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Critical review

Education

Paediatric exercise testing in clinics and classrooms: a comparative review of different assessments

BC Bongers*, M van Brussel, HJ Hulzebos, T Takken

Abstract

Introduction

Physical fitness or aerobic capacity, is an important determinant of overall health. A higher aerobic capacity can lead to many health benefits. Paediatric exercise testing is important for identifying children and adolescents at risk for major public health diseases, as well as to be able to unravel the physiological mechanisms of a reduced aerobic capacity and to evaluate intervention effects. Aerobic capacity can be defined as the maximal capacity of the pulmonary and cardiovascular systems to take up and transport oxygen to the exercising muscles and of the exercising muscles to extract and utilize oxygen from the blood during progressive exercise with large muscle groups up to maximal exertion. Throughout progressive exercise, oxygen transport enlarges due to the integrative response of different physiological systems, resulting in an increase in cardiac output, minute ventilation and the arteriovenous oxygen difference. The aim of this critical review was to discuss the different assessments of paediatric exercise testing in clinics and classrooms.

Conclusion

Cardiopulmonary exercise testing is the gold standard for determining aerobic capacity as well as for examining the physiological response to exercise. However, this test is not always feasible to perform in a non-clinical setting in large population based studies. The steep ramp test and the 20 m shuttle run test are valid and reliable non-sophisticated alternatives for predicting aerobic capacity in children and adolescents in those studies. Nevertheless, prediction equations used to estimate aerobic capacity reached during cardiopulmonary exercise testing from steep ramp test or 20 m shuttle run test performance should be interpreted with caution. Additionally, these non-sophisticated tests should not be used as a substitute for performing regular cardiopulmonary exercise testing, as they are less accurate and do not provide diagnostic or prognostic information.

* Corresponding Author
E-mail: b.c.bongers-2@umcutrecht.nl

Child Development & Exercise Center, Wilhelmina Children's Hospital, University Medical Center Utrecht, Utrecht, the Netherlands

Introduction

Childhood and adolescence are fundamental phases in life in which remarkable physiological, anatomical and psychological transformations occur due to growth and maturation. These transformations directly affect the level of physical fitness. Physical fitness is a principal concept in (clinical) exercise physiology and can be considered as an integrated measure of most, if not all, body functions involved in the performance of daily physical activity and physical exercise[1]. These body functions include aerobic capacity, body composition, muscular strength, power, speed, balance, flexibility and hand–eye coordination[2]. A high level of physical fitness in childhood and adolescence is associated with more favourable health-related outcomes concerning present and future risk for obesity, cardiovascular disease, skeletal health and mental health[1,3]. Paediatric exercise testing is a valuable, non-invasive procedure to evaluate physical fitness throughout childhood and adolescence.

Aerobic capacity is one of the most important components of health-related physical fitness. It has been found to be an important determinant of overall health, in which a higher aerobic capacity is related to a lower morbidity and mortality in healthy adults[4,5], as well as in adults with a chronic condition[6]. In children and adolescents, aerobic capacity has also been reported to be an important marker of health. For example, higher aerobic capacity is associated with lower total adiposity[7] and is inversely associated with cardiovascular risk factors[8]. In paediatric and young adult patients with congenital heart or lung disease, aerobic capacity was found to be a prognostic factor for morbidity and mortality at later age[9–12]. The measurement of maximal oxygen uptake (VO_{2max}) or peak oxygen uptake (VO_{2peak}) during a progressive cardiopulmonary exercise test up to maximal exertion is widely considered to be the gold standard for assessing aerobic capacity[13,14]. The non-invasive and dynamic nature of the performed measurements during cardiopulmonary exercise testing provides important information that can be utilized for diagnostic, prognostic and evaluative purposes. This emphasizes the significance of paediatric exercise testing to assess aerobic capacity for health screening purposes in childhood and adolescence, as well as in children with a chronic condition.

As opposed to healthy children, children with a chronic condition are often restricted in their participation in physical activities and sport

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Competing interests: none declared. Conflict of interests: none declared.
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programmes as a consequence of real or perceived limitations imposed by their condition. The chronic condition itself often causes hypoactivity, which leads to a deconditioning effect, a reduction in functional ability and a downward spiral of further hypoactivity[15]. Hypoactive children often are at greater risk for health problems that can be prevented (e.g. cardiovascular disease, obesity, pre-diabetes). Many children with a chronic condition have reduced levels of aerobic capacity. Figure 1 depicts VO_{2max}/VO_{2peak} z-scores in different chronic conditions collected in studies performed by our research group. The reduced levels of aerobic capacity are generally caused by a combination of disease-related pathophysiology, treatment (e.g. medication), hypoactivity and deconditioning.

Next to adjusting and optimising treatment and disease management, results from paediatric exercise testing are increasingly used to compose individually tailored exercise training programmes. An exercise training programme might be indicated when aerobic capacity is significantly reduced compared to sex- and age-matched normative values (i.e. lower than –2 standard deviations). Through individualized physical exercise training, the combined capacity of the pulmonary, cardiovascular, hematopoietic, neuromuscular, musculoskeletal and metabolic systems increases considerably. As a consequence, aerobic capacity, as well as the functional abilities of the child, increases. Many scientific studies in different patient populations have investigated the safety and efficacy of physical exercise training in children[16–18]. By means of randomized controlled trials, our research group has reported positive effects of exercise training interventions in various paediatric patient populations [18–22]. These studies indicate that a 'one size fits all' principle does not apply in (paediatric) exercise training physiology. An individually tailored approach is therefore recommended.

Next to a brief introduction to paediatric exercise physiology, the current review aims at providing an overview that describes how to assess aerobic capacity (VO_{2max}/VO_{2peak}) in (groups of) children using the cardiopulmonary exercise test, as well as using the steep ramp test and the 20 m shuttle run test. The steep ramp test and 20 m shuttle run test can be used to predict aerobic capacity without directly measuring VO_{2max}/VO_{2peak} in children and adolescents and therefore appear to have greater applicability in non-clinical settings when large groups of children and adolescents are tested.

