Muscle metabolism changes with age and maturation: How do they relate to youth sport performance?

Neil Armstrong,[1] Alan R Barker,[1] Alison M McManus[2]

[1]Children's Health and Exercise Research Centre, University of Exeter, Exeter, Devon, UK
[2]Centre for Heart, Lung and Vascular Health, School of Health and Exercise Sciences, University of British Columbia, Kelowna, British Columbia, Canada

Correspondence to
Professor Neil Armstrong, Children's Health and Exercise Research Centre, University of Exeter, St Lukes Campus, Heavitree Road, Exeter EX1 2LU, UK;
N.Armstrong@exeter.ac.uk

Accepted 30 March 2015
Published Online First 4 May 2015

ABSTRACT

Aim To provide an evidence-based review of muscle metabolism changes with sex-, age- and maturation with reference to the development of youth sport performance.

Methods A narrative review of data from both invasive and non-invasive studies, from 1970 to 2015, founded on personal databases supported with computer searches of PubMed and Google Scholar.

Results Youth sport performance is underpinned by sex-, age- and maturation-related changes in muscle metabolism. Investigations of muscle size, structure and metabolism; substrate utilisation; pulmonary oxygen uptake kinetics; muscle phosphocreatine kinetics; peak anaerobic and aerobic performance; and fatigue resistance; determined using a range of conventional and emerging techniques present a consistent picture. Age-related changes have been consistently documented but specific and independent maturation-related effects on muscle metabolism during exercise have proved elusive to establish. Children are better equipped for exercise supported primarily by oxidative metabolism than by anaerobic metabolism. Sexual dimorphism is apparent in several physiological variables underpinning youth sport performance. As young people mature there is a progressive but asynchronous transition into an adult metabolic profile.

Conclusions The application of recent developments in technology to the laboratory study of the exercising child and adolescent has both supplemented existing knowledge and provided novel insights into developmental exercise physiology. A sound foundation of laboratory-based knowledge has been established but the lack of rigorously designed child-specific and sport-specific testing environments has clouded the interpretation of the data in real life situations. The primary challenge remains the translation of laboratory research into the optimisation of youth sports participation and performance.

INTRODUCTION

To inform the International Olympic Committee (IOC) Consensus Statement on Youth Athlete Development this paper provides a narrative review of age-related and maturation-related changes in muscle metabolism which influence youth sport performance. The review is founded on personal databases supported with computer searches of PubMed and Google Scholar and covers the period 1970–2015. The contribution of other physiological variables to youth sport performance is acknowledged but they are addressed elsewhere in this Special Issue and integrated in the Consensus Statement. To meet the challenge of synthesising this vast topic area the paper assembles studies into coherent sections related to methodology. It critically reviews data within each section and compares findings across methodologies to integrate current knowledge.

The ethics of involving minors who volunteer to participate in research are discussed elsewhere in the Consensus Statement. Methodological limitations are discussed in the section introductions and, unless individually flagged, only rigorous studies are cited. Muscle biopsy studies with young people are sparse. Some biopsy studies with methodological flaws have therefore been included if they have significantly influenced paediatric exercise physiology over several decades but have not been replicated, usually for ethical reasons. In this case, explicit caveats about relevant aspects of the methodology are emphasised and where relevant sample sizes are noted. Each section summary reports a consensus of what is known in relation to study limitations.

MUSCLE BIOPSY STUDIES

Muscle biopsies are carried out almost routinely in adult investigations but ethical considerations have restricted the use of the technique with young people. Sparse studies of healthy youth have generally involved biopsies of the vastus lateralis of small samples of boys and focused on resting and postexercise measures. Participants have been classified by age and independent effects of maturation have not been assessed even though several studies refer to 'adolescents'. The interpretation of data from muscle biopsy studies is further confounded by large interindividual variations in fibre profiles and comparisons being made with adult data from previously published studies. Data should therefore be interpreted cautiously although some consistent patterns have emerged.

Muscle fibre size and type

Autopsy data have indicated that muscle fibre size increases in an almost linear manner with a ~20-fold increase in the cross-sectional area of both type I and type II fibres from birth to young adulthood. The per cent of type I fibres in males has been noted to decrease with age from 10 to 19 years. Trends in females are less consistent, possibly due to methodological artefacts as data from girls are sparse.[1–3] Statistically significant sex differences in per cent of type I fibres during youth have not been reported but despite underpowered experimental designs there is a consistent trend

To cite: Armstrong N, Barker AR, McManus AM. *Br J Sports Med* 2015;**49**:860–864.

with 15–24-year-old males presenting 4–15% more type I fibres than similarly aged females biopsied in the same study.[4–7]

Muscle energy stores

In the 1970s, Eriksson *et al*[8–12] published a series of influential studies of 11.6–15.5-year-old boys (n=8 or 9 per year). Resting ATP stores were observed to be invariant with age but phosphocreatine (PCr) and glycogen stores increased by ~60% over the age range studied.[8 12] Recent work using MR spectroscopy (^{31}PMRS) and modelling equations to estimate and compare high-energy phosphates confirmed Eriksson's data on the age invariance of ATP concentration but no differences in PCr concentrations between 10-year-old boys and adults were found.[13]

Muscle enzymes activity

Eriksson *et al*[11] reported resting phosphofructokinase (PFK) and succinic dehydrogenase activities in 11-year-olds to be ~33% and ~125% respectively of values they had previously reported for adults.[14] Subsequent studies confirmed the activities of oxidative enzymes to be higher in 13–15-year-olds (n=14) than in young adults (n=14),[15] higher in 6-year-olds (n=8) than in 13- (n=12) and 17-year-olds (n=13),[16] and the activities of anaerobic enzymes to be lower in 3–11-year-olds (n=20) compared to adults (n=12).[17] In contrast the activities of anaerobic enzymes were noted to be similar in 13–15-year-olds and adults although a lower ratio of glycolytic to oxidative enzyme activities was reported in the teens, with the ratio of PFK/isocitric dehydrogenase activity 93% higher in adults.[15]

