GROWTH, MATURATION AND PHYSICAL FITNESS

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7.1 AIMS

The aims of this chapter are to:

1 outline methods to assess growth and maturation

2 describe how measures of physical fitness and performance are impacted by growth and maturation

3 outline methods used to examine body weight status and composition

4 examine laboratory-based testing protocols to determine and interpret aerobic and anaerobic fitness in children and adolescents

5 present field-based testing batteries for measuring physical fitness in children and adolescents.

7.2 INTRODUCTION

Children and adolescents are encouraged to perform daily physical activity in order to promote their health and wellbeing (Department of Health, 2011). Many children and adolescents are also becoming increasingly engaged in competitive sport, receiving specialised and intensive training under the supervision of coaches (Mountjoy et al., 2008). In addition, there is a growing recognition of the role that exercise can play in the management of a paediatric diseases (Bar-Or and Rowland, 2004). Thus, there is a desire amongst researchers, healthcare practitioners, educators and coaches to measure and monitor markers of growth, maturation and physical fitness in children and adolescents.

Compared to adults, children and adolescents are a unique population and require additional considerations relating to: ethics and informed consent; interpreting data in relation to both chronological and biological age; the impact of body size and composition and using child-friendly protocols that are valid and reliable. Issues pertaining to children participating in research, including the level of risk that they should be exposed to and obtaining consent have been extensively reviewed elsewhere (Jago and Bailey, 2001, Stratton and Williams, 2007).

7.3 GROWTH AND MATURATION

7.3.1 Definition of Terms

Conceptually, growth, maturation and development are often used inter-changeably and sometimes even considered synonymously, but all three should be defined separately. Growth is a dominant biological activity during the first two decades of life and refers to the increase in size of the whole body or specific parts of the body. Changes in size are outcomes of: an increase in cell number or hyperplasia; an increase in cell size or cell hypertrophy and/or an increase in intercellular material or accretion. Maturation refers to the process of becoming fully mature and it provides an indication of the status that is attained along the way to adulthood. Maturation specifically comprises a tempo (a rate of maturity progress) and timing (maturity at a given age) in the progress towards the mature biological state. Finally, development is a broader concept, encompassing growth, maturation, learning, and experience. It can relate to cognitive, motor and emotional abilities as a child's personality grows within the lived cultural and environmental experiences. Motor development is a process by which a child acquires movement patterns and skills. It is characterized by continuous modification based upon neuromuscular maturation, growth and maturation of the body, residual effects of prior experience and new motor experiences (Malina et al., 2004).

7.3.2 Growth

A number of longitudinal studies were initiated in the 1920s in the USA and later in Europe, which served as a basis of our present knowledge on physical growth and maturation (Malina et al., 2004, Tanner, 1981). In addition, to assess the growth of specific parts of the body, appropriate anthropometric techniques have been extensively described elsewhere (Lohman et al., 1988, Norton and Olds, 1996).

Growth begins at conception and continues until the late teens or even the early twenties. The increases in total body size or individual components of the body occur throughout growth, but the predominance of each process varies with age. For example, the increase in length of lower and upper limbs precedes the increase in truncal length during adolescence. Postnatal growth patterns can be subdivided into four phases: infancy (from birth to 2 years), early childhood (pre-school), middle childhood (to adolescence) and adolescence (from 8-18 years for girls and 10-22 years for boys).

The two most common measurements of growth are height (stature) and body mass. Body mass (measured in kg) is a composite of the varying mass of the tissues within the body. Nude body mass is the correct assessment method but as this is impractical in a paediatric setting, measurements are usually made with minimal clothing (e.g. shorts and t-shirt). From birth up to two years of age, recumbent length is measured with the child lying down on their back. From two years onwards, standing height is attained with specific standardized positions adopted (Lohman et al., 1988). Both height and body mass experience diurnal variations with recumbent length and height being greatest in the morning and decreasing during the day. The opposite is exhibited with body mass as we are often the lightest in the morning, especially if voiding upon awaking. Throughout the day body mass increases, largely due to dietary intake.

Another useful measure is sitting height as it allows determination of the length of the lower extremities to that of the trunk. Sitting height is measured by subtracting the standing height from the sitting height and provides a measure of the leg length also known as subischial length. A sitting stadiometer is the recommended piece of apparatus but other arrangements can be implemented (Lohman et al., 1988). Other possible measurements include skeletal breadths/limb circumferences/skinfold thickness/head circumference and the respective ratios and proportions that can be calculated from these assessments (see Lohman et al., 1988, Malina et al., 2004).

7.3.3 Maturation

Biological maturation varies with the biological system that is selected and comprises the assessment of sexual, morphological, dental or skeletal maturation. Sexual maturation refers to the process of becoming fully sexually mature, such as reaching functional reproductive capability. Morphological maturation is often estimated through the percentage of adult stature that is attained at a given chronological age, or by using the timing of the characteristics of the adolescent growth curve such as the age at peak height velocity (PHV). Skeletal and dental maturation refers respectively to a fully ossified adult skeleton or dentition (Beunen et al., 2006, Tanner, 1981, Malina et al., 2004). Both the growth of somatic dimensions and biological maturation are under the control of hormonal and biochemical axes and their interactions are detailed elsewhere (Casazza et al., 2010). Only further consideration will be given to assessing maturation using sexual maturation and morphological measures, given their routine use in the paediatric literature.