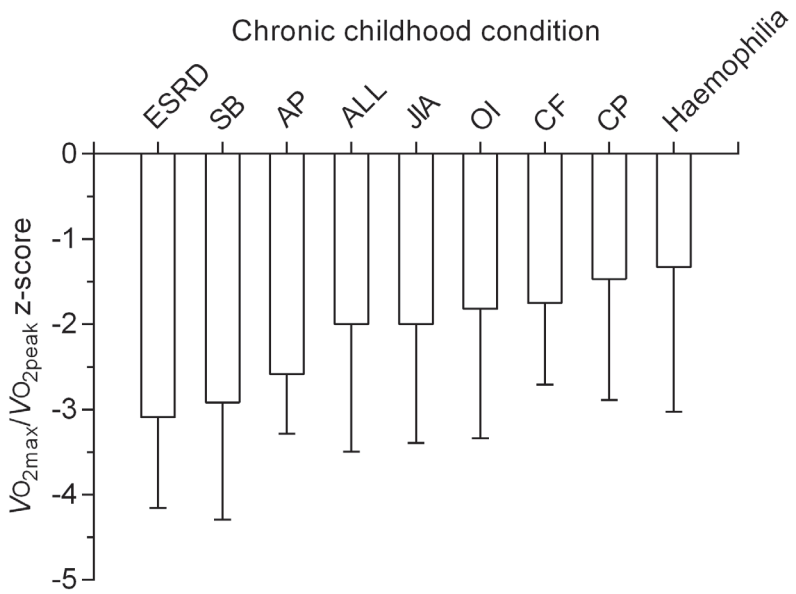

Figure 1: Aerobic capacity (VO_{2max}/VO_{2peak}) of children with a chronic condition. Abbreviations: ALL, acute lymphoblastic leukaemia; AP, achondroplasia; CF, cystic fibrosis, CP, cerebral palsy; ESRD, end-stage renal disease; JIA, juvenile idiopathic arthritis; OI, osteogenesis imperfecta; SB, spina bifida; VO_{2peak}, highest measured oxygen uptake. Note: Data is extracted from studies of our research group[18,21,23–29]. The reference values of Binkhorst et al.[30] were used to calculate z-scores.

Discussion

The authors have referenced some of their own studies in this review. These referenced studies have been conducted in accordance with the Declaration of Helsinki (1964) and the protocols of these studies have been approved by the relevant ethics committees related to the institution in which they were performed. All human subjects, in these referenced studies, gave informed consent to participate in these studies.

Paediatric exercise physiology

During physical exercise, adequate interactions are required between different physiological systems, to transport an adequate amount of oxygen and nutrients to the exercising muscles as well as to remove the metabolically produced carbon dioxide from the exercising muscles, to maintain homeostasis. Accordingly, the response of the individual physiological systems is linked to cell respiration with the aim of maintaining homeostasis (Figure 2)[31]. The cardiopulmonary system is continuously

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stressed during progressive physical exercise to facilitate an increase in oxygen transport. Oxygen transport enlarges due to increases in cardiac output (heart rate × left ventricular stroke volume), minute ventilation (breathing frequency × tidal volume) and the arteriovenous oxygen difference, when the exercising muscles require more oxygen to sustain muscular contractions. Aerobic capacity, aerobic fitness, aerobic capacity, aerobic power, maximal aerobic power, aerobic work capacity, cardiopulmonary fitness, cardiovascular fitness and VO_{2max} all refer to the same concept and can be defined as the maximal capacity of the pulmonary and cardiovascular system to take up and transport oxygen to the exercising muscles and of the exercising muscles to extract and utilize oxygen from the blood during progressive exercise with large muscle groups up to maximal exertion. According to the Fick equation[32], VO_{2max} is the product of the maximal cardiac output and the maximal arteriovenous oxygen difference. Each of the systems involved in the pathway for oxygen from the atmosphere to the mitochondria might be a physiological limiting factor for VO_{2max}. A 'true' VO_{2max} requires a clear plateau (asymptote) in oxygen uptake despite an increasing work rate (exercise intensity). Since this plateau is seldom observed in adults[33], as well as in children and adolescents[34,35], the highest measured oxygen uptake (VO_{2peak}) is often used interchangeably with VO_{2max} to define aerobic capacity.

