

# Oxford Textbook of Children's Sport and Exercise Medicine

THIRD EDITION

Edited by

**Neil Armstrong**

**Willem van Mechelen**



Oxford Textbook of

**Children's Sport  
and Exercise  
Medicine**



---

**Oxford Textbook of**  
**Children's Sport**  
**and Exercise**  
**Medicine**

---

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

**OXFORD**  
UNIVERSITY PRESS

**OXFORD**  
UNIVERSITY PRESS

Great Clarendon Street, Oxford, OX2 6DP,  
United Kingdom

Oxford University Press is a department of the University of Oxford.  
It furthers the University's objective of excellence in research, scholarship,  
and education by publishing worldwide. Oxford is a registered trade mark of  
Oxford University Press in the UK and in certain other countries

© Oxford University Press 2017

The moral rights of the authors have been asserted

Second Edition Published in 2008

Impression: 1

All rights reserved. No part of this publication may be reproduced, stored in  
a retrieval system, or transmitted, in any form or by any means, without the  
prior permission in writing of Oxford University Press, or as expressly permitted  
by law, by licence or under terms agreed with the appropriate reprographics  
rights organization. Enquiries concerning reproduction outside the scope of the  
above should be sent to the Rights Department, Oxford University Press, at the  
address above

You must not circulate this work in any other form  
and you must impose this same condition on any acquirer

Published in the United States of America by Oxford University Press  
198 Madison Avenue, New York, NY 10016, United States of America

British Library Cataloguing in Publication Data  
Data available

Library of Congress Control Number: 2016954555

ISBN 978-0-19-875767-2

Printed in Great Britain by  
Bell & Bain Ltd., Glasgow

Oxford University Press makes no representation, express or implied, that the  
drug dosages in this book are correct. Readers must therefore always check  
the product information and clinical procedures with the most up-to-date  
published product information and data sheets provided by the manufacturers  
and the most recent codes of conduct and safety regulations. The authors and  
the publishers do not accept responsibility or legal liability for any errors in the  
text or for the misuse or misapplication of material in this work. Except where  
otherwise stated, drug dosages and recommendations are for the non-pregnant  
adult who is not breast-feeding

Links to third party websites are provided by Oxford in good faith and  
for information only. Oxford disclaims any responsibility for the materials  
contained in any third party website referenced in this work.

---

# Contents

Foreword *xix*

Preface *xxi*

Contributors *xxiii*

Introduction *xxvii*

List of Abbreviations *xxix*

## PART 1

### Exercise science

#### 1 Assessment of biological maturation 3

Robert M Malina

Introduction 3

Chronological age and age groups 3

Brief overview of methods for the assessment of growth 3

Growth status 3

Growth rate 4

Assessment of maturity status 4

Skeletal age 4

Secondary sex characteristics 6

Assessment of maturity timing 7

Age at peak height velocity 7

Age at menarche 7

Other indicators of timing and interrelationships 7

Tempo of maturation 8

Non-invasive estimates of maturity status and timing 8

Percentage of predicted adult height 8

Predicted maturity offset/age at peak height velocity 8

Conclusions 9

Summary 9

References 9

#### 2 Growth and maturation 13

Adam DG Baxter-Jones

Introduction 13

Prenatal to postnatal growth 13

Statural growth 14

Types of growth data 15

Growth in stature 16

Patterns of growth 17

Growth in body mass 17

Development of shape 18

Adolescence and puberty 18

Regulation of growth and maturation 19

Biological maturity 21

Relationship of maturity to body size and function 21

Conclusions 22

Summary 23

References 23

#### 3 Developmental biodynamics: the development of coordination 25

James Watkins

Introduction 25

Development of coordination and control 26

Reference axes and degrees of freedom 27

Coordination and degrees of freedom 27

Kinematics of coordination 28

Kinetics of coordination 29

Modelling 29

Free body diagram 29

Components of net joint moment 30

Dynamical systems approach to the development of coordination 32

Self-organization and constraints 32

Coordinative structures, control parameters, and order parameters 33

Patterns, attractors, and stability 34

Cyclicity in biological systems 35

Force-driven harmonic oscillators 35

Self-optimization of coordinative structures 36

Dynamic resources 37

A dynamical systems perspective of walking in children with cerebral palsy 39

- Conclusions 39
- Summary 39
- References 40
- 4 Motor development 43**
  - David Sugden and Helen Soucie
  - Introduction 43
  - General description of change 43
  - Explanation of change 44
    - Traditional maturational explanations 44
    - Information processing and cognitive explanations 44
    - Ecological psychology and dynamic systems 45
  - Early movement development 46
    - Spontaneous movements and reflexes 46
    - Environmental affordances 47
    - Vision and visual perception development 48
  - Motor development 2–7 years of age 48
  - Motor development in later childhood 49
    - Maximum performance 49
  - Embodied cognition 50
  - Atypical motor development 50
    - Movements as early indicators of later difficulties 51
    - Children with developmental coordination disorder 51
  - Conclusions 52
  - Summary 52
  - References 52
- 5 Exercise and hormones 57**
  - Alon Eliakim and Dan Nemet
  - Introduction 57
  - Exercise and the growth hormone—insulin-like growth factor-I axis 57
    - The growth hormone—insulin-like growth factor-I axis 57
  - The effect of an exercise bout 58
    - Growth hormone 58
    - Insulin-like growth factor-I 60
  - Exercise and sex hormones 62
    - The hypothalamic-pituitary-gonadal axis 62
  - Exercise and adrenal hormones 63
    - Cortisol 63
    - Catecholamines 64
  - Conclusions 64
  - Summary 64
  - References 65
- 6 Muscle metabolism during exercise 69**
  - Neil Armstrong, Alan R Barker, and Alison M McManus
  - Introduction 69
  - Anaerobic and aerobic exercise metabolism 69
    - High-energy phosphates 69
    - Anaerobic metabolism 69
    - Aerobic metabolism 70
  - Maximal-intensity exercise 72
    - Maximal anaerobic power 73
    - Maximal aerobic power 73
    - Comparison of maximal anaerobic and aerobic power 73
  - Recovery from intermittent maximal or high-intensity exercise 73
  - Muscle biopsies 73
    - Muscle fibre types 73
    - Muscle energy stores 74
    - Muscle lactate production and blood lactate accumulation 74
    - Muscle enzymes activity 75
  - Substrate utilization 76
    - Indirect calorimetry 76
    - Stable isotope tracers 77
  - Magnetic resonance spectroscopy 78
    - Methodological issues and theoretical concepts 78
    - Intracellular thresholds 79
    - Incremental exercise to exhaustion 79
    - Constant intensity exercise 80
    - Intermittent exercise 80
    - Muscle phosphocreatine kinetics and pulmonary oxygen uptake kinetics 81
  - Pulmonary oxygen uptake kinetics 81
    - Methodological issues 81
    - Moderate-intensity exercise 81
    - Heavy-intensity exercise 81
  - Synthesis of data across methodologies 82
  - Conclusions 83
  - Summary 83
  - References 84
- 7 Muscle strength 89**
  - Mark BA De Ste Croix
  - Introduction 89
  - Defining muscle strength 89
    - Definitions of force and torque 90
  - Assessment of muscle strength 91
    - Determining strength in paediatric populations 91
  - Development of muscle strength 92
    - Age- and sex-associated changes in force/torque 92
  - Determinants of strength development 94
    - Stature, mass, and strength development 95
    - Maturation and hormonal influences on strength development 96
    - Fat-free mass and strength development 96
    - Muscle cross-sectional area and strength development 96
    - Biomechanical factors and strength development 97
  - Muscle strength and tendon/limb stiffness 98
  - Torque/force kinetics 98