7.3.4 Assessment of sexual maturation

Sexual maturation is invariably assessed using the criteria described by Reynolds and Wines (1948, 1951) which was synthesised and popularised by Tanner (1962), based on different stages of breast, genital or pubic hair development. Five discrete stages for each area are described, and the example description for pubic hair development in boys and girls is provide below and illustrated in Figure 1:

- Stage 1: pre-pubertal. The vellus over the pubes is not further developed than that over the abdominal wall. There is no pubic hair.
- Stage 2: sparse growth of long, slightly pigmented downy hair, straight or only slightly curled, appearing chiefly at the base of the penis or along the labia.
- Stage 3: considerably darker, coarser and more curled. The hair spreads sparsely over the junction of the pubes. It is at this stage that pubic hair is first seen in the usual type of black and white photo graph of the entire body; special arrangements are necessary to photograph stage 3 hair.
- Stage 4: hair now resembles adult in type, but the area covered by it is still considerably smaller than in the adult. No spread to the medial surface of the thighs.
- Stage 5: adult in quantity and type with distribution of the horizontal (or classically 'feminine') pattern. Spread to medial surface of thighs but not up to linea alba or elsewhere above the base of the inverse triangle.

The stage of sexual maturation for a given individual is assigned by visual inspection of the nude participant or from somatotype photographs from which the specific areas are enlarged. Given the intrusiveness of this method, however, self-reporting methods are often used (Morris and Udry, 1980). Validation studies of self-reported sexual maturity vary considerably depending on the age of the participants, gender, ethnicity, group characteristics (e.g. socially disadvantaged children), and the settings in which the assessments are made (Cameron, 2004) Younger children tend to overestimate and older children underestimate their stage of development, whereas boys overestimate and girls are more consistent with expert ratings.

Age at menarche, defined as the first menstrual flow, can be obtained retrospectively by interviewing a representative sample of sexually mature females. Considerable errors have been documented for the individual age at menarche, but recall data are reasonably accurate for group comparisons (Beunen, 1989, Malina et al., 2004). In contrast, data collected using a longitudinal or prospective design is more accurate through interviewing a representative samples of girls expected to experience menarche. The investigator records whether or not menstrual periods have started at the time of investigation. Thus, the longitudinal or prospective methods provide age at menarche on an individual level, whereas in a retrospective design only an estimated age at menarche for a sample is provided.

7.3.5 Morphological maturation: Prediction of adult height and maturity offset.

When percentage of predicted adult height is used as an indicator of morphological maturity, the actual measured height is expressed as a percentage of predicted adult height. The problem here is to estimate or predict adult height. Several prediction techniques have been developed (Tanner et al., 2001, Roche et al., 1975, Bayley and Pinneau, 1952), have good accuracy and are commonly used. The predictors in these techniques are actual height, chronological age, skeletal age and, in some techniques, parental height and/or age at menarche for girls. However, it has been demonstrated that reasonable accuracy can be obtained in predicting adult stature when skeletal age is replaced by chronological age (Wainer et al., 1978). Beunen et al. (1997) proposed the Beunen-Malina method for predicting adult height using four somatic dimensions (current height, sitting height, subscapular skinfold, triceps skinfold) and chronological age.

For boys 12.5–13.5 years, for example, adult height can be predicted using the following regression equation:

Adult height (cm) = 147.99 cm + 0.87 · stature (cm) – 0.77 · sitting height (cm) + 0.54 · triceps skinfold (mm) – 0.64 · subscapular skinfold (mm) – 3.39 · chronological age (years)

The main advantage of the Beunen-Malina method is that it is non-invasive as it does not require the assessment of skeletal age based on radiographs. However, the original Tanner-Whitehouse-II or more recent Tanner-Whitehouse-III method (Tanner et al., 2001) is preferred when radiographs of the hand and wrist are available. Recently the Beunen-Malina method has been extended to include prediction of adult height in girls aged 12-15 years and is applicable to European populations or population of European ancestry (Beunen et al., 2011). The Beunen-Malina-Freitas method is a non-invasive method utilising lengths, diameters, circumferences and presence or absence of menarche and proposed a number of age-specific equations.

Another non-invasive estimate of morphological or somatic maturity uses the time before or after PHV as a maturity indicator. PHV is the maximum rate of growth occurring during the adolescent growth spurt (Baxter-Jones et al., 2005). Girls begin their adolescent growth spurt on average, two years before boys (8-10 years vs 10-12 years respectively), which can confer a temporary advantage of height and body mass for girls around this time. However, boys have a higher PHV and experience, on average, two more years of pre-adolescent growth than girls. This results in adult males being, on average, 13 cm taller than adult females. During the early part of the growth spurt, rapid growth in the lower extremities is observed, while an increased trunk length occurs later, and a greater muscle mass later still. There are also noticeable regional differences in growth during adolescence. Boys, for example, have only a slightly greater increase in calf muscle mass than girls, but nearly twice the increase in muscle mass of the arm during the adolescent growth spurt (Malina et al., 2004).

To estimate somatic maturity, Mirwald et al. (2002) have developed sex-specific regression algorithms that allow for the determination of the years from PHV using a non-invasive and simple to administer anthropometrical measures on a cross-sectional basis. All that is required is a measure of standing height (cm), sitting height (cm), leg length (stature-sitting height, cm), body mass (kg) and chronological age (years). A child's age from PHV can be estimated and used to determine the age at PHV to within ± 1 year error (95% confidence intervals). For example, for a 11.6 year old boy with a maturity offset score of –2.2 years, his (predicted) age at PHV is 13.8 (± 1) years. A distinct advantage of this technique is that the age at PHV is a common marker of (somatic) maturity both within and between subject groups and across sexes. The equations are:

Boys age from PHV (years) = -9.236 + (0.0002708 · ((leg length · sitting height)) + (-0.001663 · (age · leg length)) + (0.007216 · (age · sitting height)) + (0.02292 · (body mass by height ratio expressed as percentage))

Girls age from PHV (years) = -9.376 + (0.0001882 · (leg length · sitting height) + (0.0022 · (age · leg length)) + (0.005841 · (age · sitting height)) - (0.002658 · (age · body mass)) + (0.07693 · (body mass by stature ratio expressed as a percentage))

7.4 Growth, Maturation and Performance

Somatic characteristics, biological maturation and physical performance are interrelated and young athletes typically exhibit specific maturity characteristics (Malina and Rogol, 2011). For example, young elite male athletes are generally advanced in their maturity status, whereas young female athletes tend to show late maturity status, especially in gymnastics, figure skating and ballet dancing. Thus, the assessment of biological maturity is a very important indicator of the growing child. It is therefore a valuable tool for professionals involved in the evaluation of the growth and development of children in a sports setting.

