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CHRONOLOGICAL AGE VERSUS BIOLOGICAL MATURATION: IMPLICATIONS FOR EXERCISE PROGRAMMING IN YOUTH

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Abstract:	Biological maturation is associated with significant change to a number of physiological and structural processes throughout childhood and, in particular, adolescence. Mismatched rapid growth in the long bones relative to muscular lengthening may disrupt structure, neuromuscular function, and physical performance. Practitioners who work with school-age youth should be aware of the age-related changes that typically take place during a child's development to ensure that their strength and conditioning programming is as safe and effective as possible for enhancing performance and reducing injury risk. While there are several methods available to assess biological maturation, practitioners who work with youth can benefit from assessment methods that are available and feasible, and that provide utility in the quantification of the degree and stages of biological maturation that affect motor performance in children and adolescents. This manuscript synthesizes the relevant assessment methods, and provides a rationale for understanding usable biological maturation assessment tools that can aid in the development of training program design for youth.
Response to Reviewers:	Reviewer Comments: Reviewer 1: The authors partially improved their work. In fact, I noticed few additional aspect that might be solved also in the editing of the proofs upon Editor's decision: Response: Okay, thank you I am still unsure that Figure 1 and 3 do not refer to figures published by other authors in previous studies. If this is the case, please indicate the proper references or specify "modified from ...." This statement safeguards the authors and the journal.

	Response: Figure 1 is a novel figure, which has been created by us as the authorship group, and therefore has not been published elsewhere. However, to hopefully appease the reviewer's request, we have inserted new text within the figure title indicating that it has been based on theoretical data. As a figure it graphically represents the difference between the linear development of chronological age and the non-linear development of biological maturation. This has not typically been represented by a figure, and hence we feel that this is a novel and unique figure to include in this review. We would not want this minor point to be a fatal flaw with the submission, however, we do think it adds to the understanding of the readership and therefore warrants inclusion. Please indicate (based on theoretical data, modified from ....) also for figure 3 and insert this statement in the captions under Figure 1 and 3. Response: Accepted. Reference included within the figure title, and included within text of the manuscript. Change "SUMMARY" with "PRACTICAL APPLICATIONS" Response: We feel that the previous section titled "ASSESSING GROWTH AND MATURATION: APPLICATIONS FOR PRACTITIONER" is really where the terms 'practical applications' is best placed. The "summary" section really summarises the content of the review. Once again, we would not want this minor point to be a fatal flaw with the submission, but if we do accept this recommendation and change "Summary" to "Practical Applications", there will essentially be two "practical applications" sections in the paper, and in our opinion lead to unnecessary repetition within the manuscript. Reviewer 2: No further comments, polish if revised again. Response: Okay, thank you

*Title Page (Showing Author Information)

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CHRONOLOGICAL AGE VERSUS BIOLOGICAL MATURATION: IMPLICATIONS FOR EXERCISE PROGRAMMING IN YOUTH

ABSTRACT

Biological maturation is associated with significant change to a number of physiological and structural processes throughout childhood and, in particular, adolescence. Mismatched rapid growth in the long bones relative to muscular lengthening may disrupt structure, neuromuscular function, and physical performance. Practitioners who work with school-age youth should be aware of the age-related changes that typically take place during a child's development to ensure that their strength and conditioning programming is as safe and effective as possible for enhancing performance and reducing injury risk. While there are several methods available to assess biological maturation, practitioners who work with youth can benefit from assessment methods that are available and feasible, and that provide utility in the quantification of the degree and stages of biological maturation that affect motor performance in children and adolescents. This manuscript synthesizes the relevant assessment methods, and provides a rationale for understanding usable biological maturation assessment tools that can aid in the development of training program design for youth.

KEY WORDS

Youth fitness, maturation, chronological age, somatic age, skeletal age, sexual age

INTRODUCTION

The physical and physiological assessment of athletes is often performed at various stages during a yearly cycle of training to establish the effectiveness of individual blocks of training or the overall success of the annual training plan. However, when working with either children or adolescents such changes in performance can be significantly affected by growth and maturational factors. Whilst researchers have examined the influence of growth and maturation on physical performance in youth, practical information on different classifications of maturational assessments and their proper use by practitioners is limited. Consequently, the current manuscript will critically analyse existing literature in order to (i) define the terminology associated with the different age classifications, (ii) review existing methods of assessing maturation, and (iii) demonstrate how the assessment of maturation can be of multiple benefits to practitioners. For the purpose of this manuscript the term 'practitioners' will refer globally to strength and conditioning coaches, youth sport coaches, physical education teachers, athletic trainers, physiotherapists and health care providers.

Chronological age, which is calculated as a single time point away from the date of birth, has traditionally been used in sports to group age grade teams, identify talented performers and set limits for exercise prescription. However, literature has clearly demonstrated that individuals of the same chronological age can differ markedly with respect to biological maturity [3,26,54]. Biological maturation refers to progress towards a mature state, and varies in timing and tempo, and between different bodily systems [4]. Significant inter-individual variance exists for the level (magnitude of change), timing (onset of change) and tempo (rate of change) of biological maturation. Dependent on these variables, children will be viewed as either biologically ahead of their chronological age (early-maturing individual), "on-time" with their chronological age (average-maturer), or behind their chronological age (late maturing individual) [35]. Based on theoretical data, figure 1 shows the difference in linear development of chronological age versus the non-linear development of sexual maturation in both males and females. The figure also demonstrates the theoretical differential maturation rates for early- and late-maturing individuals. The relative mismatch and wide variation in biological maturation between children of the same chronological age emphasizes the limitations in using chronological age as a determinant in global exercise prescription for school-age youth.

*****Figure 1 near here*****

Pediatric researchers and clinicians have noted the importance of considering biological maturation in order to develop appropriate training programs to optimize training adaptation and minimize activity–related injury risk [20,30,31]. In combination with training age, which is defined as the number of years an athlete has been participating in formalized training [30,46], regular monitoring of biological maturity is recommended to enable training prescription to be designed with an appreciation of the unique physical and physiological processes that are taking place as a result of maturation [30]. It is important to appreciate and understand biological maturation in youth in order to be able to distinguish whether maturation or exposure to regular exercise training is responsible for observed changes in physical performance and injury risk. Previous research within the pediatric exercise science literature has made reference to the use of various “biological indicators” [30]. However, to the best of our knowledge a comprehensive review of available methods for assessing biological maturation in children and adolescents and an explanation of how these methods and principles can be used by practitioners to design and implement safe and effective exercise programs for youth does not exist in the literature.

ASSESSMENT OF BIOLOGICAL MATURATION

While chronological age is easily determined, the assessment of biological maturity is more challenging to evaluate owing to the large inter-individual variation in magnitude, timing and tempo of the adolescent growth spurt [57]. Numerous methods have been described within the literature and are commonly categorized into skeletal, sexual or somatic maturity indicators [3]. Despite these methods varying considerably, correlations amongst the different indicators are typically moderate to high [3,35], suggesting they possess a noteworthy degree of validity in reflecting estimated biological maturation [54].

