3RD EDITION

KINANTHROPOMETRY AND EXERCISE PHYSIOLOGY LABORATORY MANUAL

TESTS, PROCEDURES AND DATA

VOLUME 1: ANTHROPOMETRY

EDITED BY
ROGER ESTON
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Kinanthropometry is the study of human body size, shape and form and how those characteristics relate to human movement and sporting performance. In this fully updated and revised edition of the classic guide to kinanthropometric theory and practice, leading international sport and exercise scientists offer a clear and comprehensive introduction to essential principles and techniques.

Each chapter guides the reader through the planning and conduct of practical and laboratory sessions and includes a survey of current theory and contemporary literature relating to that topic. The book is fully illustrated and includes worked examples, exercises, research data, chapter summaries and guides to further reading throughout.

Volume One – Anthropometry – covers key topics such as:

- Body composition, proportion and growth
- Evaluating posture, flexibility and range of motion
- Children’s physiology, maturation and sport performance
- Field work
- Statistical methods for kinesiology and sport
- Accurate scaling of data for sport and exercise sciences.

The Kinanthropometry and Exercise Physiology Laboratory Manual is essential reading for all serious students and researchers working in sport and exercise science, kinesiology and human movement.

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## CONTENTS

*List of illustrations*  
*List of contributors*  
*Preface*  
*Introduction*

### PART ONE

**Body composition, proportion and growth: implications for health and performance**

1 **Human body composition**  
   ROGER ESTON, MICHAEL HAWES, ALAN MARTIN AND THOMAS REILLY

1.1 **Aims**  
1.2 **Introduction**  
1.3 **Levels of approach**  
1.4 **Validity**  
1.5 **The chemical model**  
1.6 **Simple indices of fatness, muscularity and fat distribution**  
1.7 **The anatomical model**  
1.8 **Other considerations**  
1.9 **Practical 1: Densitometry**  
1.10 **Practical 2: Measurement of skinfolds**  
1.11 **Practical 3: Simple indices of body fat distribution**  
1.12 **Practical 4: Bioelectrical impedance analysis**  
1.13 **Practical 5: Estimation of muscle mass and regional muscularity using in vivo- and in vitro-derived equations**  
1.14 **Practical 6: Estimation of skeletal mass**  
1.15 **Practical 7: Example of a multi-component model of body composition assessment**  
1.16 **Anthropometric landmarks and measurement definitions**  
   Acknowledgements
5 Flexibility
PETER VAN ROY AND JAN BORMS

5.1 Aims 129
5.2 Introduction and historical overview 129
5.3 Theory and application of clinical goniometry 133
5.4 Laboratory sessions: Flexibility measurements with goniometry 136
5.5 Summary and conclusion 154
Further reading 156
References 156

PART THREE
Assessment of physical activity and performance 161

6 Field methods of assessing physical activity and energy balance
ANN V. ROWLANDS

6.1 Aims 163
6.2 Why estimate physical activity? The need for a valid measure 163
6.3 Energy expenditure and physical activity 163
6.4 Methods of estimating physical activity or energy expenditure 164
6.5 Considerations when using accelerometers to assess physical activity 173
6.6 Multiple measures of physical activity 175
6.7 Practical 1: Relationship between selected measures of physical activity and oxygen uptake during treadmill walking and running 176
Further reading and useful websites 177
References 178

7 Assessment of performance in team games
THOMAS REILLY

7.1 Aims 184
7.2 Introduction 184
7.3 Method of analyzing team performance 185
11 Scaling: adjusting for differences in body size

EDWARD M. WINTER AND ALAN M. NEVILL

11.1 Aims 300
11.2 Introduction 300
11.3 Historical background 301
11.4 The ratio standard: the traditional method 301
11.5 Regression standards and ANCOVA 303
11.6 Allometry and power function standards 306
11.7 Practical 1: The identification of allometric relationships 307
11.8 Practical 2: Power function ratio standards 311
11.9 Elasticity 312
11.10 Allometric cascade 313
11.11 Geometric similarity and non-isometric growth 313
11.12 Scaling longitudinal data 313
11.13 Summary 314
Appendix A 315
Appendix B 316
Acknowledgement 317
Further reading and useful websites 318
References 318