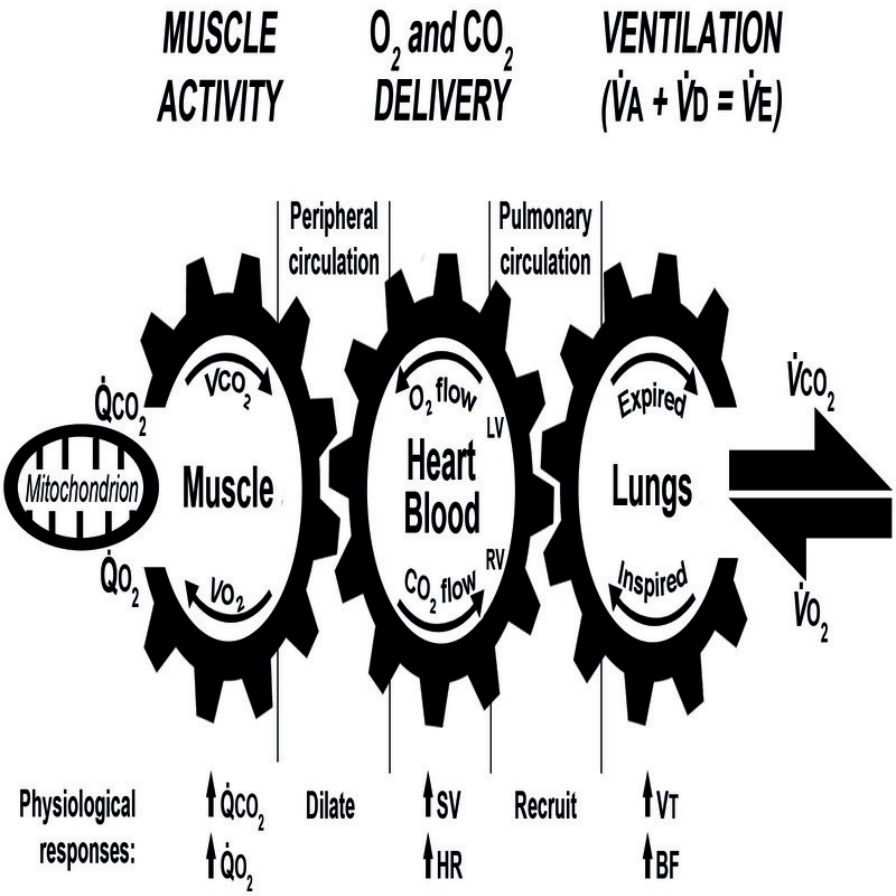

Figure 2: The integrative physiological response of the different organ systems to exercise. Abbreviations: CO_2, carbon dioxide; BF, breathing frequency; HR, heart rate; LV, left ventricle; O_2, oxygen; QCO_2, carbon dioxide production by the exercising muscles; QO_2, oxygen uptake by the exercising muscles; RV, right ventricle; SV, left ventricular stroke volume; VT, tidal volume; *V*A, alveolar ventilation; VCO_2, carbon dioxide production; *V*D, physiological dead space; *V*E, minute ventilation; VO_2, oxygen uptake. Note: Adapted from Wasserman et al.[31]

During the initial phase of progressive physical exercise, an increase in cardiac output is primarily regulated by an increase in left ventricular stroke volume, in response to an increase in the volume of blood filling the heart (the end diastolic volume), when all other factors remain constant (Frank-Starling mechanism). It is assumed that when exercise intensity increases (> 40% of VO_{2max}), cardiac output will increase mainly by an increase in heart rate. However, it is of great importance to realize that the maximal heart rate is genetically predetermined, as well as that the maximal heart rate achieved by children and adolescents is independent of age[36]. In contrast to adults, in which the maximal heart rate decreases with age according to the rule of thumb by 208 − (age × 0.7)[37], the maximal heart rate remains relatively stable around 190 beats·min^{-1} in children and adolescents[38]. Further, the maximal left ventricular stroke volume during progressive physical exercise differs significantly between children and adults. Compared to adults, children obtain a smaller left ventricular stroke volume at peak exercise, which they compensate for by a higher heart rate at peak exercise. Nevertheless, the smaller left ventricular stroke volume in children and adolescents is an important limiting factor of their oxygen transport system.

The increase in minute ventilation during the early stages of progressive physical exercise can be almost completely explained by an increase in tidal volume. When the tidal volume equals approximately 50% of the vital capacity of the lungs, minute ventilation increases merely exclusively by

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an increase in breathing frequency. During progressive physical exercise up to maximal exertion, ventilation is seldom an exercise limiting factor. Only in children and adolescents with a severely reduced lung function (< 65% of the predicted forced expiratory in one second, FEV_1), a ventilatory limitation possibly exists that limits maximal exercise capacity[39]. However, there are specific developmental aspects observable during childhood and adolescence. Minute ventilation and the efficiency of ventilation increase with age, in which the latter can be explained by a decreasing breathing frequency, coinciding with an increasing tidal volume[38].

Next to the abovementioned factors, the arteriovenous oxygen difference and the oxygen transport capacity of the blood are also of importance during physical exercise. The arteriovenous oxygen difference refers to the difference in oxygen concentration between the arterial blood and the venous blood. This represents the amount of oxygen that is extracted from the blood and utilized by the exercising muscles and organ systems. During maximal exercise, there is no difference in arteriovenous oxygen difference between pre-pubertal boys and girls[40,41]. Post-pubertally, however, there is an evident sex-difference observable, with higher arteriovenous oxygen difference values attained by boys. Adult males and females have a considerably greater maximal arteriovenous oxygen difference compared to boys and girls[42]. The latter study also demonstrated a sex-difference in adults for maximal arteriovenous oxygen difference, with higher values attained by males. During submaximal exercise, the arteriovenous oxygen difference is somewhat higher in children compared to adults[42–44]. This phenomenon can be explained by the fact that children compensate for their lower cardiac output by extracting relatively more oxygen from the blood. The oxygen transport capacity of the blood increases slowly during childhood, resulting in significant sex-differences in adulthood. On average, adult males have a higher haemoglobin concentration in their blood compared to adult women[45].

Paediatric exercise testing in clinics

The determination of oxygen and carbon dioxide concentrations in expired air at regular intervals throughout a progressive cardiopulmonary exercise test up to maximal exertion is the gold standard for the determination of VO_{2max} (aerobic capacity). In addition, the integrated response of different physiological systems (the pulmonary, cardiovascular, hematopoietic, neuromuscular, musculoskeletal and metabolic systems) can be objectively evaluated at rest, during progressive exercise up to maximal exertion and during recovery. This integrative approach and analysis of the different physiological systems are of additive value compared to the evaluation of each physiological system separately at rest, since the latter cannot reliably predict aerobic capacity and functional capacity[14]. The non-invasive and dynamic nature of the performed measurements provides the clinician with important information that can be used for diagnostic, prognostic and evaluative purposes (Table 1)[46]. It can identify physiological causes for exercise-related complaints and symptoms, as well as assess (functional) exercise capacity and exercise limiting factors, including pathophysiological changes. Therefore, cardiopulmonary exercise testing can support physiological reasoning and clinical decision-making. Next to its well-recognized value in cardiology, pulmonology and in sports medicine, many other medical specialties (e.g. metabolic disorders, oncology) are currently showing interest in the data and interpretation of cardiopulmonary exercise testing, often omitting more comprehensive assessments.

VO_{2max} or VO_{2peak}, is one of the best known and most frequently determined cardiopulmonary exercise test parameter, since it appeared to be an important determinant of overall health. For clinicians and researchers, normative values for VO_{2peak} facilitate adequate interpretation of aerobic capacity. Paediatric normative values for VO_{2peak} are depicted in Figure 3. It is however important to realize that next to VO_{2peak}, several other exercise parameters should be determined to interpret the cardiopulmonary exercise test in an adequate and complete manner. These parameters, their derivatives and perceptual responses of the child are a direct or indirect, reflection of the previously mentioned integrated physiological interactions during physical exercise. A selection of relevant exercise parameters is summarized in Figure 4.