Usually sex differences that may influence performance are minimal before adolescence. Both boys and girls experience rapid growth in height during infancy and steady growth (~ 5-6 cm per year) during childhood, before the initiation of the pubertal growth spurt leading to the attainment of PHV. Prior to adolescence, relatively minor somatic differences between boys and girls become magnified during adolescence. Following the growth spurt, girls generally display a broader pelvis and hips, with a proportionately greater trunk/leg ratio. Body composition also changes from approximately 20% body fat to 25% body fat over this period. Boys, in contrast, maintain a similar body fat (~15%) over the adolescent growth period – a change that is accompanied by a dramatic rise in lean body mass, shoulder width and leg length. Such differences between the sexes, the boys being generally leaner, more muscular, broader shouldered and narrower hipped with relatively straighter limbs and longer legs have implications for physical performance. It should be recognized that when comparing physical performances of male and female adolescents, that other factors such as motivation and changes in social interests (Smith et al., 2010) and the documented fall-off in physical activity, particularly in girls (Brodersen et al., 2007), may also influence results. The disproportionate rise in strength of boys compared with girls over the adolescent growth spurt has also been attributed to increasing levels of testosterone (Round et al., 1999).

There is no such individual as the ‘average adolescent’ performer and there is a large individual variation inherent in biological maturation and sexual differentiation that can impact youth sports performance. PHV may, on average, be between 11 and 12 years for girls and between 13 and 14 years for boys, but there may be as much as five years difference in the timing of this phenomenon, and similar variation in the development of secondary sex characteristics, between any two individuals of the same sex. Thus, a child’s chronological age is likely to bear little resemblance to their biological age, the latter being of greater importance to physical performance. This is illustrated in Figure 2 which demonstrates an early maturer to have a distinct advantage in most indices of physiological performance, whereas for the late maturer, performance is disadvantaged. This is most relevant for tasks requiring strength and power. This relationship between performance and biological maturation is also likely to be present within a single year group as a given child may be up to 11 months older than their peers. For example, Sherar and colleagues (2007) found in 619 Canadian ice hockey players aged 14-15 years old, that the birth dates (known as the relative age effect or RAE) of those players selected for the team were positively skewed, with the majority of selected players born in the months January to June. This suggests that the team selectors preferentially selected early maturing male ice hockey players with birth dates early in the selection year.

The biological events associated with growth and development, particularly over the period of adolescence, highlight the complexity of interpreting performance test scores. Thus to provide a valid interpretation of physiological and performance based measures either in the laboratory of field environment, an individual’s or a group of individuals’ level of maturity must be accounted for. As highlighted earlier, an assessment of biological maturation may be obtained from an estimation of skeletal age using radiograph techniques, or sexual maturation using illustrations of secondary sex characteristics. However, given the invasive and intrusive nature, and the requirement for trained personnel, these techniques may have limited application. More convenient and commonly applied by researchers are the methods which relate to somatic measurements and prediction of adult height or age at PHV as described in earlier sections.

Whilst most youth sports competitions are still organised based on chronological age categories, numerous researchers have questioned this approach (Williams, 2010, Baxter-Jones, 1995). These age, growth and maturational considerations are especially important when decisions are made in respect to sport selection and talent development (Malina et al., 2015), such as in the Long-Term Athlete Development (LTAD) model for talented youngsters (Ford et al., 2011). It would appear that the RAE inequalities are most prevalent within sports involving adolescent (aged 15–18 years) males and at the regional and national level in most popular sports. Therefore, organisers of sports associations need to understand the mechanisms by which the RAE inflate and subside, as well as confirm whether age effects are as strong in females and more diverse cultural settings (Cobley et al., 2009). Interestingly, when football scouts watch games knowing the shirt numbers of the players corresponds to their relative age, the selection bias is eliminated (Mann and van Ginneken, 2016). Finally, the implementation of bio-banding in sports has been initiated with favourable reports, as this categorises players according to their maturational (or body size) status rather than chronological age (Myburgh et al., 2016).

7.5 BODY COMPOSITION

7.5.1 Body weight status

One of the simplest and most commonly used measures of estimating body weight status is the Body Mass Index (BMI), or Quetelet's Index (Weight/Height^2). As stated, BMI provides a measure of excess body weight relative to height but it does not measure body fatness per se.

In growing children, particularly boys, use of this index as a measure of relative obesity may be misleading, as a large proportion of weight gain during adolescence is lean rather than adipose tissue. Thus, the BMI may increase from 17.8 $kg.m^{-2}$ to 21.3 $kg.m^{-2}$ in 11 and 16 year-old boys respectively, while the sum of four skinfolds (biceps, triceps, subscapular and iliac crest) falls from 33.7 mm to 31.5 mm over the same period. Despite this potential limitation, age and sex specific international cut-off points for 'overweight' and 'obesity' are available for children between the ages of 2 to 18 years (Cole et al., 2000). However, a recent review has suggested the accuracy of BMI to identify children with excess adiposity depends on the degree of body fatness and is only a good indicator in those who are obese (Freedman and Sherry, 2009). Finally, BMI data have been found particularly useful in predicting cardiometabolic risk. Gracia-Marco et al. (2016) recently found BMI, together with the sum of four skinfolds, waist-to-height ratio, waist circumference and lean mass to be the strongest body composition indices associated with clustered cardiovascular risk in adolescents.

