of chronological age. Estimates should be interpreted with caution, as validation studies have only been conducted in limited samples, and it was not possible to compare reliability between the South African and German assessors/devices.

specifically and future confirmatory studies may assist in understanding and contextualising our observations using experimental designs whilst accounting for these potential confounder variables. Our data further suggested that boys were more delayed in terms of maturity than girls sampled from the same school, which is in contrast to the data presented by Hawley et al. (2012). Although the underlying reasons again remain unclear, Cole et al. (2015) suggested that environmental factors may affect the processes of growth and maturation in males more than females. It is possible that socio-economic factors could explain the delayed maturity observed; however, we did not include such measures in our study.

When considering data from the two sites in our study, we must acknowledge that there could be potential differences between the ultrasound devices and assessors. Reliability tests including the devices and assessors from both sites with the same participants were not possible to conduct due to logistical and resource constraints. We also did not have the possibility of comparing our skeletal age estimates against other methods (e.g. radiography) within our specific populations. Despite a potential for bias caused by ethnicity or geographical origin, our assumptions are based on validity studies conducted in other countries also being valid in Germany and South Africa. Our comparisons of observations between countries should be interpreted with this in mind, and we encourage higher-resourced research groups to conduct additional validation studies in the future.

Could there be a maturity bias even with few "early maturing" athletes in South Africa?

Multiple studies suggest a maturity bias where national teams and development programmes appear to favour early maturing boys (Johnson et al., 2017; Curnyn et al., 2025; Malina et al., 2000; Sweeney et al.

