DEVELOPMENT OF THE YOUTH ATHLETE

NEIL ARMSTRONG

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Development of the Youth Athlete offers a single-authored, well-illustrated, evidence-based, and integrated analysis of the development and trainability of the morphological and physiological characteristics which influence sport performance in youth. The book critically analyses the development of the youth athlete in the context of current and future sport performance and long-term health and well-being. *Development of the Youth Athlete* identifies the principal controversies in youth sport and addresses them through sport-specific examples.

Presenting a rigorous assessment and interpretation of scientific data with an emphasis on underlying physiological mechanisms, the book focuses on the interactions between growth, maturation, and:

- Sport-related fitness
- Sport-specific trainability
- Sport performance
- Challenges in youth sport

Providing the only up-to-date, coherent critical discourse on youth athlete development currently available, *Development of the Youth Athlete* is essential reading for students, lecturers, sport medicine practitioners, researchers, scholars, and senior coaches with an interest in youth sport, exercise science, and sport medicine.

Neil Armstrong is Professor of Paediatric Physiology, the Founding Director of the Children's Health and Exercise Research Centre, and was the Inaugural Provost of the University of Exeter, UK. He won the only Queen's Anniversary Prize (QAP) to be awarded for research in sport medicine. The QAP was presented by HM the Queen at Buckingham Palace for '*world class work which is of outstanding quality and importance to the nation*.' His research and its impact have been disseminated through over 600 scientific publications and invited presentations in 45 countries. In addition to his earned PhD and DSc, Neil has received honorary doctorates from Universities in both Europe and North America. Uniquely, he has twice chaired the Sport Science Panel in the UK Research Assessment Exercise and chaired both the British Association of Sport and Exercise Sciences and the Physical Education Association of the UK (PEAUK). He currently chairs the Board of the European Group of Pediatric Work Physiology and serves as a member of the IOC's expert group on sport, health, and exercise in youth. He was the first scientist to be awarded Fellowship of the American (FACSM), European (FECSS), and British (FBASES) Colleges/Societies of Sport Medicine/Science and other Fellowships received have included the Royal Society of Arts, the Royal Society of Biology, the Royal Society of Health, the Higher Education Academy, the PEAUK, and the National Academy of Kinesiology (USA).

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Neil Armstrong

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Contents

Figures

Tables

Abbreviations

ATP	adenosine triphosphate
a-vO_2 diff	arterio-venous oxygen difference
B	breasts
BLA	blood lactate accumulation
BMC	bone mineral content
BMI	body mass index
CHO	carbohydrates
CHO_{endo}	endogenous carbohydrates
CHO_{exo}	exogenous carbohydrates
CI	cardiac index
CIET	constant-intensity exercise training
CMJ	counter movement jump
CMP	cycling mean power output
CO_2	carbon dioxide
COD	change of direction
CP	critical power
CPP	cycling peak power output
CS	constant speed
CV	critical velocity
D	given distance
D'	maximal distance sustainable
DEXA	dual energy X-ray absorptiometry
EA	energy availability
EDs	eating disorders
EEE	energy expended in exercise
EI	energy intake
EP	end power
DE	disordered eating
FFA	free fatty acids
FFM	fat free mass
FIFA	Fédération Internationale de Football Associations
FIG	Fédération Internationale de Gymnastique
F-VT	force-velocity test