Index 321
ILLUSTRATIONS

FIGURES

1.1 The five levels of human body composition (adapted from Wang et al. 1992). 4
1.2 Examples of underwater weighing procedures for calculating whole-body density. 8
1.3 Siri’s equation for estimation of percent fat plotted for different values of assumed density of fat free mass (dFFM) (adapted from Martin and Drinkwater 1991). 9
1.4 Dual energy x-ray absorptiometer procedure for assessing body density and body composition. 11
1.5 Analysis of body composition of a female dual energy x-ray absorptiometry. 12
1.6 Schematic section through a skinfold at measurement site (adapted from Martin et al. 1985). 13
1.7a Relationship between the changes in medial calf skinfold (mm) and performance (percentage velocity) induced after three years of intense athletic conditioning in sprint trained runners. 16
1.7b Relationship between the changes in front thigh skinfold (mm) and performance (percentage velocity) induced after three years of intense athletic conditioning in endurance trained runners (from Legaz and Eston, 2005). 16
1.8 Schematic view of the derivation of estimated muscle and bone area from a measurement of external girth. 24
1.9 Skinfold calliper technique showing correct two-handed method and with calliper aligned to natural cleavage lines of the skin. Sites shown are supraspinale, pectoral, thigh, calf, triceps and subscapular. 30
1.10 Location of the cheek and chin skinfold sites. 33
1.11 Location of the pectoral skinfold sites. 33
1.12 Location of the axilla and chest 2 skinfold sites. 33
1.13 Location of the abdominal skinfold sites. 33
<table>
<thead>
<tr>
<th>Illustration</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.14</td>
<td>Location of the skinfold sites in the iliac crest region only.</td>
<td>34</td>
</tr>
<tr>
<td>1.15</td>
<td>Location of the biceps, triceps and subscapular skinfold sites.</td>
<td>34</td>
</tr>
<tr>
<td>1.16</td>
<td>Location of the anterior thigh skinfold sites.</td>
<td>34</td>
</tr>
<tr>
<td>1.17</td>
<td>Location of the proximal and medial calf skinfold site.</td>
<td>35</td>
</tr>
<tr>
<td>2.1</td>
<td>Example of a completed anthropometric somatotype rating.</td>
<td>60</td>
</tr>
<tr>
<td>2.2</td>
<td>The Heath-Carter somatotype rating form.</td>
<td>61</td>
</tr>
<tr>
<td>2.3</td>
<td>Somatochart for plotting somatotypes (from Carter 1980).</td>
<td>63</td>
</tr>
<tr>
<td>2.4</td>
<td>A somatochart showing the regions of the somatotype categories (from Carter 1980).</td>
<td>64</td>
</tr>
<tr>
<td>2.5</td>
<td>Somatotype photographs of the same child taken at ages 7.4, 10.0, 12.5, 14.5 and 17.0.</td>
<td>70</td>
</tr>
<tr>
<td>3.1</td>
<td>References for height for British boys, with normal boy plotted.</td>
<td>80</td>
</tr>
<tr>
<td>3.2</td>
<td>References for height for British girls, with normal girl plotted.</td>
<td>82</td>
</tr>
<tr>
<td>3.3</td>
<td>Breast stages (From Tanner, 1962, with permission).</td>
<td>84</td>
</tr>
<tr>
<td>3.4</td>
<td>Genital stages (From Tanner, 1962, with permission).</td>
<td>84</td>
</tr>
<tr>
<td>3.5</td>
<td>Pubic hair stages: (a) boys; (b) girls (from Tanner, 1962, with permission).</td>
<td>85</td>
</tr>
<tr>
<td>3.6</td>
<td>Radiograph of the hand and wrist of a Belgian boy (I).</td>
<td>88</td>
</tr>
<tr>
<td>3.7</td>
<td>Radiograph of the hand and wrist of a Belgian boy (II).</td>
<td>88</td>
</tr>
<tr>
<td>3.8</td>
<td>Radiograph of the hand and wrist of a Belgian boy (III).</td>
<td>88</td>
</tr>
<tr>
<td>3.9</td>
<td>Scoring sheet for skeletal age assessment.</td>
<td>89</td>
</tr>
<tr>
<td>3.10</td>
<td>Proforma for recording the Eurofit test results.</td>
<td>95</td>
</tr>
<tr>
<td>4.1</td>
<td>The curvatures of the vertebral column.</td>
<td>105</td>
</tr>
<tr>
<td>4.2</td>
<td>The line of centre of gravity of the body.</td>
<td>107</td>
</tr>
<tr>
<td>4.3</td>
<td>MRI image of the lumbar spine.</td>
<td>107</td>
</tr>
<tr>
<td>4.4</td>
<td>Holtain anthropometer used to measure tibial length. A counter recorder is employed which gives an instant and accurate read-out of length.</td>
<td>109</td>
</tr>
<tr>
<td>4.5</td>
<td>Using the kyphometer to measure thoracic kyphosis on a subject. The angle is read off the dial on the instrument.</td>
<td>110</td>
</tr>
<tr>
<td>4.6</td>
<td>Measuring lumbar lordosis using the kyphometer.</td>
<td>110</td>
</tr>
<tr>
<td>4.7</td>
<td>A goniometer used to measure the procline angle, the angle between the spine and vertical at the level of the 7th cervical vertebra.</td>
<td>111</td>
</tr>
<tr>
<td>4.8</td>
<td>Measuring the angle at the thoraco-lumbar junction.</td>
<td>111</td>
</tr>
<tr>
<td>4.9</td>
<td>Measuring the declive angle at the lumbar-sacral junction.</td>
<td>111</td>
</tr>
<tr>
<td>4.10</td>
<td>A patient with scoliosis: a condition in which the vertical column develops a lateral curvature and vertebral rotation, frequently leading to severe physical deformity.</td>
<td>112</td>
</tr>
<tr>
<td>4.11</td>
<td>The OSI scoliometer used to measure the ATI in the spine of a scoliosis subject lying prone.</td>
<td>112</td>
</tr>
<tr>
<td>4.12</td>
<td>Formulator Body Contour Tracer used to record cross-sectional shape of the thorax in a patient with scoliosis (a lateral curvature of the spine causing a rib-hump deformity and asymmetry of the thorax).</td>
<td>113</td>
</tr>
<tr>
<td>4.13</td>
<td>Grating projection system (SIPS: Spinal Image Processing System) used for clinical evaluation of trunk shape and scoliosis.</td>
<td>113</td>
</tr>
<tr>
<td>5.1</td>
<td>A protractor goniometer.</td>
<td>133</td>
</tr>
<tr>
<td>5.2</td>
<td>The MIE hygrometer.</td>
<td>133</td>
</tr>
<tr>
<td>5.3</td>
<td>The Monus goniometer.</td>
<td>137</td>
</tr>
<tr>
<td>5.4</td>
<td>The VUB-goniometer. Patent no 899964 (Belgium).</td>
<td>137</td>
</tr>
</tbody>
</table>
5.5 Four different ways to evaluate the angle in a joint (after Rocher and Rigaud 1964): (a) true angle; (b) complementary angle; (c) supplementary angle; (d) ROM.

5.6 Proforma for Goniometric measurements.

5.7 Measurement of shoulder flexion.

5.8 Measurement of shoulder extension.

5.9 Measurement of shoulder lateral (external) rotation.

5.10 Measurement of shoulder medial (internal) rotation.

5.11 Measurement of shoulder abduction.

5.12 Measurement of shoulder horizontal adduction.

5.13 Measurement of elbow flexion.

5.14 Measurement of elbow extension.

5.15 Measurement of forearm pronation.

5.16 Measurement of forearm supination.

5.17 Measurement of wrist flexion.

5.18 Measurement of wrist extension.

5.19 Measurement of wrist radial deviation.

5.20 Measurement of wrist ulnar deviation.

5.21 Measurement of hip flexion (bent leg).

5.22 Reference lines for the measurement of hip extension described by Mundale et al. (1956).

5.23 Angle beta between the reference lines considered in the position of maximal hip flexion with the straight leg.

5.24 VUB-goniometer with second carriage.

5.25 Measurement of hip flexion (straight leg).

5.26 Measurement of hip extension.

5.27 Measurement of hip abduction.

5.28 Measurement of hip adduction.

5.29 Measurement of hip medial (internal) rotation.

5.30 Measurement of hip lateral (external) rotation.

5.31 Measurement of knee flexion.

5.32 Measurement of knee extension.

5.33 Measurement of knee medial (internal) rotation.

5.34 Measurement of knee lateral (external) rotation.

5.35 Measurement of ankle dorsiflexion.

5.36 Measurement of ankle plantar flexion.

6.1 Yamax Digi-walker SW-200 pedometer (left), ActiGraph GT1M uniaxial accelerometer (centre) and RT3 triaxial accelerometer (right).

6.2 One of the children from the study by Eston et al. (1998). He is wearing the Tritrac on his left hip, the ActiGraph accelerometer on his right hip, a heart rate monitor (BHL 6000 Medical) and three pedometers.

6.3 A typical plot of the Tritrac output during children’s activities in the laboratory. Tri x = mediolateral plane; tri y = anteroposterior plane; tri z = vertical plane; tri xyz = vector magnitude.