Muscle and blood lactate

Eriksson *et al*[12] observed muscle PCr and glycogen stores to gradually decline following exercise of increasing intensity with glycogen depletion being three times greater in 15-year-olds than in 11-year-olds. The depletion of glycogen was reflected by a corresponding increase in muscle lactate production which was higher in older boys. In his thesis Eriksson[9] hypothesised a maturation effect on muscle lactate production as he observed it to be 'almost significantly' correlated with testicular volume in eight 13-year-old boys. He postulated that boys' blood lactate accumulation (BLa) would reflect their muscle lactate production but subsequent studies have found the interpretation of BLa as a surrogate of muscle lactate to be clouded by methodological issues including mode of exercise, exercise protocol, time of sampling, site of sampling and assay technique.[18–20]

During and immediately following exercise the blood lactate/pyruvate ratio rises in an age-related manner from 7 to 17 years.[21] Studies have consistently demonstrated that the lactate threshold (TLAC) expressed as per cent peak oxygen uptake (peak VO_2) is negatively correlated with age.[22 23] A positive relationship between age and peak BLa is generally[24 25] but not always[22] observed. A compelling theoretical argument can be made for a maturational effect on the production of muscle lactate and BLa[19 25] but empirical studies have consistently failed to detect an independent effect of maturation on BLa during exercise.[22 26 27] An investigation using multiple regressions to examine the effect of salivary testosterone on the blood lactate responses to exercise of 50 12–16-year-old boys observed no significant independent effect of testosterone on BLa.[26] An analysis of 200 (100 girls) 12-year-olds classified into the maturity stages described by Tanner[28] found no relationship between stage of maturation and postWingate anaerobic test (WAnT) BLa.[27] A similar study of 119 11–16-year-old boys and girls reported no relationship between submaximal or post-peak VO_2 BLa and maturation.[22]

Summary: Taken together muscle biopsy and blood lactate studies strongly suggest that children have a well-developed capacity for oxidative metabolism during exercise but may be disadvantaged in activities predominantly supported by anaerobic metabolism when compared to adults. Muscle biopsy studies reveal little about potential maturational effects on performance and although BLa during exercise is related to age an independent relationship with maturation remains to be proven.

SUBSTRATE UTILISATION

Conventionally, the respiratory exchange ratio (RER) is used to estimate substrate utilisation. The RER is, however, unable to quantify the contribution of protein, or to clarify the various lipid (intramuscular triglyceride vs blood fatty acids in the blood) and carbohydrate (CHO) (muscle glycogen vs blood glucose) sources. It is also influenced by prior exercise and nutritional intake before and during exercise. When comparing children with adults confounding factors include children's relative hyperventilation, reduced capacity for carbon dioxide storage, faster pulmonary VO_2 (pVO_2) kinetics, earlier pVO_2 steady state attainment during moderate intensity exercise and smaller pVO_2 slow component (SC), which results in a time-dependent increase in VO_2, in exercise, above the TLAC.[29–31]

Despite the limitations of the technique, there is a consensus from numerous studies that young people oxidise a higher per cent of lipids and a lower per cent of CHOs for energy at a given relative exercise intensity than adults although age-related differences in substrate use are more evident in males than in females.[29 30 32 33] High rates of lipid oxidation during exercise decline during maturation and there is evidence that the development of an adult fuel-utilisation profile occurs during the transition from mid-puberty to late-puberty, at least in males.[34 35]

Further insights have recently emerged from a series of innovative studies using RER and ^{13}C stable isotope methodology to investigate the effects of exogenous CHO (^{13}C-enriched 6% CHO in the form of a drink, CHOexo) on substrate use during submaximal exercise. In boys, CHOexo oxidation rate expressed as a per cent of total energy expenditure was found to be inversely related to serum testosterone levels. The utilisation of CHOexo as an energy source was strongly related to pubertal status with the highest oxidation rates observed in prepubertal and early pubertal boys and the lowest in mid-pubertal to late-pubertal boys regardless of chronological age. In contrast the CHOexo oxidation rate in girls was not related to age or pubertal status despite large differences in circulating oestradiol levels.[36–38]

Summary: Data derived from the RER during submaximal exercise infer that with their enhanced ability to oxidise lipids and spare glycogen children are well-equipped for long-term moderate intensity exercise. The optimal CHO feeding regime to sustain endurance performance is unknown, but evidently is related to maturation in boys.

PULMONARY OXYGEN UPTAKE KINETICS AND MUSCLE PHOSPHOCREATINE KINETICS

A high peak VO_2 and/or peak power are prerequisites of elite performance in many sports but in others it is the ability to engage in rapid changes in exercise intensity which is paramount. Under these circumstances, it is the transient kinetics of pVO_2 and PCr which best reflect the integrated response of the pulmonary, circulatory and muscle metabolic systems.

In adults the measurement of muscle VO_2 using the Fick technique has been shown to agree with pVO_2 within ~10%.[39] This

relationship has been confirmed by simultaneously determining adults' pVO_2 kinetics and intramuscular PCr kinetics in a MR scanner.[40] The work has not been replicated with children but a close relationship between children's intramuscular PCr kinetics during prone quadriceps exercise in a MR scanner and pVO_2 kinetics during upright cycling at both the onset and offset of exercise has been demonstrated.[41] These studies demonstrate that pVO_2 kinetics has the potential to provide a non-invasive window into muscle metabolism during exercise.

