Oxford Textbook of Children's Sport and Exercise Medicine

THIRD EDITION

Edited by
Neil Armstrong
Willem van Mechelen

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Edited by

Neil Armstrong
Professor of Paediatric Physiology, Founding Director of the Children's Health and Exercise Research Centre, and Formerly Provost of the University of Exeter, United Kingdom

and

Willem van Mechelen
Professor of Occupational and Sports Medicine, Director of the Amsterdam Public Health research institute, VU University Medical Centre Amsterdam, the Netherlands

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Foreword

Physical inactivity is one of the biggest public health problems of the 21st century. Modern society has been busy engineering human energy expenditure out of life for decades. It is possible for many people to spend most of their time sitting and living at a very low-energy expenditure. Most people spend far fewer calories in household maintenance, at work, during leisure time, and in most other lifestyle activities than people did several decades ago. To address this serious problem we need initiatives in many sectors of society, including worksites, education, environmental planning, and governmental initiatives. Clinical medicine is an area where much more attention must be given to encouraging more physical activity for patients. There is a major initiative called Exercise Is Medicine, which was started in 2007 by the American Medical Association and the American College of Sports Medicine. Many other scientific and clinical organizations have joined the effort, and the programme now exists in dozens of countries around the world. Much of the early efforts have focused on getting physicians to do more patient counselling about exercise. Most of the effort has been for adults, but clearly children and adolescents are also susceptible to the aspects of modern society that have made it easier and more attractive to sit, rather than move.

Professors Armstrong and van Mechelen have not only focused on incorporating exercise into medical counselling in paediatric settings, but also on providing a comprehensive resource for clinicians and scientists teaching and researching in paediatric exercise science and sport medicine. The first two editions of their book have been very informative and influential, have received excellent reviews, and have been widely used. The new edition includes 17 new chapters on emerging topics of importance to the understanding of exercise and health in young people. The prior chapters in the book have been completely rewritten, and include the latest information on the wide variety of topics. The editors have retained a great majority of the international experts who wrote chapters in the previous editions, and there also are several new authors who have made numerous contributions to the various scientific areas on which they focus. I am extremely impressed with the overall expertise of the authors, who are an outstanding group of top-quality scientists in the multiple topics addressed in the book. I do not think it would be possible to assemble a more high-quality group of experts on these topics. They present the latest evidence-based research on a wide variety of issues.

Professors Armstrong and van Mechelen are exceptional scientists who have made many important contributions to physical activity and exercise science and medicine. They have addressed a wide variety of topics investigated by their research groups, and have publication records that are matched by few exercise scientists.

The chapters in this edition of *Children's Sport and Exercise Medicine* are all up to date and supported by strong evidence-based research. There are extensive important references in each chapter, and each chapter ends with a bulleted summary of the key points.

Dr Steve Blair
Professor (Retired)
Arnold School of Public Health
University of South Carolina

Preface

The first two editions of Paediatric Exercise Science and Medicine were welcomed by international reviewers as volumes which offered 'state of the art', evidence-based coverage of the topic by recognized leaders in the field. In the Preface to the first edition we referred to 'this emerging discipline' and in the Preface to the second edition we commented on the 'dramatic increase in published research focusing on the exercising child and adolescent'. Since publication of the second edition, experimental techniques initially pioneered with adults and new non-invasive technologies have been successfully developed and modified for use with children. The recent emergence of molecular exercise physiology has unlocked new avenues of research and knowledge in paediatric exercise science and medicine. The discipline is now well-established internationally, numerous professorial appointments have been made in international universities, postgraduate and postdoctoral research activity is flourishing, and publications in the field are growing at an ever-increasing rate. The material presented in the second edition is approaching the 10 years mark, and in a rapidly developing discipline it requires regular updating, refreshing, and re-appraising in the light of recent developments.

This edition has retained the ethos of previous editions. Each comprehensively referenced chapter critically analyses the research literature, establishes what we know, and identifies gaps in our knowledge. Where appropriate, chapters examine how recently developed experimental techniques, technologies, and methods of interpreting data have provided new insights into understanding the physically active child and adolescent. Contributors are internationally recognized experts in their field and they draw upon their own research to enrich the text and to inform and challenge readers. Chapters are cross-referenced to promote access to complementary material and each chapter ends with a bulleted summary and extensive reference list to support the rapid identification and further study of key issues.

Millions of young people enjoy and benefit from physical activity and sport participation and it is estimated that in England ~80% of youth partake in competitive sport each year. International organizations, such as the International Olympic Committee (IOC), are devoting resources to support the optimum development of the young athlete, as evidenced by the initiation of the Youth Olympics and the IOC investment in a series of Consensus Statements on youth athlete development, health of the youth athlete, and training elite young athletes. However, winning margins in elite-level sport competitions are small, and financial and other rewards for success are extremely large. Therefore, there is a concerted effort by some National Governing Bodies of sport, clubs, agents, coaches, and other interested parties to identify talented children and train them intensively from a young age to compete at an elite level. This is exemplified by English Premier League football clubs investing heavily in youth academies and comprehensive scouting networks to actively recruit and contract children still in primary schools. This activity has led to a plethora of concerns about the current and future health and well-being of young athletes.

The mass participation of children and adolescents in community sport programmes and the challenges faced by elite young athletes have resulted in a surge of research into youth sport and the development of the elite young athlete. This is reflected in the current edition, which retains its comprehensive coverage of paediatric exercise science and medicine but offers more extensive coverage of sport science and sport medicine than in previous editions. As a result the book has been retitled the *Oxford Textbook of Children's Sport and Exercise Medicine* to better describe its content.

Chapters on 17 new topics have been added to this edition, and even where chapter titles remain the same or similar to the second edition, the content has been comprehensively updated and rewritten, often by new contributors who have emerged as leading researchers in their field since the publication of the previous edition. Twenty-eight scientists and clinicians from the first edition and 45 from the second edition once again contribute to this edition, with 39 new authors from 17 countries enhancing the content.

The primary aims of the *Oxford Textbook of Children's Sport and Exercise Medicine* are to provide an up-to-date, comprehensive reference work with a sound scientific evidence-based foundation to support and challenge scientists, medical practitioners, professionals allied to medicine, senior coaches, physical educators, and students involved in youth physical activity, sport, and/or paediatric exercise science and medicine. If the book stimulates the initiation of innovative research programmes, informs best practice in children's sport and exercise medicine, and thereby contributes to the promotion of young people's personal development, health, well-being, and enjoyment of physical activity and sport, it will have served its purpose.

Neil Armstrong
Willem van Mechelen

Contributors

Neil Armstrong, PhD, DSc, Professor, Children's Health and Exercise Research Centre, St Luke's Campus, University of Exeter, Exeter, EX1 2LU, England

Willem van Mechelen, PhD, MD, Professor, Department of Public and Occupational Health, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands

Frank JG Backx, MD, PhD, Professor, Department of Rehabilitation, Physical Therapy Science and Sports, University Medical Center Utrecht, Huispostnummer W01.121, Postbus 85500, 3508 GA, Utrecht, The Netherlands

Astrid CJ Balemans, PhD, Department of Rehabilitation Medicine, VU University Medical Center Amsterdam, PO Box 7057, 1007 MB, Amsterdam and Brain Center Rudolf Magnus and Center of Excellence for Rehabilitation Medicine, University Medical Center Utrecht and De Hoogstraat Rehabilitation, Rembrandtkade 10, 3585 TM, Utrecht, The Netherlands

Saulo Delfino Barboza, Department of Public and Occupational Health, EMGO+ Institute for Health and Care Research, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands

Alan R Barker, PhD, Children's Health and Exercise Research Centre, St Luke's Campus, University of Exeter, Exeter, EX1 2LU, England

Meike Bartels, PhD, Professor, Department of Biological Psychology, Amsterdam Public Health research institute, VU University and VU University Medical Center Amsterdam, van der Boechorststraat 1, 1081 BT, Amsterdam, The Netherlands

Adam DG Baxter-Jones, PhD, Professor, College of Kinesiology, University of Saskatchewan, 87 Campus Drive, Saskatoon, Saskatchewan, S7N 5B2, Canada

Roselien Buys, PhD, Department of Rehabilitation Sciences, KU Leuven, Tervuursevest 101, Bus 1501, 3001 Leuven, Belgium

Nuala M Byrne, PhD, Professor, School of Health Sciences, University of Tasmania, Launceston, Tasmania, Australia 7250

Robert C Cantu, MD, Professor, Neurosurgery Service, Service of Sports Medicine, Emerson Hospital, Concord, MA 01742, USA

Robert V Cantu, MD, Orthopaedic Surgery, Dartmouth-Hitchcock Medical Center, One Medical Center Drive, Lebanon, NH 03756, USA

Akin Cil, MD, Division of Shoulder, Elbow and Sports Medicine, Department of Orthopaedics, University of Missouri-Kansas City, Kansas City, MO, USA

Dorine CM Collard, PhD, Mulier Instituut Centre for Research on Sports in Society, Postbus 85445, 3508 AK Utrecht, The Netherlands

Sean P Cumming, PhD, Department for Health, University of Bath, Bath, BA2 7AY, England

Annet J Dallmeijer, PhD, Department of Rehabilitation Medicine, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, PO Box 7057, 1007 MB, Amsterdam, The Netherlands

Eco JC de Geus, PhD, Professor, Department of Biological Psychology, Amsterdam Public Health research institute, VU University and VU University Medical Center Amsterdam, van der Boechorststraat 1, 1081 BT, Amsterdam, The Netherlands

Mark BA De Ste Croix, PhD, Professor, Exercise and Sport Research Centre, Oxstalls Campus, Oxstalls Lane, University of Gloucestershire, Gloucester, GL2 9HW, England

