PHYSIOLOGICAL CHANGES OF THE YOUNG ATHLETE AND THE EFFECTS ON SPORTS PERFORMANCE

By Prof Craig Williams, PhD

INTRODUCTION

In most countries throughout the world, the organisation of youth sport has become increasingly professionalised. As a consequence, it is not uncommon for some young child athletes to have had five years of training and competition experience before the age of ten. This strategy is exemplified by the catch them young philosophy (1) and is an important one for those countries intent upon maximising their talent pool for future medal success, but also if funding resources are scarce and need to be prioritised. Over the last ten years there has been a movement in the UK to recognise that children are not mini adults and need a coaching system that is pertinent to them and not a hand-me-down from adult models. The recent implementation of the Long Term Athlete Development (LTAD) plans by many UK sports associations is a positive move, which acknowledges the unique demands imposed on young athletes.

At present, paediatric scientists are a long way from understanding the long-term impact of training on children and compared to adults little is known about the trainability of young athletes. For example, adolescence is a period of accelerated growth in the cardiorespiratory, musculoskeletal and reproductive systems but scientists are still unable to truly differentiate the impact of the growth spurt from the improvements by training. These are complex issues and involve an understanding of the growth, maturation and the response to training of the different systems of the body. The purpose of this article is to discuss some of the issues that impact on the performance of young child athletes.

GROWTH AND MATURATION

Currently there is no definition of what defines a trained or elite child athlete. Most youth sport is organised by chronological age (CA) categories and success within these respective categories is often used to determine future sporting potential. However, it has been demonstrated that CA categorised competitions gives an advantage to those individuals born in the earliest part of the selection year. The relative age affect was first shown in academic educational studies and has been substantiated in youth sports. For example, in the Football Associations School of Excellence, of the 106 boys selected over a six year period for the School, 67% were born in the first quarter of the selection year and less than 2% in the last three months (2). Since then this observation has also been noted in other sports eg. tennis, swimming. An explanation of this is that older individuals who are bigger, stronger and faster than their younger counterparts are selected because of these attributes and receive more coaching leading to greater success. It is therefore important to understand the consequences of growth and maturation in the process of sporting competition.

Growth, maturation and development are often used interchangeably, however they should not be confused, as each identifies a separate domain of the child. Table 1 represents a glossary of terms, which will aid understanding of the important issues.

Growth

Growth is a continuous process, which does not necessarily have specific end points, whereas maturation does, as all children will eventually reach the fully mature adult status.

As children grow, there is an increase in height, body mass, lean and fat mass and all organs increase in size. The greatest rate of height increase is within the first year after birth, where approximately

KEY POINT

The timing (often referenced to chronological age) and tempo (rate of growth) of the maturation process will vary considerably relative to an individual's CA.

25 cm of growth is observed. During the next year approximately 12 cm per year occurs and in the following year it is on average 6 cm per year. From three years of age onwards the rate of height increase is about 3-4 cm per year. The second highest growth rate experienced by an individual is during the adolescent growth spurt when a child enters puberty. The timing of this onset of growth is earlier for girls between 8.5-10.3 years compared to boys 10.3-12.1 years (Figure 1).

On average a boy will attain his highest growth rate in height between 13.4-14.4 years of age when he can expect to grow by 9 cm in that year, whilst a girl will experience her highest growth rate approximately two years earlier at 11.4-12.2 years and increase in height by 8 cm per year. Around this time most other parameters connected to general body size (body mass, heart size etc) will also be increasing at their maximal rates. This pattern of growth is well documented through numerous longitudinal studies and forms the basis of percentile growth charts for children in the UK.