7.5.2 Body fatness

Many methods are available to assess body fatness in children such as body circumferences, skinfolds and air displacement plethysmography. In the last decades, the use of anthropometric measures of abdominal adiposity such as waist circumference, waist-to-hip ratio, or waist-to-height ratio has been employed worldwide. These measures have been suggested as alternatives to, or in addition to, BMI in assessing disease prediction in clinical practice and public health surveillance (Dobbelsteyn et al., 2001). There are, however, concerns about the reliability of these measurements (Sebo et al., 2008). For example, waist circumference can differ depending on the site at which it is measured (Wang et al., 2003). From a clinical point of view, waist circumference is a useful measure for the screening of metabolic syndrome (clustering of cardiometabolic risk factors) in children (Moreno et al., 2002).

Another method of measuring body composition in children relies on the use of skinfold thicknesses, commonly following the procedure described by Lohman et al. (1989). The prediction of percentage body fat from skinfold thickness relies on the relationship between skinfolds and body density. However, the changes in body composition during growth affect the conceptual basis for estimating fatness and leanness from body density (Armstrong and Welsman, 1997). For example, the water content of a child's fat free mass decreases from 75.2% in a 10-year old boy, to 73.6% at 18 years (Haschke, 1983) and bone density increases during childhood. Because of the above reservations, some investigators choose simply to sum the four skinfold thicknesses (biceps, triceps, subscapular and iliac crest) for use as a comparator. Alternatively, body fatness can be derived from triceps and subscapular skinfolds in children and adolescents (Slaughter et al., 1988).

From a clinical and public health point of view, measuring skinfold thicknesses or waist circumference might be an issue due the difficulty in obtaining accurate and reliable measurements. In contrast, obtaining reliable measures of BMI is much more likely since height and weight can be easily measured. Therefore, BMI is proposed in routine clinical and public health practice as a preferred measurement to identify individuals at risk of future disease.

Body fat has been also widely measured in children using two-component techniques such as air displacement plethysmography (BOD POD®). The BOD POD® method distinguishes fat mass and fat-free mass after assuming specific densities of these two tissues. However, special considerations must be taken when measuring children, especially in those with clinical conditions. BOD POD® measures the volume of air displaced by the participant and it has been shown to have a better precision than hydrodensitometry in children (Dewit et al., 2000, Nunez et al., 1999). During a test, body volume is measured twice to ensure measurement reliability. The percentage of whole body fat is calculated using standard equations (Siri, 1961, Siri, 1993). This method is expensive and time consuming (both for the researcher and participant) and not portable, meaning participants have to visit a laboratory facility. Details on the validity of using the BOD POD® method to assess body composition in children and adolescents has been reviewed elsewhere (Fields et al., 2002).

7.5.3 Bone health

The skeleton is an endocrine organ that undergoes constant remodelling especially during the childhood and adolescence years. Bone mineral content (BMC) increases from birth until the end of the second decade of life, although some bone deposition may still be acquired into the third decade (Golden et al., 2014). Childhood and adolescence is a critical period for skeletal mineralization because approximately 90% of peak bone mass has been accrued by the age of 18 years (Bachrach, 2001) and 40% to 60% of adult bone mass is accrued during the adolescent years (Baxter-Jones et al., 2011). After infancy, peak bone mineral accretion occurs at the age of 12.5 years for girls and 14.0 years for boys (Bailey et al., 2000). In children as in adults, fracture rates have been shown to be higher in individuals with a lower bone mineral density (BMD) (Faulkner et al., 2006). Therefore, the assessment of bone health is of great importance during childhood and adolescence.

Dual-energy x-ray absorptiometry (DXA) is the most widely used method to assess bone mass in children due to specific advantages in terms of availability, precision, speed, low cost and low dose of radiation (5–6 mSv for the lumbar spine, hip, and whole body, which is less than the radiation exposure of a transcontinental flight and one-tenth that of a standard chest radiograph) (Lewis et al., 1994). In addition, there are robust paediatric reference databases for children older than 5 years included within the software of the major DXA manufacturers (Zemel et al., 2013). However, caution should be given to the interpretation of the DXA results because: 1) children have not yet achieved peak bone mass, therefore *Z* scores should be used instead of T scores; 2) DXA measures two dimensional areal BMD, as opposed to three dimensional volumetric BMD, which may underestimate the true volumetric BMD in children with smaller size; 3) many children with chronic illness have delayed maturation and 4) confounding factors, such as diet and physical activity, may affect the bone parameters derived from DXA. Therefore, appropriate adjustments should be made for age, height, maturation status, body composition (lean and/or fat mass), diet and physical activity when needed (Gracia-Marco, 2016, Vlachopoulos et al., 2016b, Vlachopoulos et al., 2016a).

More quantitative imaging technologies assessing bone health have been developed, and currently the most used techniques include quantitative ultrasound (QUS) and quantitative computed tomography (QCT). QCT has an advantage over the other techniques because it measures bone volume and thus accurately computes volumetric BMD (vBMD). However, it exposes the patient to a substantial amount of radiation (effective radiation dose 60 μSv). Peripheral QCT is emerging as an attractive alternative technology because it is able to distinguish between the trabecular and cortical bone compartments, but exposes the patient to far less radiation compared to the conventional QCT (Ward et al., 2005). As an alternative to radiation, QUS emerged by using ultrasound waves to assess bone stiffness. It is considered a valid, easy to use, portable, cost and time effective and radiation-free method to assess bone health in children (Jaworski et al., 1995). These characteristics are particularly indicated to assess bone mineral status in children. In addition to BMC and vBMD, QUS provides some structural information, which may be important in determining the fracture risk (Baroncelli, 2008).