FM	fat mass
f_R	respiratory frequency
G	genitalia
GET	gas exchange threshold
GH	growth hormone
GH-IGF-1 axis	growth hormone-insulin like growth factor-1 axis
GPS	global positioning system
[Hb]	blood haemoglobin concentration
[HHb]	deoxygenated haemoglobin and myoglobin
HIIT	high-intensity interval training
HPA axis	hypothalamic-pituitary-adrenal axis
HPG axis	hypothalamic-pituitary-gonadal axis
HPT axis	hypothalamic-pituitary-thyroid axis
HR	heart rate
ICDH	isocitrate dehydrogenase
iEMG	integrated electromyogram
IGF-1	insulin-like growth factor –1
IOC	International Olympic Committee
IT	intracellular threshold
LEA	low energy availability
LLV	lean leg volume
LMM	leg muscle mass
LMV	leg muscle volume
mCSA	muscle cross-sectional area
MF	mean force output
MLSS	maximal lactate steady state
MP	mean power
MRI	magnetic resonance imaging
MRS	magnetic resonance spectroscopy
MVC	maximal voluntary contraction
NBA	National Basketball Association
NGB	National Governing Body
NIRS	near-infra red spectroscopy
NMT	non-motorised treadmill
OBLA	onset of blood lactate accumulation
OPP	optimised peak power output
PCr	phosphocreatine
peak $\dot{V}O_2$	peak oxygen uptake
PFK	phosphofructokinase
PH	pubic hair
PHV	peak height velocity
Pi	inorganic phosphate
PK	pyruvate kinase
^{31}PMRS	^{31}phosphorus magnetic resonance spectroscopy
PMV	peak muscle velocity

PP	peak power
PSV	peak strength velocity
PTMA	patellar tendon moment arm
PWV	peak weight velocity
$\dot{Q}$	cardiac output
Q	quartile
R	respiratory exchange ratio
RAE	relative age effect
RCP	respiratory compensation point
RDI	recommended daily intake
RE	running economy
RED-S	relative energy deficiency in sport
RM	repetition maximum
RS	running speed
RSS	repeated sprint sequences
RTSC	resistance training skill competence
SA	skeletal age
SDH	succinic dehydrogenase
SI	stroke index
SJ	squat jump
SRT	sit and reach test
SL	step length
SLJ	standing long jump
SR	step rate
SV	stroke volume
τ	time constant
TCA	tricarboxylic acid
TMV	thigh muscle volume
T_{LAC}	lactate threshold
TOYA	training of young athletes
T_{VENT}	ventilatory threshold
$\dot{V}_E$	pulmonary ventilation
$\dot{V}_E/\dot{V}CO_2$	ventilatory equivalent for carbon dioxide
$\dot{V}_E/\dot{V}O_2$	ventilatory equivalent for oxygen
VJ	vertical jump
$\dot{V}O_2max$	maximal oxygen uptake
V_T	tidal volume
v-$\dot{V}O_2max$	running speed at maximal oxygen uptake
W'	power-duration curvature constant
WADA	World Anti-Doping Agency
WAnT	Wingate anaerobic test
2,3-DPG	2,3-diphosphoglycerate
20mSRT	twenty metre shuttle run test

Introduction

Sport provides a positive environment for the promotion of young people's health and well-being and millions of children and adolescents worldwide enjoy recreational, community, school, club, and representative sport. Participation is at a range of levels which can be described by a performance pyramid with mass participation at the base progressing to elite sport at the peak, with selection and competition becoming more intense at each stage[1] (see Figure 0.1).

Many young people derive great pleasure from competing at the base of the pyramid, some sample higher level sport and, for a plethora of reasons, voluntarily drop-out (withdraw). Some have aspirations to perform at higher levels but are cut (excluded) for lack of attainment in a more competitive environment. Some drop-out through early specialisation as a young child in a sport inappropriate for their late adolescent physique. Other youth athletes prematurely 'retire' through acute injury, overuse injuries, or factors which include adverse personal experiences and a general inability to balance sport-life demands.[1] A select few reach the peak of the pyramid and become elite youth athletes, defined by the International Olympic Committee (IOC) as those *'with superior athletic talent, who undergo specialised training, receive expert coaching, and regularly compete at national or international level'* (2, p. 163).