6.4 A typical Tritrac trace (vector magnitude) from a school day.

6.5 The same child as in Figure 6.4. All morning was spent travelling by car.

7.1 The slalom dribble.

7.2 The straight dribble.
7.3 Field test for Rugby Union.
8.1 Mean and standard error for (a) static arm strength, and (b) vertical jump, in boys and girls versus skeletal age. Reproduced from Kemper (1985) with the permission of S Karger AG, Basel.
8.2 A group of 12-year-old schoolchildren illustrates typical variation in biological maturation at this age.
8.3 Mean motor performance scores of early-, average- and late-maturing boys in the Leuven Growth study of Belgian Boys.
8.4 Skinfold thicknesses may be measured from (a) biceps, (b) triceps, (c) subscapula and (d) iliac sites.
8.5 The measurement of oxygen uptake during treadmill exercise.
8.6 Blood lactate concentration during an incremental running test, pre and post one year's endurance training as an individual.
8.7 Identification of the LT using the non-invasive GET (A) and VT (B) methods in an 8-year-old child during a ramp-incremental cycle exercise test to exhaustion.
8.8 Kinetic profile of $O_2$ uptake ($\dot{V}O_2$) during exercise below (○) and above (●) the blood lactate threshold (LT) in a child subject exercising on a cycle ergometer.
8.9 Dynamics of quadriceps muscle Pi/PCr (●) and pH (○) (figure a) and PCr (□) and Pi (■) (figure b) determined using $^{31}$P-MRS in a boy subject during a single legged quadriceps step-incremental test to exhaustion.
8.10 An example of a peak power output-cadence curve derived from an isokinetic cycle ergometer test. The optimum peak power (849 watts) was derived using a quadratic model and corresponded to an optimal cadence of 126 rev·min$^{-1}$.
9.1 Bivariate location of each of the groups. The outline figures represent iconically the shapes of women located at the different extreme points of the anthropometric space.
9.2 The relationship between desirability (rated on a 1–7 scale) and chest-waist ratio in men. The open circles represent men’s view of themselves, and the closed squares women’s view of men (plotted from data in Furnham et al. 1990).
9.3 Face of a shop mannequin before digital manipulation.
9.4 Face of the same mannequin as in Figure 9.3, with the following manipulations: nose-lip spacing and lip-chin spacing increased; jaw widened; eye area reduced; eyebrow arching reduced; cheekbones lowered.
9.5 Ln(BMI) is shown on the X-axis, and waist-hip ratio of the Y-axis. The ellipses represent the 99%, 95%, 90%, 67% and 50% density ellipses for the US population.
9.6 Measurement dimensions for facial characteristics.
10.1 Frequency histogram of 30 male maximal oxygen uptake results (ml kg$^{-1}$ min$^{-1}$). (From Nevill et al. 1992a.)
10.2 The Q-Q plot and Tests of Normality for the example data. On a Normal plot the normal probabilities are plotted against the data.
10.3 An example of data entered into the SPSS Data Editor window.
10.4 SPSS Output containing the descriptive statistics obtained via the Explore command.
10.5 Mean power output (W) versus body mass (kg) of 16 male subjects, recorded on a non-motorized treadmill (Nevill et al. 1992b). 262
10.6 Ten-mile run times (min) versus maximal oxygen uptake (ml kg⁻¹ min⁻¹) of 16 male subjects (Costill et al. 1973). 262
10.7 Ten-mile run times, recalculated as average run speeds (m s⁻¹), versus maximal oxygen uptake results (ml kg⁻¹ min⁻¹) (Costill et al. 1973). 266
10.8 Example of an SPSS scatterplot and SPSS output for a Pearson Correlation. 270
10.9 SPSS output for a simple linear regression. 271
10.10 Interaction plot of age x knee angle on peak isometric force production in the quadriceps (Marginson et al. 2005). 282
10.11 An example of how to code between groups in SPSS. 283
10.12 SPSS output for an independent t-test. 284
10.13 SPSS output for the one-way ANOVA for k independent samples. 285
10.14 SPSS output for the Mann-Whitney test for independent samples. 286
10.15 SPSS output for the t-test correlated samples. 287
10.16 SPSS output for the one-way ANOVA with repeated measures. 288
10.17 SPSS output for the Wilcoxon test for correlated samples. 289
10.18 Data entered into the SPSS Data View sheet for the two-way mixed design ANOVA. Where 1.00 = Boys, 2 = Men in the column labelled group (Marginson et al. 2005). 289
10.19 SPSS output for the two-way mixed model ANOVA from the study of Marginson et al. (2005). 290
11.1 The effect of departures from Tanner’s (1949) ‘special circumstance’ on the difference between regression standards and the ratio standard. 302
11.2 The identification of ‘adjusted means’. Actual slopes are constrained to be parallel. 303
11.3 The relationship between optimized peak power output and lean leg volume in men (●) and women (○) (Winter et al. 1991). 306
11.4 The relationship between surface area and radius in spheres. 308
11.5 The relationship between volume and radius in spheres. 308
11.6 The relationship between ln surface area and ln radius in spheres. 309
11.7 The relationship between ln volume and ln radius in spheres. 309
11.8 The relationship between ln surface area and ln volume in spheres. 310
11.9 The relationship between surface area and volume in spheres. 310
11.10 The relationship between ln peak power output and ln lean leg volume in men (●) and women (○) (Nevill et al. 1992b). 311
11.11 The allometric relationship between peak power output and lean leg volume in men (●) and women (○) (Nevill et al. 1992b). 312

TABLES
1.1 Examples of the differences in density of the fat-free body and derived equations based on the two component densitometric model 10
1.2 Percentile values for FFM and FM index in men and women aged 18–54 years. Values taken from Schutz et al. (2002) 21
1.3 Correction factors for gas volumes at BTPS 27
1.4 Water Temperature Correction 28
<table>
<thead>
<tr>
<th>Illustration</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>Effects of changes in the assumed density of the fat-free body on per cent body fat</td>
<td>28</td>
</tr>
<tr>
<td>1.6</td>
<td>Summary of skinfold sites used in selected equations for prediction of per cent fat</td>
<td>32</td>
</tr>
<tr>
<td>2.1</td>
<td>Formulae for the calculation of the anthropometric Heath-Carter somatotype by calculator or computer</td>
<td>62</td>
</tr>
<tr>
<td>2.2</td>
<td>Anthropometric measurements of six adult male subjects</td>
<td>63</td>
</tr>
<tr>
<td>2.3</td>
<td>Formulae for calculation of SAD parameters</td>
<td>66</td>
</tr>
<tr>
<td>2.4</td>
<td>Somatotypes of 6 national level and 10 international level female middle distance runners (data from Day et al. 1977)</td>
<td>67</td>
</tr>
<tr>
<td>2.5</td>
<td>Consecutive somatotypes of 6 children from their sixth to their seventeenth birthday (data from Duquet et al., 1993)</td>
<td>69</td>
</tr>
<tr>
<td>3.1</td>
<td>Mean values for parameters in model 1 (from Preece and Baines 1978)</td>
<td>79</td>
</tr>
<tr>
<td>3.2</td>
<td>Decimals of year</td>
<td>81</td>
</tr>
<tr>
<td>3.3</td>
<td>Growth characteristics of two ‘normal boys’ (Beunen et al. 1992)</td>
<td>82</td>
</tr>
<tr>
<td>3.4</td>
<td>Fitness components and test items in selected physical fitness test batteries</td>
<td>91</td>
</tr>
<tr>
<td>3.5</td>
<td>Profile chart of the Eurofit test for 14-year-old boys</td>
<td>93</td>
</tr>
<tr>
<td>3.6</td>
<td>Profile chart of the Eurofit test for 14-year-old girls</td>
<td>94</td>
</tr>
<tr>
<td>3.7</td>
<td>Individual profile of a 14-year-old Belgian boy (Jan)</td>
<td>96</td>
</tr>
<tr>
<td>4.1</td>
<td>A sample of a data collection form</td>
<td>124</td>
</tr>
<tr>
<td>5.1</td>
<td>Flexibility norms for men (physical education and physiotherapy students 20 years of age)</td>
<td>155</td>
</tr>
<tr>
<td>5.2</td>
<td>Flexibility norms for women (physical education and physiotherapy students 20 years of age)</td>
<td>156</td>
</tr>
<tr>
<td>5.3</td>
<td>Example data for assignment questions 1 and 3. This should allow consideration of points raised in questions 4, 5, 6 and 7 also.</td>
<td>177</td>
</tr>
<tr>
<td>7</td>
<td>Performance times for a games player in a repeated sprint test</td>
<td>194</td>
</tr>
<tr>
<td>8.1</td>
<td>Prediction equations of percentage fat from triceps and subscapular skinfolds in children and youth for males and females</td>
<td>202</td>
</tr>
<tr>
<td>8.2</td>
<td>The modified Balke treadmill protocol (2-minute stages)</td>
<td>205</td>
</tr>
<tr>
<td>8.3</td>
<td>The Bruce treadmill protocol (3-minute stages)</td>
<td>205</td>
</tr>
<tr>
<td>8.4</td>
<td>The McMaster continuous cycling protocol</td>
<td>205</td>
</tr>
<tr>
<td>8.5</td>
<td>Optimal resistance for the WAnT using the Monark cycle ergometer</td>
<td>212</td>
</tr>
<tr>
<td>8.6</td>
<td>Criterion referenced health standards for the one mile run/walk test (min)</td>
<td>218</td>
</tr>
<tr>
<td>8.7</td>
<td>Normscales for British children: selected EUROFIT test battery items (adapted from Northern Ireland Fitness Survey, 1990)</td>
<td>219</td>
</tr>
<tr>
<td>8.8</td>
<td>Normscales for Dutch children: EUROFIT test battery items (adapted from van Mechelen et al., 1992)</td>
<td>221</td>
</tr>
<tr>
<td>9.1</td>
<td>Mean (SD) values for the six datasets</td>
<td>235</td>
</tr>
<tr>
<td>9.2</td>
<td>Datasheet for entering measurements of Barbie</td>
<td>245</td>
</tr>
<tr>
<td>9.3</td>
<td>Datasheet for entering measurements of Ken</td>
<td>245</td>
</tr>
<tr>
<td>10.1</td>
<td>The maximal oxygen uptake VO₂max results of 30 recreationally active male subjects (Nevill et al. 1992a)</td>
<td>252</td>
</tr>
<tr>
<td>10.2</td>
<td>Frequency table for the maximal oxygen uptake results in Table 10.1</td>
<td>252</td>
</tr>
<tr>
<td>10.3</td>
<td>Data required to calculate the correlation coefficient between mean power output (W) and body mass (kg) for example 1 (Nevill et al. 1992b)</td>
<td>264</td>
</tr>
</tbody>
</table>
10.4 Data required to calculate the correlation coefficient between 10-mile run time (min) and maximal oxygen uptake (ml kg\(^{-1}\) min\(^{-1}\)) for example 2 (Costill et al. 1973) 264