- Neuromuscular function 99  
 Methodological issues in measuring neuromuscular function 99  
 Neuromuscular feedforward and feedback mechanisms 100  
 Conclusions 100  
 Summary 100  
 References 101
- 8 Maximal-intensity exercise 105**  
 Craig A Williams and Sébastien Ratel  
 Introduction 105  
 Definition of maximal-intensity exercise 105  
 Assessment of maximal-intensity exercise 105  
 Jump tests 106  
 Monoarticular force-velocity tests 106  
 Cycle tests 106  
 Running tests 108  
 Determinants of maximal-intensity exercise 109  
 Cadence and neuromuscular inferences 109  
 Power and muscle size related inferences 110  
 Power and muscle fibre type inferences 111  
 Power and hormonal related inferences 112  
 Maximal-intensity exercise and age 112  
 Maximal-intensity exercise and sex 114  
 Maximal-intensity exercise and maturation 115  
 Conclusions 117  
 Summary 117  
 References 117
- 9 Neuromuscular fatigue 121**  
 Sébastien Ratel and Craig A Williams  
 Introduction 121  
 The conceptual framework of fatigue 121  
 Definition 121  
 Aetiology 121  
 Fatigue protocols used with children 121  
 Age-related differences in fatigue 122  
 Whole body dynamic activities 122  
 Maximal voluntary contraction 124  
 Factors underpinning age differences 125  
 Peripheral factors 125  
 Central factors 127  
 Interplay between peripheral and central factors 128  
 Conclusions 128  
 Summary 129  
 References 129
- 10 Pulmonary function 133**  
 Alison M McManus and Neil Armstrong  
 Introduction 133  
 Resting pulmonary function 133  
 Lung volumes 133  
 Flow rates 134  
 Dead space 134  
 Pulmonary responses to exercise 136  
 Breathing patterns during exercise 137  
 Responses to acute moderate-intensity exercise 137  
 Heavy, very heavy, severe, and maximal exercise 139  
 Long-term pulmonary adaptations to exercise 140  
 Breathing mechanics 140  
 Expiratory flow limitation 140  
 Control of breathing 141  
 Future avenues of research 142  
 Conclusions 143  
 Summary 143  
 References 143
- 11 Cardiovascular function 147**  
 Thomas W Rowland  
 Introduction 147  
 Measurement of cardiac output 147  
 Carbon dioxide rebreathing 148  
 Acetylene rebreathing 148  
 Doppler echocardiography 148  
 Bioimpedance cardiography 148  
 Expressing cardiac output with exercise to body size 148  
 Dynamics of cardiovascular responses to progressive exercise 149  
 Total systemic vascular resistance: observed progressive decline 149  
 Stroke volume change in various levels of exercise intensity 149  
 Left ventricular end-diastolic dimension 150  
 Myocardial systolic and diastolic function 151  
 A synthesis 152  
 Normative values 152  
 Heart rate 152  
 Stroke Volume and cardiac output 153  
 Blood pressure 154  
 The ‘meaning’ of cardiovascular fitness 154  
 Myocardial damage 156  
 Conclusions 156  
 Summary 156  
 References 157
- 12 Aerobic fitness 161**  
 Neil Armstrong and Alison M McManus  
 Introduction 161  
 Measures of aerobic fitness 161



Maximal oxygen uptake	161
Blood lactate accumulation	162
Pulmonary oxygen uptake kinetics	164
<b>Peak oxygen uptake</b>	<b>165</b>
Methodological issues	165
Peak oxygen uptake and chronological age	167
Peak oxygen uptake and body mass	168
Peak oxygen uptake and biological maturation	171
Peak oxygen uptake and sex	171
<b>Blood lactate accumulation</b>	<b>173</b>
Methodological issues	173
Chronological age, biological maturity, and sex	174
<b>Pulmonary oxygen uptake kinetics</b>	<b>174</b>
Methodological issues	174
Exercise phases, exercise domains, chronological age, and sex	175
Recovery kinetics	177
<b>Conclusions</b>	<b>177</b>
<b>Summary</b>	<b>177</b>
<b>References</b>	<b>178</b>
<b>13 Pulmonary oxygen uptake kinetics</b>	<b>181</b>
Alan R Barker and Neil Armstrong	
Introduction	181
Kinetics of oxygen uptake at the mouth and muscle	181
Exercise intensity domains	182
Methodological considerations	183
Pulmonary oxygen uptake kinetics: children and adolescents	184
Phase I	184
Moderate-intensity exercise	184
Heavy- and very heavy-intensity exercise	186
Severe-intensity exercise	187
Synthesis	187
Mechanisms	187
Muscle phosphates	187
Muscle oxygen delivery	188
Muscle fibre recruitment	190
Conclusions	191
Summary	191
References	191
<b>14 Temperature regulation</b>	<b>195</b>
Bareket Falk and Raffy Dotan	
Introduction	195
Physical and physiological child–adult differences pertinent to thermoregulation	195
Physical differences	195
Physiological differences	197
Physiological response to thermal stress	198
Physiological response to heat stress	198

Physiological response to cold stress	205
<b>Adaptation to thermal stress</b>	<b>207</b>
Heat acclimatization or acclimation	207
Training-induced adaptations to heat stress	207
Training-induced adaptations to cold stress	208

**Conclusions** 208

**Summary** 208

**References** 209

## **15 Effort perception** 213

Kevin L Lamb, Gaynor Parfitt, and Roger G Eston

**Introduction** 213

Application and description of traditional adult rating of perceived exertion scales 213