Skeletal age

Skeletal age, or "bone age", refers to the degree of biological maturation according to the development of skeletal tissue [34,35]. It should be noted that trained radiographers should perform this method of assessment, and in most cases only qualified medical personnel would be expected to analyze the radiographs. Maturation of the skeletal system involves a long-term transition from cartilaginous structures (prenatal stage of growth) to a fully developed skeleton of bones by early adulthood (Figure 2). With the use of x-rays or radiographs, and an understanding of the developmental process from early ossification to fully mature skeletal tissue, skeletal age verification is arguably the gold standard method of assessing biological maturation. Accordingly, a number of non-invasive methods of assessment exist, which rely on the use of matching a left hand-wrist radiograph to a set of pre-determined reference criteria [34]. The most commonly cited assessment tools are the Greulich-Pyle method [24], Fels method [53] and Tanner-Whitehouse method [60,61,62].

*****Figure 2 near here*****

Greulich-Pyle method

The Greulich-Pyle method, which is also viewed as an atlas-based technique, was first validated using a collection of reference radiographs from Caucasian children of high socio-economic status [24]. This method of assessment involves the radiograph of a child's left wrist being compared against the reference x-ray plates of varying levels of skeletal maturation. Skeletal age is subsequently determined as that which most closely reflects one of the standard radiographs of the atlas system. For example, if the x-ray of a 10 year old girl matches closely with the reference plate x-ray of a 12 year old, then her skeletal age would be determined as 12 and she would be deemed an early maturer. This method is based on the premise that bone tissue matures in a uniform manner, however, such an approach fails to account for individual rates of development of different bones, and therefore concerns exist with the Greulich-Pyle method for accurate determination of biological maturation. Specifically, the Greulich-Pyle method is susceptible to both over- and under-estimates of maturation based on the mismatched bone growth development and may not be applicable across diverse ethnicities [35].

Tanner-Whitehouse method

The Tanner-Whitehouse (TW) method, which has been revised twice since the original TW1 method [60], requires the practitioner to use a combination criteria that includes multiple bones of the hand and wrist (13 bone assessment including the radius, ulna and phalanges; or the 20 bone assessment incorporating the radius, ulna, phalanges and carpals). Irrespective of the assessment method (13 or 20 bone analysis), the radiographs of these bones are analyzed and compared to a series of statements and detailed shape analyses of each bone. Individual bones are given an independent maturation score, and then the cumulative score is converted to a skeletal age value. Whilst the TW1 [60] and TW2 [61] versions were validated using British children, the most recent TW3 method [62] is based upon samples derived from European, South American, North American and Japanese youth. One potential drawback of the TW3 method is that it is a fairly complex and time-consuming process, and requires a reasonable degree of subjective decision-making. The difficulty of assessment combined with the need for radiographic evaluation limit the utility of the Tanner-Whitehouse method to be used in youth training environments.

Fels method

Based on data collected between the 1930s and 1970s within the Fels Longitudinal Study [53], the Fels method provides maturity assessments for the radius and ulna, carpals and metacarpals, and phalanges. Each bone is graded according to age and sex; ratios between length and width of the epiphysis and metaphysis of the long bones are measured, and the degree of ossification for the pisiform and adductor sesamoid are recorded. Using specific software, skeletal age and standard error of estimate are then calculated. Whilst the Fels method is again a complex and time consuming process, the ability of the assessment tool to provide an estimate of the standard error of measurement is obviously of benefit for the long-term tracking of biological maturation in children and adolescents.

Whilst the aforementioned methods of assessing skeletal age are often considered as the optimal method of determining biological age, issues surrounding the cost, availability, time, need for specialist equipment and requisite assessor expertise mean that these techniques may not be accessible or indeed appropriate for most practitioners. Previous concerns surround the deliberate exposure of children to radiation that the technique warrants; however, research suggests that with modern technology the exposure is less than normal background radiation associated with everyday life [34]. More recently, dual energy x-ray absorptiometry (DEXA) has been introduced to assess skeletal development. DEXA assessments are typically faster, are more precise, can provide higher resolution images, and can be used to analyze a greater number of body regions than traditional x-ray techniques [21,25]. While radiographic assessment of maturation is considered the “gold standard,” the concerns with access and complexity of measurement limit its usage among practitioners. Accordingly, more non-invasive assessments are typically used to determine biological maturation in youth.

Sexual age

Tanner criteria

Sexual age refers to the degree of biological maturation towards fully functional reproductive capability [35]. It must be emphasized that only trained clinicians are qualified to assess sexual maturation, and at all times this should be completed with the consent and assent of the parent and child respectively. Additionally, owing to the sensitive nature of the assessment process, up-to-date criminal background checks of the assessor, and the anonymity and confidentiality of those being assessed should be maintained at all times.

Traditionally, sexual maturation has been assessed via observations of secondary sexual characteristics (breast, genitalia and pubic hair development) which are then compared against five distinct reference ‘stages’, referred to as Tanner Stages 1 (TS1), TS2, TS3, TS4 and TS5 [58]. Specifically, observation of female characteristics would include age at menarche and breast and pubic hair development, while male characteristics would include genital and pubic hair development [59]. Table 1 provides an overview of breast, genitalia and pubic hair development according to each Tanner stage [58].

*****Table 1 near here*****

In addition to the Tanner criteria, testicular volume can also be used as a means to estimate genital maturity in young males [3,50]. Qualified and experienced medical doctors can perform the Tanner assessment within a clinical setting. However, due to the invasive nature of direct visual observation of Tanner staging, and the concerns that this brings to both youth and their parents, self-assessment techniques have been used which require the child to compare their own sexual characteristics to those of reference drawings or photographs [58]. Research suggests that such techniques produce reproducible and reliable data [38], however, practitioners should be cognizant of the fact that boys typically overestimate while girls generally underestimate their own sexual development [29,65].

Despite the fact that the Tanner criteria are most often used to assess sexual maturation, certain limitations associated with the method exist. Firstly, the method has an inability to differentiate children or adolescents within stages (i.e. two children could be rated within the same stage, but one is only just at the start of the stage whilst the other child is nearing the end of the stage). Secondly, the assessment tool is unable to provide an insight into the tempo of maturation (i.e. a child may pass through the stages at a faster rate than another child of the same chronological age), thus making comparison between individuals more problematic. Finally, the Tanner criteria are confined only to the period of pubertal phase of growth and maturation, and therefore cannot be used for children or adults outside of those timeframes. This may be a limitation to those teaching or coaching pre-pubertal children or young adults, as they will be unable to ascertain where the child is in relation to the onset of puberty. Additionally, practitioners should be aware that Tanner stages are not interchangeable between different indicators (i.e. breast, genitalia and pubic hair development can occur at different tempos), and that if reporting biological age from sexual maturation, then specific stages for each indicator should be provided [35]. It must be reiterated that coaches or exercise practitioners should never perform observations of secondary sexual characteristics to determine Tanner staging; and cumulatively these limitations inhibit the utility of Tanner staging to support exercise prescription for youth.

Age at menarche

Specific to females, age at menarche is often used to determine at which age a female experiences their first menstrual period [35,54]. Despite the notion that females can recall the time point at which they started their first menstrual cycle to within approximately 3 months [28], this method of assessing biological maturation will typically be a retrospective measure (i.e. through simply asking the individual to recall the onset of their first period). Owing to the temporal delay between the onset of puberty and the subsequent onset of menarche, identifying a girl who is premenarcheal does not necessarily suggest that she is also pre-pubertal, and therefore this method of assessing sexual maturation has limitations that preclude its use in exercise- and sport-related related settings.