TABLE 1 GLOSSARY OF TERMS

- Adulthood refers to the full maturation of all biological systems. Typically represented as 18 years and older by law.
- Childhood is defined as the period from the first birthday to the beginning of puberty.
- Chronological age refers to the number of years and days elapsed since birth.
- Development refers to the interrelationship between growth and maturation in relation to the passage of time. The concept of development also includes the social, emotional, intellectual and motor realms of the child.
- Growth refers to observable step-by-step changes in quantity, measurable changes in body size, for example, height, weight and fatness.
- Infancy refers to the first year of life.
- Maturation refers to qualitative system changes, both structural and functional in nature, in the organism's progress toward maturity, for example, the change of cartilage to bone in the skeleton.
- Puberty refers to the somatic and physiological changes in children as the gonads change to the adult state. Puberty is not normally completed until the person is capable of producing a child. In England, puberty is recognised in law as 12 years for girls and 14 years for boys.
- Skeletal age refers to the maturity of the skeleton determined by the degree of ossification of the bone structure.
- Trainability refers to the responsiveness of developing individuals at different stages of growth and maturation to the training stimulus.

Maturation

Biological maturation also follows a unique pattern and similarly is not linked to a chronological time frame. Hence in a class of children there will be a range of biologically mature and immature children for the same chronological age. There are three main methods to assess maturity by:

1. Somatic (body dimensions) growth
2. Skeletal age
3. Secondary sexual characteristics.

Somatic growth

The first assessment of biological maturity relates to predicting age at peak height velocity (PHV). The age at PHV can indicate maturity but serial measurements of height must be collected prior to and after the peak rate of growth and has been limited to longitudinal growth studies. More recently, a Canadian study (3) has led to the development of specific multiple regression equations based on chronological age, body mass, height, trunk length and leg length measures which eliminate the need for yearly measurements. This equation has been used to predict the age from PHV within ± 1 year in 95% of cases. Therefore it is quick, cheap and easy to use and can be used in cross sectional studies.

Skeletal age

The second assessment of maturity is the estimation of the skeletal age. This requires an X-ray of the hand and wrist, although occasionally the knee is used. The principle of this method is that an individual more advanced in maturity will have greater bone development and a smaller amount of cartilage than a less mature person. In a group of 13 and 14 year olds, skeletal ages from 9 to 16 years have been found, demonstrating the wide variation of skeletal maturity for the same age (4). There are also concerns about whether the X-ray of the hand and wrist can accurately reflect the whole skeleton, as discrepancies of one year or more have been found between X-rays of the knee and the hand/wrist (5). However, the method is considered to be the best index of maturation but it is costly, involves a radiation dose to the individual and does require specialised equipment and trained personnel for interpretation.

Secondary sexual characteristics

The final assessment is the rating of the secondary sex characteristics, a method devised by a paediatrician, James Tanner. Tanner was responsible for conducting the classic longitudinal growth studies in the UK called the Harpenden Growth Study 1948-1971, on which much of this country's data on child growth is based. Tanner developed the characterisation of the secondary sex characteristics from earlier investigations by Reynolds and Wines in the 1950s. In brief, the breast development in girls, genitalia development in boys and pubic hair development in both sexes are categorised into five stages, as all follow a known pattern of development. These secondary sex stages are commonly known as Tanner stages. The ratings must be made by visual inspection, which is more easily accomplished in a clinical setting than a sporting one and can lead to some adolescents and parents feeling uncomfortable with this procedure. This uneasiness has led some investigators to use self-assessment methods whereby children or adolescents rate their sexual development from standardised drawings or photographs. However, there are concerns over the ability of individuals to accurately evaluate and self rate the five stages (6). Age at menarche is sometimes used as an indicator of maturity but the time when menarche occurs is relatively late compared to other somatic measures. Menarche typically occurs in non-athletes between 12.1-13.5 years with the suggestion that athletic girls experience menarche at a later age. This has lead to some concern that intensive training might delay sexual maturation but evidence for this hypothesis has yet to be conclusively provided. In the majority of girls menarche commences when the velocity of growth is declining and tends to occur post PHV and when maximum growth and height decelerations are experienced.

Timing and tempo of maturation

One of the most important factors related to maturation is the timing and tempo as the time of entering puberty will vary considerably between members of the same sex. For example, girls enter and end puberty approximately 2 years ahead of boys, whilst the average age of breast development commences in girls at 10.5 years it can start as early as 8 or as late as 13 years. It is also entirely possible for one child to move through all five Tanner stages within 2 years whilst another individual might take six years. Therefore, it is extremely important to treat each child's growth and maturation on an individual basis and not merely to compare to average normative scores.