Raffy Dotan, Faculty of Applied Health Sciences, Brock University, St Catharines, Ontario, LS2 3A1, Canada

Ulf Ekelund, PhD, Professor, Department of Sport Medicine, Norwegian School of Sport Sciences, PO Box 4014, 0806 Ulleval Stadion, Oslo, Norway

Alon Eliakim, MD, Professor, Pediatric Department, Meir Medical Center, Sackler School of Medicine, Tel-Aviv University, Israel

Roger G Eston, DPE, Professor, Alliance for Research in Exercise, Nutrition and Activity, Sansom Institute for Health Research, School of Health Sciences, University of South Australia, Adelaide, Australia

Avery D Faigenbaum, EdD, Professor, Department of Health and Exercise Science, The College of New Jersey, Ewing, NJ 08628, USA

Bareket Falk, PhD, Professor, Department of Kinesiology, Faculty of Applied Health Sciences, Brock University, St Catharines, Ontario, LS2 3A1, Canada

Rômulo A Fernandes, PhD, Department of Physical Education, School of Science and Technology, Sao Paulo State University (UNESP), Roberto Simonsen 305, 19060-900, Presidente Prudente, Brazil

Isabel Ferreira, PhD, Division of Epidemiology and Biostatistics, School of Public Health, University of Queensland, Public Health Building, Herston Road, Herston 4006, Brisbane, Queensland, Australia

David Gerrard, MD, Emeritus Professor, Dunedin School of Medicine, University of Otago, PO Box 56, Dunedin 9054, New Zealand

Marc Gewillig, PhD, MD, Professor, Cardiovascular Developmental Biology, University Hospitals Leuven, Herestraat 49—box 7003 64, 3000 Leuven, Belgium

Helge Hebestreit, PhD, MD, Professor, Paediatric Department, Julius-Maximilians University of Würzburg, Josef-Schneider Strasse 2, 97080 Würzburg, Germany

Luiz Carlos Hespanhol Junior, Department of Public and Occupational Health, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands

Maria Hildebrand, Department of Sport Medicine, Norwegian School of Sport Sciences, PO Box 4014, 0806 Ulleval Stadion, Oslo, Norway

Andrew P Hills, PhD, Professor, Sports and Exercise Science, School of Health Sciences, Faculty of Health, University of Tasmania, Building C, Room C114, Locked Bag 1322, Newnham Drive, Launceston TAS 7250, Australia

Barbara Joschtel, School of Human Movement and Nutrition Sciences, University of Queensland, Brisbane QLD 4072, Australia

Jaak Jürimäe, PhD, Professor, Institute of Sport Sciences and Physiotherapy, University of Tartu, 18 Ulikooli Street, Tartu, 50090, Estonia

Han CG Kemper, PhD, Professor Emeritus, Department of Public and Occupational Health, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands

Sandi Kirby, Professor Emerita, University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, Canada R3B 2E9

Stef Kremers, PhD, Professor, Department of Health Promotion, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre, P. Debyeplein 1, 6200 MD Maastricht, The Netherlands

Susi Kriemler, MD, Professor, Epidemiology, Biostatistics and Prevention Institute, University of Zürich, Hirschengraben 84, 8001 Zürich, Switzerland

Kevin L Lamb, PhD, Professor, Department of Sport and Exercise Sciences, Parkgate Road, University of Chester, Chester, CH1 4BJ, England

Rhodri S Lloyd, PhD, Cardiff Metropolitan University, Cardiff School of Sport, Cyncoed Campus, Cyncoed Road, Cardiff, CF23 6XD, Wales

Umile Giuseppe Longo, PhD, MD, Department of Trauma and Orthopaedic Surgery, Campus Bio-Medico University, Via Álvaro Del Portillo 200, 00128 Trigoria, Rome, Italy

Nicola Maffulli, PhD, MD, Professor, Centre for Sports and Exercise Medicine, Queen Mary University, London E1 4DG, England, and Department of Trauma and Orthopaedic Surgery, Faculty of Medicine and Surgery, University of Salerno, Italy

Per Bo Mahler, MD, Service de Santé de l'Enfance et de la Jeunesse, Canton de Genève, and La Tour Sport Medicine SOMC, Hôpital de La Tour, Meyrin, Switzerland

Robert M Malina, PhD, Professor Emeritus, Department of Kinesiology and Health Education, University of Texas at Austin, Austin, TX, USA

Ronald J Maughan, PhD, School of Medicine, University of St Andrews, North Haugh, St. Andrews, KY16 9TF, Scotland

Alison M McManus, PhD, Centre for Heart, Lung and Vascular Health, School of Health and Exercise Sciences, University of British Columbia, 1147 Research Road—ART 360, Kelowna, British Columbia, V1V 1V7, Canada

Melitta A McNarry, PhD, Applied Sports, Exercise, Technology and Medicine Research Centre, Bay Campus, Swansea University, Swansea, SA1 8EN, Wales

Ree M Meertens, Department of Health Promotion, P.O. Box 616, 6200 MD Maastricht, The Netherlands. Visiting address: P. Debijeplein 1, 6229 HA Maastricht, The Netherlands

Lyle J Micheli, MD, Professor, Children's Hospital, Boston and Harvard Medical School, 319 Longwood Avenue, Boston, MA 02115, USA

Margo Mountjoy, PhD, MD, IOC Medical Commission Games Group and Michael G DeGroote School of Medicine, McMaster University Hamilton, Ontario, Canada

Shareef F Mustapha, MD, Department of Pediatrics and Child Health, University of Manitoba, A8025-409 Tache Avenue, Winnipeg, Manitoba, R2H 2A6, Canada

Joske Nauta, PhD, Department of Public and Occupational Health, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT Amsterdam, The Netherlands

Dan Nemet, MD, Professor, Child Health and Sports Center, Meir Medical Center, Sackler School of Medicine, Tel-Aviv University, Tel-Aviv, Israel

Jon L Oliver, PhD, Cardiff Metropolitan University, Cardiff School of Sport, Cyncoed Campus, Cyncoed Road, Cardiff, CF23 6XD, Wales

Gaynor Parfitt, PhD, Alliance for Research in Exercise, Nutrition and Activity, Sansom Institute for Health Research, School of Health Sciences, University of South Australia, Adelaide, Australia

Thomas Radtke, PhD, Epidemiology, Biostatistics and Prevention Institute, University of Zürich, Hirschengraben 84, 8001 Zürich, Switzerland

Sébastien Ratel, PhD, Université Clermont Auvergne, Université Blaise Pascal, EA 3533, Laboratoire des Adaptations Métaboliques à l'Exercice en conditions Physiologiques et Pathologiques (AME2P), BP 80026, F-63171 Aubière, Cedex, France

Tony Reybrouck, PhD, Emeritus Professor, Department of Rehabilitation Sciences, KU Leuven, Tervuursevest 101, Bus 1501, 3001 Leuven, Belgium

Thomas W Rowland, MD, Professor, Tufts University School of Medicine, Boston, MA, and Pediatric Cardiologist, Baystate Medical Center, Springfield, MA, USA

Robert AC Ruiter, PhD, Professor, Department of Work and Social Psychology, Faculty of Psychology and Neuroscience, Maastricht University, 6200 MD Maastricht, The Netherlands

Nienke M Schutte, Department of Biological Psychology, EMGO+ Institute for Health and Care Research, VU University and VU University Medical Center Amsterdam, van der Boechorststraat 1, 1081 BT, Amsterdam, The Netherlands

Christopher M Shaw, MD, Division of Shoulder, Elbow and Sports Medicine, Department of Orthopaedics, University of Missouri-Kansas City, 2301 Holmes Street, Kansas City, MO, 64108, USA

Lauren B Sherar, PhD, School of Sport, Exercise and Health Sciences, Loughborough University, Epinal Way, Loughborough, Leicestershire LE11 3TU, England

Susan M Shirreffs, PhD, School of Medicine, University of St Andrews, North Haugh, St. Andrews, KY16 9TF, Scotland

James W Smallcombe, School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, Leicestershire, LE11 3TU, England

Jonathon Smith, School of Medical Sciences, University of Aberdeen, Aberdeen AB25 2ZD, Scotland

Helen Soucie, PhD, #103, 100 rue Marcel-R.-Bergeron, Bromont, Québec, J2L 0L2, Canada

Steven J Street, PhD, School of Health Sciences, University of Tasmania, Launceston, Tasmania, Australia 7250

David Sugden, PhD, Professor, School of Education, University of Leeds, Leeds, LS2 9JT, England

Christine Sundgot-Borgen, Department of Sport Medicine, Norwegian School of Sport Sciences, PO Box 4014, 0806 Ulleval Stadion, Oslo, Norway

Jorunn Sundgot-Borgen, PhD, Professor, Department of Sport Medicine, Norwegian School of Sport Sciences, PO Box 4014, 0806 Ulleval Stadion, Oslo, Norway

Anne Tiivas, National Society for the Prevention of Cruelty for Children (NSPCC), Child Protection in Sport Unit. c/o NSPCC National Training Centre, 3, Gilmour Close, Beaumont Leys, Leicester LE4 1EZ, England

Keith Tolfrey, PhD, School of Sport, Exercise and Health Sciences, Loughborough University, Epinal Way, Loughborough, Leicestershire, LE11 3TU, England

Stewart G Trost, PhD, Professor, Institute of Health and Biomedical Innovation, Queensland University of Technology, 60 Musk Ave, Kelvin Grove QLD 4059, Australia

Jos WR Twisk, PhD, Professor, Department of Epidemiology and Biostatistics, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands

Edgar GAH van Mil, PhD, MD, Department of Paediatrics, Jeroen Bosch Hospital, Henri Dunantstraat 1, 5223 GZ,'s-Hertogenbosch, The Netherlands

Evert ALM Verhagen, PhD, Department of Public and Occupational Health, Amsterdam Public Health research institute, VU University Medical Center Amsterdam, van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands

Alan Vernec, MD, World Anti-Doping Agency, 800 Place Victoria, Bureau 1700, Montreal, Quebec H4Z 1B7, Canada

Olaf Verschuren, PhD, Brain Center Rudolf Magnus and Center of Excellence for Rehabilitation Medicine, University Medical Center Utrecht and De Hoogstraat Rehabilitation, Rembrandtkade 10, 3585 TM, Utrecht, The Netherlands

Henning Wackerhage, PhD, Professor, Technical University of Munich, Uptown München-Campus D, Georg-Brauchle-Ring 60, D-80992 München, Germany

James Watkins, PhD, Emeritus Professor, College of Engineering, Swansea University, Bay Campus, Fabian Way, Swansea, SA1 8EN, Wales

Craig A Williams, PhD, Professor, Children's Health and Exercise Research Centre, St Luke's Campus, University of Exeter, Exeter, EX1 2LU, England

Richard J Winsley, PhD, Children's Health and Exercise Research Centre, St Luke's Campus, University of Exeter, Exeter, EX1 2LU, England

Darren Wisneiwski, School of Medical Sciences, University of Aberdeen, Aberdeen AB25 2ZD, Scotland

Merrilee Zetaruk, MD, Department of Pediatrics and Child Health, University of Manitoba, Section of Pediatric Sport and Exercise Medicine, 14-160 Meadowood Drive, Winnipeg, Manitoba, R2M 5L6, Canada

Introduction

Children and adolescents are not mini-adults. They are growing and maturing at their own rate, and the assessment and interpretation of their responses to exercise are complex as they progress through childhood and adolescence into adult life.

Historically, research with healthy young people has been constrained to measuring variables such as power output or the examination of blood and respiratory gas markers of exercise performance, as ethical considerations have restricted more informative research at the level of the myocyte. The development of non-invasive technologies such as ^{31}P magnetic resonance spectroscopy, near infra-red spectroscopy, and stable isotope tracers; the application of appropriate mathematical modelling techniques to interpret physical and physiological variables during growth and maturation; and the emergence of molecular exercise physiology have provided new avenues of research and novel insights which have greatly enhanced the knowledge base and research potential in children's sport and exercise medicine.

The *Oxford Textbook of Children's Sport and Exercise Medicine* provides the most comprehensive and in-depth coverage of the topic to date. It is presented in four sections, namely exercise science, exercise medicine, sport science, and sport medicine, which between them systematically address the science and medicine underpinning sport, health, and exercise during childhood and adolescence. Fifty innovative chapters are extensively referenced to promote further study and are cross-referenced across sections where appropriate to enable interested readers to easily access complementary information.

Current knowledge in exercise science is discussed in the first section of the book. As growth and biological maturation are fundamental to understanding paediatric exercise science, the book opens with a critique of methods of assessing maturation, followed by a review of the processes of growth and maturation. The next two chapters focus on developmental biomechanics and motor development. Subsequent chapters rigorously examine muscle strength and aerobic and anaerobic metabolism during exercise, and focus on 'what we know' and 'what we need to know'. The physiological responses of the muscular, pulmonary, and cardiovascular systems to exercise of various types, intensities, and durations in relation to chronological aging, biological maturation, and sex are critically reviewed. The exercise science section ends with chapters which analyse young people's kinetic responses at the onset of exercise, scrutinize their responses to exercise during thermal stress, and evaluate how the sensations arising from physical exertion are detected and interpreted during youth. Noteworthy additions to this edition include chapters devoted to peripheral and central neuromuscular fatigue and to the responses of hormones to exercise.

The beneficial effects of appropriate physical activity during adult life are well-documented, but the potential of physical activity to confer health benefits during childhood and adolescence is controversial and has not been explored fully. There is widespread concern about the prevalence of childhood physical inactivity and the supposed decline of physical activity over the last two decades, but it is difficult to determine what is fact and what is fiction. How much exercise is necessary to promote children's health and well-being? Do we know? The tremendous success of the Paralympic Games has stimulated interest in sport and exercise for youth with physical or intellectual disabilities, but evidence-based literature is sparse. Similarly, knowledge of the therapeutic role of exercise with young people with chronic diseases is growing, but much remains to be researched and, importantly, disseminated.

These health-related issues are addressed in the section on exercise medicine, which critically reviews the extant literature and explores young people's health behaviours and the role of physical activity and physical fitness in the promotion of health and well-being. The opening chapter provides a foundation by overviewing the relationship between physical activity, physical fitness, and health. Subsequent chapters are dedicated to the effects of physical activity and physical fitness on cardiovascular health, bone health, health behaviours, diabetes mellitus, asthma, cerebral palsy, eating and weight disorders, cystic fibrosis, congenital heart disease, and physical and intellectual disabilities. The assessment and systematic promotion of physical activity are addressed and a notable addition to this section is a chapter on the genetics of physical activity and physical fitness.

Participation in youth sport provides a positive environment for the promotion of enjoyment, health, and personal development, but evidence is accumulating that youth sport also presents risks to health and well-being. The growing participation of children in organized sport and intensive training (~30+ h per week) from a young age (~5–8 years); concerns over the (mis)use of nutritional supplements; the use of performance-enhancing drugs; the effect of training on normal growth and maturation; the prevalence of disordered eating and eating disorders, overtraining syndrome, child abuse in sport, and sport-related injuries; the role and potential influence of genetic factors in youth sport; and the premature involvement of youth athletes in senior international competition have brought new challenges as sport becomes ever

more pressurized, professionalized, and politicized. These issues are addressed in the sections devoted to sport science and sport medicine.

The sport science section, which consists of ten completely new chapters, begins with a review of the development of the young athlete which also serves as an introduction to the sport science and sport medicine sections. The chapter initially discusses the interaction of chronological aging, biological maturation, and sport performance in youth before identifying some of the key challenges facing the young athlete. The next chapter introduces molecular exercise physiology and examines its current and potential application to youth sport. The influence of training on growth and maturation and hormonal adaptations to training are addressed in the following chapters. Subsequent chapters evaluate the evidence underpinning current training regimens during youth and analyse aerobic, high-intensity, resistance, speed, and agility training. The penultimate chapter in the sport science section examines the prevalence, causes, and prevention of the overtraining syndrome. The final chapter in this section focuses on the rationale, ethics, development, and implementation of a physiological monitoring programme for elite young athletes.

In the European Union there are ~1.3 million annual cases of sports-related injuries requiring hospitalization for children younger than 15 years of age. Data from the American Academy of Orthopedic Surgeons show ~3.5 million annual youth sport-related injuries in the US require a medical visit. The aetiology, prevention, and treatment of sport injuries and the management of the long-term health of young athletes provide major challenges for medical practitioners, sport scientists, physiotherapists, coaches, and others supporting youth sport.

The sport medicine section opens with an insightful overview of the epidemiology and prevention of sports injuries. Subsequent chapters address the topic with specific reference to physical education, contact sports, and non-contact sports. These chapters are followed by three chapters that focus on the diagnosis and management of sport injuries to the upper extremity and trunk, the lower limbs, and the head and cervical spine. The sport medicine section concludes with four intriguing new chapters which address current concerns in youth sport about disordered eating and eating disorders, dietary supplementation, performance-enhancing drugs, and the medical management and protection of child athletes.

Overall, the *Oxford Textbook of Children's Sport and Exercise Medicine* is a comprehensive, evidence-based text in which internationally recognized scientists and clinicians enrich their contributions with their own research and practical experience and present complex scientific material in an accessible and understandable manner. The book is designed to inform, challenge, and support research scientists, medical practitioners, professionals allied to medicine, physical educators, teachers, students, and coaches. It will be of interest to all involved in the study of the exercising child and adolescent, the promotion of young people's health and well-being, youth sport, and the optimum development of young athletes.

Neil Armstrong
Willem van Mechelen

List of Abbreviations

1 RM	one repetition maximum
^{31}PMRS	^{31}P magnetic resonance spectroscopy
AAI	atlantoaxial instability
AAP	American Academy of Pediatrics
AAS	androgenic anabolic steroids
ABC	Airway, Breathing, and Circulation
ABP	Athlete Biological Passport
ABQ	Athlete Burnout Questionnaire
ACE	angiotensin-converting enzyme
ACL	anterior cruciate ligament
ACSA	anthropometric cross-sectional area
ACSM	American College of Sports Medicine
ACTH	adrenocoticotrophin
ADA	American Diabetes Association
ADHD	attention-deficit-hyperactivity disorder
ADI	atlanto-dens interval
ADO	anti-doping organization
ADP	adenosine diphosphate
ADRV	anti-doping rule violation
AGHLS	Amsterdam Growth and Health Longitudinal Study
AIIS	anterior inferior iliac spine
AIS	abbreviated injury scale
AK	adenylate kinase
AMP	adenosine monophosphate
AN	anorexia nervosa
ANGELO	ANalysis Grid for Environments Linked to Obesity
AOI	atlantooccipital instability
AP	anteroposterior
APA	American Psychological Association
ASD	autism spectrum disorder
ASD	atrial septal defect
ASIS	anterior superior iliac spine
ATLS	advanced trauma life support
ATP	adenosine triphosphate
a-vO_2 diff	arteriovenous oxygen difference
B	breasts
BABE	Bug and Bag Effort
BALCO	Bay Area Laboratory Co-Operative
BASES	British Association of Sport and Exercise Sciences
BD	body dissatisfaction
BED	binge eating disorder
BF	body fat
BIA	bioelectrical impedance analysis
BMAD	bone mineral apparent density
BMC	bone mineral content
BMD	bone mineral density
BMI	Body mass index
BMR	basal metabolic rate
BN	bulimia nervosa
BP	blood pressure
BSA	body surface area
BUA	broadband ultrasound attenuation
BW	body weight
C1-2 injury	axial spine injury
C3-7 injury	sub-axial spine injury
CA	chronological age
Ca^{2+}	calcium
CALER	Cart and Load Effort Rating
CAT	carnitine acyltransferase
CBF	cerebral blood flow
CCT	continuous cycling training
CERT	Children's Effort Rating Table
CF	cystic fibrosis
CFRDM	cystic fibrosis-related insulin-dependent diabetes mellitus
CFTR	Cystic Fibrosis Transmembrane Conductance Regulator
CG	centre of gravity
CGM	continuous glucose monitoring
CHOexo	^{13}C-labelled enriched carbohydrate
CHOs	carbohydrates
CI	confidence interval
CIET	constant-intensity exercise training
CK	creatine kinase
CMJ	countermovement jump test
CNS	central nervous system
CO_2	carbon dioxide
CON	habitual control
CP	cerebral palsy
CPo	critical power
CPET	cardiopulmonary exercise testing
CPP	cycling peak power output
CPR	cardiopulmonary resuscitation