Prior to the onset of adolescence, boys and girls will follow similar rates of maturation even though boys will consistently outperform girls in a range of biomotor skills (e.g., speed, strength and endurance) [4]. However, maturational differences become more evident upon the onset of the adolescent growth spurt, with females experiencing clear sex-specific physiological changes. Such processes include increased fat mass, differential rates of development in stature and muscular strength, commencement of menstruation, increases in joint laxity and valgus knee angle, and an increased quadriceps: hamstring utilization ratio [47]. All of these factors have been identified as potentially increasing the risk of injury in female athletes [47]. Consequently, practitioners need to possess an understanding of growth-related changes in female athletes as well as training considerations that account for sex specific differences in biological maturation.

TECHNIQUES TO DETERMINE BIOLOGICAL MATURATION IN YOUTH

Somatic Assessments

Somatic age refers to the degree of growth in overall stature, or of specific dimensions of the body (such as recumbent length). From longitudinal data, it is apparent that somatic growth is non-linear in its development, with periods of rapid growth interspersed with relative plateaus in development [57]. Common measures of somatic growth include assessments of longitudinal growth curves, prediction of age at peak height velocity (PHV), and the use of percentages and predictions of adult stature [35].

Growth rates

The processes of growth are difficult to study and consequently a number of indirect measures of body size and proportions have been established to assess overall development. The onset of sexual maturation is reflected in marked changes to the endocrine system that stimulate skeletal maturation. This can readily be observed in the rate of growth in stature and other body dimensions (such as limb lengths). The most basic level of assessment involves longitudinal anthropometric assessment of breadths, widths and lengths of specific individual landmarks: overall stature and body mass; sum of skinfolds to determine levels of adiposity; and a combination of the above to provide an estimate of somatotype. From a practical perspective, the repeated collection of height over a period of time would enable the analysis of growth curves. For example, the longitudinal assessment of stature would reveal the magnitude and rate of change of height over time (cm/year). From such growth curves age at peak height velocity (PHV) can be identified, which reflects the age at maximum rate of growth during the adolescent growth spurt (see Figure 3; modified from Stratton and Oliver [57]). The growth spurt is determined by initiation of sexual maturation and subsequent changes in endocrine function promoting rapid growth, which can be observed as changes in body size.

*****Figure 3 near here*****

Research demonstrates that PHV typically occurs at around the age of 12 years in females and 14 years in males [35]. Early-maturing youth display PHV approximately 1 year (or more) before the mean age at PHV, average-maturers experience mean age at PHV, while late-maturing youth have an age at PHV which is at least 1 year later than the mean age at PHV [3]. One issue for youth training practitioners is that the identification of age at PHV requires regular longitudinal tracking of growth from middle childhood until late adolescence. Additionally PHV can only be identified retrospectively after a peak has been observed. The collection of such data over an extended period of time may not be common practice within some sports and/or training settings, especially at an amateur level, which may hamper longitudinal analysis. For example, a youth sport coach may start working with a young athlete at the age of 14, but potentially have no data on growth changes experienced by the child in previous years. Consequently, it would be challenging to ascertain at which point in time the child started their growth spurt.

Predicting PHV

In situations where longitudinal tracking of stature and body mass are not possible (e.g. cross-sectional analysis or a short-term training block), age from PHV can be calculated using the equations proposed by Mirwald and colleagues [42]. It is acknowledged that differential growth rates exist between the legs and the trunk, with the long bones of the legs experiencing peak growth ahead of the shorter bones of the trunk. Mirwald et al. [42] created the predictive equations to incorporate this growth pattern to estimate years from PHV to within a standard error of approximately 6 months. Essentially, the equations require the attainment of chronological age (years and months), body mass, standing height and seated height, which can be used to determine years from PHV for a male (equation 1) or female (equation 2) at any given single point in time.

Maturity Offset = - 29.769 + 0.0003007•Leg Length and Sitting Height interaction - 0.01177•Age and Leg Length interaction + 0.01639•Age and sitting Height interaction + 0.445•Leg by Height ratio.

(male - equation 1)

Maturity Offset= -16.364 + 0.0002309·Leg Length and Sitting Height interaction + 0.006277·Age and Sitting Height interaction + 0.179·Leg by Height ratio + 0.0009428·Age and Weight interaction.

(female - equation 2)

Adult stature predictions

Another method of assessing somatic maturity is using percentages of predicted adult stature. Practitioners could use the percentage of adult stature to determine the maturational state of a group of young athletes. For example, if the final adult stature is predicted, then a practitioner could distinguish between a group of players who are currently the same height, but may be relatively closer to their final adult height. Consequently, a youth coach could differentiate between athletes who are genetically predisposed to be tall versus an athlete who is simply maturing at an earlier stage. Such an approach would obviously have some application for training prescription, but also for talent identification programs to determine which children were genetically predisposed for certain sports or positions where stature is advantageous. Such an approach requires the prediction of final adult stature, which does not provide any information regarding the timing and tempo of maturation. The most basic method of predicting final adult stature involves calculating midparental height and using a correction of adding or subtracting 6.5 cm for boys and girls respectively based on an average difference in stature between both sexes [28]. Calculations are shown below for males (equation 3) and females (equation 4), whereby 13 cm is added to or subtracted from the combined parental height in cm, and the result is then divided by two.

Boys mid-parental height = (mother's height + father's height+ 13) / 2

(male - equation 3)

Girls mid-parental height = (mother's height + father's height-13) / 2

(female - equation 4)

As well as midparental height, Khamis and Roche [27] developed a regression equation that also includes current stature and weight of the child, to estimate eventual adult height. Additionally, Beunen et al. [5] produced an alternative prediction model that uses chronological age, standing height, sitting height, and subscapular and triceps skinfolds, while Cole and Wright [12] developed a chart that uses the current standing height of the child and adjusts for regression to the mean to predict eventual height. Methods used to predict adult stature typically possess standard errors of approximately 3-5 cm, with the error of prediction narrowing with increasing age [12]. Since skeletal age assessments are not required, the aforementioned methods may serve as a viable assessment tool for practitioners.

Using the regression equations identified by Mirwald et al. [42] researchers have developed an alternative non-invasive method of predicting adult stature using cumulative height velocity curves [55]. Using retrospective data from previously published research [2,33,41], the method of Sherar and colleagues [55] employed regression equations to predict years from PHV [42], which in addition to the maturity specific cumulative velocity curves, were used to estimate height left to grow. Height left to grow was then added to the standing height of individuals at the time of testing to provide a final predicted adult height. These predicted heights were then validated against eventual adult heights [55]. Using 95% confidence intervals, the measurement error associated with predicting final adult height was ± 5.35 cm for males and ± 6.81 cm for females [55]. Coaches and scientists would need to decide whether this provides suitable precision and accuracy dependent on the importance of adult stature in a given sport or position. Of interest to practitioners who are directly responsible for youth exercise programming, online tools (http://taurus.usask.ca/growthutility) are available which can calculate both predicted adult stature and years from PHV based on basic anthropometric data.