The majority of evidence examining the effect of training on growth appears to support the contention that training does not affect growth. However, not all researchers support this proposition (7). These authors argue that certain adolescent athletes may be at risk of restricted growth and delayed maturation when training is very intense and nutrition is inadequate. Although the body can compensate for this deficit by diverting nutrients from the normal growth processes eg. height, final adult height is not likely to be reduced. Daly and colleagues also argue that as most studies are merely reporting the average changes, there is a failure by researchers to pay appropriate attention to the interindividual differences in skeletal growth patterns, training volumes and nutritional strategies.

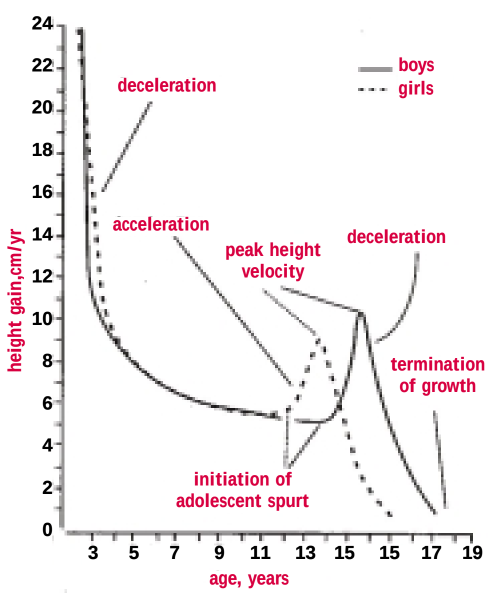

Figure 1: Velocity curve for boys and girls stature

Figure 2: Three gymnasts showing the wide variation of maturation for the same chronological age

> **KEY POINT**
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> **The definitive study to investigate the occurrence of inadequate growth in young athletes has yet to be performed but it is clearly warranted.**

CARDIOVASCULAR, RESPIRATORY AND MUSCULO-SKELETAL GROWTH

The monitoring of heart rate is a function that many coaches and children are involved in during training. Therefore understanding the changes in the heart's size is important. As children have smaller hearts than adults, they have a higher resting heart rate to compensate for a smaller stroke volume (amount of blood pumped per beat). Girls appear to have a resting heart rate on average 3-5 beats per minute higher than boys. After maturity there is a decrease in resting heart rate with age of approximately 0.8 beats per minute per year (8). Children also have a higher maximal heart rate than adults, approximately 195-220 beats per minute, but there does not appear to be a sex difference in childrens' maximal heart rate. Typical resting stroke volumes at birth, 5 and 15 years are 5 millilitres (mL), 25 mL and 85 mL respectively. With an increase in age, increases in heart size are therefore well correlated to the stroke volume increases.

Before puberty there is little difference in lung function scores between the sexes both at rest and in exercise. Young children tend to hyperventilate (rapid breathing) more than adults during exercise and ventilate more air in order to consume one litre of oxygen. As a result of increasing body size, the ability of the body to maximally consume oxygen during exercise increases. By approximately 11 years of age boys have a maximal aerobic capacity of 2.0 litres per minute and girls is 1.85 litres per minute. By age 17 years maximal aerobic power is 3-3.5 litres per minute for boys and 2-2.5 litres per minute for girls (Figure 3). Although there are differences between the sexes after puberty, the differences are smaller between age groups. This indicates that the body size and composition are important determinants of aerobic power. Early maturing boys and girls, who are bigger in size, especially if the increase in body size is due to increases in muscle rather than fat, will have a higher aerobic power output.

During puberty there is a substantial increase in the muscle mass of boys' compared to girls. At age 5, boys' muscle mass is estimated to be as high as 42% of total body mass, increasing to 54% by age 17. For girls, muscle mass increases from approximately 30% before puberty to 40-45% at age 17 years. The other important change in body composition is the increase in body fat between boys and girls. At 6 years of age, boys have ~11% of body fat which increases to 15% at 17 years of age. Girls have been found to have a body fat of