7.6 FITNESS TESTS

Physical fitness can be defined as characteristics that relate to a person's ability to perform physical activities that require aerobic capacity, endurance, strength or flexibility, and is determined by inherited and environmental factors (Caspersen et al., 1985). In the context of children and adolescents, measures of physical fitness may be performed from a research, health or performance perspective. In a performance context, while muscular strength, speed, agility, coordination and flexibility are important determinants of athletic performance, the literature has focussed on measures of aerobic and aerobic fitness as they are fundamental to athletic events and team sports (Barker and Armstrong, 2011). As for health and wellbeing, physical fitness is considered an important marker of health, not only in adulthood but also in childhood (Ortega et al., 2008). Children and adolescents with elevated levels of cardiorespiratory fitness (CRF), otherwise known as aerobic fitness, are associated with a lower risk of cardiovascular disease risk (Ruiz et al., 2015) and improved skeletal health (Gracia-Marco et al., 2011), quality of life (Morales et al., 2012) and mental health (Ruiz et al., 2009). Muscular fitness has also gained attention in the last decade. A high muscular fitness in youth is related to reduced clustering of cardiovascular disease risk factors, independent of CRF (Artero et al., 2011b) and is related to premature death in adulthood (Ortega et al., 2012). Finally, in addition to CF and muscular fitness, other fitness components such as flexibility and speed/agility have gained attention from the health perspective (Ruiz et al., 2009). Unfortunately, children and adolescents' performance in tests designed to measure CRF has declined over the last three decades and is not fully explained by increasing levels of body fatness (Tomkinson, 2007, Tomkinson and Olds, 2007). Consequently, there have been recent calls for widespread surveillance of CRF in youth (Kaminsky et al., 2013).

7.6.1 LABORATORY BASED FITNESS TESTS

Although more commonly used in the research setting, laboratory based measures of physical fitness in children and adolescents have typically focused on developing protocols to measure aerobic and anaerobic fitness.

Aerobic fitness

The participation in physical activity, whether in the form of recreational activity or sporting performance, requires the effective integration of the cardiovascular, respiratory and muscular systems to support the metabolic demands of exercise (Wasserman et al., 2005). Three of the key parameters of aerobic fitness are: maximal oxygen uptake ($\dot{V}O_{2\ max}$); blood lactate threshold, and oxygen cost of exercise (exercise economy). The collective measurement of these parameters permits a comprehensive assessment of the aerobic fitness in children and adolescents and have been used to understand the effect of growth and maturation (Cooper et al., 1984), exercise training (McNarry et al., 2011) and disease (Saynor et al., 2014). Although the measurement of $\dot{V}O_{2\ max}$ is likely to be the most important outcome for characterising aerobic fitness of an individual within a health context, for the child athlete the measurement of choice will depend on the objectives of the assessment and predictive power of sporting performance (Barker and Armstrong, 2011).

Maximal oxygen uptake

The single best indicator of aerobic fitness in children and adolescents is $\dot{V}O_{2\ max}$ (Armstrong and Welsman, 1994), which represents the limit of the respiratory, cardiovascular and muscular systems to transport and utilise O_2 during exercise. The measurement of $\dot{V}O_{2\,max}$ is typically performed in the laboratory setting using either a treadmill (motorised) or cycle ergometer, although other ergometers (e.g. arm cranking) may be used. It is important that the child is adequately familiarised to the ergometer. In some cases, bespoke paediatric cycle ergometers with different arm crank lengths and handle bar and/or seat adjustments may be required for very small children.

Protocols for maximal exercise testing in children can be classified as continuous or discontinuous. The latter may be more suitable when testing with younger children who are unlikely to have little prior experience of a maximal effort and may require verbal support during the rest periods (Stratton and Williams, 2007). Continuous treadmill protocols for children generally involve either a modified Balke protocol, in which treadmill speed is held constant while the gradient is increased every minute by 2%, or a modified Bruce protocol. The advantage of the Balke protocol is that it only requires the child to cope with changes in one variable (grade). Alternatively, treadmill protocols are available where the gradient remains constant (1%) and starting at a speed of 5 $km \cdot hr^{-1}$ the speed is increased 0.5 $km \cdot hr^{-1}$ every 30 s until exhaustion (Thackray et al., 2016).

An appropriate cycle ergometer protocol is the well-established McMaster protocol where the starting power output and increments in power output every 2 minutes are based on stature. An alternative protocol on the cycle ergometer is a ramp-incremental exercise test where power output increases as a linear function of time rather than in step increments. This protocol is well tolerated by children of all ages and allows for the determination of all three parameters of aerobic function ($\dot{V}O_{2\,max}$, blood lactate threshold and the O_2 cost of exercise) within 6-10 min (McNarry et al., 2011, Cooper et al., 1984). For children as young as 8-10 years, a ramp increment of 10 W per minute is suitable, whereas 15 W per minute for 10-13 year old children, and up to 20 W per minute for 14-17 year old children.

The primary criterion for determination of $\dot{V}O_{2\,max}$ in children and adolescents is the that close to exhaustion, in a well-motivated participant, $\dot{V}O_2$ will no longer increase linearly with the exercise intensity, but display a plateau (Armstrong and Welsman, 1994). However, it is well documented that only ~ 20-40% of children and adolescents display a $\dot{V}O_2$ plateau, and that a large proportion may see an accelerated or linear increase in $\dot{V}O_2$ at exhaustion (Barker et al., 2011b). Thus, the term 'peak $\dot{V}O_2$' rather than $\dot{V}O_{2\,max}$ has been adopted as the appropriate terminology in children and adolescents and a number of secondary criteria have been proposed to verify a maximal effort (Leger, 1996, Armstrong and Welsman, 2008):

- Heart rate $\geq$ 200 beats·min^{-1} during treadmill exercise or $\geq$ 195 beats·min^{-1} during cycling or a heart rate within 85-95% of age predicted maximum
- Respiratory exchange ratio (RER) $\geq$ 1.00
- Blood lactate concentration $\geq$ 6 mmol·L^{-1}
- Extreme forced ventilation, or subjective signs of exhaustion (e.g. facial flushing, intense effort)