Estimation and production of exercise effort 213

The study of perceived exertion in children: a historical perspective 214

The development of child-specific rating scales 214

Pictorial versions of the Children's Effort Rating Table (CERT) 215

OMNI scales 216

Independent validation of the pictorial versions of the CERT and OMNI scales 218

Methodological issues in children's effort perception research 218

  Anchoring effort perceptions 218

  Intermittent versus continuous exercise protocols 219

Effort perception scales: promoting and regulating physical activity levels 219

**Conclusions** 220

**Summary** 220

**References** 220

## **PART 2**

### **Exercise medicine**

## **16 Physical activity, physical fitness, and health** 225

Lauren B Sherar and Sean P Cumming

**Introduction** 225

Defining physical activity, sedentary behaviour, and fitness 226

Physical activity and health 227

  Overweight and obesity 228

  Cardiometabolic risk and type 2 diabetes mellitus 228

  Bone health 229

  Psychological health 230

  Other health issues 231

Physical activity and future health status 231

  Direct effects 231

  Indirect effects 231

- Prevalence of activity, inactivity, and sedentary behaviour 232
- Guidelines for physical activity 232
- Fitness and health 233
- Which is more important—physical activity or fitness? 233
- Physical activity and risks to the child 234
- Conclusions 234
- Summary 234
- References 235
- 17 Physical activity, cardiopulmonary fitness, and cardiovascular health 239**
  - Isabel Ferreira and Jos WR Twisk
  - Introduction 239
  - Physical activity and cardiopulmonary fitness in youth and cardiovascular disease later in life 239
  - Tracking of physical activity and cardiorespiratory fitness through childhood and adolescence to adulthood 240
  - Cardiometabolic risk factors 240
    - Physical activity and cardiorespiratory fitness, and cardiometabolic risk factors in youth 240
    - Cardiometabolic risk factors in youth and cardiometabolic risk factors or cardiovascular disease in adulthood 244
    - Physical activity and cardiorespiratory fitness in youth and later-life cardiometabolic risk factors 244
  - Pre-clinical signs of earlier vascular aging 245
    - Atherosclerosis versus arterial stiffness 245
    - Physical activity and cardiorespiratory fitness and markers of early vascular aging in youth 245
    - Physical activity and cardiorespiratory fitness in youth and markers of early vascular aging in adulthood 247
  - Conclusions 249
  - Summary 249
  - References 250
- 18 Physical activity and bone health 255**
  - Han CG Kemper and Rômulo A Fernandes
  - Introduction 255
  - Growth of bone 255
  - Methods of measurement of bone mass 256
    - Anthropometrics 256
    - Radiographics 256
    - Dual energy X-ray absorptiometry 256
    - Quantitative computed tomography 256
    - Quantitative ultrasound 257
  - Mechanisms of bone formation 257
  - Natural course of bone mass development 258
  - Development of bone density before puberty 258
    - Development of bone density during puberty 259
    - Age at which maximal bone mass is reached (peak bone mineral density) 259
- Effects of physical activity and physical fitness on bone mass 260
  - Randomized controlled trials 260
  - Systematic review of randomized control trials 261
  - Long-term effects of physical activity 261
  - Importance of physical activity in puberty 262
  - Physical exercise, inflammation, and bone mass 262
- Conclusions 263
- Summary 263
- References 263
- 19 Sport, physical activity, and other health behaviours 267**
  - Stewart G Trost and Barbara Joschtel
  - Introduction 267
    - Sports participation and other health behaviours 267
    - Cigarette smoking 267
    - Smokeless tobacco 279
    - Alcohol use 280
    - Illegal drug use 280
    - Anabolic steroid use 281
    - Dietary practices 282
    - Inappropriate weight-control practices 282
    - Sexual risk behaviours 283
    - Violence 283
  - Physical activity and other health behaviours 284
    - Cigarette smoking 284
    - Smokeless tobacco 284
    - Alcohol use 285
    - Illegal drug use 285
    - Anabolic steroid use 286
    - Dietary practices 286
    - Inappropriate weight-loss practices 286
    - Sexual risk behaviours 286
    - Violence 287
  - Conclusions 287
  - Summary 287
  - References 288
- 20 Genetics of physical activity and physical fitness 293**
  - Nienke M Schutte, Meike Bartels, and Eco JC de Geus
  - Introduction 293
    - Individual differences 293
  - The principles of family, twin, animal, and molecular genetic studies 293
    - Family studies 293
    - Twin studies 293
    - Animal studies 294
    - Molecular genetic studies 294
  - Quantitative genetics of physical activity and exercise behaviour 294
    - Total physical activity 295
    - Voluntary exercise behaviour 296

Molecular genetics findings for physical activity and exercise behaviour	297
Quantitative genetics of physical fitness	297
Maximal oxygen uptake	297
Other fitness phenotypes	298
Molecular genetics findings for physical fitness	298
Genes and environment	299
Implications for paediatrics	300
Conclusions	300
Summary	300
References	300

## 21 The assessment of physical activity 303

Maria Hildebrand and Ulf Ekelund

Introduction	303
Key concepts in measuring physical activity	303
Definitions and dimensions of physical activity	303
Measurement metrics of physical activity	304
Reliability, validity, accuracy, and responsiveness of physical activity assessment methods	304
Methods of physical activity assessment	305
Criterion methods	306
Subjective methods	307
Objective methods	308
How to choose the right measurement method	310
Conclusions	311
Summary	311
References	311

## 22 Systematic promotion of physical activity 315

Stef Kremers, Ree M Meertens, and Robert AC Rutter

Introduction	315
Planned health promotion	315
Health promotion and physical activity	316
Problems and problem-causing factors	316
Determinants of physical activity	316
Systematic development of physical activity-promoting interventions	319
Implementation and diffusion of health promotion interventions	320
Conclusions	321
Summary	321
References	322

## 23 Exercise, physical activity, and diabetes mellitus 325

Edgar GAH van Mil

Introduction	325
Definition of diabetes mellitus	325
Diagnostic criteria for diabetes mellitus in childhood and adolescence	325
Classification of diabetes mellitus	325

The aetiology and incidence of type 1 diabetes mellitus	325
The clinical spectrum of type 1 diabetes mellitus	326
The management of type 1 diabetes mellitus	326

The importance of physical activity for the diabetic patient	327
Physical activity	327
The effect of physical activity on the patient with type 1 diabetes mellitus	328
Strategies to optimize performance and prevent complications in type 1 diabetes mellitus	330
Short-acting insulin analogues and basal insulins	332
New technologies leading to more possibilities in monitoring and adapting to the effects of physical activity in type 1 diabetes mellitus	332

Conclusions 332

Summary 332

References 333

## 24 Exercise, physical activity, and asthma 337

Helge Hebestreit, Susi Kriemler, and Thomas Radtke

Introduction	337
Exercise-induced asthma	337
Children at risk	337
Symptoms of exercise-induced asthma	337
Pathophysiology of exercise-induced bronchoconstriction	337
Late response	338
Refractory period	338
Diagnosing exercise-induced asthma	338
Physical activity and exercise capacity of children and adolescents with asthma or exercise-induced asthma	338
Exercise-related benefits to children with asthma	338
Improvements in fitness	339
Psychological benefits	339
Reduction in asthma symptoms and exercise-induced asthma	339
Does regular exercise reduce airway inflammation?	339
Can physical training cause asthma?	339
Exercise testing in children with asthma or suspected exercise-induced asthma	339
Indications	339
Who should not be tested?	340
Preparation before the test and safety procedures	340
Conducting the exercise challenge	340
Criteria to identify exercise-induced asthma with an exercise challenge	341
Reliability of bronchial responsiveness to a standardized exercise challenge	341
Prevention of exercise-induced asthma and exercise counselling	341
Control of asthma	341