Pulmonary oxygen uptake kinetics

Resolution of pVO_2 kinetics in children has proved challenging. As the range of potential exercise intensities is lower in children than in young adults the scope of the metabolic transitions to exercise possible within each exercise domain is reduced.[42] In addition, children's inherently erratic breathing pattern, low signal-to-noise ratio and large interbreath fluctuations reduce confidence in resolving parameters of the pVO_2 kinetics response, in particular the primary time constant (τ).[43] The issue is further compounded by several studies not adhering to strict definitions of exercise domains, using suboptimal numbers of repeated transitions, not reporting CIs and applying a confusing array of analytical models with limited physiological rationales.[44–47]

The advent of on-line breath-by-breath analysis systems and appropriate mathematical modelling procedures has allowed rigorous investigation of the kinetics of pVO_2 during youth.[44–47] Simultaneous analysis of pVO_2 kinetics, beat-by-beat heart rate kinetics, cardiac output (using thoracic impedance), blood deoxygenation kinetics (using near infra-red spectroscopy) and the introduction of experimental models such as priming exercise, manipulation of pedal rates and control of respiratory gases (eg, hypoxic/hyperoxic stimuli) have provided intriguing insights into paediatric exercise metabolism.[31 48–51]

Slow pVO_2 kinetics is associated with a greater depletion of intramuscular high-energy phosphates and accumulation of lactate and hydrogen ions. The mechanisms underlying the SC in exercise above TLAC remain speculative but appear to be a function of muscle fibre distribution, motor unit recruitment and the matching of oxygen delivery to active muscle fibres. In adults it has been demonstrated that the τ of the exponential rise of the pVO_2 kinetics response to exercise corresponds with indices of aerobic fitness and that the amplitude of the SC is closely associated with the fatigue process and related to indices of anaerobic fitness.[52 53] In contrast, during youth no relationships between peak VO_2 and τ or the SC and fatigue have been reported.[54–56]

Rigorous investigations have demonstrated unequivocally that the SC and the τ response to exercise above the TLAC increase with age from childhood through to young adulthood although independent maturational effects remain to be demonstrated.[55–57] These data provide compelling evidence that at the onset of exercise young people have a higher potential for oxidative metabolism than adults. The attenuated SC is in agreement with young people being fatigue resistant. During exercise above but not below TLAC boys display a faster τ and a smaller SC than girls which is also in accord with muscle biopsy data.[54 55 58]

Muscle phosphocreatine kinetics

^{31}PMRS studies are constrained by exercising in a small bore tube and the need to synchronise data acquisition with the rate of muscle contraction which can be challenging for children. Interpretation of existing paediatric ^{31}PMRS data is clouded through interstudy differences in body position (eg, supine; prone), exercise protocols (eg, intermittent exercise; incremental exercise; constant intensity exercise), muscle(s) interrogated (eg, forearm; calf; thigh), types of muscle contractions (eg, isometric; isotonic), classification of participants (eg, teens grouped by chronological age without reference to maturity; pooling of data from mixed sex groups) and data normalisation. Moreover, the technique is expensive and sample sizes are generally small. Sparse data from ^{31}PMRS studies should be interpreted in the context of these limitations.

Incremental exercise studies to exhaustion using ^{31}PMRS have revealed age-related and sex-related modulation of muscle metabolism during high-intensity exercise with children relying less on anaerobic metabolism than adults[59 60] and boys less than girls, possibly because of girls' more advanced level of maturation in relation to chronological age.[60] The age-related data have been replicated during high-intensity intermittent exercise although no sexual dimorphism has been reported.[61]

The interpretation of some ^{31}PMRS studies[62 63] comparing the recovery from exercise of children and adults is confounded by significant age differences in pH at exhaustion.[64 65] However, rigorous investigations have consistently observed young people's faster re-synthesis of PCr during recovery from exhaustive exercise and concluded that young people have a greater mitochondrial oxidative capacity than adults.[66 67] PCr recovery from fatiguing isometric exercise has been shown to be ~33% faster in boys than men with no difference in PCr recovery time between girls and women.[62] Notably, the rapid recovery of skeletal muscle PCr concentration has been reported to be negatively related to linear growth velocity.[68]

Two studies of responses to high-intensity constant work rate exercise have not identified statistically significant age[69] or maturational[70] differences in metabolic responses but large SDs, small sample sizes and differences of ~42–66% between groups in end-exercise PCr or PCr kinetics during exercise infer possible biological significance.

Summary: Rigorously designed and executed ^{31}P MRS and pVO_2 kinetics studies with young people are sparse but taken together the data support an age and/or maturation influence on muscle energetics, with children relying more on oxidative metabolism during high-intensity exercise than adults. Young people's pVO_2 and PCr kinetics data are consistent with an enhanced oxidative enzymatic profile and sex-related and age-related differences in per cent of type I muscle fibres and recruitment of higher threshold (type II) motor units.

MAXIMAL (OR PEAK) AEROBIC AND ANAEROBIC PERFORMANCE

Young people's aerobic and anaerobic performance has been assessed in laboratories for several decades with techniques becoming more refined over time.[20 71] Data from thousands of young people are remarkably consistent and the relationship of aerobic and anaerobic performance with age is well-established. The (mis)interpretation of data in relation to body size has, however, masked physiological understanding during growth and maturation.

Peak oxygen uptake

Peak VO_2 is widely recognised as the best single measure of young people's aerobic fitness and values collated from studies of ~5000 children show boys' and girls' peak VO_2 to increase, in an almost linear manner, by ~150% and ~80% respectively from 8 to 16 years.[72] Sparse longitudinal studies generally concur with cross-sectional data.[73] A longitudinal study, founded on 388 data points analysed using multilevel

modelling, reported boys' peak VO_2 to almost double from 11 to 17 years. Girls' values increased by ~50% and the sex difference increased from ~10% to 35%.[74]

Boys' progressive rise in muscle mass accounts for much of the increasing sex difference in peak VO_2 as it not only facilitates oxygen utilisation but also augments venous return. Boys' peak VO_2 may be further supplemented by an increase in blood haemoglobin concentration during late teens.[73–75] The prepubertal sex difference in peak VO_2 has been attributed to boys' greater stroke index,[76–78] boys' higher maximal arterial-venous oxygen difference[79] and differences in the balance between oxygen delivery to and utilisation in the muscles.[80]

Although the fallacy of expressing peak VO_2 in ratio with body mass (mL/kg/min) has been documented for over 65 years[81] it is still widely used. Using ratios a different picture emerges with girls' peak VO_2 declining, from ~8 to 18 years, from ~45 to 35 mL/kg/min and boys' peak VO_2 remaining essentially unchanged at ~48–50 mL/kg/min.[72 73] This methodology is informative in relation to the performance of youth athletes who carry their body mass (eg, track athletes).[82] Elite youth athletes have values ~50% higher than their untrained peers when peak VO_2 is expressed in this manner.[83] However, during growth body mass increases at a greater rate than peak VO_2 and comparative studies expressing peak VO_2 in ratio with body mass favour children and have confused our understanding of aerobic fitness during growth and maturation.[84–86] When body mass is controlled for appropriately using allometry or multilevel modelling boys' values have been shown to progressively increase from childhood into young adulthood. Girls' peak VO_2 increases from childhood to mid-teens and then shows no observable decline into young adulthood.[87]