10.5 Six gymnasts ranked on performance by two independent judges 267

10.6 Data required to calculate the regression line between average 10-mile (16.1 km) run speed (m s\(^{-1}\)) and maximal oxygen uptake (ml kg\(^{-1}\) min\(^{-1}\)) for example 2 (Costill et al. 1973) 267

10.7 Blood lactate concentrations recorded at 70% of VO\(_2\)max 273

10.8 The maximal oxygen uptake results (ml kg\(^{-1}\) min\(^{-1}\)) of five groups of elite Olympic sportsmen (n=6), results from Johnson et al. (1998) 275

10.9 ANOVA to compare the maximal oxygen uptake results (ml kg\(^{-1}\) min\(^{-1}\)) of five groups of elite Olympic sportsmen 277

10.10 The calf muscle’s time-to-peak tension recorded in milliseconds (ms) of elite sportsmen 277

10.11 Leg strength in newtons (N) before and after isometric training 278

10.12 Estimates of percentage (%) body fat at baseline, 3 months and 6 months into the cycling programme 280

10.13 ANOVA table to compare the estimates of percentage body fat (%) recorded during the cycling programme 280

10.14 The percentage body fat, before and after an aerobics course, and the corresponding differences and ranked differences (ignoring signs) 281

10.A.1 The critical values of the \(t\)-distribution 292

10.A.2 The critical values of the F-distribution at the 5% level of significance (one-tailed) 293

10.A.3 The critical values of the F-distribution at the 2.5% level of significance (one-tailed) or 5% level of significance for a two-tailed test 295

10.A.4 The critical values of the Mann–Whitney U statistic at the 5% level of significance (two-tailed) 297

10.A.5 The critical values of the Wilcoxon T statistic for correlated samples (two-tailed) 297

11.1 Absolute and natural logarithm values (ln) for lean leg volume (LLV) and optimized peak power output (OPP) in men and women 305

11.2 Absolute and natural logarithm values (ln) of radii, surface areas and volumes in spheres 307
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ANTHROPOMETRY

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The subject area referred to as kinanthropometry has a rich history, although the subject itself was not formalised as a discipline until the International Society for Advancement of Kinanthropometry (ISAK) was established in Glasgow in 1986. The Society supports its own international conferences and publication of proceedings linked with these events. Until the publication of the first edition of Kinanthropometry and Exercise Physiology Laboratory Manual: Tests, Procedures and Data by the present editors in 1996, there was no laboratory manual that would serve as a compendium of practical activities for students in this field. Accordingly, the text was published under the aegis of ISAK in an attempt to make good the deficit.

Kinanthropometrists concern themselves with the relation of structure and function of the human body, particularly within the context of movement. Kinanthropometry has applications in a wide range of areas including, for example, biomechanics, ergonomics, growth and development, human sciences, medicine, nutrition, physical therapy, healthcare, physical education and sports science. Initially, the idea for the book was motivated by the need for a suitable laboratory resource that academic staff could use in the planning and conduct of class practicals in these areas.

The content of the first edition in 1996 was designed to cover specific teaching modules in kinanthropometry and other academic programmes, mainly physiology, within which kinanthropometry is sometimes subsumed. It was intended also to include practical activities of relevance to clinicians, for example, measuring metabolic functions, muscle performance, physiological responses to exercise, posture and so on. In all cases the emphasis was placed on the anthropometric aspects of the topic. By the time of the second edition in 2001, all the original chapters were updated and seven new chapters were added, mainly concerned with physiological topics. Consequently, it was decided to separate the overall contents of the edition into two volumes, one focusing on anthropometry practicals whilst the other contained largely physiological topics.

It seems that 6–7 years is a reasonable life cycle for a laboratory-based text in a field that is expanding. In the third edition, the structure of the previous two volumes has been retained without the need for any additional new chapters. Nevertheless, all chapters in both volumes have been altered
and updated – some more radically than others needed to be. New content is reflected in the literature trawled, the new illustrations included and changes in the detail of some of the practical laboratory exercises.

The content of both volumes is oriented towards laboratory practicals, but offers much more than a series of laboratory exercises. A comprehensive theoretical background is provided for each topic so that users of the text are not obliged to conduct extensive literature searches in order to place the topic in context. Each chapter contains an explanation of the appropriate methodology and, where possible, an outline of specific laboratory-based practicals. Across all the content is an emphasis on tests, protocol and procedures, data collection and handling and the correct interpretation of observations. The last two chapters in Volume 1 are concerned with basic statistical techniques and scaling procedures, which are designed to inform researchers and students about data analysis. The information should promote proper use of statistical techniques for treating data collected on human participants as well as avoid common abuses of basic statistical tools.

Many of the topics included within the two volumes called for unique individual approaches and so a rigid structure was not imposed on contributors. Nevertheless, in each chapter there is a clear set of aims for the practicals outlined and an extensive coverage of background theory. As each chapter is independent of the others, there is an inevitable reappearance of concepts across chapters, including those of efficiency, metabolism, maximal performance, measurement error and issues of scaling. Nevertheless, the two volumes represent a collective set of experimental sessions for academic programmes in kinanthropometry and exercise physiology.

It is hoped that this third edition in two volumes will stimulate improvements in teaching and instruction strategies in kinanthropometry and physiology. In this way, editors and authors will have made a contribution towards furthering the education of the next generation of specialists concerned with the relation between human structure and function.