- Select the least asthmogenic activity 341
- Select the right time to exercise 341
- Prevention of exercise-induced asthma shortly before and during exercise 342
- Treatment of exercise-induced asthma 342
- Anti-doping rules and exercise-induced asthma 342
- Conclusions 342
- Summary 342
- References 343
- 25 Exercise, physical activity, eating and weight disorders 347**
  - Andrew P Hills, Steven J Street, and Nuala M Byrne
  - Introduction 347
    - A central concern: fear of fatness 347
  - Eating and weight disorders 348
    - Contrasting scenarios: overnutrition and physical inactivity, undernutrition and excessive physical activity 348
  - Obesity 348
    - Treatment and management 348
  - Exercise, diet, and behavioural interventions 349
    - From treatment and management to prevention 349
    - Body satisfaction during the growing years: implications for eating and weight disorders 351
    - The influence of body composition on disordered eating tendencies of adolescents 352
    - Exercise motivations of adolescents 352
  - Anorexia nervosa, bulimia nervosa, and binge eating disorder 352
    - Aetiology of anorexia and bulimia nervosa 353
    - The dieting and eating disorder continuum 354
    - Prevalence of eating disorders 354
    - Binge eating disorder 354
    - Prevention, treatment and management 354
  - Conclusions 355
  - Summary 355
  - References 355
- 26 Exercise, physical activity, and cerebral palsy 361**
  - Annet J Dallmeijer, Astrid CJ Balemans, and Olaf Verschuren
  - Introduction 361
    - Cerebral palsy 361
    - Classification 361
  - Exercise testing and physical fitness 361
    - Exercise testing 361
    - Aerobic fitness 363
    - Anaerobic fitness 363
    - Aerobic and anaerobic field tests 364
    - Muscle strength 365
    - Walking economy 365
  - Training effects 365
    - Aerobic training 365
    - Anaerobic training 367
    - Strength training 367
  - Physical activity 368
    - Physical activity in cerebral palsy 368
    - Sedentary behaviour 368
  - Training recommendations 368
    - Aerobic training 368
    - Anaerobic training 369
    - Muscle strength training 369
  - Conclusions 370
  - Summary 370
  - References 370
- 27 Exercise, physical activity, and cystic fibrosis 373**
  - Susi Kriemler, Thomas Radtke, and Helge Hebestreit
  - Introduction 373
  - Cystic fibrosis-related pathologies and exercise tolerance 373
    - General 373
    - Respiratory system 373
    - Cardiac system 375
    - Habitual physical activity 375
    - Nutrition, muscle mass, and muscle function 376
    - Diabetes 377
    - Osteopenia/osteoporosis 377
    - Dehydration 377
  - Beneficial effects of exercise and physical activity 378
  - Harmful effects of exercise and physical activity 378
  - Exercise testing and recommendations 379
  - Selection of the type of sport and training 380
  - Conclusions 381
  - Summary 381
  - References 381
- 28 Exercise, physical activity, and children with physical or intellectual disabilities 387**
  - Merrilee Zetaruk and Shareef F Mustapha
  - Introduction 387
    - A brief historical note 387
  - Benefits of exercise and sport participation for children with physical or intellectual disabilities 387
  - Children with sensory impairments 389
    - The deaf child 389
    - The blind child 389
  - Children with physical impairments 389
    - Children with cerebral palsy 390
    - Children with myelomeningocele 390
    - Children with spinal cord injuries 391
    - Amputees 392
    - Specialized equipment and prosthetic devices for sport 393
    - Wheelchair sports 394

Children with intellectual disability	395
Down syndrome	395
Special Olympics	397
Conclusions	397
Summary	397
References	398

## 29 Exercise, physical activity, and congenital heart disease 401

Roselien Buys, Tony Reybrouck, and Marc Gewillig

Introduction 401

Commonly used parameters to assess exercise performance and aerobic exercise function in children with cardiac disease 401

Cardiorespiratory response to exercise in specific congenital heart defects 403

    Left-to-right shunts 403

    Valvular heart lesions 403

    Cyanotic heart disease 403

    Rhythm disturbances and conduction defects 404

Habitual physical activity in children with congenital heart disease 405

Natural evolution of aerobic exercise performance and daily level of physical activity in children with congenital heart disease 405

Exercise recommendations and rehabilitation of children with congenital heart disease 406

Conclusions 407

Summary 407

References 407

## PART 3

### Sport science

## 30 Development of the young athlete 413

Neil Armstrong and Alison M McManus

Introduction 413

Genetics 413

Chronological age, biological maturity, and the young athlete 413

    Biological maturation 413

    Body size and shape 414

    Body mass 414

    Body composition 415

    Muscle strength 415

    Muscle metabolism 416

    Aerobic fitness 416

    Anaerobic fitness 418

    Resistance to fatigue 418

    Speed 418

Chronological age, biological maturity, and performance in youth sport 419

Early specialization in youth sport 419

Chronological age-group sport 420

    The relative age effect 420

    Chronological age deception 420

Risks to young athletes' health and well-being 421

    Physical, psychological, and sexual abuse 421

    Coach and parental pressure 422

    Financial exploitation 422

    Performance-enhancing drugs 422

    Dietary supplementation, disordered eating, and eating disorders 423

    Sport injuries 423

Conclusions 424

Summary 424

References 424

## 31 Molecular exercise physiology 429

Henning Wackerhage, Jonathon Smith, and Darren Wisniewski

Introduction 429

    Definition of and introduction to molecular exercise physiology 429

Development of key exercise organs 429

    The development of muscle: myogenesis 430

    The development of tendons 430

    The formation of bone: chondrogenesis and osteogenesis 431

    Mechanical signals and cell differentiation 431

    Epigenetic regulation of development: does maternal nutrition and exercise affect the offspring? 431