Short-term power output

Laboratory research on anaerobic performance has focused on the assessment of external power output using variants of the WAnT in which cycling peak power (CPP) is determined over a 1 s or 5 s period and cycling mean power (CMP) over the 30 s test period. CMP, although primarily supported by anaerobic energy sources, includes an unquantified contribution from aerobic metabolism which has been estimated to vary between ~10% and 44% and is higher in young people than in adults probably due to their faster pVO_2 kinetics.[88 89]

There is an almost linear increase in CPP from ~7 to 12 years, with girls often outscoring similar aged boys due to their more advanced stage of maturation. From ~13 years boys experience a marked increase in CPP through to young adulthood resulting in a ~50% sex difference by age 17 years.[90–92] Using the force-velocity test to determine CPP (or optimal peak power, OPP) girls' and boys' values have been reported to increase by 295% and 375%, respectively, from 7 to 17 years.[92]

CPP increases at a greater rate than body mass through adolescence. The determinants of enhanced CPP during maturation include changes in muscle fibre size, muscle fibre type and muscle metabolism. A series of longitudinal studies has demonstrated MRI-determined thigh muscle volume to be prominently and significantly related to CPP[93] and OPP.[94] However, neuromuscular factors, particularly the ability of young adults to better recruit and more fully use higher threshold (type II) motor units than children also play a crucial role in optimising OPP and/or CPP.[95]

Independent of age there is an asynchronous contribution of maturation to peak anaerobic and aerobic performance, which was clearly demonstrated in a study of 200 (100 girls) 12-year-olds. Children were classified according to the stages of maturation described by Tanner.[28] Boys and girls in maturity stage 4 for pubic hair were reported to have, respectively, 32% and 25% higher peak VO_2 and 66% and 51% higher CPP scores than those in stage 1. With body mass appropriately controlled for using allometry, the differences between stages 4 and 1 in peak VO_2 and CPP were 14% and 31%, respectively, in boys and 12% and 20%, respectively, in girls.[27 96]

Summary: Both peak anaerobic and aerobic performances increase with age and maturation but at different rates. Longitudinal data on the same children show that from 12 to 17 years CPP increases by ~65% in girls and ~120% in boys. Relative increases in peak VO_2 are somewhat smaller at ~25% in girls and ~70% in boys.[74 93]

RECOVERY FROM SHORT-TERM MAXIMAL-INTENSITY OR HIGH-INTENSITY EXERCISE

The rate of recovery from maximal-intensity or high-intensity exercise has been studied using a range of methodologies, including intermittent 'all-out' cycling or running tests or maximal isokinetic contractions on a variety of ergometers and dynamometers. Young people have consistently been reported to recover more rapidly than adults from intermittent bouts of maximal or high-intensity running[97 98] and cycling exercise[99 100] and maximal isokinetic contractions.[101 102] However, analysing the relative fatigue and recovery rate of children and adults is complex as their maximal short-term performance or power output is not comparable. Subjective exertion may be identical but maximal power output is lower in children and this applies to any given percentage of maximal power. It can therefore be argued that as children generate lower power their faster recovery from high-intensity exercise is not directly comparable to adults because they have less to recover from.[103]

Nevertheless, the consensus from numerous investigations is that the ability to recover from bouts of high-intensity exercise undergoes a gradual decline from childhood to adulthood in males whereas in females an adult profile is established by 14–15 years of age.[104–106] This resistance to fatigue has been attributed to young people having enhanced oxidative capacity, faster recovery kinetics of cardiorespiratory variables, more rapid PCr re-synthesis, differential motor unit recruitment and usage, better acid-base regulation and lower production and/or more efficient removal of metabolic by-products than adults.[103 105 106]

Summary: Children recover from short-term maximal-intensity and high-intensity exercise faster than adults. There are persuasive physiological hypotheses for their resistance to fatigue in this context but the exercise models used cannot refute the view that adults' slower recovery is simply a direct consequence of their ability to generate more power.

SPORT PERFORMANCE ACROSS MATURATION

It is not unusual to see preschool children in sport induction programmes and participating in organised competitive sport as young as 6–8 years of age. Youth athletes therefore experience several years of training and competition across maturation. Success in youth sport is underpinned by a range of physiological variables which operate in a sport-specific manner and are dependent on the progress of individual biological clocks. Their influence can be illustrated by perusing the asynchronous development of world best performances in relation to age and sex in track events primarily supported by different energy systems (figure 1). Changes in body size and composition and increases in muscle strength significantly affect performance but track world best performances illustrate quite nicely the changes in muscle metabolism described herein.