The IOC consensus statement on youth athletic development articulated a clear vision of the goal of youth sport being to: *'Develop healthy, capable and resilient young athletes, while attaining widespread, inclusive, sustainable and enjoyable participation and success for all levels of individual achievement'* (3, p. 843). Sporting events to support this goal are present at all levels of the performance pyramid with most popular sports including athletics, badminton, basketball, football, gymnastics, handball, hockey, rowing, sailing, skating, swimming, table tennis, and volleyball offering a performance pyramid of youth sport competition from club-level tournaments to annual or bi-annual World championships for both boys and girls. To support international multi-sport competition, in 2010 the IOC initiated the Youth Olympic Games, held over 12 days every 4 years, bringing together ~3,800 talented 15–18 year-olds from over 200 countries. In 2012 the Youth Winter Olympic Games were launched, assembling ~1,100 youth athletes over 10 days.

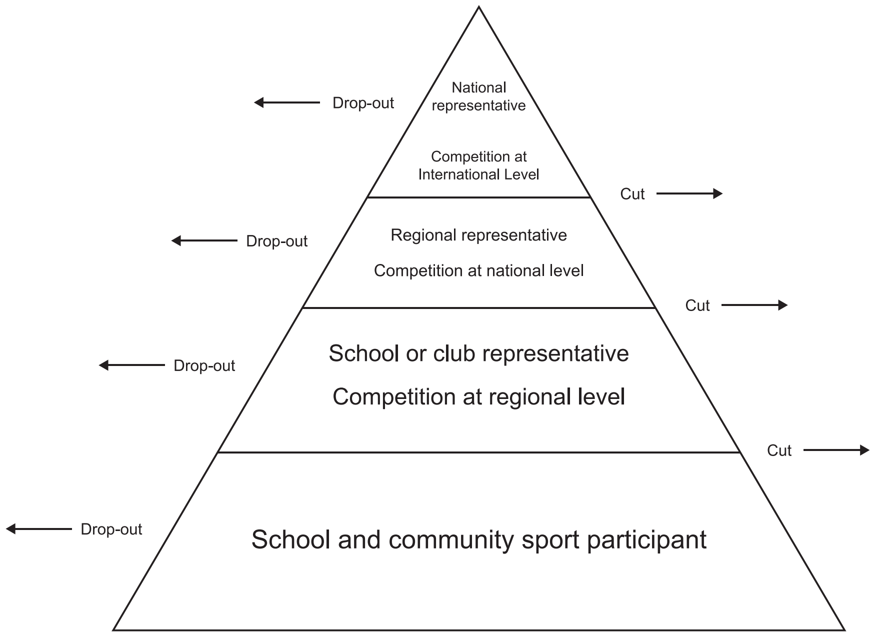

Figure 0.1 Youth athlete performance pyramid

The figure shows levels of participation as youth athletes drop-out or are cut as competition becomes more intense.

Reprinted from Armstrong and McManus[1] with permission.

In a letter to the Times during the 2016 Olympic Games, a former Olympian described how to be eligible to row for the UK in the 1972 Games he had to confirm that he had received no remuneration to compete and had adhered to the principle that full training for the Olympics must not normally exceed an aggregate of 30 days and in no case exceed 60 days in one calendar year. How things have changed. . . . In youth sport, there are growing concerns about the effects of intensive training on normal growth and maturation, the prevalence of disordered eating (DE) and eating disorders (EDs), the (mis)use of nutritional supplements and performance-enhancing drugs, the development of the overtraining and relative energy deficiency in sport (RED-S) syndromes, sport-related injuries, and non-accidental violence, as youth sport becomes more pressurised, professionalised, and politicised.

The involvement of some children in organised youth sport begins as young as 5–6 years of age. By their early teens some girls and boys are training twice each day, 5–6 days per week, totalling 30–40 $h \cdot wk^{-1}$ of training, for 11–12 months of the year. A 13 year-old competed in the 2016 Olympic Games and an 11 year-old took part in the 2018 Commonwealth Games. Drug violations were recorded in the 2010 and 2014 Youth Olympics and a 16 year-old had her gold medal rescinded in the 2014 Commonwealth Games for drug abuse. Formula One racing team McLaren contracted 15 year-old Lewis Hamilton, a talented go-kart driver, for US$2,000,000 before he had a driving licence. Jennifer Capriati had won US$1,000,000 in tennis prize money alone by the time she was 16 years of age.[4] English football clubs have ~12,000 boys from 8 years of age contracted to their academies. In 2017, Manchester City 'bought' a 13 year-old from Southend United's academy for an initial fee of £175,000 which will rise to £250,000 if the boy eventually signs professional forms, and substantially more if he is subsequently 'sold-on'. His parents have moved to North West England with him.[5]