The signal transduction model of adaptation 432

Genetics 432

    Introduction to genetics and exercise 432

    Sequence variations: large and small effects 434

    Genotypic and phenotypic associations 434

    The genetics of development, maturation, and body height 434

    Genetics of endurance and strength-related traits 435

    Genetic testing 436

Conclusions 437

Summary 437

References 437

## 32 The influence of physical activity and training on growth and maturation 441

Robert M Malina

Introduction 441

Historical background 441

Physical activity  $\neq$  training 441

Indicators of growth and maturation 442

- Physical activity, growth and maturation in the general population 442
- Height and weight 442
  - Body composition 442
  - Maturation 443
- Growth and maturity characteristics of young athletes 443
- Limitations of studies of young athletes 443
  - Size attained 443
  - Body composition 444
  - Maturity status and timing 444
- Training for sport and the growth and maturation of young athletes 445
- Studies from Poland and the former Czechoslovakia 445
  - Training of Young Athletes study 446
  - Other studies 447
  - Overview of longitudinal studies 447
  - Two persistent questions 447
  - Training and body composition 449
- Conclusions 450
- Summary 450
- References 450
- 33 Hormones and training 455**
- Jaak Jürimäe
- Introduction 455
- Sport training and the growth hormone-insulin-like growth factor-I axis 456
- Sport training and the hypothalamic-pituitary-gonadal axis 457
- Sport training and the hypothalamic-pituitary-adrenal axis 459
- Sport training and the peripheral signals of energy homeostasis 459
- Leptin 459
  - Adiponectin 460
  - Ghrelin 461
- Conclusions 462
- Summary 462
- References 462
- 34 Aerobic trainability 465**
- Melitta A McNarry and Neil Armstrong
- Introduction 465
- Peak oxygen uptake 465
- Influence of training on peak oxygen uptake 465
  - Mechanistic bases of training adaptations on peak oxygen uptake 466
- Lactate and gas exchange thresholds 467
- Influence of training on lactate and gas exchange thresholds 468
  - Mechanistic bases of training adaptations on lactate and gas exchange thresholds 468
- Exercise economy 468
- Pulmonary oxygen uptake kinetics 468
- Influence of training on pulmonary oxygen uptake kinetics 469
  - Mechanistic bases of training adaptations on pulmonary oxygen uptake kinetics 470
- Parameters of aerobic fitness and sport performance 470
- Maturation threshold 470
- Methodological issues 471
- Conclusions 472
- Summary 472
- References 472
- 35 High-intensity interval training 477**
- Keith Tolfrey and James W Smallcombe
- Introduction 477
- High-intensity interval training and the young performance athlete 477
- Cardiorespiratory fitness 478
  - Explosive strength 482
  - Sport-specific performance outcomes 483
- High-intensity interval training for health 483
- Cardiorespiratory fitness 483
  - Body size and composition 486
  - Biochemical metabolites 487
  - Vascular health 488
- Time efficiency and enjoyment of high-intensity interval training 489
- Conclusions 489
- Summary 489
- References 490
- 36 Resistance training 493**
- Avery D Faigenbaum and Rhodri S Lloyd
- Introduction 493
- Resistance training and physical development 493
- Effectiveness of youth resistance training 494
- Physiological mechanisms for strength development 494
  - Detraining and persistence of training-induced gains 494
  - Risks and concerns 495
  - Maximum strength testing 495
- Potential benefits of youth resistance training 496
- Bone health 496
  - Adiposity and metabolic health 497
  - Motor skills and sports performance 497
  - Injury reduction in youth sport 498
- Youth resistance-training guidelines 498
- Choice and order of exercises 499
  - Training intensity and volume 499



Rest interval between sets and exercises 500  
 Repetition velocity 500  
 Training frequency 500  
 Long-term physical development 500