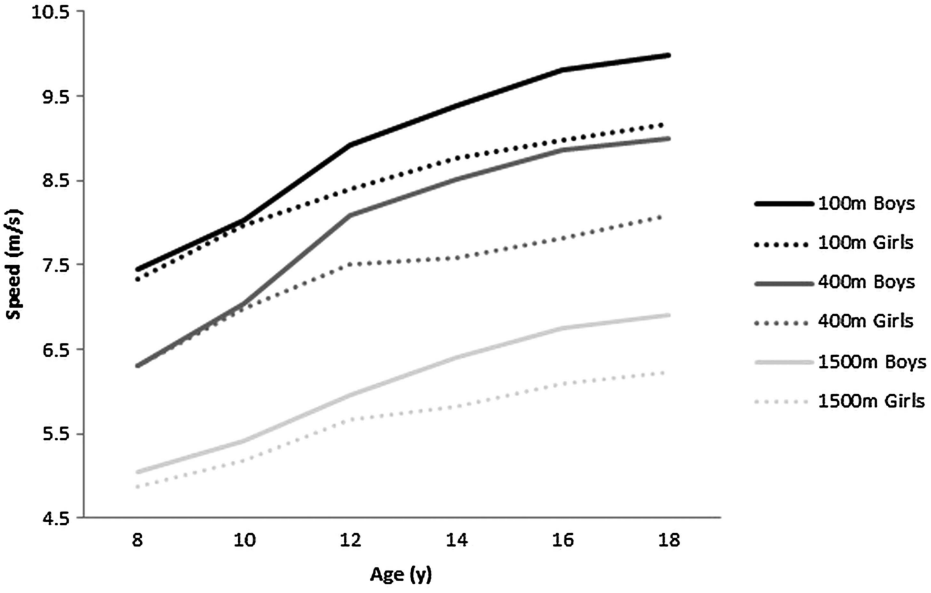

Figure 1 Average speed of World best performances in 100, 400 and 1500 m track events in relation to age and sex. The 100 m sprint is primarily supported by the catabolism of phosphocreatine and anaerobic glycolysis with ~10% of the energy being provided by aerobic metabolism. During youth, a 400 m sprint is ~60–70% supported by anaerobic metabolism, predominantly glycolysis, with minor support from aerobic sources. The 1500 m is a ~80% aerobic event although increases in pace (eg, final sprint) have high anaerobic components.

The value of applying laboratory findings to youth athlete development is readily apparent. However, experimental limitations such as exercising within a constrained space (eg, ^{31}PMRS), exercising on laboratory rather than sport-specific ergometers (eg, running on elevated treadmills or cycling against high resistances), extrapolating resting and recovery measures to exercise situations (eg, muscle biopsies), and the general lack of rigorously designed, ecological, child-specific and sport-specific testing environments have confounded the practical application of laboratory data to real life situations.

The specific effect and magnitude of changes in physiological variables measured in the laboratory on subsequent athletic performance during youth are still to be elucidated. Will a change in a single physiological variable impact on subsequent performance? Should coaches focus on maintaining one physiological variable (eg, peak VO_2) in parallel with improving a related variable (eg, running economy)? It may take several years of training for some factors related to performance to improve and this is compounded in youth by asynchronous development of aspects of muscle metabolism. In a context in which extremely small changes in performance can be the difference between winning and losing should the laboratory scientist be more concerned with statistical significance or the smallest worthwhile effect?

We still have much to learn about the application of paediatric physiology to athletic performance but the development of a comprehensive scientific foundation and an understanding of both the benefits and limitations of data generated in the laboratory provide a platform to inform decision-making by those involved in promoting optimal athlete development during youth.

CONCLUSION

The introduction of recent developments in technology has provided new insights into developmental muscle metabolism. Data from a number of sources are remarkably consistent but lack ecological validity. Nevertheless, coaches and exercise scientists working in youth sport need to understand the changes (or plateaus) in performance which might be more related to individual biological clocks than training if they are to provide optimum support to young athletes. Paediatric sport science is rapidly evolving and a sound foundation of knowledge has been established. The primary challenge remains the translation and utility of what is discovered in the laboratory to optimising youth sports participation and performance.

What are the new findings?

- Physiological data collected over the past 45 years using techniques ranging from invasive muscle biopsy studies to non-invasive ^{31}PMR spectroscopy studies present a remarkably consistent picture:
  - Children are better equipped for exercise supported by oxidative metabolism than by anaerobic metabolism.
  - As children mature there is a progressive but asynchronous transition into an adult metabolic profile with a greater increase in performances supported by anaerobic metabolism than in performances supported by oxidative metabolism.
  - Resistance to fatigue and the ability to recover from bouts of high-intensity exercise undergo a gradual decline from childhood into young adulthood in males whereas in females an adult profile is established by mid-puberty.
- Laboratory data are consistent but may lack ecological validity:
  - The primary challenge remains the translation of what is discovered in the laboratory to optimising youth sport participation and performance.

How might it impact on clinical practice in the near future?

This review provides clinicians with current knowledge of muscle metabolism during exercise in youth. It provides an evidence-based foundation to inform decision-making by clinicians and others involved in promoting optimal athlete development during youth.

Contributors NA searched the literature and drafted and edited all versions of the manuscript. ARB and AMM provided critical input on all versions of the manuscript. All authors approved the final versions of the manuscript.