The drive to discover or create future sport stars has resulted in numerous 'talent identification' and 'long-term athlete development' programmes. But in youth sport, performance changes in an individualised, non-linear, and sex-specific manner which is extremely difficult to predict. Even amongst youth athletes identified as talented and selected from an early age for inclusion in training programmes that are specifically designed for the development of elite performance very few (~0.02–0.46% depending on sport[6]) become elite adult athletes. The limited success of talent identification and development programmes is not surprising as they are generally not founded on evidence-based science.

The present book examines the period from age 5–6 years when involvement in organised sport and training might begin, through adolescence, and up to and including 18 years of age. It is concerned with all youth athletes who have committed to club membership and are regularly training, frequently competing, and seeking to perform at a higher level. *Development of the Youth Athlete* is coherently structured to analyse systematically the development and trainability of the morphological and physiological characteristics which influence sport performance in youth. Throughout the book the importance of rigorous assessment and interpretation of data is emphasised.

The opening four chapters describe and evaluate the interactions between sport performance, growth, and maturation. Exercise and sport performance in relation to the development of metabolic and hormonal responses and changes in nutritional status and energy availability (EA) are explored. Gymnastics is used as a case study to investigate the effects of long-term intensive training and related factors, such as DE, EDs, low EA, RED-S, overtraining, and injuries on growth and maturation. The complex interactions between gymnasts and their environment are addressed and the challenges identified extrapolated to youth athletes in other sports. Chapter 5 reviews the development and trainability of sport-related motor performances and attributes of fitness including running, throwing, jumping, agility, and flexibility. The following five chapters focus on muscle strength, maximal and high-intensity exercise, aerobic fitness, and sport performance. The assessment, interpretation, and development of strength, power, intermittent high-intensity running and cycling, resistance to fatigue, maximal oxygen uptake ($\dot{V}O_2max$), blood and respiratory gas thresholds, critical power, running economy, and pulmonary $\dot{V}O_2$ kinetics, are analysed in relation to sport performance. The efficacies of resistance training, high-intensity interval training, and continuous-intensity exercise training programmes are investigated, compared, and contrasted. The mechanisms underpinning growth-, maturation-, and training-induced changes in physiological variables and sport performance are comprehensively analysed. The final chapter addresses chronological age-group sport and efforts to provide a level playing field for performance.

The primary aim of *Development of the Youth Athlete* is to provide a scientific evidence-based foundation to support and challenge athletes, paediatric sport scientists, professionals allied to medicine, senior coaches, administrators, physical educators, and students involved in youth sport. If *Development of the Youth Athlete* promotes understanding of the morphological and physiological development and trainability of youth athletes and contributes, even in a small way, to the enjoyment, success, health, and well-being of those participating in youth sport at all levels of the performance pyramid it will have served its purpose.

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1 Growth, maturation, and youth sport

Growth and maturation are often used together to describe the journey from childhood through adolescence into young adulthood but they do not necessarily follow the same time clock. They are related, occur concurrently, and interact, but they refer to specific processes which are each subject to genetic and environmental influences. It is difficult to partition the processes of growth from maturation, but the primary distinction is that all healthy children attain maturity whereas adult body size, body shape, and body composition vary widely. The common point of reference is chronological age.

Growth signifies an increase in the size of the body as a whole or any of its constituent parts. Body size increases in a non-linear manner with wide individual variations and is itself a major influence on performance in several sports. Different parts of the body grow at different rates and times, resulting in changes in body shape which also profoundly affect sport performance. Maturation is defined by its timing and tempo. Timing refers to the chronological age at which specific events occur (e.g. the appearance of pubic hair) and tempo refers to the rate at which maturation progresses to maturity (e.g. through defined stages of the appearance of secondary sex characteristics). Maturation occurs in all biological systems but the timing of the onset of maturation and the rate of progression to maturity varies with the biological system studied.