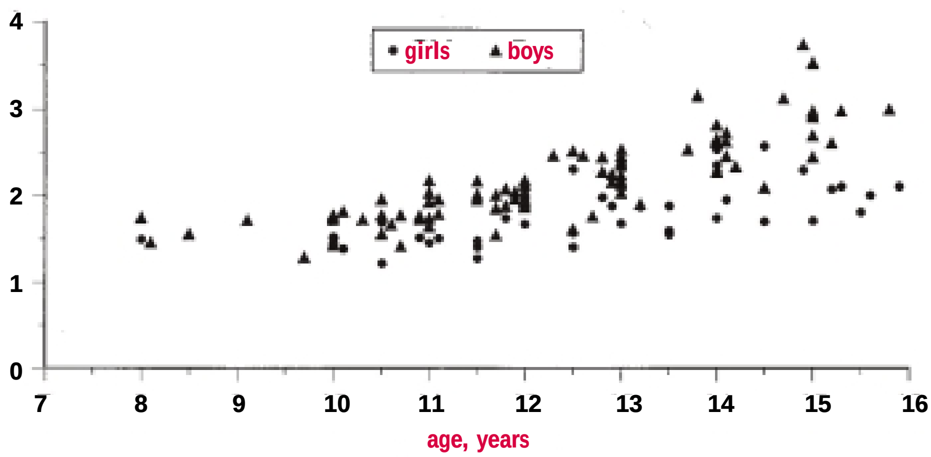

Figure 3: Peak oxygen uptake by boys and girls (reproduced from Winsley RJ, 1997)

14% at 6 years increasing to 25% by 17 years. Greater muscle mass and lower body fat is considered to be an important advantage for boys compared to girls. This is because the involvement of a greater amount of muscle mass will enhance performance whilst the additional increase in fat mass for girls must be carried during weight bearing activities eg. running and will decrease mechanical efficiency.

Boys who are mature for their chronological age are on average taller, heavier and have higher weight-to-height ratios than those boys who are late maturers. Also early maturing boys gain advantages in increased shoulder breadth and upper body muscle mass. These body changes are associated with increases in strength and power. These changes in muscle strength and power also translate to increases in aerobic power that further enhance sports performance. Girls who are early maturers are also taller, heavier with greater weight-to-height ratios than their same aged female peers. Early female maturers also have broader hips and shorter legs, which are associated with increased body fatness and can be disadvantageous in some sports. Interestingly, late maturing girls exhibit more linear physiques, less weight-to-height ratio, less fatness, relatively longer legs and lower hip-to-shoulder ratios, traits indicative of successful sporting performance. However, even though the physiological differences associated with maturity are less pronounced in girls than boys, it is not usual for early maturing girls to dominate female sport.

TEMPERATURE REGULATION

The physiological differences between children, adolescents and adults are particularly pertinent when temperature regulation is considered. Significant differences in body size and surface area create problems and disadvantage young children in the heat and the cold. Due to the larger surface area to body mass ratio, children will absorb heat quicker than adults, as well as losing heat during colder environments. When children gain heat more quickly than adults, they are further disadvantaged by a lower sweating rate compared to adults. This is partly because children have a delayed sweating mechanism, as a higher core body temperature needs to be reached before sweating commences. Therefore, children are more reliant on conductive cooling to lose heat and less on evaporative sweating mechanisms. Children may be more at risk from heat related injuries in humid conditions and coaches should ensure adequate rest periods and fluids. There is still more that needs to be investigated regarding temperature regulation, as the published literature is, at present confined to no more than 18 papers (9). There is some suggestion of a maturity effect regarding the sweating response, but like many other studies a lack of control of other confounding variables makes conclusions tentative.

TRAINING

Influences of training

The evidence to support the proposition that children are as trainable as adults is equivocal. This is due to a number of confounding variables:

1. Many studies have not measured or monitored maturity status and hence children in the training study start at different maturity stages.
2. Many studies are too short and contain too few participants to be statistically valid.
3. The training adaptations are difficult to differentiate from the effects of growth and maturation.
4. Issues of quantifying the training load in relation to establishing a dose-response pattern remain unresolved.
5. For ethical reasons measurements must be non-invasive and therefore determining the mechanisms of the adaptations remains limited.

Despite these confounding factors, there is an increasing opinion that children and adolescents are perhaps as trainable as adults, especially in relative percentage terms, but more research is required in this area.