Competing interests None declared.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 Oertel G. Morphometric analysis of normal skeletal muscles in infancy, childhood and adolescence. *J Neurol Sci* 1988;88:303–13.
2 Lexell J, Sjostrom M, Nordlund AS, *et al*. Growth and development of human muscle: a quantitative morphological study of whole vastus lateralis from childhood to adult age. *Muscle Nerve* 1992;15:404–9.
3 Jansson, E. Age-related fiber type changes in human skeletal muscle. In: Maughan RJ, Shirreffs SM, eds. *Biochemistry of exercise IX*. Champaign, IL: Human Kinetics, 1996:297–307.
4 Jansson E, Hedberg G. Skeletal muscle fibre types in teenagers: relationship to physical performance and activity. *Scand J Med Sci Sports* 1991;1:31–44.
5 Glenmark BC, Hedberg G, Jansson E. Changes in muscle fibre type from adolescence to adulthood in women and men. *Acta Physiol Scand* 1992;146:251–9.
6 Komi PV, Karlsson J. Skeletal muscle fibre types, enzyme activities and physical performance in young males and females. *Acta Physiol Scand* 1978;103: 210–18.
7 du Plessis MP, Smit PJ, du Plessis LAS, *et al*. The composition of muscle fibers in a group of adolescents. In: Binkhorst RA, Kemper HCG, Saris WHM, eds. *Children and exercise XI*. Baltimore: University Park Press, 1985:323–4.
8 Eriksson BO, Karlsson J, Saltin B. Muscle metabolism during exercise in pubertal boys. *Acta Paediatr Scand* 1971;217:154–7.
9 Eriksson BO. Physical training, oxygen supply and muscle metabolism in 11–13-year-old boys. *Acta Physiol Scand Suppl* 1972;384:1–48.
10 Eriksson BO, Gollnick PD Saltin B. Muscle metabolism and enzyme activities after training in boys 11–13 years old. *Acta Physiol Scand* 1973;87:485–99.
11 Eriksson BO, Gollnick PD, Saltin B. The effect of physical training on muscle enzyme activities and fiber composition in 11-year-old boys. *Acta Paediatr Belg* 1974;28:245–52.
12 Eriksson BO, Saltin B. Muscle metabolism during exercise in boys aged 11 to 16 years compared to adults. *Acta Paediatr Belg* 1974;28:257–65.
13 Garoid L, Binzoni T, Ferretti G, *et al*. Standardisation of ^{31}phosphorus-nuclear magnetic resonance spectroscopy determinations of high energy phosphates in humans. *Eur J Appl Physiol Occup Physiol* 1994;68:107–10.
14 Gollnick PD, Armstrong RB, Saubert CW, *et al*. Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. *J Appl Physiol* 1972;33:312–19.
15 Haralambie G. Enzyme activities in skeletal muscle of 13–15-year-old adolescents. *Bull Eur Physiopathol Respir* 1982;18:65–74.
16 Berg A, Kim SS, Keul J. Skeletal muscle enzyme activities in healthy young subjects. *Int J Sports Med* 1986;7:236–9.
17 Kaczor JL, Ziolkowski W, Popinigis J, *et al*. Anaerobic and aerobic enzyme activities in human skeletal muscle from children and adults. *Pediatr Res* 2005;57: 331–5.
18 Williams JR, Armstrong N, Kirby BJ. The influence of site of sampling and assay medium upon the measurement and interpretation of blood lactate responses to exercise. *J Sports Sci* 1992;10:95–107.
19 Welsman JR, Armstrong N. Assessing post-exercise blood lactates in children and adolescents. In Van Praagh E, ed. *Pediatric anaerobic performance*. Champaign, Il: Human Kinetics, 1998;137–53.
20 Armstrong N, Welsman JR. Assessment: aerobic fitness. In: Armstrong N, Van Mechelen W, eds. *Paediatric exercise science and medicine*. 2nd edn. Oxford: Oxford University Press, 2008;97–108.
21 Pianosi P, Seargeant L, Haworth JC. Blood lactate and pyruvate concentrations, and their ratio during exercise in healthy children: developmental perspective. *Eur J Appl Physiol* 1996;71:518–22.
22 Williams JR, Armstrong N. The influence of age and sexual maturation on children's blood lactate responses to exercise. *Pediatr Exerc Sci* 1991;3:111–20.
23 Pfitzinger P, Freedson P. Blood lactate responses to exercise in children: part 2. Lactate threshold. *Pediatr Exerc Sci* 1997;9:299–307.
24 Beneke R, Hutler M, Leithauser RM. Anaerobic performance and metabolism in boys and male adolescents. *Eur J Appl Physiol* 2007;101:671–7.
25 Pfitzinger P, Freedson P. Blood lactate responses to exercise in children: part 1. Peak lactate concentration. *Pediatr Exerc Sci* 1997;9:210–22.
26 Welsman JR, Armstrong N, Kirby BJ. Serum testosterone is not related to peak VO_2 or submaximal blood lactate response in 12–16 year-old males. *Pediatr Exerc Sci* 1994;6:120–7.
27 Armstrong N, Welsman JR, Kirby BJ. Performance on the Wingate anaerobic test and maturation. *Pediatr Exerc Sci* 1997;9:253–61.
28 Tanner JM. *Growth at adolescence*. 2nd edn. Oxford:Blackwell, 1962:28–39.
29 Mahon AD, Timmons BW. Application of stable isotope tracers in the study of exercise metabolism in children: a primer. *Pediatr Exerc Sci* 2014;26:3–10.
30 Aucouturier J, Baker JS, Duche P. Fat and carbohydrate metabolism during submaximal exercise in children. *Sports Med* 2008;38:213–38.
31 Armstrong N, Barker AR. Oxygen uptake kinetics in children and adolescents: a review. *Pediatr Exerc Sci* 2009;21:130–47.
32 Boisseau N, Delamarche P. Metabolic and hormonal responses to exercise in children and adolescents. *Sports Med* 2000;30:405–22.