There are different methodologies to perform a cardiopulmonary exercise test and many exercise laboratories use their own standardized protocols. When a child's performance is compared to reference values, it is necessary to standardize the cardiopulmonary exercise test according to the testing procedures and methodology that were used to establish the reference values[46]. In addition, the choice of an appropriate exercise protocol is dependent on the complaints and symptoms, as well as on the fitness level of the child. The Bruce protocol is the most frequently used protocol in children and adolescents using a treadmill for cardiopulmonary exercise testing[47]. However, important physiological measurements during exercise, including the electrocardiogram and blood pressure, are easier to assess and of better quality using a cycle ergometer. Moreover, maximal work rate can be assessed accurately using a cycle ergometer, which is not feasible when using a treadmill. When performing a cardiopulmonary exercise

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test using a cycle ergometer, the Godfrey protocol[48] is very convenient to use in children and adolescents. The Godfrey protocol consists of a three-minute warming up, after which the work rate (exercise intensity) increases each minute until voluntary exhaustion. Initial work rate and work rate increments are based on the child's body height (10, 15 or 20 W·min^{-1} for a body height < 125 cm, 125–150 cm and > 150 cm, respectively). In children with a chronic condition, a ramp version of the Godfrey protocol is more appropriate. In the ramp version of this protocol, there is an (almost) linear increase in WR (2, 3 or 4 W·12 s^{-1}), instead of each minute, to determine the patient's maximal work rate more precisely. Throughout the exercise test, the pedalling frequency should be kept constant between 60 and 80 revolutions per minute and peak exercise is defined as the point at which the pedalling frequency drops definitely from 60 revolutions per minute, despite strong verbal encouragement.

For an adequate and complete interpretation of the acquired exercise data, it is essential that the participant performs a maximal effort. Although the integrated physiological response to exercise is measured objectively during cardiopulmonary exercise testing, performance during exercise testing depends on the motivation of the participant. Consequently, motivating and encouraging the participant prior to and during the cardiopulmonary exercise test is very important, especially in children. As already mentioned, the levelling-off of oxygen uptake despite continuing exercise and increasing work rate is considered the best evidence of a maximal effort. The absence of a clear plateau in oxygen uptake at the end of an exercise test results in a dilemma. Has the participant performed an effort at or near, the maximal level, despite the lack of a plateau in oxygen uptake? There are other objective physiological criteria available for this decision. For paediatric populations, Armstrong and Welsman[49] recommend to use heart rate as well as the respiratory exchange ratio (carbon dioxide production divided by the oxygen uptake) at VO_{2peak} as additional objective criteria to assess the quality of the performed effort. More specifically, they recommend a heart rate at VO_{2peak} of at least ≥ 95% of 195 beats·min^{-1} and a respiratory exchange ratio at VO_{2peak} of at least 1.00 as supplementary criteria of a maximal effort during cardiopulmonary exercise testing. Subjective criteria of a maximal effort (e.g. sweating, facial flushing, unsteady walking, running or biking and clear unwillingness to continue exercising despite strong encouragement) are also valuable factors in drawing this conclusion. Finally, it is possible to verify whether the attained VO_{2peak} reflects true VO_{2peak} by completing a supramaximal exercise test with respiratory gas analysis following cardiopulmonary exercise testing[50]. When using a treadmill for cardiopulmonary exercise testing, the child then performs a supramaximal treadmill test at 110% of their maximum achieved speed for a maximum of

Table 1 Indications to perform cardiopulmonary exercise testing in paediatric medicine

Cardiopulmonary exercise testing as a diagnostic test
Assessment of aerobic capacity (VO_{2max}/VO_{2peak})
Assessment of exercise limiting factors, including pathophysiological changes
Assessment of heart rhythm and heart rate
Assessment of blood pressure response
Assessment of exercise-induced bronchoconstriction or dysfunctional breathing
Assessment of exercise-induced symptoms (chest pain, dyspnoea, increased fatigability)
Cardiopulmonary exercise testing for the assessment of disease severity
Heart disease:
Assessment of exercise-induced arrhythmias and repolarisation disturbances
Assessment of myocardial ischemia
Assessment of disease severity after surgical correction
Assessment and optimisation of pacemaker function
Respiratory disease:
Assessment of gas exchange abnormalities
Assessment of overall pulmonary gas exchange
Assessment of hypoxia
Assessment of the need for lung transplantation
Cardiopulmonary exercise testing as a prognostic test
Assessment of the course of a progressive disease (regular follow-up)
Assessing other (additional) potential contributing factors to exercise limitation
Cardiopulmonary exercise testing as an evaluative test
Assess suitability, establishing a baseline and assessing the effectiveness of an intervention programme
Pre-operative or pre-treatment screening (e.g. lung transplantation, chemotherapy)
Assessment of the efficacy of a surgical correction
Assessment of the effects of medication on the response to exercise

Abbreviations: VO_{2max}, maximal oxygen uptake; VO_{2peak}, highest measured oxygen uptake.
Note: Adapted and modified from Bongers et al.[46]