CPT	carnitine palmitoyl-transferase
Cr	creatine
CR 10	Category-Ratio 10 scale
CRF	cardiorespiratory fitness
CRH	corticotropine-releasing hormone
CSF	cerebrospinal fluid
CT	computerized tomography
CTE	chronic traumatic encephalopathy
CVC	cutaneous vascular conductance
CVD	cardiovascular disease
D2	dopamine-2 receptor
DAI	diffuse axonal injury
DCCT	Diabetes Control and Complications Trial
DCD	developmental coordination disorder
DE	disordered eating
DEXA	dual energy X-ray absorptiometry
DHEA	dehydroepiandrosterone
DILIN	Drug-Induced Liver Injury Network
DIP	distal interphalangeal
DISI	dorsal intercalated segment instability
DIT	diet-induced thermogenesis
DJ	drop jump
DLW	doubly labelled water
DMAA	Methylhexanamine, or 1,3-dimethylamylamine
DNA	deoxyribonucleic acid
DNMT	DNA methyltransferase
DOMS	delayed onset muscle soreness
DPA	dual photon absorptiometry
DS	Down syndrome
DSHEA	US Dietary Supplements Health and Education Act 1994
DSM-5	Diagnostic and Statistical Manual of Mental Disorders, 5th Edition
DT	drive for thinness
DZ	dizygotic
EA	energy availability
EAR	estimated average requirement
ECG	electrocardiogram
ECSS	European College of Sport Science
ED	eating disorder
EEE	energy expended in exercise
EELV	end-expiratory lung volume
EG	Prohibited List Expert Group
EI	energy intake
EIA	exercise-induced asthma
EILV	end-inspiratory lung volume
EMD	electromechanical delay
EMG	electromyography
EnRG	environmental research framework for weight gain prevention
EP	effector proteins
E-P	Eston-Parfitt
EPO	erythropoietin
ERV	expiratory reserve volume
ESA	Erythropoietin Stimulating Agent
ET	endurance training
EYHS	European Youth Heart Study
FDA	US Food and Drug Administration
FDHO	force driven harmonic oscillator
FDP	flexor digitorum profundus
FEV_1	forced expiratory volume in 1 s
FFAs	free fatty acids
FFM	Fat-free mass
FI	fatigue index
FIFA	Federation Internationale de Football Associations
FM	Fat mass
FMD	flow mediated dilation
fMRI	functional magnetic resonance imaging
FMS	fundamental movement skill
FN	femoral neck
F_{opt}	optimal force
FOR	functional overreaching
f_R	respiratory frequency
FRC	functional reserve capacity
FRV	functional residual volume
FSA	UK Food Standards Agency
FSH	follicle-stimulating hormone
F-V	force-velocity
FVC	forced vital capacity
G	genitalia (penis, scrotum, testes)
Gb	DNA base pair
GCS	Glasgow Coma Scale
GDR	German Democratic Republic
GET	gas exchange threshold
GH	growth hormone (somatotrophin)
GHBP	GH binding protein
GHRH	growth hormone-releasing hormone
GlobalDRO	Global Drug Reference Online
GLUT	glucose transporter
GM	general movements
GMFCS	Gross Motor Function Classification System
GnRH	gonadotropin-releasing hormone
GP	Greulich-Pyle
GRAV	gravitational moment
GWAS	genome-wide association studies
HAT	histone acetyltransferase
HDAC	histone deacetylase
HDL	high-density lipoprotein
HDL-C	high-density lipoprotein cholesterol
HHb	deoxygenated haemoglobin and myoglobin
HIIT	high-intensity interval training
HIT	high-intensity training
HLA	human leukocyte antigen
HOMA-IR	homeostatic model assessment for insulin resistance
HPG	hypothalamic-pituitary-gonadal axis
HR	heart rate
HRmax	maximum heart rate
HRQoL	health-related quality of life
HRR	heart rate reserve
HRV	heart rate variability
HS	heel strike
hs-CRP	high-sensitivity C-reactive protein
HTO	high take-off
HVT	high-volume training
Hz	hertz
IAAF	International Association of Athletic Federations
IBSA	International Blind Sports Association
IBU	International Biathlon Union

IC	inspiratory capacity
ICDH	isocitrate dehydrogenase
IGFBP	IGF-I binding protein
IGF-I	insulin-like growth factor 1
IL-6	interleukin 6
IM	Intervention Mapping
IMT	intima-media thickness
IOC	International Olympic Committee
IPC	International Paralympic Committee
IPS	information processing systems
iPSC	induced pluripotent stem cells
IQ	intelligence quotient
IRMS	isotope ratio mass spectrometry
IRV	inspiratory reserve volume
ISCD	International Society for Clinical Densitometry
ISTUE	International Standard for Therapeutic Use Exemptions
ISU	International Skating Union
ITs	intercellular thresholds
J	joule(s)
kcal	kilocalorie(s)
KDH	α-ketoglutarate dehydrogenase
KTS	Knowledge Transfer Scheme
L	litre(s)
LCL	lateral collateral ligament
LDH	lactate dehydrogenase
LDL-C	low-density lipoprotein cholesterol
LEA	low energy availability
LEN	Ligue Européenne de Natation
LGBT	lesbian, gay, bisexual, and transgender
LH	luteinizing hormone
LHRH	luteinizing-hormone-releasing hormone
LL	leg length
LLV	lean leg volume
LMPA	light-to-moderate physical activity
LogMAR	Logarithm of the Minimal Angle of Resolution
LS	lumbar spine
LTM	lean tissue mass
LTO	low take-off
LTV	lean thigh volume
LV	left ventricular
$m\dot{V}O_2$	muscle oxygen uptake
MAC	Medications Advisory Committee
MAS	maximal aerobic speed
MCL	medial cruciate ligament
MCP-ulnar	metacarpophalangeal-ulnar
mCSA	muscle cross-sectional area
MCT	moderate-intensity continuous training
MDM	motion dependant moment
MEFV	maximal expiratory flow-volume
MetS	metabolic syndrome
MHC	major histocompatibility complex
min	minute(s)
mL	millilitre(s)
MLSS	maximal lactate steady state
MODY	Maturity Onset Diabetes of the Young
MP	mean power output
MPA	moderate physical activity
MPST	Muscle Power Sprint Test
MRC	Medical Research Council
MRI	magnetic resonance imaging
MRS	magnetic resonance spectroscopy
MRT	mean response time
MTU	muscle tendon unit
MUS	generalized muscle moment
MVC	maximal voluntary contraction
MVPA	moderate-to-vigorous physical activity
MVV	maximal voluntary ventilation
MyoD	muscle-making transcription factor
MZ	monozygotic
NaCl	sodium chloride
NAD	nicotinamide adenine dinucleotide
NADO	national anti-doping organization
$NADP^+$	nicotinamide adenine dinucleotide phosphate
NBA	National Basketball Association
NET	net joint moment
NFL	National Football League
NFOR	non-functional overreaching
NGB	National Governing Body
NHANES	US National Health and Nutrition Examination Survey
NHIS	US National Health Interview Survey
NIRS	near-infrared spectroscopy
NMT	non-motorized treadmill
NPH	Neutral Protamine Hagedorn
NSAID	non-steroidal anti-inflammatory drug
NSPCC-CPSU	National Society for the Protection of Cruelty to Children—Child Protection in Sport Unit
NYHA	New York Heart Association
O_2	oxygen
OCD	osteochondritis dissecans
OGDH	2-oxoglutarate dehydrogenase
OPP	optimized peak power
ORIF	open reduction and internal fixation
OSA	obstructive sleep apnoea
OSFED	other specified feeding or eating disorder
OTS	overtraining syndrome
OUES	oxygen uptake efficiency slope
$p\dot{V}O_2$	pulmonary oxygen uptake
PA	physical activity
PaO_2	partial pressure of arterial oxygen
$PaCO_2$	partial pressure of arterial carbon dioxide
PAEE	physical activity energy expenditure
PAI	physical activity intensity
PAL	physical activity level
PBMD	peak bone mineral density
PCERT	Pictorial Children's Effort Rating Table
PCr	phosphocreatine
PCSA	physiological cross-sectional area
PDAY	Pathobiological Determinants of Atherosclerosis in Youth
PDH	pyruvate dehydrogenase
PE	physical education
PED	performance-enhancing drug
PEFR	peak expiratory flow rate
$P_{ET}CO_2$	end tidal carbon dioxide
PFK	phosphofructokinase
PH	pubic hair
PHV	peak height velocity
Pi	inorganic phosphate