Aerobic or endurance type training

Young athletes have a greater cardiac function than their sedentary peers with a larger heart volume and chamber size compared to non-athletic children. Although there is some concern about children and endurance exercise, a number of studies have found no adverse effect of intense endurance training on the heart of the child athlete. In one study the echocardiography of a group of 9-14 year old boys involved in a 4 km road race, showed no evidence of changes in left ventricular contractility (10). Based on the limited data there does not appear to be any indication that intense training of the child athlete injures the heart, but clearly more studies of a longitudinal nature and with more sports is warranted.

Training studies designed to increase aerobic power have generally shown that children are able to improve their aerobic power by ~5-10 % relative to body mass. This is similar to adult training studies (11). Interestingly, most of the studies conducted that examined the aerobic trainability of children have been conducted on children aged 8-11 years. There are considerably fewer studies from 13 years onwards which is when the increase in sports specialisation training often occurs (12). As many cross sectional and longitudinal studies have only involved school children and adolescents who are perhaps not genetically predisposed to elite sporting performance and have imposed the minimal level of training stimuli, it should be no surprise that the resulting adaptations are minimal. Coaches working with elite child athletes under a more rigorous training schedule in an academy or national squad, would be able to monitor and record more impressive adaptations of their athletes. It is this type of information that is needed to be shared between coaches, sports scientists and physiotherapists.

One future area of research is the consequences of prolonged exercise on the lower muscle glycogen stores of children and whether this leads to relatively earlier depletion than seen in adults during exercise (13). Linked to this potential research is the suggestion that children have a greater utilisation of fat stores during exercise (possibly as a consequence of lower glycogen stores) (14,15).

Anaerobic or sprint type training

Physiological adaptations due to anaerobic or sprint type training are mainly confined to the skeletal muscle and nervous system and have not been studied extensively in children. This is mostly due to methodological reasons because studies require invasive techniques such as a muscle biopsy. Although this technique has been used on children, firstly by Eriksson in the 1970s (16) and later by Fournier (17), Haralambie (18) and Glenmark (19), the results have been equivocal. There is some evidence that the enzyme profile begins to change during puberty but whether this is a more growth mediated or hormonal change, or both is still unclear. It has been shown that profound changes to testosterone levels in boys occurs during the pubertal growth spurt but other hormones such as growth hormone (GH), insulin-like growth factor 1 (IGF-1) cannot also be ignored, however relating the increase to improvements in performance is difficult to demonstrate.

Invasive methods have shown ATP and CP levels to be similar at rest compared to adults, however newer non-invasive methods using magnetic resonance spectroscopy (MRS) has shown some differences in children compared to adults during intensive exercise (unpublished data, CHERC). Although short duration sprint exercise (<10 seconds) appears to be easily accommodated by children, longer sprint exercise between 30 and 180 seconds appears to be limited compared to adults. Recent work from our laboratory has also attempted to link the fatigue of anaerobic metabolism and recovery from sprint exercise (20). Although it is assumed children require a shorter rest period than adults when participating in maximal sprint type exercise, the methodologies designed to examine this question have not addressed the issue of unequal amounts of work done between children and adults.

TABLE 2. BASES RECOMMENDATIONS FOR RESISTANCE TRAINING (BASES 2004)

1. All young people should be encouraged to participate in safe and effective resistance exercise at least twice a week.
2. Resistance exercise should be part of a balanced exercise and physical education programme.

Strength training

Strength training has remained a controversial topic in relation to children and training, mainly due to concerns about the potential for injury. The initial consensus was that children were not able to adapt to the strength training stimuli. The design of experiments examining strength training in children has suffered similar methodological issues as outlined earlier. One of the key pieces of evidence that was used to suggest that children could not benefit from strength training was a lack of hypertrophy. Although strength often improved, it was postulated that this was due to an improvement in the nervous system. More recent work in this area has concluded that relative strength (expressed as a percentage change pre to post training values) is as trainable in adults and children. To date, the differences between adults and children in terms of the absolute strength gains have been hypothesised to be due to muscle mass differences.