Comparison of methods

While slight variations in somatic, sexual and skeletal maturation are evident throughout adolescence, research suggests that the different indicators (skeletal, sexual and somatic) used to assess biological maturation possess moderate to high relationships ($r > 0.70$ [6]). Consequently, while skeletal age is still viewed as the gold standard method of assessing biological maturation, practitioners can use alternative assessment methods to aid in the design and progression of their training prescription. Factors such as the availability of equipment, requirement of expertise for analysis, degree of invasiveness of assessment methods, time and cost implications, and the degree of measurement error associated with the assessment method that is used to assess biological age need to be considered. Of note, legal and ethical issues surrounding any method of assessing biological maturation should be considered in addition to local guidelines from school boards and sports centers.

Frequency of assessment

Minimal evidence exists to indicate whether there is an optimal frequency for which to assess the status of maturation in children. However, it is recommended that to monitor for the onset of the growth spurt, basic somatic measurements should be taken by the practitioner approximately every three months [13,35]. Such a time frame should enable worthwhile changes in growth to take place and avoid attention being given to small, insignificant natural fluctuations in standing or seated height that children may demonstrate on a daily basis. Additionally, due to the time constraints associated with practice, competition, travel, academic timetables and other commitments, assessments every three months should avoid excessive time being devoted within the overall athletic development program, and therefore enable practitioners to assign more time and attention to technical competency, conditioning for injury prevention and overall athletic performance enhancement.

ASSESSING GROWTH AND MATURATION: APPLICATIONS FOR PRACTITIONER

Training prescription

The concept of long-term physical development of youth athletes has received increased attention within the literature [18,30]. Whilst there has been much contention over the lack of supporting evidence for previous long-term athlete development models [18], certain training modalities would appear to be more appropriate at specific stages of maturation. Resistance training is now recognized as an essential component of a young athlete's development program for performance, health and injury-reducing benefits [32]. Modes of strength and conditioning inclusive of plyometrics and weightlifting exercises (clean and jerk, snatch and their derivatives) can be promoted in youth training programs on the proviso that those designing and delivering the programs are suitably qualified to teach all forms of resistance training [32].

In terms of resistance training, a physical education teacher or strength and conditioning coach would be ill advised to prescribe hypertrophy-based resistance training to a child who has not yet experienced the pubertal growth spurt due to limited concentrations of anabolic hormones [32]. Instead, pre-pubertal children should be prescribed a resistance training program that focuses on enhancing muscle strength, function and control due to the high degree of plasticity in neuromuscular function during this developmental period [32,45]. Due to their increased tissue pliability [15], children can typically recover more quickly from fatigue-inducing resistance training sessions than adults [16,66], and consequently children can often be prescribed shorter rest intervals than adolescents or adults. However, technical competency during resistance training sessions should be carefully monitored at all times, and practitioners should consider a child's cognitive development which can influence one's ability to follow instructions and perform simple as well as complex movements [45].

Furthermore, the importance of having fun in a supportive environment should not be overlooked. Consequently, many of the popular commercial metabolic high-intensity training programs that entail high volumes of work with insufficient recovery are deemed inappropriate for youth. Such programs risk de-emphasizing the development and maintenance of proper technique and allow for poorly performed repetitions as clients attempt to reach a pre-determined number of repetitions at any cost. Irrespective of the training mode employed, being able to determine the degree of biological maturity of a young athlete would hopefully assist the decision making processes of the strength and conditioning coach to accurately prescribe resistance training sessions appropriate for the individual's stage of development. Practically, a strength and conditioning coach could also make use of maturational assessments to divide a large cohort of youth players according to maturational status (i.e. pre-PHV, circa-PHV and post-PHV), which would help ensure that players of similar physical maturity were training synonymously.

Monitoring training adaptation

Practitioners will routinely administer testing batteries to establish the effectiveness of a training intervention. However, uniquely children and adolescents can experience performance adaptations (e.g. increase in jump height and sprint speed) purely as a result of growth and maturation. Consequently, when working with a child or adolescent, a practitioner should monitor maturational status to help evaluate any changes in performance in response to a training intervention. Furthermore, pediatric research suggests that practitioners can use basic anthropometric measures commonly incorporated within non-invasive measures of maturity to assess training-induced changes in lower limb volumes and composition in youth athletes [9]. Adult data suggest that basic anthropometric measurements can also be used to determine skeletal mass properties [23], however equivalent research has not been completed on youth populations.

Whilst it is important that practitioners determine the effectiveness of their program, and that they take into account the measurement error associated with any mode of testing, it is also important that maturational assessments are routinely taken to help explain changes in performance throughout childhood and adolescence. For example, knowledge of biological maturation could be of use to practitioners to help explain fluctuations in motor skill competency. ‘Adolescent awkwardness’ is a developmental phenomenon that refers to a temporary disruption in basic motor skill execution resulting from the early onset of the adolescent growth spurt [49,51]. Adolescent awkwardness typically occurs approximately 6 months pre-PHV, and longitudinal monitoring of leg length and use of the regression equation of Mirwald and colleagues [42] can assist practitioners in identifying youth who are potentially at risk. Adolescent awkwardness will typically involve adolescents experiencing a temporary disruption in motor coordination simply as a result of growth and maturation as opposed to any training-induced performance decrement. For youth experiencing this developmental phenomenon, it is recommended that training volume-loads are modified to avoid excessive loadings during the phase of rapid skeletal growth, and to provide sufficient opportunity for individuals to re-learn motor control patterns. This would also serve as an appropriate stage of development to refine key fundamental movement skills, in order to maintain levels of physical literacy and limit the chances of potentially injurious technical deficiencies being acquired, such as poor landing mechanics.

Talent identification

Whilst some limitations exist with non-invasive indicators of maturity, if used appropriately they can ensure that less mature players who are technically gifted within the same chronological age group are not routinely disadvantaged owing to maturity associated differences in physical and functional variables [37]. For example, maturity status has been identified as a significant contributor to aerobic fitness [10], anaerobic power [8], explosive power [17,36,63], sprinting [36,63] and change of direction speed [63] in young athletes (11-16 years). Furthermore, it has been shown that early-maturing youth are typically at an advantage for physical performance tests owing to their relatively greater levels of muscle strength, explosive power and running speed [39]. Additionally, through the use of simple, non-invasive maturational assessments, it could be established that an early-maturing youth has been selected for a specific position despite the fact that a later-maturing individual is predicted as having a taller adult stature. Consequently, any talent identification process must acknowledge and account for maturity-related variation in performance. The relative age effect (RAE) is a phenomenon whereby youth who are born early in the selection year are routinely selected ahead of those born later in the year [11,44]. Such a selection bias is often due to the older children possessing greater size, strength and speed, and having gained more exposure to their chosen sport(s) [56]. Consequently, less mature children might not be selected for competitions despite possessing good levels of skill, or may volitionally drop out of a sport due to a lack of perceived competence or lack of success [14]. The bias for the selection of earlier maturing individuals is exacerbated by the likelihood that these individuals will also receive greater opportunities for expert coaching and training [7].