PIP	proximal interphalangeal
PK	pyruvate kinase
P_{max}	maximal power
PMV	peak muscle mass velocity
PP	peak power output
PSF	preferred step frequency
PSV	peak strength velocity
PWV	pulse wave velocity
$\dot{Q}$	cardiac output
$\dot{Q}_{CAP}$	capillary blood flow
QCT	quantitative computed tomography
R	respiratory exchange ratio
RAE	relative age effect
RCT	randomized controlled trial
RDI	recommended daily intake
RED	relative energy deficiency
RED-S	Relative Energy Deficiency in Sport
REE	resting energy expenditure
REST-Q	Recovery Stress Questionnaire
RH	relative humidity
rhEPO	recombinant human erythropoietin
RM	repetition maximum
RNA	ribonucleic acid
RPE	rate of perceived exertion
RQ	respiratory quotient
RSI	reactive strength index
RV	residual volume
RWT	Roche-Wainer-Thissen method
s	second(s)
SA	skeletal age
SaO_2	oxygen saturation
SAR	serious adverse reaction
SARM	Selective Androgen Receptor Modulator
SBJ	standing broad (long) jump
SBP	systolic blood pressure
SCD	sudden cardiac death
Scx	scleraxis gene symbol
SD	standard deviation
SDH	succinic dehydrogenase
SDT	self-determination theory
SIS	second-impact syndrome
SIT	sprint interval training
SJ	squat jump
SLI	specific language impairment
SMS	somatostatin
SNP	single nucleotide polymorphism, or snip
SOS	speed of sound
SP	signal transduction proteins
SPA	single photon absorptiometry
SPECT	single photon emission computed tomography
SRT	Shuttle Run Test
SV	stroke volume
τ	time constant (tau)
T:C	testosterone:cortisol ratio
T:E	testosterone:epitestosterone ratio
T1DM	type 1 diabetes mellitus
T_2	transverse relaxation time
T2DM	type 2 diabetes mellitus
TAG	triacylglycerol
T_{body}	body temperature
TC	total cholesterol
TCA	tricarboxylic acid
TD	typically developing
TDI	tissue Doppler imaging
TEE	total energy expenditure
TEF	thermic effect of feeding
TFCC	triangular fibrocartilage complex
TGA	transposition of the great arteries
T_{LAC}	lactate threshold
TLC	total lung capacity
TMW	total mechanical work
T*n*	thyroid hormone (e.g. T3)
ToF	Tetralogy of Fallot
TOYA	Training of Young Athletes study
T_{re}	rectal temperature
TRIPP	Translation Research into Injury Prevention Practice
TSH	thyroid stimulating hormone (thyrotrophin)
T_{sk}	skin temperature
TT	time trial
TUE	Therapeutic Use Exemption
TUE EG	Therapeutic Use Exemption Expert Group
TUEC	Therapeutic Use Exemption Committee
T_{VENT}	ventilatory threshold
TW	Tanner-Whitehouse
TW2	Tanner-Whitehouse method edition two
TW3	Tanner-Whitehouse method edition three
UCI	Union Cycliste Internationale
UNICEF	United Nations International Children's Emergency Fund
URTI	upper respiratory tract infection
USADA	United States Anti-Doping Agency
UUS	unexplained underperformance syndrome
$\dot{V}_A$	alveolar ventilation
$\dot{V}CO_2$	carbon dioxide output
$\dot{V}_E$	pulmonary ventilation
$\dot{V}O_2$	oxygen uptake
$\dot{V}O_2$ max	maximal oxygen uptake
VA	voluntary activation
VC	vital capacity
V_D	physiologic dead space
VISI	volar intercalated segment instability
VJ	vertical jump
VLDL	very low-density lipoprotein
V_{opt}	optimal pedalling velocity
VPA	vigorous physical activity
VSD	ventricular septal defect
V_T	tidal volume
VTI	velocity-time integral
W	watt(s)
WADA	World Anti-Doping Agency
WAnT	Wingate anaerobic test
WHO	World Health Organization
y	year(s)
YPDM	Youth Physical Development Model
YRBS	Youth Risk Behaviour Survey

PART 1

Exercise science

CHAPTER 1

Assessment of biological maturation

Robert M Malina

Introduction

The focus of this chapter is on the assessment of biological maturation of children and adolescents. Maturation refers to progress towards the biologically mature state, which varies among tissues, organs, and systems of the body. Tempo or rate of maturation varies considerably among systems of the body and among and within individuals. Outcomes of the underlying biological processes of maturation are observed, assessed, and/or measured to provide an indication of progress towards the mature state (maturity).

It is difficult to separate maturation from growth. Growth refers to the increase in the size of the body as a whole and of its parts as the child progresses from birth to adulthood (of course, allowing for prenatal growth). The processes of growth and maturation occur concurrently and are related. Moreover, indicators of growth are used in deriving estimates of maturation.

Selected methods and issues in the measurement of growth status and estimated rate are initially considered. Methods for the assessment of biological maturity status and timing, and several non-invasive estimates of status and timing are subsequently considered.

Chronological age and age groups

Chronological age (CA) is the basic reference in studies of growth and maturation. Chronological age is calculated as the difference between date of measurement and date of birth, and is ordinarily expressed as a decimal of the whole year. Children and adolescents are commonly sorted into single year CA groups, which vary depending on the method of grouping. For example, 9 years can include children between 9.0 through 9.99 years, so that the midpoint of the age group is 9.5 years, or can include children 8.50 through 9.49 years, so that the midpoint of the age group is 9.0 years. The method of grouping should be specified. Depending on the purpose of a study and sample sizes, half-year age groups can also be used.

It is common in studies of youth athletes that participants are separated into competitive age groups which often span 2 years, for example, under 12 (U12), where participants are not yet 13 years of age. The age groups are defined by age at a specific date, e.g. 1 January of the competitive year. In the context of issues related to growth and maturation, athletes are often measured at different points of the year and as such the CAs of some athletes may exceed the upper limit of the competitive age group.

Brief overview of methods for the assessment of growth

Growth status

Growth status refers to the size attained at the date of observation. Height and weight are the primary indicators of growth status. The pattern of growth and associated variation in height and weight are well documented. Height, or more appropriately standing height, is the distance from the standing surface to the top of the skull (vertex). Sitting height, the distance from the flat sitting surface to the top of the skull, is often measured and provides information on upper body segment length. Standing height minus sitting height provides an estimate of leg or lower body length. The ratio of sitting height to height provides an indication of relative body proportions, i.e. relative trunk or relative leg length.

Weight is a measure of body mass which is heterogeneous in composition. Body mass is often partitioned into fat-free mass (FFM) and its two major components, lean tissue mass (LTM) and bone mineral content (BMC), and fat mass (FM).

Standard methods for the measurement of weight, standing height, and sitting height are described elsewhere.[1–3] Measurements should be made by trained individuals using standard techniques. Quality control is essential, i.e. accuracy and reliability of measurements, and measurement variability within and between technicians.[2,4]

Methods for the assessment and quantification of body composition have been driven by technology and have advanced considerably.[5,6] Descriptions are beyond the scope of this discussion. Dual energy X-ray absorptiometry (DEXA) and bioelectrical impedance analysis (BIA) are often used in paediatric sports medicine and science. It is essential that underlying assumptions and limitations of both technologies and others as applied to youth be recognized.

Height and weight increase gradually through childhood, increase at an accelerated rate during adolescence (growth spurt), and then slowly increase into late adolescence. Growth in height stops in the late teens or early twenties, whereas weight often continues to increase. Fat free mass, LTM, and BMC have a growth pattern like height and weight and each has an adolescent spurt, while FM increases more gradually with CA. Relative fatness (% fat) increases during childhood but declines during adolescence in males and continues to increase at a slower pace in females during adolescence. The decline in % fat in males is due to the rapid growth in FFM.[2]

The body mass index ([weight (kg)/ height (m^2)], BMI), is commonly used to classify youth as overweight or obese, i.e. excess weight-for-height, although at the other extreme, low weight-for-height is a concern in some sports. The BMI has limitations as an indicator of adiposity. It is significantly correlated with both FFM and FM in normal weight youth[7] and is perhaps more closely associated with LTM rather than FM among relatively thin youth.[8] The latter applies to elite youth female artistic gymnasts among whom the BMI was more closely correlated with the FFM index (DEXA FFM adjusted for height) than the FM index (FM adjusted for height); the association with the FFM index was also stronger among gymnasts in the lower half of the BMI distribution (Malina, unpublished).