Using these criteria, the within-subject error for determining peak $\dot{V}O_2$ in children and adolescents has a coefficient of variation (CV) of ~ 5% (Welsman et al., 2005). Recent studies, however, have shown that the use of secondary criteria to verify a $\dot{V}O_{2\,max}$ in children and adolescents are invalid as these criteria occur at a 'sub-maximal' $\dot{V}O_2$ and can falsely reject a 'true' $\dot{V}O_{2\,max}$ (Barker et al., 2011b, Robben et al., 2013). These studies concluded that the use of secondary criteria should be abandoned and proposed the use of supra-maximal testing following a short rest after the initial incremental test to confirm the measurement of a 'true' $\dot{V}O_{2\ max}$ (Figure 3). For example, using the $\dot{V}O_2$ profile across both tests, Barker and colleagues (2011b) were able to identify a $\dot{V}O_2$ plateau in ~ 95% of their participants. This combined ramp and supramaximal protocol has been applied to children with expiratory flow limitation (Robben et al., 2013) and cystic fibrosis (Saynor et al., 2013), highlighting the broad application of this protocol to determine $\dot{V}O_{2\ max}$ in children and adolescents.

Blood lactate threshold

The measurement of blood lactate during exercise provides a powerful marker of sub-maximal aerobic fitness. In children, the blood lactate threshold can be determined through capillary blood samples obtained at various steady-state points of discontinuous incremental exercise protocol. Blood lactate concentration can be plotted against variables such as running speed or $\dot{V}O_2$, and the point at which an increase in blood lactate above baseline occurs is referred to as the lactate threshold. An improvement in aerobic fitness is characterised by a lower blood lactate at a given power output, or the ability to attain a higher power output for a given fixed blood lactate concentration. The use of fixed blood lactate concentrations are less prone to observer error associated with the subjective determination of the lactate threshold and provide a sensitive means of quantifying the effect of training and growth and maturation on sub-maximal aerobic fitness. However, as the commonly used 4.0 $mmol \cdot L^{-1}$ fixed blood lactate concentration may occur at ~ 90% peak $\dot{V}O_2$ in 13-14 year old adolescents, the 2.0 or 2.5 $mmol \cdot L^{-1}$level may be a more appropriate marker of sub-maximal aerobic fitness (Williams and Armstrong, 1991). Knowledge of the blood lactate threshold or fixed blood lactate concentration may be especially useful for youth athletes as they are correlated with endurance performance and enable the identification of training zones (Barker and Armstrong, 2011).

The requirement for repeated capillary blood samples to determine the lactate threshold may be unappealing and traumatic for some children. Therefore, one of its non-invasive surrogates, the gas exchange threshold (GET) or ventilatory threshold (VT), can be employed to monitor sub-maximal aerobic fitness. A positive correlation exists between the VT and the blood lactate threshold when expressed as an absolute $\dot{V}O_2$ (r=0.91) and as a percentage of $\dot{V}O_{2\,max}$ (r=0.82) in children, demonstrating excellent criterion validity (Anderson and Mahon, 2007). Furthermore, both the GET and VT are reliable in children, demonstrating a CV of ~ 6-8% (Fawkner *et al*., 2002). The GET/VT have been shown to be sensitive to monitoring changes in aerobic fitness during growth and maturation and in response to exercise training in young people (Mahon and Cheatham, 2002). Lastly, as the GET/VT typically occurs at ~ 55-65% $\dot{V}O_{2\,max}$ in children, its measurement may be a more judicious choice when the goal is to determine aerobic fitness in children who are contraindicated to exercise (e.g. disease groups), or experience difficulties in exercising at higher intensities (Hebestreit et al., 2000).

Oxygen cost of exercise

The oxygen cost of exercise (exercise economy) is defined as the $\dot{V}O_2$ required to exercise at a given sub-maximal speed or power output and can be determined using both treadmill (for measurement of running economy) and cycling exercise protocols. This measuring provides insight into the energy cost to perform submaximal tasks and in youth athletes is an important determinant of running and swimming performance (Ali Almarwaey et al., 2003, Unnithan et al., 2009). The accurate measurement of the oxygen cost of exercise requires an exercise protocol that imposes increments in power output or speed that are at least 3 minutes in duration and at an exercise intensity below the lactate threshold. This ensures the attainment of steady-state exercise and the oxygen cost of exercise can then be determined from the $\dot{V}O_2$ response between the 2nd and 3rd minutes. The oxygen cost of exercise may also be determined from a ramp based incremental exercise test, where power output increases as a linear function of time. By plotting $\dot{V}O_2$ as a function of power output, the slope between the two variables provides the $\dot{V}O_2$ increase per minute per W ($mL \cdot min^{-1} \cdot W^{-1}$). This technique has successfully been used to monitor changes in aerobic fitness during growth and maturation (Cooper et al., 1984) and in children with a chronic disease (Saynor et al., 2014, Moser et al., 2000).

Anaerobic fitness

In comparison to aerobic fitness, the direct measurement of the anaerobic energy turnover during whole body exercise is restricted to invasive procedures such as the muscle biopsy technique (Eriksson, 1980), which is ethically questionable in the healthy child. However, some groups have used ^{31}P-magnetic resonance spectroscopy to determine the muscle phosphates (e.g. PCr, ATP) and cellular pH under non-invasive conditions, which allows a direct insight into anaerobic energy metabolism during exercise in young people (Barker and Armstrong, 2010). This technique is, however, still in its infancy and has received little investigation due to the financial burden of the specialist equipment required and the restricted type of exercise that can be performed whilst lying inside the bore of a magnetic resonance scanner. Although providing valuable information regarding the muscle metabolic response during exercise in healthy (Barker et al., 2010, Tonson et al., 2010) and diseased (Wells et al., 2011) children, this technique lacks context with exercise and performance in the 'real world' (Beneke et al., 2005).