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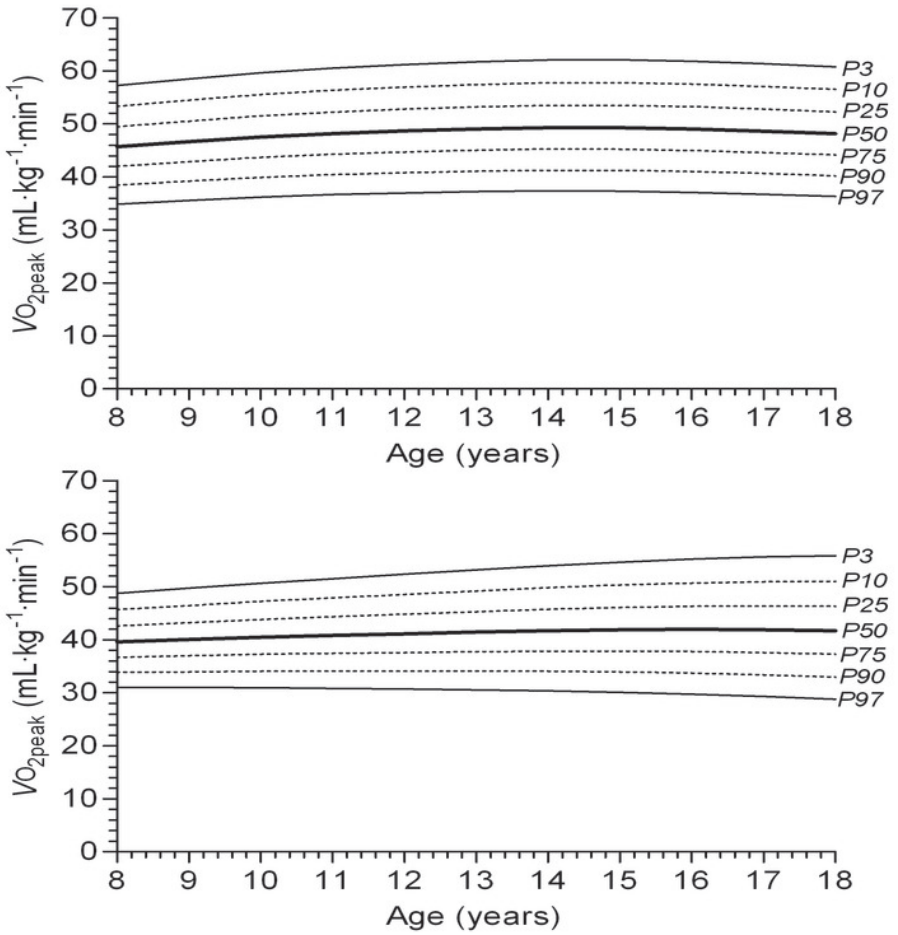

Figure 3: Age-related centile charts for aerobic capacity (VO_{2peak}) for boys (upper graph) and girls (lower graph) separately. Abbreviations: VO_{2peak}, highest measured oxygen uptake. Note: Adapted from Bongers et al.[38]

3 minutes[51]. In the case of using a cycle ergometer for cardiopulmonary exercise testing, the child performs a supramaximal cycle test to exhaustion at 110% of the reached peak work rate (WR_{peak}) to verify VO_{2peak}[52].

Performance at a cardiopulmonary exercise test on a cycle ergometer is primarily measured by the attained VO_{2peak} and the achieved peak work rate WR_{peak}. Aerobic capacity or VO_{2peak}, can be determined reliably in children[53]. When it is expected that a paediatric patient has a significantly reduced aerobic capacity, an exercise protocol in which the work rate increases more slowly is preferred. If the work rate increases too fast, the maximal cardiopulmonary exercise test will be terminated prematurely, without maximally stressing the pulmonary, cardiovascular and metabolic systems. The latter indicates that the child performed a submaximal effort, which severely restricts the interpretation of the cardiopulmonary exercise test. The ideal duration for a maximal cardiopulmonary exercise test is between 6 and 10 minutes for children[54] and between 8 and 12 minutes for adolescents and adults[55] and depends on the child's fitness. Experience has shown that children from six years of age can validly perform a cardiopulmonary exercise test in an exercise laboratory[56]. There is still debate concerning the minimal age for performing a cardiopulmonary exercise test, since there are large inter-individual differences. The main premise is that the child is able to understand instructions, as well as to cooperate according to these instructions. A necessity for measuring younger children is the availability of special equipment such as a paediatric treadmill or cycle ergometer, especially for children below 125 cm. In the Wilhelmina Children's Hospital of the University Medical Centre Utrecht, children as young as 4 to 5 years of age are tested successfully. A disadvantage of measuring these young children is the fact that additional tests (e.g. lung function tests) are often not possible.

Paediatric exercise testing in classrooms

Traditionally, exercise testing has almost exclusively focused on the assessment of the oxygen transport system. However, particularly in extramural care or when evaluating large groups of children, performing respiratory gas analysis measurements is sometimes not feasible due to the expense, the need for special equipment and the required trained staff. Moreover, using a face mask or mouth piece might frighten (young) children. Due to these limitations, standardized cardiopulmonary exercise testing remains underused in daily (clinical) practice[58,59], despite its well-known clinical value. This underlines the need for non-sophisticated paediatric exercise testing procedures that do not require respiratory gas analysis measurements. This might help to increase the utilisation of paediatric exercise testing; however, such an exercise test does not provide any diagnostic or prognostic information. Nevertheless, it can serve as a simple health screening tool that offers an indication concerning a child's exercise tolerance. In addition, such non-sophisticated exercise tests can also be used for evaluative purposes. Examples of