Growth rate

The increment in height or other dimensions between two observations provides an estimate of growth rate, or tempo of growth. Measurements are not always taken at prescribed dates or intervals; as such, observed increments need to be adjusted for the actual interval between measurements. Increments are influenced by technical errors of measurement at each observation, and, in the case of estimated leg length, are influenced by measurement error in both height and sitting height. Diurnal and seasonal variation affects increments, especially estimates over shorter durations, e.g. 3–6 months. Height and especially sitting height show significant diurnal variation, while seasonal variation in height occurs in some parts of the world. Height measurements taken after a period of physical activity or training (running, jumping, etc.) are less than those taken after a period of rest. The recommendation of the Long Term Athlete Development model[9] for quarterly height measurements to estimate velocities and monitor the velocity curve in the context of the adolescent spurt thus has major limitations.[10]

Growth rates decline with increasing CA during childhood, reach a nadir at the onset of the spurt (take-off), increase to a maximum (peak height velocity, PHV) and then decline until growth ceases.[2] Distributions of increments vary within CA intervals and also tend to be skewed.[11] Annual or semi-annual height increments have been used in studies of youth athletes to estimate growth rates relative to a reference for non-athletes,[12–14] and at times to estimate the potential influence of training on growth rate.[15] Reference values for estimated growth rates have been reported.[10,11,16,17]

Assessment of maturity status

Maturity status refers to the level or state of maturation at the CA of observation. Indicators of skeletal and pubertal maturation are used most often. Dental maturation is another indicator, although it generally proceeds independently of other indicators.[2] If longitudinal data during childhood and adolescence and a measure of adult height are available, expressing height attained at a specific CA as a percentage of adult height can be used as an indicator of maturity status. This indicator is discussed in more detail later in this chapter in the section entitled, Percentage of predicted adult height.

Skeletal age

Skeletal maturation is estimated as skeletal age (SA) derived from evaluation of the bones of the hand and wrist viewed on a standard radiograph. Each bone goes through a series of changes from initial ossification, which begins prenatally in some bones, to the adult state. The changes in each bone are used to mark progress from immaturity to maturity and are the basis for assessing SA of the hand-wrist. The process is based on the assumption that specific features of each bone as noted on a radiograph occur regularly and in an irreversible order, and as such provide a record of the progress of each bone towards maturity. Other parts of the skeleton, e.g. knee and foot and ankle, have also been used to derive estimates of SA.[2]

Three methods are commonly used to estimate SA of the hand-wrist. Each method calls for the hand-wrist radiograph of a child to be compared to specific criteria; ratings are subsequently converted to a SA specific to the method. Indicators of maturity defined for specific bones in each method are somewhat arbitrary and suggest discrete steps in a continuous process.[2,18–21]

Greulich-Pyle method

The Greulich-Pyle method (GP)[22] is an extension of the method initially described by Todd.[23] It is sometimes called the atlas method and was developed on well-off American white children from Cleveland, Ohio. The method calls for each individual bone of the hand-wrist to be rated relative to sex-specific standard plates representing specific SAs from infancy through adolescence; plate descriptions note variation in SAs of individual bones. The method may require interpolation between the standard plates. An SA is assigned to each bone and the median of the SAs is the estimate of SA for the child. In practice, however, the GP method is most often applied by comparing the radiograph as a whole to the pictorial standards, and assigning the SA of the standard to which the radiograph most closely matches. As such, variation in level of maturity among individual bones is overlooked.

Tanner-Whitehouse method

The Tanner-Whitehouse (TW)[24–27] method was developed on British children. The method specifies criteria and associated maturity scores for 20 bones: the radius, ulna, metacarpals and phalanges of the first, third, and fifth digits (long bones), and for the carpals except the pisiform.[24,25] The scores for the 20 bones are summed into a skeletal maturity score; the 7 carpals and 13 long bones each contribute 50% to the skeletal maturity score. The maturity score is converted to a SA. Potential problems in assigning age equivalents to maturity point scores have been noted.[18,28] The first revision of the TW method (TW2)[26] did not change the criteria for maturity indicators and scores, and provided SAs based on 20 bones (TW2 20 Bone SA), for the carpals (TW2 Carpal SA), and for the radius, ulna, and short bones (TW2 RUS SA). British children were the reference for the first two versions of the TW method.

The most recent version, TW3,[27] eliminated the 20 Bone SA and retained the RUS (TW3 RUS) and Carpal (TW3 Carpal) SAs. The tables for the conversion of RUS maturity scores to SAs were modified, while those for Carpal scores were not. Reference values for TW3 RUS SA were based on a composite of the original British series, and Belgian (Flemish), Italian, Spanish, Argentine, Japanese, and American children and adolescents surveyed in the late 1960s through mid-1990s; the American sample was from a well-off area in the Houston, Texas region. The reference for TW3 Carpal SA was the original British series. Ages at attaining skeletal maturity with the RUS protocol were lowered from 18.2 to 16.5 years in boys and from 16.0 to 15.0 years in girls.

Fels method

The Fels method was based on participants in the Fels Longitudinal Growth Study of children from middle-class families in south-central Ohio.[29] The method specifies criteria for the radius, ulna, carpals, and metacarpals and phalanges of the first, third, and fifth rays. Grades are assigned to each bone depending on CA and sex. Ratios of linear measurements of the widths of the epiphysis and metaphysis of the long bones are also used, and the presence (ossification) or absence of the pisiform and adductor sesamoid is noted. Grades assigned to the individual bones and width measurements are entered into a programme that calculates SA and standard error; the latter provides an estimate of the error of the assigned SA, which is not available with the other methods. The computational procedures weight the contributions of specific indicators depending on CA and sex in the derivation of a SA; as such, the method is to some extent calibrated relative to CA.

Skeletal age

The SA assigned to the radiograph of an individual represents the CA at which a specific level of maturity of the hand-wrist bones was attained by the reference sample, upon which the method of assessment was developed. It is an indicator of biological maturity status, i.e. the level of maturity of the bones of the hand and wrist at the CA of observation. An individual who has attained skeletal maturity is simply noted as skeletally mature; an SA is not assigned. Skeletal age has meaning when expressed relative to CA. Is it equivalent? Is it advanced? Is it delayed? The difference between SA and CA (SA minus CA) and the ratio of SA to CA (SA/CA) are often used in studies.

Skeletal ages derived with each of the three methods, though related, are not equivalent as criteria, methods, and references differ among methods. Skeletal ages based on the GP and Fels methods, and the revisions of the TW method (TW2 20 Bone, TW2 RUS, TW3 RUS) in a sample of German boys[30–32] are summarized in Table 1.1. Heights of the boys matched, on average, the medians of current US reference data. Standard deviations for SA are three to four times larger than those for CA. Mean SAs with each method vary and overlap within each CA group, except for the lower SAs with the most recent TW revision. Beginning at 9–10 years, TW3 RUS SAs are consistently lower than TW2 RUS SAs.

Although not indicated in Table 1.1, a number of boys were skeletally mature, especially with the TW method (1 each at 14 and 15 years, 5 at 16 years) compared to the GP (2 at 16 years) and Fels (1 at 16 years). Numbers of skeletally mature boys were larger at 17 years (GP 9, Fels 11, TW 17). The discrepancy between the TW and both the GP and Fels methods likely relates to criteria for the radius and ulna. The final stage with the TW method is as follows 'fusion of the epiphysis and metaphysis has begun'.[27(pp.63,65)] Time between onset and completion of union of the radius and ulna is not considered. Many youth are thus classified as skeletally mature although the epiphysis and diaphysis of each bone are still in the process of fusing. The GP and Fels methods both consider beginning through complete fusion of the distal radius and ulna.

Skeletal maturation varies considerably among individuals of the same CA and fluctuates above and below 1 year (Table 1.1). This is consistent with other studies.[20] Normal variation in SA within CA groups is generally accepted as plus and minus three standard deviations except as maturity is approached.

The difference between SA and CA (SA minus CA) is often used to classify youth into contrasting maturity groups using a band of ± 1.0 year which approximates standard deviations for SAs within specific CA groups. Use of narrower bands is affected by errors associated with assessments. Skeletal maturity sets a ceiling effect which may limit some maturity groupings. This is relevant in studies of male athletes where many have attained skeletal maturity at 15, 16, and 17 years; the number attaining maturity is greater with TW RUS.[20]

Overview of skeletal age

Skeletal age can be used throughout the postnatal maturation period in contrast to other maturity assessment methods, which are limited to puberty and adolescence. Estimates of SA by each method are reasonably precise and reliable, although inter- and intra-observer variability should be reported. The use of SA is often criticized because specific training is required to learn the protocol(s). This is a shallow criticism as anthropometry, body

Table 1.1 Skeletal ages with five different methods of assessment in boys.

	Skeletal Ages, years											
	CA, years		GP		Fels		TW2 20 Bone		TW2 RUS		TW3 RUS	
N	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
26	8.4	0.3	8.3	0.9	8.1	0.9	8.3	0.9	8.0	1.0	8.0	0.9
23	9.5	0.3	10.1	1.0	9.6	1.0	9.8	0.9	9.8	1.2	9.4	0.9
22	10.5	0.3	10.2	1.0	9.7	1.0	10.1	1.2	9.9	1.1	9.5	0.8
20	11.5	0.2	11.0	0.8	10.7	1.2	11.2	0.9	11.3	1.2	10.5	0.9
31	12.4	0.3	12.1	1.0	12.2	1.5	12.6	1.5	12.6	1.6	11.6	1.3
22	13.5	0.3	12.8	1.0	13.0	1.4	13.5	1.4	13.5	1.6	12.3	1.5
23	14.3	0.3	13.8	1.0	14.2	1.1	14.8	1.1	14.9	1.3	13.8	1.0
20	15.4	0.3	14.9	0.8	15.4	0.9	15.8	0.8	15.9	0.9	14.9	1.0
10	16.5	0.3	15.8	0.8	16.5	0.8	16.8	0.8	17.0	0.8	16.0	0.8

Source data from Kujawa KI. Skeletal maturation in boys: Comparison of methods and relationships to anthropometry and strength. Doctoral dissertation, University of Texas at Austin; 1977.

composition assessment, and more specific laboratory protocols also need specific training.

Major limitations of SA are expenses associated with the radiographs per se, the need for qualified individuals to take them, and radiation exposure. With modern technology, exposure to radiation presents minimal risk, 0.001 millisievert, which is less than natural background radiation and radiation exposure associated with the equivalent of 3 $h \cdot day^{-1}$ television viewing.[33,34] The lack of qualified individuals knowledgeable of the different assessment protocols and interpretations is a major limitation in the sport sciences.