Conclusions 502

Summary 502

References 502

### 37 Speed and agility training 507

Jon L Oliver and Rhodri S Lloyd

Introduction 507

Speed 507

Natural development of speed 507

Growth, maturation, and spatio-temporal  
 determinants of speed 509

Speed training 509

Short-term speed training interventions 509

Longitudinal monitoring of speed  
 in sporting populations 511

Agility 511

Testing agility 512

Natural development of agility 512

Change-of-direction-speed 513

Perceptual and decision-making processes 513

Agility training 514

Effect of targeted training on change-of-direction-speed 514

Effect of targeted training on perceptual  
 and decision-making processes 514

Conclusions 515

Summary 515

References 515

### 38 Overtraining syndrome 519

Richard J Winsley

Introduction 519

Clarity among complexity 519

Why we should care about overtraining  
 in the young athlete 519

Definition of overtraining 519

Prevalence rates 520

Signs and symptoms of overtraining  
 syndrome in children 520

Markers of overtraining syndrome  
 in young athletes 521

Causes 522

Are training loads responsible? 522

Coach and parent pressure 522

Lack of perceived control 523

Active burnout and entrapment 523

Single identity 523

Perfectionist traits 523

Early specialization 524

Recovery and prevention 524

Conclusions 525

Summary 525

References 525

### 39 Physiological monitoring of elite young athletes 527

Neil Armstrong and Alan R Barker

Introduction 527

Rationale for physiological monitoring 527

Ethics of physiological monitoring 528

Development of a physiological  
 monitoring programme 528

Validity 528

Reliability 528

Physiological variables and sport performance 529

Identification and selection of physiological tests 529

Primary components of physiological  
 monitoring programmes 530

Body composition 530

Muscle strength 530

Anaerobic fitness 531

Aerobic fitness 531

Field tests 534

Scientist, coach, and athlete relationship 534

Conclusions 534

Summary 535

References 535

## PART 4

### Sport medicine

#### 40 Epidemiology and prevention of sports injuries 541

Joske Nauta, Willem van Mechelen,  
 and Evert ALM Verhagen

Introduction 541

Conceptual models for sports injury  
 prevention 541

Sequence of prevention 541

Translation research into injury prevention  
 practice framework 542

Knowledge transfer scheme 543

Research in sports injuries 543

Defining sports injury 543

Sports injury incidence 544

The severity of sports injuries 544

Research design 545

Conclusions 545

Summary 545

References 545

## 41 Epidemiology and prevention of injuries in physical education 547

Dorine CM Collard, Joske Nauta, and Frank JG Backx

Introduction 547

Injury incidence 547

Risk of injury in physical education classes 548

Physical education versus (un-)organized sport 548

Gender 549

Age 549

Aerobic fitness, weekly physical activity, and body composition 549

Location of injury 549

Type of injury and injury mechanism 550

Acute injuries 550

Overuse injuries 550

Severity of injuries 551

Nature of the injury 551

Nature of the treatment 551

Costs of the treatment 551

Time lost from (un)organized sport or school 551

Aetiology 551

Prevention 552

Conclusions 553

Summary 553

References 553

## 42 Epidemiology and prevention of injuries in competitive contact sports 555

Joske Nauta and Evert ALM Verhagen

Introduction 555

Soccer 555

Epidemiology of soccer injuries 555

Preventative strategies 556

American football 556

Epidemiology of American football injuries 556

Preventative strategies 557

Ice hockey 557

Epidemiology of ice hockey injuries 557

Preventative strategies 558

Basketball 558

Epidemiology of basketball injuries 558

Preventative strategies 559

Martial arts 559

Epidemiology of martial arts injuries 559

Preventative strategies 560

Wrestling 560

Epidemiology of wrestling injuries 560

Preventative strategies 561

Conclusions 561

Summary 561

References 561

## 43 Epidemiology and prevention of injuries in competitive non-contact sports 565

Luiz Carlos Hespanhol Junior, Saulo Delfino Barboza, and Per Bo Mahler

Introduction 565

Bicycling 565

Epidemiology of cycling injuries 565

Aetiology of cycling injuries 565

Preventative strategies 566

Dance 566

Epidemiology of dance injuries 566

Aetiology of dance injuries 566

Preventative strategies 567

Gymnastics 567

Epidemiology of gymnastics injuries 567

Aetiology of gymnastics injuries 567

Preventative strategies 568

Running 568

Epidemiology of running injuries 568

Aetiology of running injuries 568

Preventative strategies 568

Skiing and snowboarding 569

Epidemiology of skiing and snowboarding injuries 569

Aetiology of skiing and snowboarding injuries 569

Preventative strategies 569

Swimming 569

Epidemiology of swimming injuries 570

Aetiology of swimming injuries 570

Preventative strategies 570

Tennis and badminton 570

Epidemiology of tennis and badminton injuries 570

Aetiology of tennis and badminton injuries 570

Preventative strategies 571

Volleyball 571

Epidemiology of volleyball injuries 571

Aetiology of volleyball injuries 571

Preventative strategies 572

Conclusions 572

Summary 572

References 572

## 44 Upper extremity and trunk injuries 577

Christopher M Shaw, Akin Cil, and Lyle J Micheli

Introduction 577

Upper extremity injuries 577

Shoulder injuries 577

Elbow injuries 582

Wrist and hand injuries 586

Trunk injuries 589

General 589

Spondylolysis and spondylolisthesis 590

Discogenic disorders 592

Scoliosis 593



Scheuermann's disease 593

Fractures 593

Mechanical back pain 593

Conclusions 594

Summary 594

References 594

#### 45 Lower limb injuries 599

Umile Giuseppe Longo and Nicola Maffulli

Introduction 599

The musculoskeletal system in childhood 599

Different metabolic and psychological aspects of childhood in sport 599

Endogenous risk factors 599

Epidemiology of lower limb injuries 600

Injury characteristics and severity 600

Ligament, muscle, and tendon injuries 600

Muscle injuries 600

Ligament injuries 601

Tendinopathy 601

Joint injuries 602

Hip 602

Knee 602

Foot 602

Bone injuries 602

Epiphyseal injuries 602

Fractures 603

Avulsion fractures and apophysitis 606

Osteochondritis dissecans 607

Stress fractures 607

Legg-Calve-Perthes disease 607

Tarsal coalitions and sinus tarsi problems 607

Navicular problems 608

Prevention 608

Conclusions 608

Summary 608

References 609

#### 46 Injuries to the head and cervical spine 613

Robert V Cantu and Robert C Cantu

Introduction 613

Types of head injury 613

Concussion 613

Post-concussion syndrome 614

Malignant brain oedema and second-impact syndrome 615

Intracranial haemorrhage 615

Epidural haematoma 616

Subdural haematoma 616

Subarachnoid haemorrhage 616

Intracerebral haematoma 617

Diffuse axonal injury 617

Skull fracture 617

Sports helmets and head injury 618

Cervical spine injuries 618

Epidemiology 618

Initial assessment 619

Imaging 619

Fractures 620

Neuropraxias 620

Ligamentous injury 621

Treatment 622

Return to play 622

Conclusions 623

Summary 623

References 623

#### 47 Nutrition and eating disorders 625

Christine Sundgot-Borgen and Jorunn Sundgot-Borgen

Introduction 625

Energy and nutrient requirements for young athletes 625

Energy 625

Macronutrients 626

Micronutrients 627

Disordered eating and eating disorders 629

The continuum of disordered eating 629

Prevalence of disordered eating and eating disorders 629

Risk factors for the development of disordered eating and eating disorders 630

Consequences and complications 630

Prevention of eating disorders in athletes 631

Recovery from eating disorders 632

Treatment of eating disorders in athletes 632

Ethical and methodological considerations in sport and exercise medicine research 632

Conclusions 633

Summary 633

References 633

#### 48 Dietary supplements 637

Ronald J Maughan and Susan M Shirreffs

Introduction 637

Prevalence of supplement use 637

Ethical issues in supplement use 638

Supplements in a balanced diet 638

Assessing nutrient intake and status 639

Supplements and health 639

Macronutrients 639

Vitamins and minerals 640

Supplements and performance 640

Assessing performance and supplement effects 641

Supplements that may benefit performance 641

Risks of supplement use 641

Quality assurance issues in the supplement industry 641

- Adverse health effects 642
- Positive doping outcomes for athletes 642
- Conclusions 643
- Summary 643
- References 643
- 49 Doping and anti-doping 645**
  - Alan Vernec and David Gerrard
  - Introduction 645
  - A brief history of doping in sport 645
    - Early history 645
    - Creation of the World Anti-Doping Agency and the World Anti-Doping Code 646
    - Young athletes in elite sport are subject to financial and competitive pressures 646
  - Classes of prohibited substances 646
    - Evolution of the Prohibited List 646
    - Criteria for inclusion of substances and methods on the Prohibited List 647
    - Categories of the Prohibited List 647
    - The principle of Strict Liability 647
  - Therapeutic Use Exemption 648
    - A brief history 648
    - Fairness in sport and the Therapeutic Use Exemption process 648
    - Diagnostic criteria 649
  - Roles and responsibilities of physicians 649
    - Fundamental responsibilities 649
    - Health and rights of young athletes 649
    - Supporting clean athletes and anti-doping initiatives 650
    - Knowledge of prohibited substances in sport 650
    - Awareness of the Therapeutic Use Exemption Process 650
    - Understanding major doping side effects 650
    - Ethical responsibilities of physicians 651
  - Current anti-doping strategies 651
    - Anti-doping rule violations 651
    - Use or attempted use: The Athlete Biological Passport 651
    - Out-of-competition testing and whereabouts 652
    - Investigations 652
    - Possession, administration, complicity, and prohibited association 652
  - Advanced analytical techniques 653
    - Anti-doping analytical methods 653
    - Pharmaceutical industry collaboration with the World Anti-Doping Agency 653
    - Designer drugs 653
    - Sample storage and re-analysis 654
    - Anti-doping research 654
  - The ethics and values of sport 654
    - Why fight against doping? 654
    - Values of sport 654
    - What is values-based education? 654
    - Vulnerability to doping 655
    - Recognizing doping 655
  - Conclusions 655
  - Summary 656
  - References 656
- 50 Protecting child athletes: medical mismanagement and other forms of non-accidental violence 659**
  - Margo Mountjoy, Sandi Kirby, and Anne Tiivas
  - Introduction 659
  - Protecting child athletes from forms of non-accidental violence 660
    - Non-accidental violence: the science base 660
    - Groups of children in sport vulnerable to non-accidental violence 662
    - Medical mismanagement: a form of non-accidental violence in sport 664
    - Child athlete protection in sport 665
    - Action plan 668
  - Conclusions 668
  - Summary 669
  - References 669
- Index 671**