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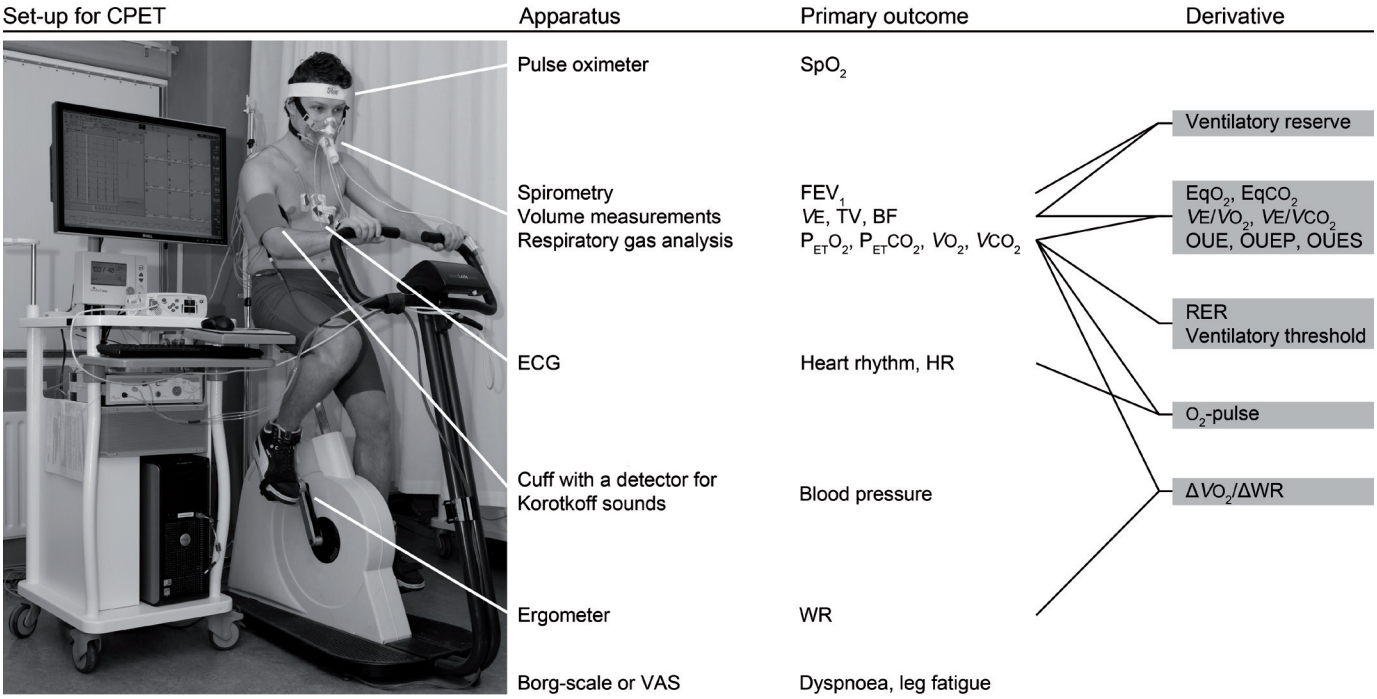

Figure 4: Selection of important parameters measured during cardiopulmonary exercise testing in paediatric populations. Abbreviations: BF, breathing frequency (breaths·min^{-1}); CPET, cardiopulmonary exercise testing; ECG, electrocardiogram; EqO_2, ventilatory equivalent for oxygen; $EqCO_2$, ventilatory equivalent for carbon dioxide; FEV_1, forced expiratory volume in one second (L); HR, heart rate (beats·min^{-1}); OUE, oxygen uptake efficiency; OUEP, oxygen uptake efficiency plateau; OUES, oxygen uptake efficiency slope; $P_{ET}CO_2$, partial end-tidal carbon dioxide tension (mmHg); $P_{ET}O_2$, partial end-tidal oxygen tension (mmHg); RER, respiratory exchange ratio; SpO_2, peripheral oxygen saturation (%); TV, tidal volume (L); VAS, visual analogue scale; VCO_2, carbon dioxide production (L·min^{-1}); VE, minute ventilation (L·min^{-1}); VE/VCO_2, slope of the relationship between the minute ventilation and carbon dioxide production; VE/VO_2, slope of the relationship between the minute ventilation and oxygen uptake; VO_2, oxygen uptake (L·min^{-1}); $\Delta VO_2/\Delta WR$, oxygen cost of work (mL·min^{-1}·W^{-1}); WR, work rate (W). Note: Adapted and modified from Bongerset al.[57]

non-sophisticated maximal exercise tests are the steep ramp test and the 20 m shuttle run test. These tests do not require respiratory gas analysis measurements.

The steep ramp test is a short-time maximal exercise test performed on a cycle ergometer, in which the work rate increases relatively fast (about six times faster) compared to the regular cardiopulmonary exercise test. Originally, the steep ramp test was used to determine and optimise interval exercise training intensity in adult patients with chronic heart failure[60,61]. As described in these studies, the steep ramp test protocol consists of 3 minutes of unloaded cycling, after which the work rate increases by 25 W every 10 seconds up to maximal exertion. To make the exercise test suitable for paediatric populations, a modified steep ramp test protocol is highly recommendable. For children and adolescents, the test starts after a 3-minute warming up at 25 W, by applying resistance to the ergometer with increments of 10, 15 or 20 W·10 s^{-1}, depending on the child's body height (< 120 cm, 120–150 cm and > 150 cm, respectively)[57]. Test duration will be approximately 4 to 7 minutes (including the 3-minute warming up), depending on the child's fitness. During the steep ramp test, the pedalling frequency should be kept constant between 60 and 80 revolutions per minute and peak exercise is defined as the point at which there is a sustained drop in pedalling frequency from 60 revolutions per minute, despite strong verbal encouragement. The attained WR_{peak} represents the primary outcome measure of the steep ramp test, which can be measured reliably (intraclass correlation coefficient of 0.986, minimal detectable change of 30.9 W, which corresponds to 11%) and is highly correlated to the VO_{2peak} achieved during regular cardiopulmonary exercise testing using a cycle ergometer in healthy children and adolescents (r = 0.958)[62]. Steep ramp test performance thus provides an indication of a child's aerobic capacity. Based on the strong correlation between the

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VO_{2peak} attained during a cardiopulmonary exercise test and the WR_{peak} reached during the steep ramp test, the following equation can be used to predict VO_{2peak} achieved during a cardiopulmonary exercise test from steep ramp test performance (WR_{peak}): VO_{2peak} cardiopulmonary exercise test (mL·min^{-1}) = (8.262·WR_{peak} steep ramp test in W) + 177.096 (R^2 = 0.917, with a standard error of the estimate [SEE] of 237 mL·min^{-1})[62]. Although the SEE is comparable to a study in which steep ramp test performance (WR_{peak}) was used to predict aerobic capacity in adult cancer survivors (SEE of 308 mL·min^{-1})[63], this prediction equation should be interpreted with caution, since it has not yet been cross-validated in a large representative sample. The conversion to VO_{2peak} might be unnecessary, because there are sex- and age-related normative values for steep ramp test performance available that facilitate adequate interpretation of steep ramp test performance in children and adolescents between 8 and 19 years old (Figure 5)[64].