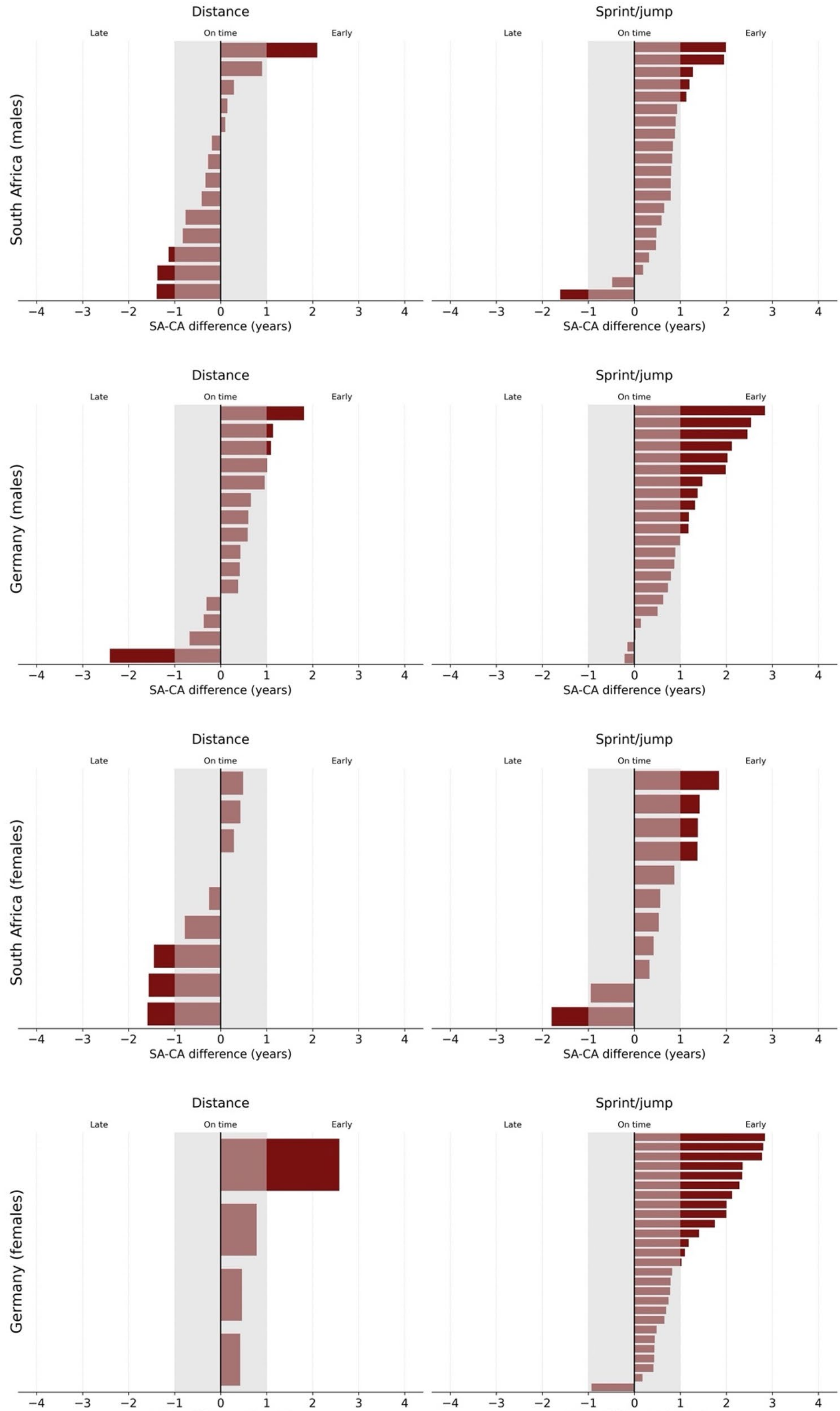

Figure 4. Individual data from South African and German male and female participants in athletics development programmes by event group. Late = Skeletal age >1 year in delay of chronological age. On-time = Skeletal within 1 year of chronological age. Early = Skeletal age >1 year in advance of chronological age. Estimates should be interpreted with caution, as validation studies have only been conducted in limited samples and it was not possible to compare reliability between the South African and German assessors/devices.

2023; Hill et al., 2020; Niklasson et al., 2024). This would likely stem from advantages related to male puberty (e.g. size and muscle mass) (Malina et al., 2004) which provides earlier maturing athletes with a "head start" in terms of physical fitness (e.g. strength, sprinting speed) (Gundersen et al., 2024). This may again impact how coaches perceive overall performance (Hill et al., 2023). Our observations suggest that less than 10% of South African academy players are "early" maturing using conventional cut-offs, whilst more than a quarter are "late." Boys in the athletics programme displayed a more balanced distribution, with roughly even numbers of "early" and "late" maturing athletes. At face value, these patterns could indicate an absence of a maturity bias, or even a preference for late maturing football players. This may, however, be misleading since school learners were even later maturing (only one "early" maturing participant). It therefore appears that football and athletics programmes still favoured *earlier* maturing individuals. This highlights the importance of including comparison data from "non-selected" individuals when interpreting maturity estimations in sporting populations. Additional validation of classification cut-offs may also be required when methods are used outside the population from which they were developed. For example, researchers have highlighted that methods derived from children born nearly a century ago in the USA (e.g. the Greulich-Pyle method) must be used cautiously in South Africa (Govender & Goodier, 2018; Minty et al., 2025), and that population-level trends towards earlier maturity may require re-evaluation of existing standards (Boeyer et al., 2018). It has been suggested that variations between ethnicities and geographic origins are less pronounced than inter-individual differences within groups, and likely matter less than environmental factors (Beunen et al., 2006; Hochberg, 2016). Still, this should be considered when interpreting our findings.

Although few studies describe the maturity of girls selected to football and athletics programmes, there are indications that the physiological differences associated with female puberty (e.g. increased fat mass and less pronounced gains in muscle mass) (Malina et al., 2004) lead to a different distribution of players in terms of maturity compared to males. For example, there were no significant associations between skeletal age and physical performance in Norwegian adolescent female football players (Gundersen et al., 2024). In Ireland, U15 and U16 national team football players were slightly earlier maturing than population averages (Sweeney et al., 2025), but these effects were smaller than in males (Sweeney et al. 2023). Data from other settings also indicate that female football players were slightly taller and heavier than population norms (Malina et al., 2021), whilst females participating in athletics have been shown to be taller, but not heavier, than non-sports participants (Kozieł et al., 2024). Our findings are in line with this, with no significant differences between school and athletics samples, although athletes on average were almost ten months in advance. German football players were, however, more than a year delayed in maturity compared to school learners; speculatively, this could indicate that delayed maturity may be an advantage. This may, however, depend on athletes' age, where early maturity timing may be beneficial in terms of size prior to increases in fat mass, with an associated negative effect of early maturity once this starts. The impact of maturity in itself could also be lower if the pool of high-level athletes is smaller and females are not provided the same resources as males (e.g. coaches, facilities).

Differences between football positions and athletics events

Football positions and athletics event groups may favour different body types and physical characteristics (O'Connor et al. 2007; Sebastiá-Rico et al., 2023). In our sample, male goalkeepers and defenders were roughly one year advanced in maturity compared to midfielders. This is similar to findings from Ireland and Scotland, where central defenders and goalkeepers have been identified as earlier maturing (Curnyn et al., 2025; Sweeney et al. 2023). No significant differences were observed for German female players, although defenders appeared the most advanced in maturity. In athletics, sprinters/jumpers were roughly a year in advance of distance runners, which is in line with observations of more skeletally mature male jumpers/sprinters in Belgian athletics, and slightly delayed maturity of distance runners in the USA (Eisenmann & Malina, 2002; Malina et al., 1986). If our observations are confirmed in future studies, they may indicate the presence of coach or athlete self-selection biases towards positions and events that benefit individuals' current physical characteristics; these questions should, however, be explored in quantitative confirmatory studies or with qualitative designs. These nuances would also indicate that researchers should report the distribution of events and positions in studies of biological maturity, as this may affect overall outcomes.