Roger Eston
Thomas Reilly
The third edition of this twin-volume text covers both anthropometry (Volume 1) and exercise physiology (Volume 2). These volumes are complementary in covering areas related to sport and exercise sciences, physical therapy and healthcare professionals. Across all the content is an emphasis on tests, protocol and procedures, data collection and analysis and the correct interpretation of observations.

The first edition of this book was published as a single volume in 1996. The book has been used widely as a laboratory manual in both undergraduate and post-graduate programmes and in the continuous education and development workshops of a number of professional bodies. The subject area referred to as kinanthropometry has a rich history although the subject itself was not formalised as a discipline until the International Society for Advancement of Kinanthropometry (ISAK) was established in Glasgow in 1986. The Society supports its own international conferences and publication of Proceedings linked with these events. Until the publication of the first edition of *Kinanthropometry and Exercise Physiology Laboratory Manual: Tests, Procedures and Data* by the present editors in 1996, there was no laboratory manual that would serve as a compendium of practical activities for students in this field. Accordingly, the text was published under the aegis of ISAK in an attempt to make good the deficit, later expanded into two volumes to reflect related areas and topics.

Kinanthropometrists are concerned about the relation between structure and function of the human body, particularly within the context of movement. Kinanthropometry has applications in a wide range of areas including, for example, biomechanics, ergonomics, growth and development, human sciences, medicine, nutrition, physical therapy, healthcare, physical education and sports science. Initially, the idea for the book was motivated by the need for a suitable laboratory resource that academic staff could use in the planning and conduct of class practicals in these areas.

The content of the first edition in 1996 was designed to cover specific teaching modules in kinanthropometry and other academic programmes, mainly physiology, within which kinanthropometry is sometimes subsumed. It was intended also to include practical activities of relevance to clinicians; for example, measuring metabolic functions, muscle performance, physiological responses
to exercise, posture and so on. In all cases the emphasis was placed on the anthropometric aspects of the topic. By the time of the second edition in 2001, all the original chapters were updated and seven new chapters were added, mainly concerned with physiological topics. Consequently, it was decided to separate the overall contents of the edition into two volumes, one focusing on anthropometry practicals whilst the other contained largely physiological topics.

In the current revised edition, the ways in which anthropometry and physiology complement each other on academic programmes in the sport and exercise sciences are evident in the practical laboratory sessions across the two volumes. The structure of the previous two volumes has been retained, without the need for any additional new chapters. Nevertheless all chapters in both volumes have been altered and updated – some more radically than others needed to be. New content is reflected in the literature trawled, the new illustrations included and changes in the detail of some of the practical laboratory exercises. New authors are also included where appropriate. The most radical changes in Volume 1 have been introduced by the new authors in Chapters 1, 8 and 10. The initial chapter on body composition analysis has been re-vamped to acknowledge developments in this field and discard some of the field methods now deemed obsolete or discredited. Chapter 8 has been restructured and contains further information on growth and development and aerobic metabolism in children, in accordance with recent developments in the field. Chapter 10 has been re-worked so that the ubiquitous use of SPSS in data analysis is more directly recognised. In Volume 2, the new authors have also introduced substantial changes to Chapters 3, 9 and 10. The third chapter on lung function has been restructured and contains more recent population-specific regression equations for predicting lung function. Chapter 9 has been reworked and introduces new concepts and content, particularly in perceived exertion, and Chapter 10 has been rewritten to reflect the considerable and significant advances in knowledge regarding oxygen uptake kinetics and critical power in the last eight years.

We regret, earlier in 2008, the death of William Duquet co-author of Chapter 2 with J. E. L. Carter. Completion of the chapter was his last professional contribution to the literature on kinanthropometry before his passing. Apart from his many likeable and personable characteristics – especially as a caring mentor and tutor – he will be remembered for the methodical manner in which he approached and conducted his professional work. This chapter should stand as a tribute by which we can remember him.

As with the very first edition, the content of both volumes is oriented towards laboratory practicals, but offers much more than a series of laboratory exercises. A comprehensive theoretical background is provided for each topic so that users of the text are not obliged to conduct extensive literature searches in order to place the topic in context. The book therefore serves as a ‘one-stop shop’ for writing up the assignments set on each topic. Each chapter contains an explanation of the appropriate methodology and, where possible, an outline of specific laboratory-based practicals. Across all the content is an emphasis on tests, protocol and procedures, data collection and handling and the correct interpretation of observations. The last two chapters in Volume 1 are concerned with basic statistical techniques and scaling procedures, which are designed to inform researchers and students about data analysis. The information should promote proper use of statistical techniques for treating data collected on human participants as well as avoid common abuses of basic statistical tools. Nevertheless, there is a common emphasis on rigour throughout all the chapters in each volume and guidance on the reduction of measurement error.

Many of the topics included within the two volumes called for unique individual approaches and so a rigid structure was
not imposed on contributors. Nevertheless, in each chapter there is a clear set of aims for the practicals outlined and an extensive coverage of background theory. As each chapter is independent of the others, there is an inevitable reappearance of concepts across chapters, including those of efficiency, metabolism, maximal performance, measurement error and issues of scaling. Nevertheless, the two volumes represent a collective set of experimental sessions for academic programmes in kinanthropometry and exercise physiology.

It is hoped that this third edition in two volumes will stimulate improvements in teaching and instruction strategies in kinanthropometry and physiology. In this way, editors and authors will have made a contribution towards furthering the education of the next generation of specialists concerned with the relation between human structure and function.

Roger Eston
Thomas Reilly
PART ONE

BODY COMPOSITION, PROPORTION AND GROWTH: IMPLICATIONS FOR HEALTH AND PERFORMANCE
CHAPTER 1

HUMAN BODY COMPOSITION

Roger Eston, Michael Hawes, Alan Martin and Thomas Reilly

1.1 AIMS

The aims of this chapter are to develop understanding in:

- body composition models;
- chemical versus anatomical partitioning;
- levels of validity and the underlying assumptions of a variety of methods;
- the theory and practice of the best-known techniques: underwater weighing, plethysmography;
- dual-energy x-ray absorptiometry, skinfolds and bioelectric impedance;
- the importance of body fat distribution and how it is measured; and
- sample specificity and the need for caution in applying body composition equations.

1.2 INTRODUCTION

The assessment of body composition is common in fields as diverse as medicine, anthropology, ergonomics, sport performance and child growth. Much interest still centres on quantifying body fatness in relation to health status and sport performance, but there are good reasons to measure the amounts of other constituents of the body. As a result, interest in techniques for assessing body composition has grown significantly in recent years as new technologies have been applied to compositional problems. The traditional method of densitometry is no longer regarded as the ‘gold standard’ for determining per cent body fat because of better appreciation of the frequent violation of one of its basic assumptions. Despite the increasing number of methods for assessing body composition, validation is still the most serious issue, and because of this there is confusion over whether one method is more accurate than another. In this chapter we examine the important methods, investigate their validation hierarchy, provide practical details for assessing many body constituents and suggest directions for future research.

It is common to explain human structure in terms of increasing organizational complexity ranging from atoms and molecules to the anatomical, described as a hierarchy of cell, tissue, organ, system and organism. Body composition can be viewed as a fundamental problem of quantitative anatomy, which may be approached at any organizational level, depending on the nature of the constituents.
of interest (Figure 1.1). Knowledge of the interrelationship of constituents within a given level or between levels is also important and may be useful for indirectly estimating the size of a particular compartment (Wang et al. 1992).