To provide a sound foundation for interpreting the development of the youth athlete this chapter critically examines methods of assessing growth and maturity status and explores changes in body size, body shape, and body composition. In accord with the extant literature, the terms puberty and adolescence are used interchangeably, unless otherwise stated age refers to chronological age, and maturity status refers to biological maturity status. Youth and young people are used as generic terms encompassing ages 5–18 years.

Heritable traits

Stature is a highly heritable trait with a heritability estimate of 80%. Body mass is more susceptible to environmental influences than stature, with a heritability estimate of 40%. The heritability of fat free mass (FFM) is estimated to be 60–90%. Although data vary with populations studied it has been estimated that 50–90% of the variance in the timing of skeletal and sexual maturation is explained by genetic factors. The heritability of the timing and velocity of the adolescent growth spurt has been estimated as 90% with the heritability of age at peak height velocity (PHV) estimated as 85%. The heritability of age at menarche has been reported to be as high as 95% although other studies have estimated its heritability as nearer 50%.[1]

In sports where heritable morphological characteristics are thought to be particularly advantageous (e.g. shortness in gymnastics and tallness in basketball) familial characteristics are reputed to play a significant role in selection for elite youth sport. It is alleged that 2.26 m tall former Houston Rockets centre Yao Ming's tall, basketball playing parents (father 2.17 m; mother 1.91 m) were brought together for breeding purposes by the Chinese basketball federation.[2] But suffice to say, for the moment, that in addition to beneficial morphology success in basketball (and other sports) is influenced by numerous traits involving hundreds of thousands of causative alleles.[3]

Assessment and interpretation

Evaluating the development of the youth athlete is contingent on being able to understand growth and maturity status in relation to chronological age. To interpret adequately the extant literature in the context of youth athletes it is therefore necessary to be aware of both the strengths and limitations of current methodology. The conclusions of numerous published studies of youth athletes are confounded by spurious analyses of growth and/or maturity status being used to interpret data and elucidate aspects of youth sport performance.

Growth status

Growth status refers to the size attained at the date of observation. If growth status is to be monitored accurately quality control is vital and all anthropometric measurements should be taken by trained personnel using standardised techniques.[4] Stature and body mass are the primary indicators of growth status with the sitting height-to-stature ratio often used as an indicator of leg length. For the measurement of stature and body mass the youth athlete should ideally be nude but measures are normally taken wearing minimal indoor clothing with no shoes. Stature is reported to the nearest 0.01 m and body mass to the nearest 0.1 kg. Normative percentile data for the stature and body mass of healthy youth are readily available[5] but, as they are classified by chronological age with no indication of maturity status, they should be applied to youth athletes with extreme caution.

Both stature and body mass vary diurnally. Stature decreases gradually by 1–2 cm during the course of the day due to compression of the intervertebral cartilages. Daily changes in body mass may reach 1 kg, due to variation in body water and/or gastrointestinal contents although also influenced by physical activity, diet, energy balance, and phase of the menstrual cycle.[6] Diurnal variations in stature and body mass should be controlled or at least acknowledged in studies of youth athletes, particularly in studies involving serial measurements of the same individuals.

Critical reviews of underwater weighing, air displacement plethysmography, dual energy X-ray absorptiometry (DEXA), and bioelectrical impedance analysis have documented the complexity of assessing the body composition of youth athletes.[7] The application of technologies such as magnetic resonance imaging (MRI) has opened up fertile avenues of investigation[e.g.8] but there is a paucity of research and most paediatric sport science investigations are founded on surface anthropometry.