The 20 m shuttle run test[65] is one of the most widely used field exercise tests to predict aerobic capacity of children and adolescents. During the test, the child runs back and forth on a 20 m course and thereby crosses the 20 m line. Children and

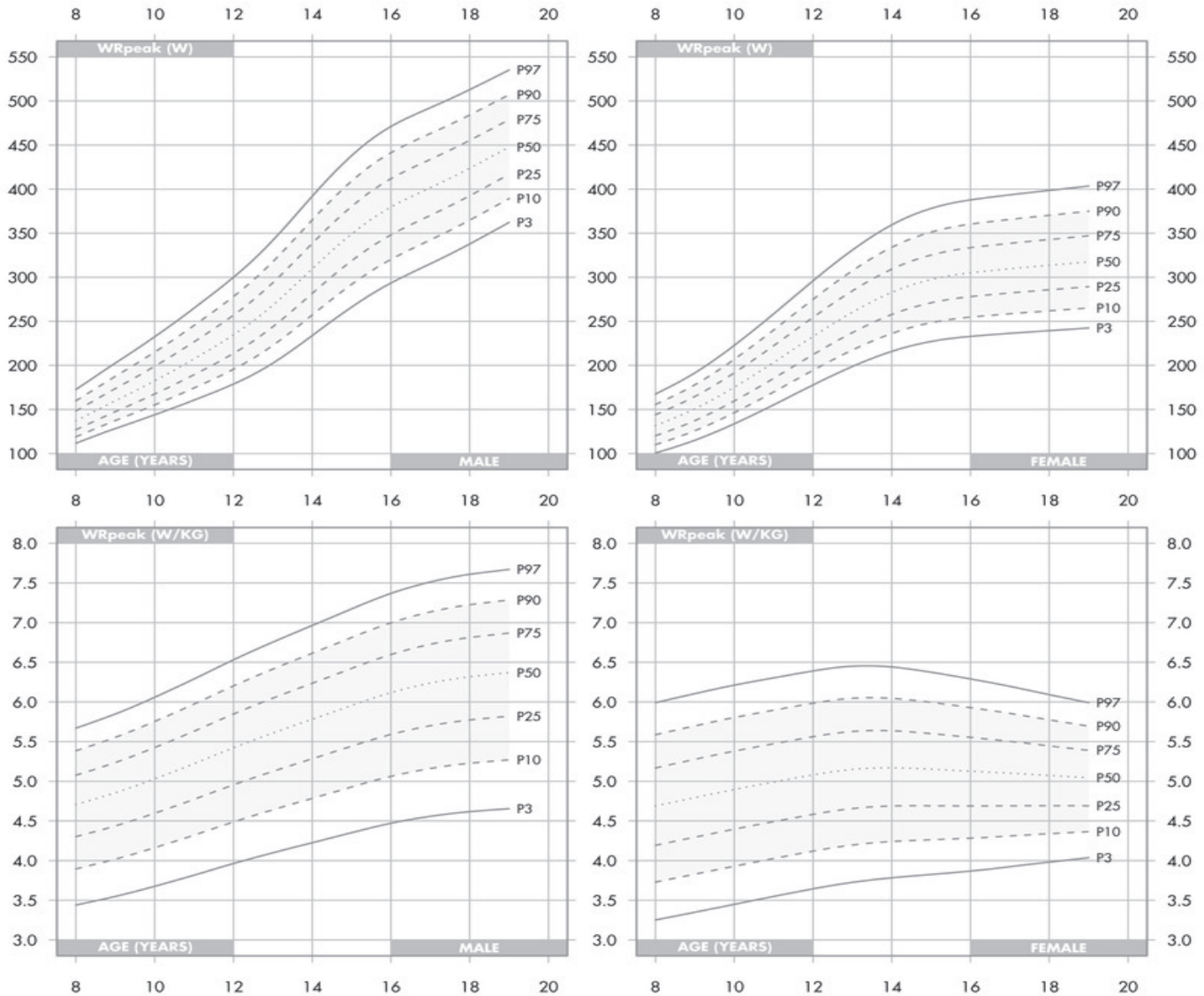

Figure 5: Age-related centile charts for the absolute peak work rate (upper graphs) and peak work rate normalised for body mass (lower graphs) attained at the steep ramp test for boys and girls separately. Abbreviations: WR_{peak}, highest attained work rate. Note: Adapted from Bongers et al.[64]

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adolescents have to pace themselves in accordance with audio signals emitted from a pre-recorded tape. Frequency of the sound signals is increased by 0.5 km·h^{-1} every minute (1 minute is equal to 1 stage) from a starting speed of 8.5 km·h^{-1} (stage 1). However, modified protocols are used in daily practice as well. The test is finished when the participant fails to reach the 20 m line concurrent with the audio signals on two consecutive occasions. Test duration will be about 3 to 10 minutes, depending on the child's fitness. A large number of children can be tested simultaneously during the 20 m shuttle run test, which enhances participant motivation. The attained maximum running speed or the last stage completed, is the main outcome measure of the 20 m shuttle run test that can be obtained reliably in children and adolescents[66–68]. In a study in healthy children between 8 and 15 years of age, an intraclass correlation coefficient of 0.890 was found for the number of completed shuttles[66]. Further, high correlation coefficients were found between VO_{2peak} determined during regular cardiopulmonary exercise testing on a treadmill and the number of completed stages (r = 0.760)[69] and maximal running speed (r = 0.760)[70] achieved at the 20 m shuttle run test. Hence, 20 m shuttle run test performance provides information concerning a child's aerobic capacity. The equation of Léger et al.[65] can be used to predict VO_{2peak} reached during cardiopulmonary exercise testing from the result of the 20 m shuttle run test: VO_{2peak} cardiopulmonary exercise test (mL·kg^{-1}·min^{-1}) = 31.025 + (3.238·speed 20 m shuttle run test in km·h^{-1}) − (3.248·age in years) + (0.1536·speed·age), in which speed is dependent on the last completed stage: speed (km·h^{-1}) = 8 + (0.5·last stage completed). This prediction equation has an R^2 of 0.504 and a (rather large) SEE corresponding to 5.9 mL·kg^{-1}·min^{-1} and has been cross-validated in small samples. A study in healthy children between 8 and 15 years of age reported a significant, but modest, correlation coefficient between the predicted and measured VO_{2peak} (r = 0.570)[66]. More recently, a study[71] in healthy adolescents between 13 and 19 years of age reported a SEE of 6.5 mL·kg^{-1}·min^{-1} for the prediction equation of Léger et al. Ruiz and colleagues[71] cross-validated several prediction equations that predict VO_{2peak} from the result of the 20 m shuttle run test[65,70,72,73] and concluded that equations to estimate VO_{2peak} from the result of the 20 m shuttle run test should not be used at an individual level. Moreover, predicting aerobic capacity might be of less interest, as there are sex- and age-related normative values for 20 m shuttle run test performance on children and adolescents between 6 and 17 years of age (Table 2)[65].