---

# 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, L2S 3A1, Canada

**Ulf Ekelund**, PhD, Professor, Department of Sport Medicine, Norwegian School of Sport Sciences, PO Box 4014, 0806 Ullevål 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, L2S 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 Hespagnol 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 Ullevål 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 Trigatoria, 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. Debyeplein 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 DeGroot 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 Ullevål Stadion, Oslo, Norway
- Jorunn Sundgot-Borgen**, PhD, Professor, Department of Sport Medicine, Norwegian School of Sport Sciences, PO Box 4014, 0806 Ullevål 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 Verrec**, 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 Wisniewski**, 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  $^{31}\text{P}$  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	BF	body fat
<sup>31</sup> P MRS	<sup>31</sup> P magnetic resonance spectroscopy	BIA	bioelectrical impedance analysis
AAI	atlantoaxial instability	BMAD	bone mineral apparent density
AAP	American Academy of Pediatrics	BMC	bone mineral content
AAS	androgenic anabolic steroids	BMD	bone mineral density
ABC	Airway, Breathing, and Circulation	BMI	Body mass index
ABP	Athlete Biological Passport	BMR	basal metabolic rate
ABQ	Athlete Burnout Questionnaire	BN	bulimia nervosa
ACE	angiotensin-converting enzyme	BP	blood pressure
ACL	anterior cruciate ligament	BSA	body surface area
ACSA	anthropometric cross-sectional area	BUA	broadband ultrasound attenuation
ACSM	American College of Sports Medicine	BW	body weight
ACTH	adrenocorticotropic hormone	C1-2 injury	axial spine injury
ADA	American Diabetes Association	C3-7 injury	sub-axial spine injury
ADHD	attention-deficit-hyperactivity disorder	CA	chronological age
ADI	atlanto-dens interval	Ca <sup>2+</sup>	calcium
ADO	anti-doping organization	CALER	Cart and Load Effort Rating
ADP	adenosine diphosphate	CAT	carnitine acyltransferase
ADRV	anti-doping rule violation	CBF	cerebral blood flow
AGHLS	Amsterdam Growth and Health Longitudinal Study	CCT	continuous cycling training
AIIS	anterior inferior iliac spine	CERT	Children's Effort Rating Table
AIS	abbreviated injury scale	CF	cystic fibrosis
AK	adenylate kinase	CFRDM	cystic fibrosis-related insulin-dependent diabetes mellitus
AMP	adenosine monophosphate	CFTR	Cystic Fibrosis Transmembrane Conductance Regulator
AN	anorexia nervosa	CG	centre of gravity
ANGELO	ANalysis Grid for Environments Linked to Obesity	CGM	continuous glucose monitoring
AOI	atlantooccipital instability	CHOexo	<sup>13</sup> C-labelled enriched carbohydrate
AP	anteroposterior	CHOs	carbohydrates
APA	American Psychological Association	CI	confidence interval
ASD	autism spectrum disorder	CIET	constant-intensity exercise training
ASD	atrial septal defect	CK	creatine kinase
ASIS	anterior superior iliac spine	CMJ	countermovement jump test
ATLS	advanced trauma life support	CNS	central nervous system
ATP	adenosine triphosphate	CO <sub>2</sub>	carbon dioxide
a-vO <sub>2</sub> diff	arteriovenous oxygen difference	CON	habitual control
B	breasts	CP	cerebral palsy
BABE	Bug and Bag Effort	CPo	critical power
BALCO	Bay Area Laboratory Co-Operative	CPET	cardiopulmonary exercise testing
BASES	British Association of Sport and Exercise Sciences	CPP	cycling peak power output
BD	body dissatisfaction	CPR	cardiopulmonary resuscitation
BED	binge eating disorder		



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

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



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

# PART 1

---

## Exercise science

- 1 Assessment of biological maturation** 3  
Robert M Malina
- 2 Growth and maturation** 13  
Adam DG Baxter-Jones
- 3 Developmental biodynamics: the development of coordination** 25  
James Watkins
- 4 Motor development** 43  
David Sugden and Helen Soucie
- 5 Exercise and hormones** 57  
Alon Eliakim and Dan Nemet
- 6 Muscle metabolism during exercise** 69  
Neil Armstrong, Alan R Barker, and Alison M McManus
- 7 Muscle strength** 89  
Mark BA De Ste Croix
- 8 Maximal intensity exercise** 105  
Craig A Williams and Sébastien Ratel
- 9 Neuromuscular fatigue** 121  
Sébastien Ratel and Craig A Williams
- 10 Pulmonary function** 133  
Alison M McManus and Neil Armstrong
- 11 Cardiovascular function** 147  
Thomas W Rowland
- 12 Aerobic fitness** 161  
Neil Armstrong and Alison M McManus
- 13 Pulmonary oxygen uptake kinetics** 181  
Alan R Barker and Neil Armstrong
- 14 Temperature regulation** 195  
Bareket Falk and Raffy Dotan
- 15 Effort perception** 213  
Kevin L Lamb, Gaynor Parfitt, and Roger G Eston



# 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.<sup>1-3</sup> 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.<sup>2,4</sup>

Methods for the assessment and quantification of body composition have been driven by technology and have advanced considerably.<sup>5,6</sup> 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.<sup>2</sup>

The body mass index ( $[\text{weight (kg)} / \text{height (m}^2\text{)}]$ , 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<sup>7</sup> and is perhaps more closely associated with LTM rather than FM among relatively thin youth.<sup>8</sup> 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<sup>9</sup> for quarterly height measurements to estimate velocities and monitor the velocity curve in the context of the adolescent spurt thus has major limitations.<sup>10</sup>

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.<sup>2</sup> Distributions of increments vary within CA intervals and also tend to be skewed.<sup>11</sup> 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,<sup>12–14</sup> and at times to estimate the potential influence of training on growth rate.<sup>15</sup> Reference values for estimated growth rates have been reported.<sup>10,11,16,17</sup>

### 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.<sup>2</sup> 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.<sup>2</sup>

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.<sup>2,18–21</sup>

### Greulich-Pyle method

The Greulich-Pyle method (GP)<sup>22</sup> is an extension of the method initially described by Todd.<sup>23</sup> 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)<sup>24–27</sup> 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.<sup>24,25</sup> 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.<sup>18,28</sup> The first revision of the TW method (TW2)<sup>26</sup> 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,<sup>27</sup> 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.<sup>29</sup> 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<sup>30–32</sup> 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.’<sup>27(pp.63,65)</sup> 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.<sup>20</sup> 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  $\pm 1.0$  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.<sup>20</sup>

### 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.

N	Skeletal Ages, years											
	CA, years		GP		Fels		TW2 20 Bone		TW2 RUS		TW3 RUS	
	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 · day<sup>-1</sup> television viewing.<sup>33,34</sup> 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.<sup>35–41</sup> 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,<sup>42,43</sup> but its validity has been questioned.<sup>44</sup> Use of DEXA scans of the hand-wrist for the assessment of SA have also been proposed.<sup>45–47</sup> Automated methods for the assessment of SA are increasingly available.<sup>27,48–50</sup> The procedures are generally based upon the GP and TW methods and are largely designed for clinical use. The BoneXpert method<sup>49</sup> 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.<sup>2,21</sup> 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<sup>51</sup> 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.<sup>52</sup>