The bulk of research has focussed on the power output profile generated during short-term 'all out' cycling or treadmill exercise as a means of assessing anaerobic fitness in children (Van Praagh, 2000). The mechanical power output achieved is equivalent to between two and three times the power output obtained during a $\dot{V}O_{2\,max}$ test, and as such is considered to reflect energy turnover via anaerobic pathways (Williams, 1997). Interpreting the metabolic basis of the power output profile generated during ‘all out’ short-term exercise is, however, not straight forward. It has been estimated that ~ 21% of the total energy turnover during a 30 s all out cycling Wingate anaerobic test (WAnT) is provided via oxidative metabolism whereas PCr and anaerobic glycolysis represented ~ 34% and ~ 45% of the total energy turnover in children respectively (Beneke et al., 2007). Moreover, children can elicit >90% of their $\dot{V}O_{2\ max}$ within 60-90 s of commencing ‘all out’ cycling exercise (Williams et al., 2005, Barker et al., 2011a). Thus, while the energetic provision of ATP is largely anaerobic during short-term ‘all out’ exercise, there is a significant oxidative contribution and should be considered when interpreting the data from such tests, especially those of longer duration (>30 s).

The measurement of mechanical power output to reflect anaerobic performance is invariably determined during ‘all out’ exercise bouts lasting between 1-60 s. The power output indices that are subsequently used to quantify anaerobic performance are (Bar-Or, 1996):

- Peak power, defined as the highest mechanical power output that can be elicited by the contracting muscles during a given ‘all out’ exercise bout. This should occurs within 1-5 s of the onset of exercise.
- Mean power, defined as the average mechanical power that is achieved during a given ‘all out’ short-term bout, which is thought to reflect the local muscle endurance or the muscles’ ability to sustain power output during the exercise bout.
- The fatigue index, which represents the percentage decline in the final power output when expressed relative to peak power:

  Fatigue index (%) = ((peak power – final power) / peak power) × 100

  The fatigue index is however, less reliable the peak or mean power output measures (Naughton et al., 1992).

Cycling tests

The Wingate anaerobic test (WAnT) is the most researched test of anaerobic performance in children. The WAnT test requires the participant to pedal 'as fast as they can' against a fixed resistance on a braked ergometer for 30 s. The breaking force typically used is 0.74 newtons (N) per kg of body mass ($N \cdot kg^{-1}$, or 7.5% body mass) for cycling exercise, although this may not be optimal. Santos et al. (2002) demonstrated in a group of 9-10 year old children and 14-15 year old adolescents that the optimal breaking force required to elicit peak power output was 0.69 ± 0.10 and 0.93 ± 0.14 $N \cdot kg^{-1}$ for males and 0.82 ± 0.18 and 0.82 ± 0.10 $N \cdot kg^{-1}$ for females respectively. This indicates that the optimal breaking force for the WAnT protocol is related to age and sex, and that the prescription of a fixed force (7.5% body mass) is unlikely to yield the participant's optimum peak power output during a WAnT. The WAnT has been examined more extensively than any other anaerobic performance test for several paediatric populations (abled, disabled, and trained) and found to be highly valid and reliable (Sutton et al., 2000).

If the measurement of a 'true' maximal power output is required, then variable breaking forces should be used to obtain the optimum force and velocity parameters which elicit maximal power output. To determine maximal power output, participants can perform a force-velocity test. After an adequate warm-up and familiarisation procedure, the participant performs a number of 5-8 s 'all out' sprints on a cycling ergometer at a range of braking forces. For example, Santos et al. (2002) required children and adolescents to perform 5-8 s 'all out' cycling bouts at randomly assigned braking forces ranging from 0.30 to 1.08 $N \cdot kg^{-1}$ on a Monark 814 ergometer, with a 5 minute rest (1 min active recovery and 4 min rest) allowed between each bout. Using the relationship between braking force and velocity to calculate the peak power output for each sprint, the resulting values can be plotted against its corresponding breaking force. The apex of the parabolic relationship between power output and breaking force, allows the peak power output to be obtained alongside the optimal breaking force that is required to elicit 'maximal' power output for the participant (Figure 4). The within participant reliability (mean bias ± 95% limits of agreement) for determining the maximum power output using this technique is -16.7 ± 38.3 W in 14-15 year olds (Santos et al., 2002).

Treadmill tests

To increase testing specificity with regard to performing every day physical activities (e.g. jogging, running) and sports where body mass is not transported, non-motorized treadmill (NMT) ergometers have been developed to study anaerobic performance. Wearing a belt at the waist, the participant attains maximal velocity whilst running 'all-out' on a NMT. Power output is calculated using the horizontal strain placed on the belt and the treadmill velocity. This methodology has been used in order to examine short-term power output (5 to 30 s) in children under conditions where body weight is transported. The study by Sutton et al. (2000) used an adapted version of the non-motorized treadmill test (called the Exeter Nonmotorized Treadmill Test [ExNMT]) and reported the test-retest reliability 27 and 15 W for peak and mean power output respectively, which compares well with the WAnT.

As the power output profile during a single 'all-out' test may not fully reflect the physiological characteristics of team sports, it has been suggested that test protocols should be adapted to reflect the pattern of running within a given sport (Meckel et al., 2009). For example, Oliver et al. (2006) have found excellent reliability (< 8% CV) for a range of velocity and power output derived indices during a repeated sprints test consisting of seven 5 s sprints on a NMT separated by 25 s of light running in untrained adolescent boys. This work has been developed further to include repeated sprints within a NMT test that mimicked the physiological demands over one half of a soccer match in school-level players (Oliver et al., 2007). The sport-specific test was shown to yield good to excellent test-retest reliability for total distance covered (2.5-3.8% CV), peak and mean power output (5.9-7.9% CV), and peak and mean velocity (3.8% CV). The physiological stress (~ 85-90% peak heart rate and blood lactate ~ 6-7 $mmol \cdot L^{-1}$) during the protocol was similar to previously reported data in young people during soccer matches.