Through the use of maturation indicators, coaches can make informed judgments of performance by considering how mature the young athlete is in relation to their peers. Maturity-related differences in height and weight can start to emerge from 6 years of age, which continue to increase with adolescence [35], and thus early maturing youth stand to possess a size advantage from early in life. Using predictive methods of maturation (most likely percentage of predicted adult stature), those early-maturing individuals could be identified who are demonstrating advanced growth trends due to early skeletal maturation. Additionally, the natural development of numerous performance measures has been shown to peak around the time of PHV or PWV. Therefore, practitioners should not presume rapid gains around this period are due to training interventions employed.

Early sport-specialization

There appears to be an increase in the number of preadolescent youth who specialize in a single sport [1,43]. This may include regular exposure to sport-specific training, regularly participating in a high proportion of competitions, and/or competing in multiple teams within the same sport [43]. Within the scope of early sport specialization, it is likely that the timing and tempo of maturation will lead to individuals being identified for specific positions within a team. For example, early maturing individuals may be selected for size-related positions in those sports where additional height may be advantageous (e.g. basketball, volleyball or netball). This situation can lead to youth not only being exposed to higher volumes of sport-specific training, but also a narrow range of position-specific movement skills.

This notion has recently been identified within the literature, with Fransen et al. [19] showing that youth who spent many hours in a variety of sports performed better in gross motor coordination and standing broad jump performance than those who specialized early in one sport. Additionally, research indicates that youth who specialize early in a sport are at an increased risk of overtraining and overuse injury as well as burnout (i.e., stress-induced withdrawal) [1,40,48,64]. In the instance of a strength and conditioning coach working with a young athlete who has specialized early in a single sport, the training focus should be dedicated to enhancing global movement skills, improving muscle weakness and/or imbalances, and promoting self-esteem and perceptions of confidence.

SUMMARY

It is essential that practitioners working with youth recognize the unique requirements of children and adolescents, and that they can appreciate the influence of biological maturation on athletic performance and development as it relates to exercise programming. The current manuscript reviewed available methods for assessing biological maturation, and demonstrated how specific assessment tools are available that can be used in sport settings and youth training facilities. In summary, this review has addressed the following questions for practitioners working with youth:

What is the relative importance of assessing biological maturation?

- Biological maturation should be viewed as an additional variable to consider when designing exercise programs for youth, however, it should not drive training prescription on its own.

How do the different assessment strategies compare in terms of accuracy and applicability?

- It is generally accepted that the gold standard method of determining biological maturation is via skeletal age assessment, however for a number of ethical, financial, resource and time constraints, practitioners are advised to assess maturation from basic somatic measurements.

Which assessment strategy should be used if testing individuals in a cross-sectional analysis, or an individual for the first time?

- For cross-sectional and first time assessments, where the current status of maturation is unknown and there is no prior information relating to longitudinal growth, then the use of age at PHV predictions are recommended.

Which assessment strategy should be used for long-term tracking of individuals?

- Where practitioners will be working with young athletes for an extended period of time, then it is advised that longitudinal tracking of stature, limb length and body mass are taken, allowing growth curves to be utilized.

How often should assessments be taken for the monitoring of biological maturation?

- Basic somatic measurements should be taken by the practitioner approximately every three months to enable the identification of any worthwhile changes in growth.

How can the assessment of biological maturation be of use to practitioners?

- Assessing maturation can inform talent identification, assist in avoiding the negative effects of the RAE, aid program design, and help practitioners determine if their programs are providing benefits beyond the level of expected natural development.

REFERENCES

1. American Academy of Pediatrics. Committee on Sports Medicine and Fitness. Intensive training and sports specialization in young athletes. *Pediatrics* 106: 154-157, 2000.
2. Bailey, DA. The Saskatchewan pediatric bone mineral accrual study: bone mineral acquisition in the growing years. *Int J Sports Med* 18: 191-194, 1997.
3. Baxter-Jones, ADG, Eisenmann, JC, and Sherar LB. Controlling for maturation in pediatric exercise science. *Ped Exerc Sci* 17: 18-30, 2005.
4. Beunen, GP and Malina, RM. Growth and biological maturation: relevance to athletic performance, in: *The Young Athlete*. H Hebestreit, O Bar-Or O, eds..Oxford, Blackwell Publishing, 2008, pp 3-17.
5. Beunen, GP, Malina, RM, Lefevre, J, Claessens, A, Renson, R, and Simons J. Prediction of adult stature and noninvasive assessment of biological maturation. *Med Sci Sport Exer*c 29: 225-230, 1997.
6. Bielicki, T, Koniarek, J, Malina, RM. Interrelationships among certain measures of growth and maturation rate in boys during adolescence. *Ann Hum Biol* 11: 201-210, 1984.
7. Capranica, L, and Millard-Stafford, ML. Youth Sport Specialization: How to Manage Competition and Training? *Int J Sports Physiol Perf* 6: 572-579, 2011.
8. Carvalho, HM, Coelho-e-Silva, MJ, Gonçalves, CE, Philippaerts, RM, Castagna, C, and Malina, RM. Age-related variation of anaerobic power after controlling for size and maturation in adolescent basketball players. *Ann Hum Biol* 38: 721-727, 2011.
9. Carvalho, HM, Coelho-e-Silva, MJ, Franco, S, Figueiredo, AJ, Tavares, OM, Ferry, B, Hidalgo-Hermanni, I, Courteix, D, and Malina, RM. Agreement between anthropometric and dual- energy X-ray absorptiometry assessments of lower-limb

volumes and composition estimates in youth-club rugby athletes. *Appl Physiol Nutr Metab* 37: 463-471, 2012.

10. Carvalho, HM, Coelho-E-Silva, MJ, Eisenmann, JC, and Malina, RM. Aerobic fitness, maturation, and training experience in youth basketball. *Int J Sports Physiol Perform* 8: 428-434, 2013.
11. Cobley, S, Baker, J, Wattie, N, and McKenna, J. Annual age-grouping and athlete development: A meta-analytical review of relative age effects in sport. *Sports Med,* 39: 235-256, 2009.
12. Cole, TJ, and Wright, CM. A chart to predict adult height from a child’s current height. *Ann Hum Biol* 38: 662-668, 2011.
13. D’Hemecourt, P. Overuse injuries in the young athlete. *Acta Paediatr* 98: 1727-1728, 2009.
14. Delorme, N, and Raspaud, M. The relative age effect in young french basketball players: a study on the whole population. *Scan J Med Sci Sports* 19: 235-242, 2009.
15. Eston, R, Byrne, C, and Twist, C. Muscle function after exercise-induced muscle damage: considerations for athletic performance in children and adults. *J Exerc Sci Fitness* 1: 85–96, 2003.
16. Faigenbaum, AD, Ratamess, N, McFarland, J, Kaczmarek, J, Coraggio, M, Kang, J, and Hoffman, J. Effect of rest interval length on bench press performance in boys, teens and men. *Pediatr Exerc Sci* 20: 457–469, 2008.
17. Figueiredo, AJ, Goncalves, CE, Coelho, ESMJ, and Malina, RM. Youth Soccer Players, 11-14 Years: Maturity, Size, Function, Skill and Goal Orientation. *Ann Hum Biol* 36: 60-73, 2009.
18. Ford, PA, De Ste Croix, MBA, Lloyd, RS, Meyers, R, Moosavi, M, Oliver, J, Till, K, and Williams, CA. The long-term athlete development model: physiological evidence and application. *J Sports Sci* 29: 389–402, 2011.
19. Fransen, J, Pion, J, Vandendriessche, J, Vandorpe, B, Vaeyens, R, Lenoir, M, and Philippaerts, RM. Differences in physical fitness and gross motor coordination in

boys aged 6–12 years specializing in one versus sampling more than one sport. *J Sports Sci* 30: 379–386, 2012.