Both the steep ramp test and the 20 m shuttle run test have many advantages as non-sophisticated paediatric exercise tests to predict aerobic capacity, because of their objectivity, standardisation, reliability, validity and availability of normative data. However, equations to predict aerobic capacity (VO_{2peak}) from steep ramp test or 20 m shuttle run test performance have a large prediction error and therefore should be interpreted with caution. Moreover, these tests cannot be used as a substitute for performing a regular cardiopulmonary exercise test (gold standard), as they are less accurate and do not provide diagnostic or prognostic information. It is therefore recommended to refer children with a significantly reduced performance during the steep ramp test or the 20 m shuttle run test for an extensive progressive cardiopulmonary exercise test to evaluate the integrative physiological response of the cardiovascular, pulmonary and musculoskeletal system to progressive exercise up to maximal exhaustion. By performing a cardiopulmonary exercise test, the presence of co-morbidities can be investigated as well. Table 3 summarizes the advantages and disadvantages of the cardiopulmonary exercise test,

Table 2 Age-related normative data for the last completed stage and corresponding speed at the 20 m shuttle run test for boys and girls separately

	Boys		Girls	
Age (years)	Stage number	Speed (km·h^{-1})	Stage number	Speed (km·h^{-1})
6	3.62 ± 1.36	9.81 ± 0.68	3.37 ± 1.08	9.69 ± 0.54
7	3.91 ± 1.55	9.96 ± 0.78	3.46 ± 1.22	9.73 ± 0.61
8	4.87 ± 1.75	10.46 ± 0.87	4.06 ± 1.54	10.03 ± 0.77
9	5.53 ± 1.90	10.77 ± 0.95	4.52 ± 1.40	10.26 ± 0.70
10	6.24 ± 1.77	11.12 ± 0.89	4.92 ± 1.50	10.46 ± 0.75
11	6.66 ± 1.84	11.33 ± 0.92	5.19 ± 1.64	10.60 ± 0.82
12	7.17 ± 2.03	11.59 ± 1.02	5.49 ± 1.64	10.74 ± 0.82
13	7.42 ± 1.99	11.71 ± 1.00	5.25 ± 1.82	10.63 ± 0.91
14	7.96 ± 1.93	11.98 ± 0.97	4.82 ± 1.75	10.41 ± 0.88
15	8.50 ± 2.19	12.25 ± 1.10	5.24 ± 1.83	10.62 ± 0.92
16	8.90 ± 2.04	12.45 ± 1.02	5.23 ± 1.74	10.62 ± 0.87
17	9.26 ± 2.02	12.63 ± 1.01	5.48 ± 1.77	10.74 ± 0.89

Note: Adapted from Léger et al.[65] Values are corresponding to Dutch norm values for boys and girls between 12 and 16 years of age[74].

For citation purposes: *Bongers BC, van Brussel M, Hulzebos HJ, Takken T.* Paediatric exercise testing in clinics and classrooms: a comparative review of different assessments. OA Epidemiology 2013 Sep 01;1(2):14.

Competing interests: none declared. Conflict of interests: none declared.
All authors contributed to conception and design, manuscript preparation, read and approved the final manuscript.
All authors abide by the Association for Medical Ethics (AME) ethical rules of disclosure.

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Table 3 A comparison between the cardiopulmonary exercise test, steep ramp test and 20 m shuttle run test: advantages and disadvantages

	Cardiopulmonary exercise test	Steep ramp test	20 m shuttle run test
Validity	Gold standard	+	+
Reliability	+	+	+
Physiological measurements	+	+	–
Work rate determination	+	+	–
Safety	+	+	+/–
Preparation time	–	+	+
Costs	–	+/–	+
Portability	–	+/–	+
Appropriateness for children	> 6 years of age	> 6 years of age	> 6 years of age
Test duration	10–15 min,[a] 1 child per test	4–7 min,[a] 1 child per test	3–10 min, > 10 children per test

[a]: including warming up.
Note: + advantage, +/– neutral, – disadvantage.

steep ramp test and 20 m shuttle run test.

Conclusion

Cardiopulmonary exercise testing is the gold standard for determining aerobic capacity as well as for examining the integrated physiological response to exercise. Results from cardiopulmonary exercise testing are appreciated for diagnostic, prognostic and evaluative purposes. However, performing respiratory gas analysis measurements in a non-clinical setting in large population-based studies is not always feasible due to the expense, the need for special equipment and the required trained staff. The steep ramp test and the 20 m shuttle run test are valid and reliable non-sophisticated alternatives that have greater applicability in those studies for predicting aerobic capacity in children and adolescents as well as for evaluating intervention effects. Nevertheless, cardiopulmonary exercise testing remains necessary in some clinical pictures, due to the possibility of measuring the integrative physiological response of the pulmonary, cardiovascular, hematopoietic, neuromuscular, musculoskeletal and metabolic systems to maximal exercise.

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Competing interests: none declared. Conflict of interests: none declared.
All authors contributed to conception and design, manuscript preparation, read and approved the final manuscript.
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For citation purposes: *Bongers BC, van Brussel M, Hulzebos HJ, Takken T.* Paediatric exercise testing in clinics and classrooms: a comparative review of different assessments. OA Epidemiology 2013 Sep 01;1(2):14.

Competing interests: none declared. Conflict of interests: none declared.
All authors contributed to conception and design, manuscript preparation, read and approved the final manuscript.
All authors abide by the Association for Medical Ethics (AME) ethical rules of disclosure.

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Competing interests: none declared. Conflict of interests: none declared.
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