1.3 LEVELS OF APPROACH

At the first level of composition are the masses of approximately 50 elements that comprise the atomic level. Total body mass is 98% determined by the combination of oxygen, carbon, hydrogen, nitrogen, calcium and phosphorous, with the remaining 44 elements comprising less than 2% of total body mass (Keys and Brozek 1953). Technology is available for measurement in vivo of all of the major elements found in humans. Current methods usually involve exposure of the subject to ionising radiation, which places severe restrictions upon the utility of this approach. Examples of body composition analysis at this level are the use of whole-body potassium 40 (40K) counting to determine total body potassium, or the use of neutron activation to estimate the body’s nitrogen or calcium. The primary importance of the atomic level is the relationship of specific elements to other levels of organization, as in estimating total body protein stores from its nitrogen content, for example. The great scarcity of the required instrumentation makes this level inaccessible to all but a few researchers.

The molecular level of organization is made up of more than 100,000 chemical compounds, which may be reduced to five main chemical groupings: lipid, water, protein, carbohydrate (mainly glycogen) and mineral. Some confusion arises with the term lipid, which may be defined as those molecules that are insoluble in water but soluble in organic solvents such as ether. Though there are many forms of lipid found in the human body, by far the most common is triglyceride, the body’s main caloric reservoir, with a relatively constant density of 0.900 g.ml⁻¹. Other forms of lipid typically comprise less than 10% of total body lipid and have varying densities, for example phospholipids (1.035 g.ml⁻¹) and cholesterol (1.067 g.ml⁻¹) (Keys and Brozek 1953). Lipid is often categorised as ‘essential’ or ‘non essential’ on the
basis of function. Essential (or non-adipose) lipids are those without which other structures could not function, for example lipid found in cell membranes and nervous tissue. Though commonly taken to be about 3-5% of body mass, data from the only five cadavers in which non-adipose lipid has been measured suggest much greater variability (Martin and Drinkwater 1991). The term ‘fat’ is sometimes used to refer to adipose tissue. To avoid confusion, the term ‘fat’ will be used interchangeably with the term ‘lipid’ and will not refer to adipose tissue.

Any measure of total body fat (such as per cent fat by underwater weighing or skinfold calliper) gives a single value that amalgamates all body fat regardless of function or location. The remainder, after removal of all fat, is the fat-free mass (FFM), composed of fat-free muscle, fat-free bone, fat-free adipose tissue and so on. The lean body mass (LBM) is the FFM with the inclusion of the essential (non-adipose) lipids; however, LBM is sometimes erroneously used as a synonym for FFM. It should be clear that there is no means of direct in vivo measurement of the fat compartment, so fat must always be estimated indirectly, as for example, by measuring body density. Other molecular compartments may be estimated by isotope dilution (total body water), dual-energy x-ray absorptiometry (DXA, bone mineral content), neutron activation analysis of nitrogen (total body protein).

At the cellular level the body is divided into total cell mass, extra-cellular fluid (ECF) and extra-cellular solids (ECS). The total cell mass is comprised of all the different types of cells including adipocytes, myocytes and osteocytes. There is no direct method of measuring discrete cell masses or total cell mass.

The ECF includes intravascular plasma and extravascular plasma (interstitial fluid). This fluid compartment is predominantly water and acts as a medium for the exchange of gases, nutrients and waste products, and may be estimated by isotope dilution methods. The ECS includes organic substances such as collagen and elastin fibres in connective tissue, and inorganic elements such as calcium and phosphorous, which are found predominantly in bone. The ECS compartment cannot be directly measured although several of its components may be estimated by neutron activation analysis.

The fourth level of organization includes tissues, organs and systems, which, although of differing levels of complexity, are functional arrangements of tissues. The four categories of tissue are connective, epithelial, muscular and nervous. Adipose and bone are forms of connective tissue, which, together with muscle tissue, account for about 75% of total body mass. Adipose tissue consists of adipocytes together with collagen and elastin fibres, which support the tissue. It is found predominantly in the subcutaneous region of the body, but is also found in smaller quantities surrounding organs, within tissue such as muscle (interstitial) and in the bone marrow (yellow marrow). The density of adipose tissue ranges from about 0.92 g.ml⁻¹ to 0.96 g.ml⁻¹ according to the proportions of its major constituents, lipid and water, and declines with increasing body fatness.

There is no direct method for the in vivo measurement of adipose tissue mass, but advances in medical imaging technology (ultrasound, magnetic resonance imaging, computed tomography) allow accurate estimation of the areas of adipose and other tissues from cross-sectional images of the body. Tissue areas from adjacent scans may be combined by geometric modelling to predict regional and even total volumes accurately, if the whole body is scanned. Although there is limited access and high cost associated with these techniques, they have the potential to serve as alternative criterion methods for the validation of more accessible and less costly methods for the assessment of body composition.

Bone is a specialised connective tissue with an elastic protein matrix, secreted by osteocytes, onto which is deposited a calcium phosphate-based mineral, hydroxyapatite, which provides strength and rigidity.
density of bone varies considerably according to such factors as age, gender and activity level. The range of fresh bone density in cadaveric subjects has been reported as 1.18–1.33 g.ml\(^{-1}\) (Martin \textit{et al.} 1986). The mass of bone mineral may be accurately estimated by dual energy x-ray absorptiometry (DXA), but DXA-derived bone densities are areal densities (i.e. g.cm\(^{-2}\)) and are therefore subject to bone size artifacts.

Muscle tissue is found in three forms, skeletal, visceral and cardiac. Its density is relatively constant at about 1.065 g.ml\(^{-1}\) (Mendez and Keys 1960; Forbes \textit{et al.} 1953), although the quantity of interstitial adipose tissue within the tissue will introduce some variability. Surprisingly, there are few methods for quantifying the body’s muscle mass; of these, the medical imaging techniques appear to be the most accurate, while anthropometry and urinary creatinine excretion have both been used.

The other tissues, nervous and epithelial, have been regarded as less significant tissues in body composition analysis. As a result, attempts have not been made to quantify these tissues; they are usually regarded as residual tissues.

The \textit{whole body} or organismic level of organization considers the body as a single unit dealing with overall size, shape, surface area, density and external characteristics. Clearly these characteristics are the most readily measured and include stature, body mass and volume.

The five levels of organization of the body provide a useful framework within which the different approaches to body composition may be situated. It is evident that there must be inter-relationships between levels, which may provide quantitative associations facilitating estimates of previously unknown compartments. The understanding of inter-relationships between levels of complexity also helps guard against erroneous interpretation of data determined at different levels. As an example, body lipid is typically assessed at the molecular level while the quantity of muscle tissue, in a health and fitness setting, is addressed at the tissue or system level by means of circumference measurements and correction for skinfold thicknesses. The two methods are incompatible in the sense that they overlap by both including the interstitial lipid compartment.

Since the whole-body level is not strictly a compositional level and the atomic and cellular levels are of very limited interest to most people, the organizational system reduces to two levels: the molecular and tissue levels. This is then identical to the two-level system proposed by Martin and Drinkwater (1991), the \textit{chemical} and \textit{anatomical} levels—a system which will be used here.

1.4 VALIDITY

The validity of a method is the extent to which it accurately measures a quantity whose true value is known. Body composition analysis is unusual in that only cadaver dissection can give truly valid measures, but almost no validation had been carried out this way. In fact, there is not a single subject for whom body density and body fat (by dissection and ether extraction) have been measured. This has resulted in the acceptance of an indirect method, densitometry, as the criterion for fat estimation.