20. Gabbett, TJ, Johns, J, and Riemand, M. Performance changes following training in junior rugby league players. *J Strength Cond Res* 22: 910-917, 2008.
21. Gilsanz, V. Pediatric assessment of skeletal growth. *Rev Esp Endocrinol Pediatr* 1(suppl.): 11-18, 2001.
22. Gilsanz, V, and Ratib, O. Hand bone age – a digital atlas of skeletal maturity. Springer-Verlang, pp. 37-92, 2005.
23. Gobbo, LA, Ritti-Dias, RM, Avelar, A, Silva, AM, Coelho-e-Silva, MJ, and Cyrino, ES. Changes in skeletal muscle mass assessed by anthropometric equations after resistance training. *Int J Sports Med* 34: 28-33, 2013.
24. Greulich, WW and Pyle, SI. Radiographic atlas of skeletal development of the hand and wrist. 2nd rev edn. California, USA: Stanford University Press. 1959.
25. Kemper, HCG. Skeletal development during childhood and adolescence and the effects of physical activity. *Ped Exerc Sci* 12: 198-216, 2000.
26. Kemper, HCG and Verschuur, R. Maximal aerobic power in 13- and 14-year –old teenagers in relation to biological age. *Int J Sport Med* 2: 97-100, 1981.
27. Khamis, HJ and Roche, AF. Predicting adult stature without using skeletal age: the Khamis-Roche method. *Pediatrics* 94: 504-547, 1994.
28. Koo, MM and Rohan, TE. Accuracy of short-term recall of age at menarche. *Ann Hum Biol* 24: 61-64, 1997.
29. Leone, M and Comtois, AS. Validity and reliability of self-assessment of sexual maturity in elite adolescent athletes. *J Sports Med Phys Fitness* 47: 361-365, 2007.
30. Lloyd, RS and Oliver, JL. The Youth Physical Development model: a new approach to long-term athletic development. *Strength Cond J* 34: 61-72, 2012.
31. Lloyd, RS, Oliver, JL, Meyers, RW, Moody, JA, and Stone, MH. Long-term athletic development and its application to youth weightlifting. *Strength Cond J* 34: 55-66, 2012.

32. Lloyd RS, Faigenbaum, AD, Stone, MH, Oliver, JL, Jeffreys, I, Moody, JA, Brewer, C, Pierce, K, McCambridge, TM, Howard, R, Herrington, L, Hainline, B, Micheli, LJ, Jaques, R, Kraemer, WJ, McBride, MG, Best, TM, Chu, DA, Alvar, BA, and Myer, GD. Position statement on youth resistance training: the 2014 International consensus. *Br J Sports Med* in press.
33. Maes, HHM, Beunen, GP, Vlitinck, RF, Neale, MC, Thomis, M, Eynde, BV, Lysens, R, Simons, J, Derom, C, and Derom, R. Inheritance of physical fitness in 10-year old twins and their parents. *Med Sci Sports Exer* 28: 1479-1491, 1996.
34. Malina, RM. Skeletal age and age verification in youth sport. *Sports Med* 41: 925-947, 2011.
35. Malina, RM, Bouchard, C, and Bar-Or, O. Growth, maturation, and physical activity. Champaign, IL: Human Kinetics. 2004.
36. Malina, RM, Eisenmann, JC, Cumming, SP, Ribeiro, B, and Aroso, J. Maturity-Associated Variation in the Growth and Functional Capacities of Youth Football (Soccer) Players 13-15 Years. *Eur J Appl Physiol* 91: 555-562, 2004.
37. Malina, RM, Coelho, E, Silva, MJ, Figueiredo, AJ, Carling C, and Beunen GP. Interrelationships among invasive and non-invasive indicators of biological maturation in adolescent male soccer players. *J Sports Sci* 30: 1705-1717, 2012.
38. Matsudo, SMM and Matsudo, VKR. Self-assessment and physician assessment of sexual maturation in Brazilian boys and girls: concordance and reproducibility. *Am J Hum Biol* 6: 451-455, 1994.
39. Matthys, SP, Vaeyens, R, Coelho-E-Silva, MJ, Lenoir, M, and Philippaerts, R. The contribution of growth and maturation in the functional capacity and skill performance of male adolescent handball players. *Int J Sports Med* 33: 543-549, 2012.
40. Micheli, L, and Natsis, KI. Preventing injuries in team sports: what the team physician needs to know. In: F.I.M.S. Team Physician Manual. 3rd edn. L.J. Micheli,

F. Pigozzi, K.M. Chan, W.R. Frotnera, N. Bachl, A.D. Smith, and S.T. Alenabi, eds. London: Routledge, 2013. pp. 505–520.

41. Mirwald, RL. The Saskatchewan Growth and Development Study, in: *Kinanthropometry, 2nd rev edn.* M. Ostyn, G. Beunen, and J. Simons, eds. Baltimore: University Park Press. 1978.

42. Mirwald, RL, Baxter-Jones, ADG, Bailey, DA, and Beunen, GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc* 34: 689-694, 2002.

43. Mostafavifar, AM, Best, TM, and Myer, GD. Early sport specialisation, does it lead to long-term problems? *Br J Sports Med* in press.

44. Musch, J, and Grondin, S. Unequal competition as an impediment to personal development: A review of the relative age effect in sport. *Dev Rev* 21: 147-167, 2001.

45. Myer, GD, Kushner, AM, Faigenbaum, AD, Kiefer, A, Kashikar-Zuck, S and Clark, JF. Training the Developing Brain, Part I: Cognitive Developmental Considerations for Training Youth. *Curr Sports Med Rep* 12: 304-310, 2013.

46. Myer, GD, Lloyd, RS, Brent, JL, and Faigenbaum, AD. How young is “too young” to start training? *ACSM’s Health Fit J* 17: 14-23, 2013.

47. Myer, GD, Ford, KR, Divine, JG, Wall, EJ, Kahanov, L, and Hewett, TE. Longitudinal assessment of noncontact anterior cruciate ligament injury risk factors during maturation in a female athlete: a case report. *J Athl Train* 44: 101-109, 2009.

48. National Association for Sport and Physical Education. Guidelines for participation in youth sport programs: specialization versus multi-sport participation [Position statement]. Reston, VA. 2010.

49. Philippaerts, RM, Vaeyens, R, Janssens, M, Renterghem, BV, Matthys, D, Craen, R, Bourgois, J, Vrjens, J, Beunen, G, and Malina, RM. The relationship between peak height velocity and physical performance in youth soccer players. *J Sports Sci* 24: 221-230, 2006.

50. Prader, A. Testicular size: assessment and clinical importance. *Triangle* 7: 240-243, 1966.

51. Quatman-Yates, CC, Quatman, CE, Meszaros, AJ, Paterno, MV, and Hewett, TE. A systematic review of sensorimotor function during adolescence: a developmental stage of increased motor awkwardness? *Br J Sports Med* 46: 649-655, 2012.