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.<sup>2</sup>

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.<sup>2</sup> Of relevance, a recent study has concluded that ‘... preoperative Tanner staging performed by orthopedic surgeons is unreliable.’<sup>53(p.1229)</sup>

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.’<sup>54(p.197)</sup> On the other hand, agreement to within one stage was suggested as potentially useful in epidemiological surveys of youth,<sup>55</sup> 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).<sup>56,57</sup> 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.<sup>58</sup>

### 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 mean 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.<sup>59</sup> 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.<sup>60</sup> 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 ( $\text{cm} \cdot \text{year}^{-1}$ ). Allowing for normal variation, mean ages at PHV are reasonably similar in longitudinal studies of European and North American youth.<sup>2,61,62</sup> 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.<sup>2,63–66</sup>

#### 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<sup>65</sup> and Polish<sup>63,64</sup> 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.<sup>59</sup>

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.<sup>2</sup>

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,<sup>67</sup> 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.<sup>2,21</sup>

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.<sup>2,62,68–70</sup>

Analyses of ages at attaining several different maturity indicators in two longitudinal series highlight interrelationships among maturity timing during adolescence.<sup>71–73</sup> 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.<sup>73</sup> 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  $\geq 30$  ng · DL<sup>-1</sup>).<sup>74</sup>

## 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.<sup>75,76</sup> 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.<sup>36</sup> Single year rates of maturation expressed as maturity points per year of the American children<sup>35</sup> overlapped the mean rates and ranges for British children.<sup>28</sup> 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.<sup>77</sup> 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  $\pm$  standard deviations) between B2 and B3 and between PH2 and PH3 in Swiss girls were, respectively,  $1.4 \pm 0.8$  years, and  $1.8 \pm 1.0$  years, while intervals between G2 and G3 and between PH2 and PH3 in Swiss boys were, respectively,  $1.7 \pm 1.0$  years and  $1.3 \pm 0.9$  years.<sup>78,79</sup> The intervals between the transition into puberty (B2, G2, PH2) and the mature state (B5, G5, PH5) were, on average,  $2.2 \pm 1.1$  years for breast and  $2.7 \pm 1.1$  years for pubic hair development in Swiss girls, and  $3.5 \pm 1.1$  years for genital and  $2.7 \pm 1.0$  years for pubic hair development in Swiss boys.<sup>78,79</sup> 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.<sup>80</sup> 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.<sup>2</sup> A commonly used general clinical guide without SA is mid-parent target height, based on the average of the heights of both parents.<sup>81</sup> The protocol has a large associated error of  $\sim 9$  cm. The protocol developed in the Fels Longitudinal Growth Study<sup>82</sup> 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<sup>82</sup> has been used as an indicator of maturity status in studies of physical activity and of youth athletes.<sup>83</sup> Maturity status based on percentage of predicted adult height had moderate concordance with classifications of maturity status based on SA in youth American football<sup>84</sup> and soccer<sup>85</sup> 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.<sup>86</sup> The protocol has been validated in an independent sample of boys 13–16 years of age from the Madeira Growth Study,<sup>87</sup> 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.<sup>66</sup> 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.<sup>83</sup>

Results of validation studies in longitudinal samples of Polish children from the Wrocław Growth Study<sup>63,64</sup> and American children from the Fels Longitudinal Study<sup>65</sup> 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 ( $SE = SD/\sqrt{n}$ ) of the prediction equations were 0.59 for boys and 0.57 for girls.<sup>66</sup>

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.<sup>88</sup>

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.<sup>65</sup>

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.<sup>89</sup> 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.

## References

1. Lohman TG, Roche AF, Martorell R, eds. *Anthropometric standardization reference manual*. Champaign: Human Kinetics; 1988.
2. Malina RM, Bouchard C, Bar-Or O. *Growth, maturation, and physical activity*, 2nd ed. Champaign, IL: Human Kinetics; 2004.
3. Cameron N. The measurement of human growth. In: Cameron N, Bogin B (eds.) *Human growth and development*, 2nd ed. London: Academic Press; 2012. p. 487–513.
4. Malina RM. Anthropometry. In: PJ Maud, C Foster (eds.) *Physiological assessment of human fitness*. Champaign, IL: Human Kinetics; 1995. p. 205–219.
5. Heymsfield SB, Lohman TG, Wang Z, Going SB, (eds.) *Human body composition*, 2nd ed. Champaign, IL: Human Kinetics; 2005.
6. Zemel B. Body composition during growth and development. In: Cameron N, Bogin B (eds.) *Human growth and development*, 2nd ed. London: Academic Press; 2012. p. 461–486.
7. Malina RM, Katzmarzyk PT. Validity of the body mass index as an indicator of the risk and presence of overweight in adolescents. *Am J Clin Nutr*. 1999; 70(Suppl): 131S–136S.
8. Freedman DS, Wang J, Maynard LM, Thornton JC, Mei Z, Pierson RN, et al. Relation of BMI to fat and fat-free mass among children and adolescents. *Int J Obes*. 2005; 29: 1–8.
9. Balyi I, Way R. *The role of monitoring growth in long-term athlete development*. Canadian Sport Centres/Centres Canadiens Multisports: Canadian Sport for Life; 2009. Available at <http://canadiansportforlife.ca/sites/default/files/resources/MonitoringGrowth%281%29.pdf>
10. Marshall WA. Evaluation of growth rate in height over periods of less than one year. *Arch Dis Child*. 1971; 46: 414–420.
11. Baumgartner RN, Roche AF, Himes JH. Incremental growth tables: supplementary to previously published charts. *Am J Clin Nutr*. 1986; 43: 711–722.
12. Eisenmann JC, Malina RM. Growth status and estimated growth rate of young distance runners. *Int J Sports Med*. 2002; 23:168–173
13. Malina RM. Attained size and growth rate of female volleyball players between 9 and 13 years of age. *Pediatr Exerc Sci*. 1994; 6: 257–266.
14. Malina RM, Eveld DJ, Woynarowska B. Growth and sexual maturation of active Polish children 11–14 years of age. *Hermes, Tijdschrift van het Instituut voor Lichamelijke Opleiding* [Journal of the Institute of Physical Education, Catholic University of Leuven, Belgium]. 1990; 21: 341–353.
15. Daly RM, Caine D, Bass SL, Pieter W, Broekhoff J. Growth of highly versus moderately trained competitive female artistic gymnasts. *Med Sci Sports Exerc*. 2005; 37: 1053–1060.
16. Roche AF, Himes JH. Incremental growth charts. *Am J Clin Nutr*. 1980; 33: 2041–2052.
17. Kelly A, Winer KK, Kalkwarf H, et al. Age-based reference ranges for annual height velocity in US children. *J Clin Endocrinol Metab*. 2014; 99: 2104–2112.