In addition to the five levels of organization, there are three levels of validation in body composition, as in the assessment of body fat, for example. At level I, total fat mass is measured directly by cadaver dissection, i.e. ether extraction of lipid is carried out for all tissues of the body. At level II, some quantity other than fat is measured (e.g. body density or the attenuation of an x-ray beam in DXA), and a quantitative relationship is established to enable fat mass to be estimated from the measured quantity. At level III, an indirect measure is again taken (e.g. skinfold thickness or bioelectrical impedance) and a regression equation against a level II method, typically densitometry, is derived. Thus level III methods are \textit{doubly} indirect in that they
incorporate all the assumptions of the level II method they are calibrated against, as well as having their own inherent limitations. The regression approach also means that methods, such as skinfold thickness measurement, are highly sample-specific, since the quantitative relationship between skinfold thickness and body density depends on many variables including body hydration, bone density, relative muscularity, skinfold compressibility and thickness, body fat patterning and the relative amount of intra-abdominal fat. This, along with the use of different subsets of skinfold sites, is why there are several hundred equations in the literature for estimating fat from skinfolds.

Calibration of level III methods against densitometry also precludes the possibility of validating any level III method against densitometry, as this is merely a circular argument. For example, the computed per cent body fat by bioelectrical impedance analysis (BIA) cannot be validated by underwater weighing, on the basis that both methods give similar values, because the BIA equations are based on regression against per cent fat by underwater weighing. To validate BIA against densitometric values, the actual impedance values derived from the BIA machine should be used. It should be clear that assessment of body composition is far from an exact science and all methods should be scrutinised for the validity of their underlying assumptions. For the purposes of this chapter, it is convenient to separate assessment methods by the type of constituent they measure: chemical or anatomical.

1.5 THE CHEMICAL MODEL

At the chemical level, the body is broken down into various molecular entities. A model may consist of any number of components, with the simple requirement that when added together they give total body mass. The simplest chemical model is the well-known two-component model consisting of the fat mass and the fat-free mass (FFM).

Since the great majority of body composition techniques have this partition as their aim, this will be covered in some detail here.

1.5.1 Densitometry: Underwater weighing and plethysmography

The 2-component chemical densitometric model: Densitometry is an approach to estimating body fatness based on the theory that the proportions of fat mass and FFM can be calculated from the known densities of the two compartments and the measured whole-body density (Keys and Brozek 1953). In essence, the theory is based on the following assumptions and procedures (for the complete derivation see Martin and Drinkwater 1991):

The body, of mass M, is divided into a fat component of mass (FM) and density (df) and a fat-free component of mass (FFM) and density (dffm). The masses of the two components must add up to the body’s mass (M) and the volumes (mass/density) of the two components must add up to the body’s volume. If D is the whole-body density, then combining these two equations and rearranging gives per cent fat, F:

\[ F = \frac{100d_fd_{ffm}}{d_{ffm} - d_f} \left( \frac{1}{D} - \frac{100d_f}{d_{ffm} - d_f} \right) \]  

This equation contains three unknowns; it is solved by assuming values for \(d_f\) and \(d_{ffm}\) and measuring D. The standard assumptions are \(d_f = 0.900\) g.ml\(^{-1}\) and \(d_{ffm} = 1.100\) g.ml\(^{-1}\); although as explained in more detail later, the numeric value of \(d_{ffm}\) has been questioned recently as more accurate estimates have become available. Putting these respective values in to equation (1) results in Siri’s equation for per cent fat:

\[ F = \frac{495}{D} - 450 \]

a) Hydrodensitometry: Whole-body density, D, is then determined, usually by measuring
body volume by underwater weighing or similar technique (Figure 1.2a and b). Underwater, or hydrostatic, weighing is based on Archimedes’ principle, which states that the upthrust on a body fully submerged in a fluid is equal to the weight of fluid that it displaces. Therefore the weight of water displaced by a submerged body is its weight in air minus its weight in water. Dividing this by the density of water gives the body’s gross volume. This must be corrected for lung volume and gastrointestinal gas. If the underwater weight is obtained when the subject has completely exhaled (residual volume), then this value must be subtracted from the body’s gross volume, along with a correction for gastrointestinal gas, usually taken to be 100 ml. Though some systems measure residual volume at the same time as the underwater weight, it is typically determined outside the underwater weighing tank, by the subject exhaling maximally and then breathing within a closed system that contains a known quantity of pure oxygen (Wilmore et al. 1980). Nitrogen is an inert gas; hence the quantity of N₂ inhaled and exhaled as part of air does not change in response to metabolic processes. Therefore the quantity of N₂ in the lungs after maximum exhalation is representative of the residual volume. This remaining N₂ is diluted by a known quantity of pure oxygen during several breaths of the closed circuit gas. Analysis of the resulting gas mixture from the closed circuit system yields the dilution factor of N₂ and since N₂ is present in a fixed proportion in air, the residual volume can be calculated. This procedure and the necessary calculations are described in section 1.9.3.

**Density of the fat-free body: measurement and assumptions**

If these procedures are carried out by an experienced technician, the determination of corrected whole body density is both accurate and precise. However, the two-compartment hydrodensitometric model assumes an FFM density of 1.1000 g.cm⁻³, which is invariant of age, gender, genetic endowment and training. These assumptions about the component densities must be scrutinised. The fat compartment of the body consists primarily of triglyceride, which has a constant density of nearly 0.900 g.ml⁻¹. There are small quantities of other forms of lipid in the body located in the nervous system and within the membrane of all cells. Though the density of

*Figure 1.2a and 1.2b Examples of underwater weighing procedures for calculating whole-body density.*
these lipids is greater than that of triglyceride, the relatively small quantity of each has little effect upon overall density of body lipid. Thus the density of body fat may be accepted as relatively constant at 0.900 g.ml\(^{-1}\). However, the second assumption is much less tenable, since the density of the FFM has never been measured, and the value of 1.100 g.ml\(^{-1}\) assigned by Behnke more than 50 years ago was acknowledged to be only an estimate (Keys and Brozek 1953). This density is based on analyses of just three male cadavers, ages 25, 35 and 46 years (Brozek et al. 1963). In the absence of a direct measurement this value has remained in use, and it is only with the recent ability to measure bone mineral density and total body water, along with data from the Brussels Cadaver Study and elsewhere, that the extent of the variability of the fat-free density has been appreciated. On the basis of available evidence, the standard deviation of the fat-free density has been estimated at 0.02 g.ml\(^{-1}\) (Martin and Drinkwater 1991). This may not appear to be problematic, since it corresponds to a coefficient of variation of less than 2%. However, equation (1) is particularly sensitive to changes in fat-free density. An example will demonstrate this. If a lean male has a whole-body density, D = 1.070 g.ml\(^{-1}\), then estimated body fat by the Siri equation is 12.6%. If his fat-free density is actually 1.12 g.ml\(^{-1}\) rather than the assumed value of 1.100 g.ml\(^{-1}\), then from equation (1) his true fat is 19.1%. Conversely, if his fat-free density is 1.080 g.ml\(^{-1}\), his true fat is 4.7% (Figure 1.3). In the former situation the Siri equation gives a 43% underestimate, in the latter a 168% overestimate. It is important to note therefore that subjects with fat-free densities greater than 1.100 g.ml\(^{-1}\) will have their per cent fat underestimated by the Siri equation. This can lead to anomalous values that are lower than the generally accepted lower limit for essential fat of about 3–4%. Some athletes who combine leanness with a high fat-free density may even yield a negative per cent fat, which occurs when the measured whole-body density is greater than 1.100 g.ml\(^{-1}\). Ethnic factors also contribute to error. Schutte et al. (1984) have estimated that fat-free density in Black Americans is 1.113 g.ml\(^{-1}\). If this is true, then there is an underestimate of about 5% fat in assuming a fat-free density of 1.100 g.ml\(^{-1}\) in a non-athletic Black population whose whole-body densities are in the range 1.06–1.10 g.ml\(^{-1}\). The error will be greater in an athletic population, particularly in ‘power athletes’ whose bone density is high. Conversely, those with low fat-free densities will have their per cent fat overestimated. This applies particularly to older subjects, especially women. This is also true for lean female athletes with chronic amenorrhea, and its resultant bone loss. Densitometric evaluation of per cent fat in children requires a sliding value for fat-free density from the 1.063 g.ml\(^{-1}\) for newborns suggested by Lohman et al. (1984), to the adult value of 1.100 g.ml\(^{-1}\) at physical maturity, but it is difficult to attribute a particular value to a given child, without information on sexual maturation.