52. Roche, A, and Sun, S. Human growth: assessment and interpretation. Cambridge: Cambridge University Press. 2003.

53. Roche, AF, Chumlea, WC, and Thissen, D. Assessing the Skeletal Maturity of the Hand-Wrist: Fels method. Springfield, IL: Charles C Thomas. 1988.

54. Rowland, TW. Children's Exercise Physiology. Champaign, IL: Human Kinetics. 2005.

55. Sherar, LB, Mirwald, RL, Baxter-Jones, ADG, and Thomas, M. Prediction of adult height using maturity-based cumulative height velocity curves. *J Pediatrics* 147: 508-514, 2005.

56. Sherar, LB, Baxter-Jones, AD, Faulkner, RA, and Russell, KW. Do physical maturity and birth date predict talent in male youth ice hockey players? *J Sports Sci* 25: 879-886, 2007.

57. Stratton, G and Oliver, JL. The impact of growth and maturation on physical performance, in: *Strength and Conditioning for Young Athletes: Science and Application*. R.S. Lloyd, and J.L. Oliver, eds. Oxford: Routledge Publishing. pp. 3-18, 2013.

58. Tanner, JM. Growth at Adolescence, 2nd rev edn. Oxford: Blackwell. 1962.

59. Tanner, JM. Foetus Into Man. London: Castlemead. 1989.

60. Tanner, JM, Whitehouse, RH, and Healy, MJR. A new system for estimating skeletal maturity from the hand and wrist, with standards derived from a study of 2,600 healthy British children. Paris: International Children's Centre, 1962.

61. Tanner, JM, Whitehouse, RH, Cameron, N, Marshall, WA, Healy, MJR, and Goldstein, H. Assessment of skeletal maturity and prediction of adult height (TW2

method). New York: Academic Press. 1975.

62. Tanner, JM, Healy, MJR, Goldstein, H, and Cameron, N. Assessment of skeletal maturity and prediction of adult height (TW3 method), 3rd rev edn. London: Saunders. 2001.

63. Vaeyens, R, Malina, RM, Janssens, M, Van Renterghem, B, Bourgois, J, Vrijens, J, and Philippaerts, RM. A Multidisciplinary Selection Model for Youth Soccer: The Ghent Youth Soccer Project. *Br J Sports Med* 40: 928-934, 2006.

64. Valovich-McLeod, TC, Decoster, LC, Loud, KJ, Micheli, LJ, Parker, T, Sandrey, MA, and White, C. National Athletic Trainers' Association position statement: prevention of pediatric overuse injuries. *J Athl Train* 46: 206–220, 2011.

65. Williams, RL, Cheyne, KL, Houtkooper, LK, and Lohman TG. Adolescent self-assessment of sexual maturation: effects of fatness classification and actual sexual maturation stage. *J Adolesc Health Care* 9: 480-482, 1988.

66. Zafeiridis, A, Dalamitros, A, Dipla, K, Manou, V, Galanis, N, and Kellis, S. Recovery during high-intensity intermittent anaerobic exercise in boys, teens and men. *Med Sci Sports Exerc* 37: 505–512, 2005.

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FIGURE CAPTIONS

Figure 1. Differences in developmental trends of chronological age and biological maturation of early- and late-maturing boys (left) and girls (right), based on theoretical data.

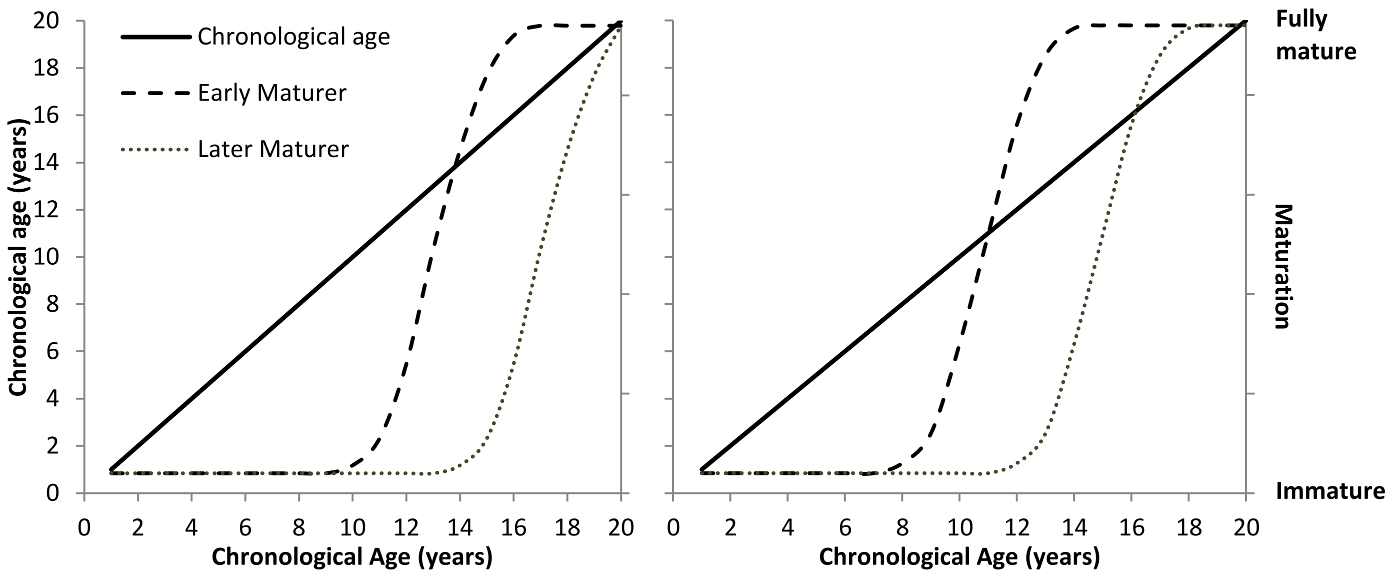
Figure 2. Reference image radiographs of the left wrist for males (top) and females (bottom) at 12 months, 6 years, 12 years and 18 years of age. Reprinted with permission from Gilsanz and Ratib [22]

Figure 3. Change in growth rates (cm/yr) with chronological age (years) for early, average and late-maturing individuals based on theoretical data (figure adapted from Stratton and Oliver [57])

TABLE CAPTIONS

Table 1. Distinct stages of sexual development for pubic hair, male genitalia and breasts (adapted from [52])