Practical implications

Our study cannot confirm the existence of maturity selection biases across sports and positions/events. If such biases are confirmed in future studies, it is still difficult for development programmes to affect individuals' maturity status, as selection processes typically happen from around 10–13 years of age. Based on our observations, and those of previous research, it is possible that certain athletes (e.g. early maturing athletes to sprint/jump events and as goalkeepers and defenders – and later maturing athletes to distance events and midfield positions) are selected on the basis of a temporary size and performance advantage that may not persist into adulthood (Curnyn et al., 2025; Sweeney et al. 2023). This would warrant investigations into why these patterns occur, in order to improve talent development programmes. There is a risk of inefficiency in development programmes if doors are closed to athletes with certain maturity profiles, or if athletes are not allowed to sample different sports, positions and events prior to maturity.

Maturity profiling may assist in raising awareness and reducing potential maturity-related selection biases (Hill et al., 2023); however, this is not always easily implemented. Skeletal maturity assessments are not readily available in all settings due to associated costs and logistical challenges. Where sports environments in higher-income settings have often turned to anthropometric equations, these can also be challenging to implement. For example, the Khamis-Roche method (Khamis & Roche, 1994) is commonly used in academy football (Salter et al., 2021; Arenas et al., 2024) but requires biological parent heights. This is difficult to obtain in South Africa where few children live with both parents (21.3% do not live with any parents and only 32.7% live with both) (Stats SA et al., 2021). In the absence of objective indicators of maturity, stakeholders in development programmes should strive to educate themselves and their coaches on natural patterns of growth and maturity during adolescence, and remain cognisant that between-athlete differences in maturity status, timing and tempo may skew their perception of athletic potential.

Methodological considerations

Although we provide skeletal age estimations from a relatively large sample of athletes from two countries, including school learners for comparison, our results must be interpreted in light of several limitations. First, we acknowledge that the study was motivated by questions asked by coaches in the field, preliminary observations, and patterns observed in previous literature (e.g. potentially delayed maturity in South African adolescents and maturity biases in sports). This has inevitably influenced choices made in the study (e.g. analyses and comparisons), and may have biased our interpretations of the observations, although we have attempted to be open about the exploratory nature of this study and to moderate our claims. Second, we used a convenience sample due to significant logistical challenges in organising skeletal age assessments with a wider range of talent programmes and schools. As such, our sample may not represent the maturity status of athletes in other development programmes or schools within South Africa and Germany. Third, there were slight differences in the time of day for assessments, although they were always conducted prior to activity. Fourth, although the method used to estimate skeletal age has been considered comparable to traditional radiographic methods (Rachmiel et al., 2017; Cumming et al., 2024), we acknowledge that it has not been thoroughly validated in diverse populations. The findings of this study therefore assume that the results from validation studies with Israeli and Spanish adolescents can be extrapolated to German and South African adolescents. The restriction of assessments to three anatomical sites, and the protected algorithm used to estimate skeletal age, introduces additional uncertainty. We could also not assess reliability between assessors or devices in Germany and South Africa, which may have introduced systematic error in comparisons between countries. Finally, we used an exploratory study design, and any patterns or underlying mechanisms must be confirmed in future studies entangling causal pathways.

Conclusion

We report the skeletal maturity, derived from an ultrasound device, of adolescent athletes selected to football and athletics programmes in South Africa and Germany, plus a comparison sample of school learners from both countries. If our exploratory observations are confirmed in future studies, they may suggest that South African adolescents are delayed in maturity compared to Germany, and that different sports, athletics events and football positions cater for athletes specific maturity profiles. We highlight the importance of contextualising results from maturity assessments in sports populations against local comparison groups when addressing these questions. Awareness around these topics may assist stakeholders and coaches in ensuring more equitable selection processes and efficient development programmes that do not favour individuals with temporary maturity-driven advantages. Our observations must be confirmed in future confirmatory studies with adequate error control, to better understand the presence of – and underlying reasons for – any maturity-associated selection biases. This appears particularly interesting to pursue within LMICs and in female sports.

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Author contributions

CRediT: **Eirik H. Wik**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualisation, Supervision, Writing – original draft; **Sean P. Cumming**: Methodology, Supervision, Writing – review & editing; **Sindiso Dube**: Investigation, Writing – review & editing; **Odelia van Stryp**: Investigation, Writing – review & editing; **Wayne Derman**: Supervision, Writing – review & editing; **Ludwig Ruf**: Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Supervision, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data deposition

A full research dataset will be uploaded to Stellenbosch University's SUNScholarData repository upon publication. This will not be publicly available, as the parents of some participants did not consent to sharing of data with journals and other investigators.

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Data availability statement

The data that support the findings of this study are available on request from the first author (EHW), but limited to participants where parents consented to this use of their data. The data are not publicly available due to ethical restrictions, as parents of participants could opt in or out of making their data available for sharing with journals and other investigators during the consent process.

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