7.6.2 Field based fitness tests

The use of laboratory tests to measure physical fitness in children is not always appropriate or feasible, and several batteries of field tests have been proposed mainly to cater for large scale population studies and/or the educational environment. Comparing an individual's score in a particular fitness test with normative values stratified for age and sex is currently common practice in assessing an individual's fitness status. However, fitness reference values are region specific and this is important from a comparison perspective. For example, normative values for a number of fitness reference values are available from different countries such as America (Pate et al., 2006, Carrel et al., 2012, Tremblay et al., 2010), Asia (Tomkinson et al., 2007), Africa (Olds et al., 2006) and Europe (Ortega et al., 2011, De Miguel-Etayo et al., 2014). Recently, however, international age and sex specific normative data for CRF has been published based on 1,142,026 children and adolescents from 50 countries and provide a powerful tool for profiling and monitoring fitness (Tomkinson et al., 2016).

Field-based testing also has utility from a screening perspective, which may enable a more targeted approach for identifying and monitoring children with an elevated risk of disease. For example, using data on 4,500 9 or 15 year olds from the European Youth Heart Study, Adegboye et al. (2011) published age and sex specific cut-offs for CRF that predict elevated cardiometabolic risk. However, it should be noted that other cut-offs for a ‘healthy’ CRF exist in youth (Welk et al., 2011), with no consensus in the literature.

7.7 FITNESS TEST BATTERIES

The ALPHA (Assessing Levels of PHysical Activity and fitness) project developed a field-based fitness test battery for children and adolescents (6-18 years of age) after conducting three systematic reviews relating to criterion-related validity (Castro-Pinero et al., 2010), measurement reliability (Artero et al., 2011a) and relationship with health (Ruiz et al., 2009). Based on these comprehensive reviews, the ALPHA fitness-test battery (Ruiz et al., 2011) was developed and proposed the following tests as a high priority: the 20 m shuttle-run test for CRF; the handgrip strength and standing long-jump tests for assessing musculoskeletal fitness, and waist circumference and BMI as anthropometric measures of body composition (Figure 5). In an extended version of the battery, measuring skinfold thickness was also deemed desirable.

At the European level, the IDEFICS (Identification and revention of Dietary- and lifestyle-induced health EFfects In Children and infantS) study was the first to provide reference values for children (6 to 10.9 years of age) (De Miguel-Etayo et al., 2014) using a battery of tests adapted from the ALPHA battery (Ruiz et al., 2011). The battery included: the 20 m shuttle run test (CRF), handgrip strength and standing long jump tests (upper and lower muscular fitness), 40-m sprint test (speed/agility fitness), back-saver sit-and-reach test (flexibility) and the flamingo test (balance), which are valid, reliable and feasible for health monitoring in this population (Castro-Pinero et al., 2010). In adolescents, the HELENA (Healthy Lifestyle in Europe by Nutrition in Adolescence) study used established fitness tests to provide novel normative data across in European adolescents across 10 counties (Ortega et al., 2011). In this study, the handgrip strength and bent arm hang tests were used to assess upper-body muscular fitness, the standing long jump, squat jump, counter-movement jump and Abalakov tests were used to assess lower-body muscular fitness, the 4 x 10 m shuttle run test was used to assess speed/agility, the back-saver sit and reach test was used to assess flexibility and finally, the 20 m shuttle run test was used to assess CRF.

Recently, a proposal of a field-based fitness-test battery in preschool children, the PREFIT battery (fieldbased FITness testing in PREschool children) was published (Ortega et al., 2015). PREFIT was not proposed for those aged 2 due to their motor and cognitive development. The PREFIT battery includes the following tests: the 20 m shuttle-run test for assessing CRF, the handgrip-strength and the standing long-jump tests for assessing muscular fitness (upper and lower-body, respectively), and the 4 x 10-m shuttle-run and one-leg-stance tests for assessing motor fitness, i.e. speed/ agility and balance, respectively. In addition, BMI and waist circumference are also recommended as anthropometric markers (Figure 6).

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FIGURE CAPTIONS

Figure 1. The five discrete stages of pubic hair development in boys (A) and girls (B). Taken from Tanner (1962) with permission.

Figure 2. Mean motor performance scores of early-, average- and late-maturing boys in the Leuven Growth study of Belgian Boys. Adapted from Malina and Bouchard (1991) with permission.

Figure 3. Determination of maximal oxygen uptake ($\dot{V}O_{2\ max}$) using a combined ramp-supramaximal cycling protocol. The $\dot{V}O_2$ response in a 9-year-old boy during the ramp and supramaximal cycle test is separated by ~ 15 min of recovery. The vertical dotted lines represent the start and end of the incremental and supramaximal bouts. The highest $\dot{V}O_2$ from the ramp test was 1.65 $L \cdot min^{-1}$ which is denoted by the horizontal dotted line. Note that despite a 5% increase in power output during the supramaximal bout, the highest $\dot{V}O_2$ recorded was 1.57 $L \cdot min^{-1}$, thus illustrating the attainment of $\dot{V}O_{2\ max}$ despite no plateau evident in the initial ramp test. Adapted from Barker and Armstrong (2011) with permission.

Figure 4. An example force-velocity (●, primary y-axis) and a force-power output (○, secondary y-axis) profile derived from a force-velocity test consisting of six different breaking forces. The maximum power output is identified by the horizontal dotted line and its corresponding optimum breaking force is identified by the vertical dotted line. Adapted from Barker and Armstrong (2011) with permission.

Figure 5. High-priority fitness tests in children and adolescents according to the ALPHA project.

Figure 6. Proposal of a fitness-test battery for preschool children aged 3-5 years (The PREFIT Battery).