Skinfold thicknesses (typically converted to and expressed as % body fat) and body mass index (body mass/stature^2 [$kg \cdot m^{-2}$]; BMI) are routinely used to describe the body composition of youth athletes but both measures display serious limitations. The prediction of body fat relies on the relationship between skinfold thicknesses and body density but changes in body composition during childhood and adolescence confound the conceptual bases for estimating fatness and leanness from body density.[9] Moreover, the relationship between skinfolds and body fat varies with athletic group and ethnicity.[10] If this method is used it is therefore critical to select conversion equations which have been validated using the population under study. Child-specific estimates of body fat from skinfold thicknesses have been proposed but are dependent on predictive equations which were not developed on youth athletes. The most extensive research with youth athletes has focused on high school wrestlers[11] and research on other athlete groups is sparse. For the purpose of monitoring youth athletes over time the present writer recommends serial observations and subsequent analysis of the raw anthropometric data without introducing additional errors by converting skinfolds to % body fat.

Young people are frequently classified as 'overweight' or 'obese' on the basis of BMI but with adolescents a high BMI is not necessarily indicative of excess fatness. The maximum rate of increase in BMI is concomitant with the adolescent growth spurt where, in boys, a large proportion of body mass gain is in FFM rather than fat mass (FM). In adolescent boys, skinfold thicknesses decrease as BMI increases although this is not likely to be the case in adolescent girls. In the normal population sex differences in BMI are small during childhood, increase during adolescence, and persist into young adulthood. In a population of youth athletes, optimal BMIs (and their components) vary with sport (e.g. shot putter vs endurance runner) and in team games with position played (e.g. rugby winger vs prop forward). The contextual interpretation of youth athletes' BMI must therefore be approached vigilantly.[12]

Maturity status

The assessment of maturity status is complex and no single method of assessment presents a complete description of the process, although correlations between indicators of maturity status are generally moderate to high. Different biological systems mature at different rates and maturity status is best expressed in accord with the system investigated. In sport science maturity status is typically defined in relation to skeletal age (SA) or the appearance of secondary sex characteristics. Both methods have a clearly defined endpoint. Skeletal maturity denotes a fully ossified skeleton and sexual maturity signifies a fully functional reproductive capability but the different maturational processes do not follow the same time line and stage of development of secondary sex characteristics cannot be accurately predicted from SA.[13]

Skeletal age

The estimation of SA is founded on the assumption that specific features of each bone occur regularly in an irreversible order and provide a record of the progress of each bone towards maturity. The assessment requires a radiograph usually of the hand and wrist and a comparison of bones to specific criteria with ratings converted to a SA in accord with the method of analysis selected. Three methods of evaluation of SA are routinely used, the Greulich-Pyle method,[14] the Tanner-Whitehouse method(s),[15] and the Fels method.[16] Estimations of SA by different methods are related but not equivalent. Moreover, inter- and intra-observer variation in assessment of SA should be reported but seldom is.[17]

Skeletal age has been proposed (and on some occasions ill-advisably used) as a means of confirming eligibility for age-group sport but athletes' chronological age cannot be ascertained from SA. Limitations include: i) large inter-individual differences in skeletal maturation among athletes of the same chronological age; ii) variation between the youth athletes investigated and the reference sample from which the method was developed; iii) ethnic variation within the athlete group; and iv) many youth athletes attain skeletal maturity by 15 or 16 years of age.[18,19]

Skeletal age is interpreted by expressing it in relation to chronological age (i.e. SA minus chronological age) and classifying youth athletes into groups using bands of ±1.0 year and terminology such as on-time-, delayed- (–1.0 year), and advanced- (+1.0 year) maturation. This methodology is used in Figure 1.1 to illustrate the relationship between delayed-, on-time-, and advanced-maturation and selection for elite or representative sport squads. In this case 293 players recruited into the Manchester United Football Academy, classified in age-group squads from under 9 years (U9) to under 16 (U16) in relation to their SAs. The increasing prevalence of those presenting advanced-maturation in the older squads (i.e. when decisions about professional contracts are made) at the expense of those presenting on-time- and delayed-maturation is readily apparent (Figure 1.1).[20]

Secondary sex characteristics

In contrast to SA, the assessment of secondary sex characteristics is limited to the pubertal years. Various characteristics including testicular volume, facial