Methods for assessing and assigning SA are based on samples of European ancestry. Applications of the GP and TW protocols have shown ethnic variation.[35–41] Applications of the Fels method to youth of different ethnic groups are not available. It is relevant to note that ethnic identification of youth in some countries is not permitted.

Other protocols

Other protocols for the assessment of skeletal maturity of the hand-wrist are available and have been used primarily in the clinical setting. However, application and validation of these and perhaps other protocols in the context of the sport sciences are limited.

Skeletal age based on ultrasound assessment of the maturity status of the distal radius and ulna, scaled relative to the GP method, has been proposed,[42,43] but its validity has been questioned.[44] Use of DEXA scans of the hand-wrist for the assessment of SA have also been proposed.[45–47] Automated methods for the assessment of SA are increasingly available.[27,48–50] The procedures are generally based upon the GP and TW methods and are largely designed for clinical use. The BoneXpert method[49] is unique in that it derives an 'intrinsic' bone age based on the bone borders (shapes) and wavelet texture on images of 15 bones: radius, ulna, the 5 metacarpals, and the 8 phalanges in the first, third, and fifth rays of Danish children. The 'intrinsic' bone ages are subsequently calibrated to GP and TW RUS SAs.

Secondary sex characteristics

Secondary sex characteristics are limited to the pubertal years. Characteristics in males include pubic hair (PH), genitalia (G, penis, scrotum, testes), testicular volume, voice change, and facial and axillary hair. Characteristics in females include PH, breasts (B), axillary hair, and menarche.[2,21] Facial hair and voice change in boys and axillary hair in both sexes generally develop late during puberty and are not widely used.

Pubertal stages

The five stages of PH, G, and B described by Tanner[51] are commonly used to assess pubertal status. Stages are labelled PH1 through PH5, B1 through B5, and G1 through G5. Stage 1 of each characteristic indicates the prepubertal state—absence of overt development, although hormonal changes that trigger puberty may already be under way. Stage 2 marks the overt development of each characteristic; B2 and G2 are typically the first overt sign of the transition into puberty, but PH2 may precede B2 and G2 in a minority of youth. Stages 3 and 4 mark progress in pubertal maturation; the respective stages are sometimes labelled as mid- and late-puberty. Stage 5 indicates the mature state.

The stages are specific to the respective characteristics in each sex and are not equivalent, i.e. B3 ≠ PH3, G3 ≠ PH3, B3 ≠ G3, PH3 in girls ≠ PH3 in boys, and so on. The term 'Tanner stages' is often used in the literature without indicating which characteristic was assessed. The characteristic(s) assessed should be specified.

Stages are discrete categories superimposed on the continuous process of sexual maturation. A youngster is either in a stage or not in a stage at the time of assessment; there are no intermediate stages. Stage at time of assessment provides no information on when the youngster entered the stage (timing) or how long he/she has been in the stage.

Maturation of the neuroendocrine system involving the hypothalamic-pituitary-gonadal-adrenal axes drives the overt development of the characteristics. Gonadal hormones drive the initial development of B and G, while adrenal hormones drive the initial development of PH in both sexes.[52]

Direct assessments of stage of pubertal development are made at clinical examination. Self-assessments are often used in non-clinical settings; they require privacy, good quality photographs of the stages, simplified descriptions, and a mirror to assist in process. Some self-assessment scales include pictures or drawings of the stages, and questions regarding facial and axillary hair in males and axillary hair and menarcheal status in girls.[2]

There is need for quality control, including intra- and inter-observer reliability in assessment of stages, and concordance between self-assessments and those of experienced assessors. Overall reproducibility by experienced assessors is generally good, about 80% of agreement in assigning stages, but lower percentages have been reported.[2] Of relevance, a recent study has concluded that ' … preoperative Tanner staging performed by orthopedic surgeons is unreliable'.[53(p.1229)]

Accuracy of self-assessments is a concern, but opinions vary depending upon purpose of study. Based on self-assessments of pubertal status in three annual visits of girls between 11 and 14 years and assessments by trained examiners, it was concluded that ' … self-assessment can substitute for examiner evaluation only when crude estimates of maturation are needed'.[54(p.197)] On the other hand, agreement to within one stage was suggested as potentially useful in epidemiological surveys of youth,[55] even though concordance between self- and physician-assessments indicated limited accuracy. Concordance between and among self-assessment scales currently in use needs further evaluation.

Testicular volume

Testicular volume provides a more direct estimate of genital maturity in boys. The method requires palpation of the testes in order to match their size with a series of models of known volume (Prader orchidometer).[56,57] The ellipsoid models have the shape of the testes and range from 1 to 25 mL; a volume above 4 mL marks the beginning of puberty. The method is used primarily in the clinical setting. Sonography can also be used to estimate testicular volume.[58]

Menarcheal Status

Although age at menarche is an indicator of maturity timing, menarcheal status (pre or post) is an indicator of maturity status. It is specifically useful in single year CA groups. Among girls spanning several years, classifications by menarcheal status are confounded by CA per se, i.e. an 11-year-old premenarcheal girl is quite different physically and behaviorally from a 14-year-old premenarcheal girl.

Analytical concerns

Stages of PH, B, and G are variably reported. Ratings for individuals are periodically combined into a mean of B and PH, or of G and PH; there is no such thing as a mean stage. The stages are not equivalent and should be considered separately. Stages are also reported 3+or 4+. A youngster is either in a stage or not in a stage; there are no intermediate stages. Studies often report means stages of PH, B, or G by CA at observation; although potentially of interest in showing trends, distributions of stages within each CA group would be more informative.

It is common to group youngsters by stage of puberty independent of CA. This presents problems associated with variation by stage within a CA group and by CA within a stage. For example, within single year CA groups of soccer players 11–14 years of age, boys in less advanced stages of PH tend to be younger, shorter, and lighter, on average, than players in more advanced stages who are older, taller, and heavier. Additionally, among players grouped by stage of PH, younger boys tend to be, on average, shorter and lighter than older boys who are taller and heavier.[59] Classifications of girls by stages of PH, B, or menarcheal status within single year CA groups 13–17 years of age would likely yield similar results.

Overview of secondary sex characteristics

Secondary sex characteristics are limited to the interval of puberty and reflect changes in several hormonal axes of the neuroendocrine system. Stages are somewhat arbitrary and discrete, and direct assessment is often considered invasive, especially outside the clinical setting. Cultural sanctions may limit or prohibit assessment of secondary sex characteristics in some groups. Concordance of clinical and self-assessments is variable and needs further study. Stages of puberty are also variably reported and present analytical concerns.

Assessment of maturity timing

Maturity timing refers to the CA at which specific maturational events occur. The two most commonly used indicators of timing are age at PHV and age at menarche. Both are limited to the adolescent period and require longitudinal data for estimation.

Age at peak height velocity

Age at PHV is the estimated CA at the maximum rate of growth in height during the adolescent spurt. Onset of the spurt occurs when growth velocity in height reaches its minimum in late childhood (age at take-off), followed by acceleration to a maximum rate (PHV), and then by deceleration until growth in height terminates in the late teens/early twenties. Age at PHV is ordinarily estimated from serial height measurements of individuals taken annually or semi-annually from late childhood through adolescence. Historically, growth rates from individual height records were graphically plotted to identify take-off, peak, and eventual cessation of growth. Mathematical modeling or fitting of individual height records is currently used and a variety of methods are available.[60] Estimated ages at PHV vary somewhat among methods but are generally more uniform for age at PHV than for peak velocity of growth in height ($cm \cdot year^{-1}$). Allowing for normal variation, mean ages at PHV are reasonably similar in longitudinal studies of European and North American youth.[2,61,62] Variation in age at PHV among individuals is considerable. In longitudinal samples of British, Swiss, Polish, Belgian, Canadian, and American youth, estimated ages at PHV ranged from 9.0–15.0 years in individual girls and 11.1–17.3 years in individual boys.[2,63–66]

Age at menarche

Age at menarche refers to the timing of the first menstrual flow. At each regularly scheduled visit/observation in longitudinal studies (usually 3–6 months, but annually in some studies), girls and/or their mothers are interviewed whether or not menarche has occurred. If menarche occurred between visits, further questions pinpoint the specific date/age when the first menstrual flow occurred. This is labeled the prospective method. Prospectively recorded ages at menarche in longitudinal studies of American[65] and Polish[63,64] girls ranged from 10.77–15.25 years and 10.49–16.30 years, respectively.

Longitudinal studies generally follow subjects across adolescence so that early and late maturing girls are included. Depending on ages at which short-term longitudinal studies start and finish, there is potential risk that early and late maturing girls may be excluded.

Ages at menarche based on the prospective method are sometimes confused with estimates based on the *status quo* method. The method requires two bits of information in a cross-sectional sample spanning 9 through 17 years: CA, and whether or not menarche has occurred (yes/no). The data are subsequently analyzed with probits or logits to derive a median age at menarche for the sample. The *status quo* method is used in surveys, including a limited number of surveys of youth athletes.[59]

Ages at menarche can also be obtained retrospectively from late adolescents and adults who are asked to recall when they experienced their first menstruation. The method relies on memory, i.e. recall of the age when first menstrual flow occurred. In addition to potential errors with memory per se, reported ages are influenced by recall bias (the shorter the recall interval, the more accurate the recall, and vice versa) and a tendency to report whole years, typically age at the birthday before menarche.[2]

Estimates of age at menarche using the retrospective method with samples of young adolescents are biased. Girls who have not yet attained menarche are excluded from the estimates. Some late maturing girls may not attain menarche until 15 or 16 years, or perhaps later. In a nationally representative sample of American girls, 90% attained menarche by 13.75 years,[67] but 10% of girls attained menarche after this age.