33 Riddell MC. The endocrine response and substrate untilization during exercise in children and adolescents. *J Appl Physiol* 2008;105:725–33.
34 Stephens BR, Cole AS, Mahon AD. The influence of biological maturation on fat and carbohydrate metabolism during exercise in males. *Int J Sport Nutr Exerc Metab* 2006;16:166–79.
35 Riddell MC, Jamnik VK, Iscoe KE, *et al*. Fat oxidation rate and the exercise intensity that elicits maximal fat oxidation decreases with pubertal status in young male subjects. *J Appl Physiol* 2008;105:742–8.
36 Timmons BW, Bar-Or O, Riddell MC. Oxidation rate of exogenous carbohydrate during exercise is higher in boys than in men. *J Appl Physiol* 2003;94:278–84.
37 Timmons BW, Bar-Or O, Riddell MC. Energy substrate utilization during prolonged exercise with and without carbohydrate intake in preadolescent and adolescent girls. *J Appl Physiol* 2007;103:995–1000.
38 Timmons BW, Bar-Or O, Riddell MC. Influence on age and pubertal status on substrate utilization during exercise with and without carbohydrate intake in healthy boys. *Appl Physiol Nutr Metab* 2007;32:416–25.
39 Grassi B, Poole DC, Richardson RS, *et al*. Muscle O_2 uptake kinetics in humans: implications for metabolic control. *J Appl Physiol* 1996;80:988–98.
40 Rossiter HB, Ward SA, Doyle VL, *et al*. Inferences from pulmonary O_2 uptake with respect to intramuscular (phosphocreatine) kinetics during moderate exercise in humans. *J Physiol (Lond)* 1999;518:921–32.
41 Barker AR, Welsman JR, Fulford J, *et al*. Muscle phosphocreatine and pulmonary oxygen uptake kinetics in children at the onset and offset of moderate intensity exercise. *Eur J Appl Physiol* 2008;102:727–38.
42 Fawkner SG, Armstrong N. The slow component response of $\dot{V}O_2$ to heavy exercise in children. In: Reilly T, Marfell-Jones M, eds. *Kinanthropometry VIII*. Oxford: Routledge, 2003:105–13.
43 Potter CR, Childs DJ, Houghton W, *et al*. Breath-to-breath noise in the ventilatory and gas exchange responses of children to exercise. *Eur J Appl Physiol* 1998;80:118–24.
44 Fawkner SG, Armstrong N. Oxygen uptake kinetic response to exercise in children. *Sports Med* 2003;33:651–9.
45 Fawkner SG, Armstrong N. Can we confidently study $\dot{V}O_2$ kinetics in young people? *J Sports Sci Med* 2007;6:277–85.
46 Fawkner SG, Armstrong N. Modelling the $\dot{V}O_2$ kinetic response to heavy intensity exercise in children. *Ergonomics* 2004;47:1517–27.
47 Fawkner SG, Armstrong N. Modelling the $\dot{V}O_2$ kinetic response to moderate intensity exercise in children. *Acta Kinesiol Univ Tartu* 2002;7:80–4.
48 Barker AR, Trebilcock E, Breese B, *et al*. The effect of priming exercise on oxygen uptake kinetics, muscle oxygen delivery and utilisation, muscle activity and exercise tolerance in boys. *Appl Physiol Nutr Metab* 2014;39:308–17.
49 Breece BC, Armstrong N, Barker AR, *et al*. The effect of pedal rate on pulmonary O_2 uptake kinetics during very heavy intensity exercise in trained and untrained boys and men. *Resp Physiol Neurobiol* 2011;177:149–54.
50 Springer C, Barstow TJ, Wassermann K, *et al*. Oxygen uptake and heart rate responses during hypoxic exercise in children and adults. *Med Sci Sports Exerc* 1991;23:71–9.
51 McNarry MA, Welsman JR, Jones AM. Influence of training and maturity status on the cardiopulmonary responses to ramp incremental cycle and upper body exercise in girls. *J Appl Physiol* 2011;110:375–81.
52 Poole DC, Jones AM. Oxygen uptake kinetics. *Compr Physiol* 2012;2:933–96.
53 Rossiter HB. Exercise: kinetic considerations for gas exchange. *Compr Physiol* 2011;1:203–44.
54 Fawkner SG, Armstrong N, Potter CR, *et al*. Oxygen uptake kinetics in children and adults after the onset of moderate intensity exercise. *J Sports Sci* 2002;20:319–26.
55 Fawkner SG, Armstrong N. Longitudinal changes in the kinetic response to heavy intensity exercise in children. *J Appl Physiol* 2004;97:460–6.
56 Breese BC, Williams CA, Barker AR, *et al*. Longitudinal changes in the oxygen uptake response to heavy intensity exercise in 14–16 year old boys. *Pediatr Exerc Sci* 2010;22:314–25.
57 Breese BC, Barker AR, Armstrong N, *et al*. Effect of baseline metabolic rate on pulmonary O_2 uptake kinetics during very heavy intensity exercise in boys and men. *Resp Physiol Neurobiol* 2012;180:223–9.
58 Fawkner SG, Armstrong N. Sex differences in the oxygen uptake kinetic response to heavy intensity exercise in prepubertal children. *Eur J Appl Physiol* 2004;93:210–16.
59 Zanconato S, Buchthal S, Barstow TJ, *et al*. ^{31}P-magnetic resonance spectroscopy of leg muscle metabolism during exercise in children and adults. *J Appl Physiol* 1993;74:2214–18.
60 Barker AR, Welsman JR, Fulford J, *et al*. Quadriceps muscle energetics during incremental exercise in children and adults. *Med Sci Sports Exerc* 2010;42:1303–13.
61 Kappenstein J, Ferrauti A, Runkel B, *et al*. Changes in phosphocreatine concentration of skeletal muscle during high-intensity intermittent exercise in children and adults. *Eur J Appl Physiol* 2013;113:2769–79.
62 Kuno S, Takahashi H, Fujimoto K, *et al*. Muscle metabolism during exercise using phosphorus-31 nuclear magnetic resonance spectroscopy in adolescents. *Eur J Appl Physiol* 1995;70:301–4.