Figure 1



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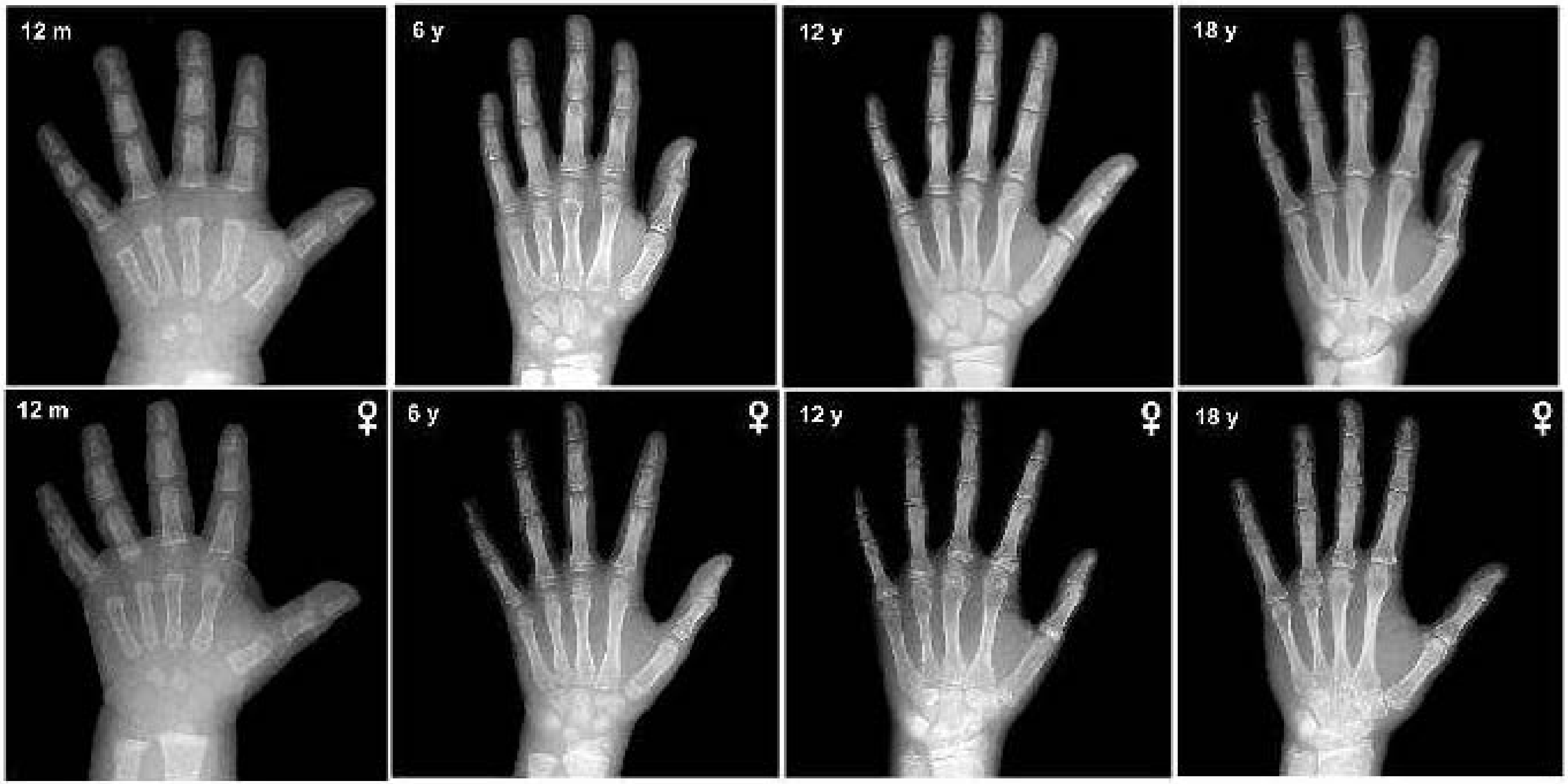

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Figure 3

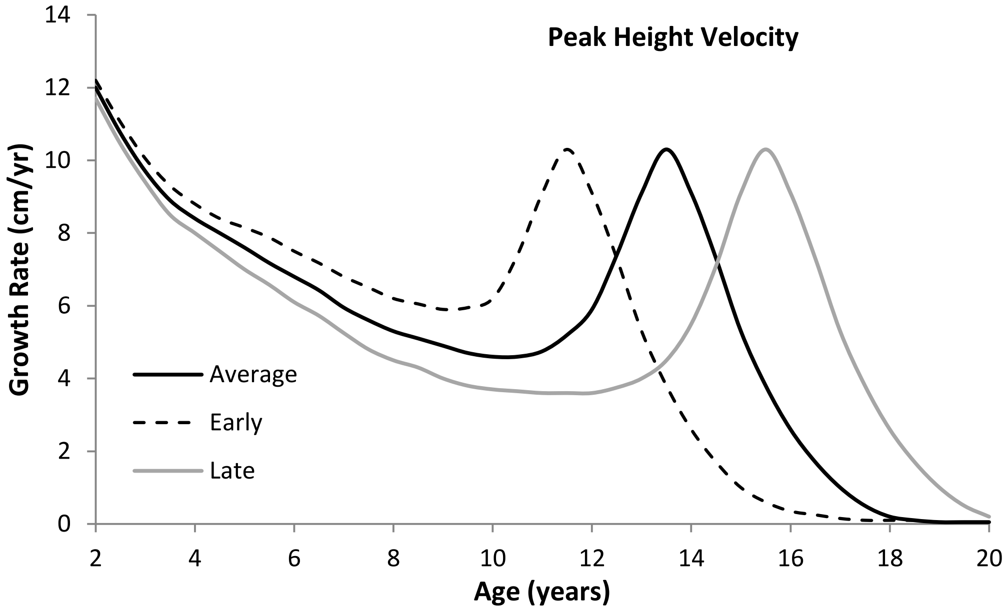

Figure 3. Change in growth rates (cm/yr) with chronological age (years) for early, average and late-maturing individuals based on theoretical data (figure adapted from Stratton and Oliver [57])

Table 1

Table 1. Distinct stages of sexual development for pubic hair, male genitalia and breasts (adapted from Roche and Sun, 2003, p.9-13)

Pubic Hair Development	
Stage 1	Pigmented pubic hair is absent. Fine non-pigmented hair over the pubis is similar to that over the abdominal wall.
Stage 2	Minimal growth of long, slightly pigmented pubic hair, that is straight or slightly curled, appearing mainly at the base of the penis or along the labia.
Stage 3	Pubic hair is considerably darker and more curled than stage 2, and spreads sparsely around the base of the penis or labia.
Stage 4	Pubic hair resembles adult type, but less area is covered. The hair covers pubis or mons veneris, but does not extend to the medial surfaces of the thighs.
Stage 5	Pubic hair is adult type and is distributed in a typical male or female pattern with spread to the surfaces of the thighs.
Male Genitalia Development	
Stage 1	Testes, scrotum and penis are roughly the same size and shape as in childhood.
Stage 2	Enlargement of the testes and scrotum. The skin of the scrotum is reddened and the texture is thinner and more wrinkled. There is minimal change in size of the penis.
Stage 3	Penis is enlarged predominantly in length, and there is further enlargement of the testes. The scrotum now hangs further below the base of the penis.
Stage 4	Further enlargement of the penis with increase in breadth, and development of the glans penis. Continued development of the testes and scrotum, and an increased darkening of the skin of the scrotum.
Stage 5	Genitalia are deemed to be fully mature and resemble adult size and shape.
Breast Development	
Stage 1	Minimal change from childhood, with only a slight elevation of the nipple.
Stage 2	Elevation of the areola, and a reasonably firm area of breast tissue can be palpated.
Stage 3	Further enlargement of the breast and areola without separation of the contours. The breast clearly has a feminine appearance.
Stage 4	Areola and nipple project to form a mound above level of breast, and there is an increase in adipose tissue deposition.
Stage 5	Breasts are now deemed to be resemble a fully mature state. Recession of the areola to the contour of the breast, causing the nipple to project from the areola, which is darkened in colour.

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5th July 2013

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