Other indicators of timing and interrelationships

Assuming longitudinal data are available, other potential maturity indicators can be estimated, e.g. age at take-off, ages at peak velocity for body weight, estimated leg length or sitting height, and ages at attaining specific SAs, stages of pubertal development, or specific percentages of adult height. A summary of mean ages at take-off and at PHV, and mean ages of onset for selected stages of sexual maturation noted in European and American longitudinal studies have been summarized.[2,21]

Although data are not extensive, the differential timing of growth spurts in body dimensions other than height, components of body composition, and functional performances relative to age at PHV are of interest in the sport sciences. Available data suggest the following trends in estimated mean ages at peak velocities of several dimensions, tissues, and functions occur relative to age at PHV: leg

length—before PHV (both sexes); peak $\dot{V}O_2$—same time as PHV (both sexes); weight, sitting height, LTM, BMC, FM, static strength (both sexes), and power (boys)—after PHV.[2,62,68–70]

Analyses of ages at attaining several different maturity indicators in two longitudinal series highlight interrelationships among maturity timing during adolescence.[71–73] Common indicators in the two longitudinal series included ages at PHV and menarche, ages at attaining stages of pubertal development, ages at attaining specific SAs, and percentages of adult height. The analyses indicated a general maturity factor in both sexes underlying the timing of maturity indicators during the interval of the adolescent spurt. The analyses for boys indicated a second factor which loaded on ages at attaining SAs of 11 and 12 years, 80% of adult height, and early stages of pubic hair and genital development. These indicators are characteristic of early puberty or early adolescence, and suggest a degree of independence of ages at attaining (i.e. timing) several maturity markers characteristic of late pre-puberty or early puberty.[73] The preceding observations are based on ages at attaining specific maturity indicators. Longitudinal data for 30 boys indicated considerable variation in SA at the time of pubertal onset (serum testosterone ≥30 ng · DL^{-1}).[74]

Tempo of maturation

Tempo refers to the rate at which maturation progresses. Data are limited. Estimated increments in GP SAs in a longitudinal sample of American children approximated 1 year; variation was considerable and was associated in part with maturity status, i.e. early versus late.[75,76] In a mixed longitudinal sample of American white and black girls 6–12 years, mean single year velocities for TW2 20 Bone SAs varied between 0.66–1.14 years per year and standard deviations varied between 0.33–0.52; corresponding mean single year velocities for boys varied between 0.75–1.27 years per year and standard deviations ranged from 0.32–0.60 years.[36] Single year rates of maturation expressed as maturity points per year of the American children[35] overlapped the mean rates and ranges for British children.[28] Observations in a longitudinal series of 34 boys suggested that annual increments (years per year) in TW2 SAs (presumably 20 bone) increased during the interval of puberty and the growth spurt; increments appeared to reach a peak near PHV.[77] Allowing for limited data, it is important to ask whether a skeletal year equals a chronological year.

Similar questions can be asked of the tempo of transition from one pubertal stage to the next, but data for the time between stages are not extensive. Evidence from the Zurich Longitudinal Study indicated the following trends. The intervals (means ± standard deviations) between B2 and B3 and between PH2 and PH3 in Swiss girls were, respectively, 1.4 ± 0.8 years, and 1.8 ± 1.0 years, while intervals between G2 and G3 and between PH2 and PH3 in Swiss boys were, respectively, 1.7 ± 1.0 years and 1.3 ± 0.9 years.[78,79] The intervals between the transition into puberty (B2, G2, PH2) and the mature state (B5, G5, PH5) were, on average, 2.2 ± 1.1 years for breast and 2.7 ± 1.1 years for pubic hair development in Swiss girls, and 3.5 ± 1.1 years for genital and 2.7 ± 1.0 years for pubic hair development in Swiss boys.[78,79] The standard deviations for the transition through puberty for each characteristic approximated 1 year and highlighted the variation in tempo of maturation of secondary sex characteristics within and among individuals.

Non-invasive estimates of maturity status and timing

Given logistical difficulties in conducting longitudinal studies spanning adolescence, concern for minimal radiation exposure with hand-wrist X-rays, and cultural perceptions of the assessment of secondary characteristics, there is considerable current interest in the sport sciences in non-invasive estimates of biological maturation. Two estimates are currently used. Percentage of predicted adult height attained at the time of observation provides an estimate of maturity status, while predicted maturity offset or time before age at PHV provides an estimate of maturity timing.

Percentage of predicted adult height

Although age at attaining specific percentages of adult height has been used in analyses of longitudinal data, the use of percentage of predicted adult height at a given age as a maturity indicator was apparently proposed by Roche and colleagues.[80] Given two youngsters of the same CA, the one closer to adult height is advanced in maturity compared to a youth further removed from adult height. Percentage of predicted adult height at a given age provides an estimate of maturity status.

Height prediction is standard practice in many clinical settings, but the commonly used clinical protocols require an estimate of SA.[2] A commonly used general clinical guide without SA is mid-parent target height, based on the average of the heights of both parents.[81] The protocol has a large associated error of ~9 cm. The protocol developed in the Fels Longitudinal Growth Study[82] predicts adult height from CA, height, and weight of the child and mid-parent height in children and adolescents 4–17 years.

Percentage of predicted adult height based upon the Khamis-Roche equations[82] has been used as an indicator of maturity status in studies of physical activity and of youth athletes.[83] Maturity status based on percentage of predicted adult height had moderate concordance with classifications of maturity status based on SA in youth American football[84] and soccer[85] players. The protocol requires further validation. The prediction equations were developed on samples of European ancestry, which probably limits their utility among youth of non-European ancestry.

Equations developed on youth 13–16 years of age from the Leuven Longitudinal Study of Belgian Boys use CA, current height, sitting height, and the subscapular and triceps skinfolds.[86] The protocol has been validated in an independent sample of boys 13–16 years of age from the Madeira Growth Study,[87] but apparently has not been used in studies of physical activity and youth athletes.

Predicted maturity offset/age at peak height velocity

Equations for the prediction of maturity offset, time before or after PHV, have been developed.[66] Predicted age at PHV is estimated as CA minus maturity offset. The sex-specific equations incorporate CA, height, weight, sitting height, and estimated leg length (height minus sitting height). Predicted offset was suggested as a categorical variable, pre- or post-PHV, i.e. an indicator of maturity status, but has been used to estimate maturity status and timing.[83]

Results of validation studies in longitudinal samples of Polish children from the Wrocław Growth Study[63,64] and American children from the Fels Longitudinal Study[65] from 8 to 18 years highlight several limitations of the maturity offset prediction protocol:

First, within the age range of the two longitudinal studies, intra-individual variation in predicted offset and ages at PHV was considerable.

Second, predicted maturity offset and in turn predicted age at PHV were dependent upon CA at prediction and probably age-associated variation in body size. Predicted maturity offset decreased and estimated age at PHV increased, on average, with CA at prediction.

Third, standard deviations of mean predicted ages at PHV indicated reduced ranges of variation which increased from 8 to 16 years, 0.29–0.47 years in girls and 0.26–0.68 years in boys. Standard errors (SE = SD/√n) of the prediction equations were 0.59 for boys and 0.57 for girls.[66]

Fourth, predictions of maturity offset and age at PHV were affected by individual differences in observed ages of PHV as evident in comparisons of youth of contrasting maturity status. Among early maturing boys and girls classified by observed ages at PHV, predicted ages at PHV were later than observed ages at PHV, while among late maturing boys and girls classified by observed ages at PHV, predicted ages were earlier than observed ages at PHV. Trends were similar for contrasting maturity groups of girls based on ages at menarche. Observations for a longitudinal sample of 13 female artistic gymnasts were consistent with those for late maturing girls.[88]

Fifth, predicted age at PHV appears to be useful close to the time of actual age at PHV in average (on time) maturing boys within a narrow age range, 13.00–15.00 years; this range includes the standard deviation around mean age at PHV in average maturing boys. The protocol appears to overestimate age at PHV more so in girls than in boys; nevertheless, predicted age at PHV may be useful among some average and late maturing girls.[65]

Application of the maturity offset prediction equations depends, of course, on the purpose of a specific study, and the limitations of predicted values should be recognized. Revised equations have been reported.[89] Chronological age and sitting height in boys and CA and height in girls are the predictors, although an alternative equation for boys using CA and height is reported. The new equations require validation in independent samples and also in samples of athletes.

Conclusions

Though related, indicators of maturity status and timing are not equivalent. Currently used predictors of maturity status and timing have limitations and require further validation and care in application.

Summary

- The processes of growth and maturation occur concurrently and are related.
- Growth status—size attained at the time (chronological age [CA]) of observation, and growth rate—increment between observations, are basic to the assessment of growth. Indicators of growth are also used in deriving estimates of maturation.
- Maturity status refers to the state of maturation at the time of observation. Indicators of skeletal and pubertal maturity status are used most often.
- Maturity timing refers to the CA at which specific maturational events occur. Chronological age at peak height velocity (PHV) and CA at menarche are used most often.
- Skeletal age is the only maturity indicator that spans childhood through adolescence; other indicators (pubertal status, CA at PHV, CA at menarche) are limited to the interval of puberty and the growth spurt.
- Tempo refers to the rate at which maturation progresses. Data are limited.
- There is increasing interest in the application of non-invasive indicators of maturation. Percentage of predicted adult height attained at the time of observation provides an estimate of maturity status, while predicted maturity offset or time before age at PHV provides an estimate of maturity timing. Both have limitations and require further validation and care in application.

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