63 Taylor DJ, Kemp GJ, Thompson CH, *et al*. Ageing: effects on oxidative function of skeletal muscle *in vivo*. *Mol Cell Biochem* 1997;174:321–4.
64 Tonson A, Ratel S, Le Fur Y, *et al*. Muscle energetics changes throughout maturation: a quantitative ^{31}PMRS analysis. *J Appl Physiol* 2010;109:1769–78.
65 Barker AR, Armstrong N. Insights into developmental muscle metabolism through the use of ^{31}P-magnetic resonance spectroscopy: a review. *Pediatr Exerc Sci* 2010;22:350–68.
66 Ratel S, Tonson A, Le Fur Y, *et al*. Comparative analysis of skeletal muscle oxidative capacity in children and adults: a 31P MRS study. *Appl Physiol Nutr Metab* 2008;33:720–7.
67 Willcocks RJ, Fulford J, Armstrong N, *et al*. Muscle metabolism during fatiguing isometric quadriceps exercise in adolescents and adults. *Appl Physiol Nutr Metab* 2014;39:439–45.
68 McCormack SE, McCarthy MA, Farilla L, *et al*. Skeletal muscle mitochondrial function is associated with longitudinal growth velocity in children and adolescents. *J Clin Endocrinol Metab* 2011;96:E1612–18.
69 Willcocks RJ, Williams CA, Barker AR, *et al*. Age-and sex-related differences in muscle phosphocreatine and oxygenation kinetics during high-intensity exercise in adolescents and adults. *NMR Biomed* 2010;23:569–77.
70 Peterson SR, Gaul CA, Stanton MM, *et al*. Skeletal muscle metabolism during short-term high intensity exercise in prepubertal and pubertal girls. *J Appl Physiol* 1998;87:2151–6.
71 Van Praagh E. Testing anaerobic performance. In: Hebestreit H, Bar-Or O, eds. *The young athlete*. Oxford: Blackwell, 2008:469–85.
72 Armstrong N, Welsman JR. Assessment and interpretation of aerobic fitness in children and adolescents. *Exerc Sport Sci Rev* 1994;22:435–76.
73 Armstrong N, McManus AM, Welsman JR. Development: aerobic fitness. In: Armstrong N, Van Mechelen W, eds. *Paediatric exercise science and medicine*. 2nd edn. Oxford: Oxford University Press 2008:269–82.
74 Armstrong N, Welsman JR. Peak oxygen uptake in relation to growth and maturation in 11–17 year old humans. *Eur J Appl Physiol* 2001;85:546–51.
75 Armstrong N, Welsman JR, Nevill AM, *et al*. Modeling growth and maturation changes in peak oxygen uptake in 11–13 year olds. *J Appl Physiol* 1999;87:2230–6.
76 Rowland TW. Cardiovascular function. In: Armstrong N, Van Mechelen W, eds. *Paediatric exercise science and medicine*. 2nd edn. Oxford: Oxford University Press, 2008:256–67.
77 Rowland T, Goff D, Martel L, *et al*. Influence of cardiac functional capacity on gender differences in maximal oxygen uptake in children. *Chest* 2000;17: 629–35.
78 Vinet A, Mandigout S, Nottin S, *et al*. Influence of body composition, hemoglobin concentration, and cardiac size and function on gender differences in maximal oxygen uptake in prepubertal children. *Chest* 2003;124:1494–9.
79 Winsley RJ, Fulford J, Roberts AC, *et al*. Sex difference in peak oxygen uptake in prepubertal children. *J Sci Med Sport* 2009;12:647–51.
80 McNarry MA, Farr C. Middlebrooke A, *et al*. Aerobic function and muscle deoxygenation dynamics during ramp exercise in children. *Med Sci Sports Exerc* (in press).
81 Tanner JM. Fallacy of per-weight and per-surface area standards and their relation to spurious correlation. *J Appl Physiol* 1949;2:1–15.
82 Nevill A, Rowland TW, Goff D, *et al*. Scaling or normalizing maximum oxygen uptake to predict 1-mile run time in boys. *Eur J Appl Physiol* 2004;92: 285–8.
83 Armstrong N, Tomkinson GR, Ekelund U. Aerobic fitness and its relationship to sport, exercise training and habitual physical activity during youth. *Br J Sports Med* 2011;45:849–58.
84 Baxter-Jones A, Goldstein H, Helms P. The development of aerobic power in young athletes. *J Appl Physiol* 1993;75:1160–7.
85 Welsman JR, Armstrong N. Statistical techniques for interpreting body size-related exercise performance during growth. *Pediatr Exerc Sci* 2000;12:112–17.
86 Welsman JR, Armstrong N. Interpreting exercise performance data in relation to body size. In: Armstrong N, Van Mechelen W, eds. *Paediatric exercise science and medicine*. 2nd edn. Oxford: Oxford University Press, 2008:13–21.
87 Welsman JR, Armstrong N, Nevill AM, *et al*. Scaling peak VO_2 for differences in body size. *Med Sci Sports Exerc* 1996;28:259–65.
88 Chia M, Armstrong N, Childs D. The assessment of children's performance using modifications of the Wingate anaerobic test. *Pediatr Exerc Sci* 1997;9:80–9.
89 McNarry MA, Welsman JR, Jones AM. The influence of training and maturity status on girls' responses to short-term, high-intensity upper- and lower-body exercise. *Appl Physiol Nutr Metab* 2011;36:344–52.
90 Van Praagh E, Dore E. Short-term muscle power during growth and maturation. *Sports Med* 2002;32:701–28.
91 Armstrong N, Welsman JR, Chia MY. Short term power output in relation to growth and maturation. *Br J Sports Med* 2001;35:118–24.
92 Martin RJ, Dore E, Twisk J, *et al*. Longitudinal changes of maximal short-term peak power in girls and boys during growth. *Med Sci Sports Exerc* 2004;36:498–503.
93 De Ste Croix MB, Armstrong N, Chia MY, *et al*. Changes in short-term power output in 10–12 year-olds. *J Sports Sci* 2001;19:141–8.
94 Santos AMC, Welsman JR, De Ste Croix MB, *et al*. Age and sex related differences in optimal peak power. *Pediatr Exerc Sci* 2002;14:202–12.
95 Dotan R, Mitchell C, Cohen R, *et al*. Child-adult differences in muscle activation—a review. *Pediatr Exerc Sci* 2012;24:2–21.
96 Armstrong N, Welsman JR, Kirby BJ. Peak oxygen uptake and maturation in 12-year olds. *Med Sci Sports Exerc* 1998;30:165–9.
97 Ratel S, Williams CA, Oliver J, *et al*. Effects of age and recovery duration on performance during multiple treadmill sprints. *Int J Sports Med* 2006;27:1–8.
98 Ratel S, Williams CA, Oliver J, *et al*. Effects of age and mode of exercise on power output profiles during repeated sprints. *Eur J Appl Physiol* 2004;92:204–10.
99 Chia M. Power recovery in the Wingate anaerobic test in girls and women following prior sprints of short duration. *Biol Sport* 2001;18:45–53.
100 Hebestreit H, Mimura K, Bar-Or O. Recovery of muscle power after high-intensity short-term exercise: comparing boys and men. *J Appl Physiol* 1993;74:2875–80.
101 Zafeiridis A, Dalamitros A, Dipla K, *et al*. Recovery during high-intensity intermittent anaerobic exercise in boys, teens and men. *Med Sci Sports Exerc* 2005;37:505–12.
102 Paraschos I, Hassani A, Bassa E, *et al*. Fatigue differences between adults and prepubertal males. *Int J Sports Med* 2007;28:958–63.
103 Falk B, Dotan R. Child-adult differences in the recovery from high-intensity exercise. *Exerc Sport Sci Rev* 2006;34:107–12.
104 Dipla K, Tsirini T, Zafeiridis A, *et al*. Fatigue resistance during high-intensity intermittent exercise from childhood to adulthood in males and females. *Eur J Appl Physiol* 2009;106:645–53.
105 Ratel S, Duche P, Williams CA. Muscle fatigue during high-intensity exercise in children. *Sports Med* 2006;36:1031–65.
106 Ratel S, Lazaar N, Williams CA, *et al*. Age differences in human skeletal muscle fatigue during high-intensity intermittent exercise. *Acta Paediatr* 2003;92:1248–54.