More research work is required to differentiate the neurological and the hypertrophy effects due to training, as this appears to be a key difference between children and adult responses to training. It is not clear whether prepubertal children lack the ability to sufficiently recruit all their muscles and therefore gain maximal activation from the training overload. Alternatively, neurological developments might take place with age which are then superimposed onto the increases in muscle mass and hormonal influences to substantially increase strength and effect performance. The British Association of Sport and Exercise Sciences has recently published guidelines for resistance exercise in young people (21). BASES advocate that providing resistance exercise is developmentally appropriate, carefully supervised and taught positively for both sport and health reasons, it can be beneficial to youngsters.

INJURIES

As children and adolescents are participating in intensive sports at younger and younger ages, there are concerns about the increased risk of injury. However, the published literature does not support such a proposition. Case study reports and anecdotal information are common but a much more thorough approach is warranted to track these young athletes. Injury studies have tended to conclude that injury rates are similar in adults and younger groups (22) and similar between male and female young athletes (23) but surveillance injury methodologies do vary. However, it is acknowledged that the causes of the injuries between adults and children differ.

Due to the differences in the growing bone of young athletes and adult bone, epiphyseal fractures or avulsion injuries are more common than ligamentous damage (24). Similarly, as the metaphysic of the long bone is more resilient and elastic than in adult bone, greenstick fractures are more common. Excessive repetitive sporting movements can lead to subchondral stress fractures, as even though the articular cartilage of growing bones in children is of a greater depth than adults it can undergo remodelling. These fractures can regress to osteochondrosis dissecans in the articular cartilage of the elbow, knee and ankle if untreated. The other area of concern is the relatively weak tendon bone attachment which if over exerted can lead to apophysitis eg. Osgood-Schlatters or Severs disease. Factors which contribute to the incidence of apophyseal injuries, have been identified; including weakened growth cartilages compared to the supporting muscle-tendon attachment, poor flexibility and increased tracking on the tendon insertion sites (25). The American College of Sports Medicine has suggested that many of the injuries diagnosed in adolescence are preventable and advocate pre-participation screening and regular visits to sports medicine personnel (26). However, before this strategy is embarked upon, sports scientists must make a more unified attempt to quantify and monitor the training volume at the time of rapid growth and development if they are to fully understand the impact of training.

CONCLUSION

The earliest training studies involving children invariably included a wide range of sporting and physiological capabilities that are not typical of child athletes who regularly train and compete nationally. Consequently, evidence that children were as trainable as adults was equivocal. More recent studies examining children training under more intense training volumes and for longer durations (> 6 months) are showing that children are, in relative percentage terms, comparable to adults. Additionally, this comparability becomes stronger as the adolescent moves through the maturational stages until adult status is attained (27). After this period physiological adaptations, as a consequence of training, are likely to be due to the training stimulus and a minor component due to statural growth and maturation components.

Well constructed experiments, which have adequately controlled for growth and maturation in order to explain the effect of training on selected physiological variables are rare. This has lead to conflicting opinions particularly in relation to the issue of training and injuries and whether training affects growth. More work is urgently needed in these areas. It is important to appreciate the many positive benefits of children being involved in sport but children are not mini adults. Therefore, a coach whilst nurturing sporting talent must do so in the knowledge of the individual athletes growth and maturational stages.

THE AUTHOR

Prof Craig Williams has been involved in the coaching and research of paediatric physiology for over twenty years. He is currently Associate Director of the Children's Health and Exercise Research Centre (CHERC), School of Sport and Health Sciences, University of Exeter and has published extensively in journals including Sports Medicine, Journal of Applied Physiology, Pediatric Exercise and British Journal of Sports Medicine. He is regularly consulted by such organisations as the British Cycling Federation, British Gymnastics and English Cricket Board on aspects related to the growth, maturation and training of young athletes.

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ADDITIONAL RESOURCES

- Intensive training and sports specialisation in young athletes. Committee on Sports Medicine and Fitness. Pedatrics 2000;106: 154-157 http://www.pediatrics.org/cgi/content/full/106/1/154
- The Child growth Foundation has a dedicated website related to percentiles for height and body mass of U.K. children http://www.healthforallchildren.co.uk
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