For these reasons, it is best to use a population-specific formula if the density of the fat-free body is known or can be assumed. Table 1.1 shows examples of how the equation varies according to differences in the density of the fat-free body. Examples of how variations in the density of the fat-free
body impacts on the calculation of per cent body when compared to the Siri equation is shown in Figure 1.3 and Table 1.5.

b) Air Displacement Plethysmography:

Though body volume for the determination of body density has primarily been assessed by underwater weighing and Archimedes’ principle, a more direct approach is to measure the volume of a fluid that the body displaces. Simple water displacement, while in principle an excellent approach, is limited in practice by the difficulty of measuring accurately the change in water level before and after submersion of the body. Alternatively, body volume can be measured using air displacement plethysmography. Currently one commercial system is available, the Bod Pod (Life Measurement, Inc. Concord, CA). Compared with hydrodensitometry, the Bod Pod offers a much quicker assessment that is much less demanding on the subjects and can be safely used in virtually any adult subject population. This equipment consists of a test chamber large enough to hold an adult, separated by a diaphragm from a reference chamber. Vibration of the diaphragm induces pressure changes, which allow determination of the test chamber volume, first with then without the subject, permitting the measurement of the subject’s volume (Dempster and Aitkins 1995). A number of corrections are required for surface area, clothing and lung volume.

Several studies have tested the validity of air displacement plethysmography using established methods of body composition assessment with mixed results. Although some studies have suggested that the Bod Pod yields biased results (Demerath et al. 2002; Radley et al. 2003; Ball and Altena 2004), others have reported agreement between the Bod Pod and established methods (Levenhagen et al. 1999; McRory et al. 1995). Reliability appears to be excellent (Noreen and Lemon 2006) and although it is reported to detect changes in fat and fat-free mass (Secchiutti et al. 2007), a study to compare actual changes in body composition as a result of diet or training compared to a more established criterion has yet to be completed. Plethysmography is subject to the same errors as underwater weighing when using the Siri or similar equation to convert density into per cent fat.

Because of the uncertainty regarding the assumption of constancy of the FFM and the

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Table 1.1 Examples of the differences in density of the fat-free body and derived equations based on the two component densitometric model

<table>
<thead>
<tr>
<th>Population</th>
<th>Age</th>
<th>Gender</th>
<th>Estimated density of FFB (g.cc)*</th>
<th>Derived equations from estimated density of FFB to predict % fat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Race</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>African American</td>
<td>9–17</td>
<td>Female</td>
<td>1.088</td>
<td>(521 / Db) – 479</td>
</tr>
<tr>
<td></td>
<td>18–32</td>
<td>Male</td>
<td>1.113</td>
<td>(470 / Db) – 422</td>
</tr>
<tr>
<td></td>
<td>24–79</td>
<td>Female</td>
<td>1.106</td>
<td>(483 / Db) – 437</td>
</tr>
<tr>
<td>Caucasian</td>
<td>7–12</td>
<td>Male/Female</td>
<td>1.086</td>
<td>(525 / Db) – 484</td>
</tr>
<tr>
<td></td>
<td>13–16</td>
<td>Male</td>
<td>1.094</td>
<td>(507 / Db) – 464</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>1.093</td>
<td>(510 / Db) – 466</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17–19</td>
<td>Male</td>
<td>1.098</td>
<td>(499 / Db) – 454</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>1.095</td>
<td>(505 / Db) – 462</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–80</td>
<td>Male</td>
<td>1.100</td>
<td>(495 / Db) – 450</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>1.097</td>
<td>(501 / Db) – 457</td>
<td></td>
</tr>
</tbody>
</table>

* The FFB density values are largely taken from Heyward and Stolarzyk (1996) and Heyward and Wagner (2004). The formulae have been calculated independently by the authors from the assumed FFB density values.
HUMAN BODY COMPOSITION

1.5.2 Dual-energy x-ray absorptiometry

Bone densitometry instruments have evolved from single- to dual-photon to DXA over the last three decades and widespread availability of whole-body scanners has made their use for body composition far more feasible (Lohman 1996). The DXA unit consists of a bed on which the subject lies supine, while a collimated dual-energy x-ray beam from a source under the bed passes through the subject. The beam’s attenuation is measured by detectors above the subject, and both source and detector move so that either the whole body or selected regions of the subject are scanned in a rectilinear fashion (Figure 1.4). Some systems use a pencil beam; others use an array of beams and detectors for faster scanning. The dual energy of the beam allows quantification of two components in each pixel. In boneless regions these are fat and a lean component. It should be noted that the lean component is actually all the fat-free, bone mineral-free constituents; this is not muscle, as some mistakenly believe. In bone mineral-containing pixels, the three component system must be reduced to two components, bone mineral and a soft tissue component, which contain an assumed fat-to-lean ratio. Strategies for estimating this ratio vary by manufacturer but consist in part of extrapolation of the measured fat-to-lean ratios of soft tissue pixels adjacent to bone. In this way, the fat, bone mineral and lean content of each pixel is determined (Kohrt 1995). Summing these for all pixels gives the composition of the whole body (Figure 1.5). Thus DXA uses a three-component chemical model of the body, and can therefore be compared with underwater weighing. Comparison of per cent fat determined by underwater weighing and DXA show differences that are correlated with bone mineral density (BMD) probably reflecting the effect of BMD on the fat-free density.

DXA is accepted as one of the most valid methods of body composition analysis (Prior et al. 1997; Kohrt 1998). It has been validated against various multicompartiment models in young (Prior et al. 1997; Clasey et al. 1999), old (Clasey et al. 1999) and a wide age range of healthy sedentary individuals (Gallagher et al. 2000). As a level II method the component values are calibrated against standards. The quality of the body composition assessment is therefore dependent only on the theoretical and practical aspects of the DXA technology. It does not rely on calibration against underwater weighing, unlike skinfold assessment.

A whole-body DXA scan can give regional composition as well as whole-body values, but precision values are considerably poorer than for the whole body. The default breakdown consists of six to seven regions: head, torso, pelvis and four limbs, but other segments can be defined by the operator. Since DXA does not suffer the basic weakness of densitometry, in that there is no requirement for constant density of the FFM, it has the potential to
become the criteria for fat estimation. It is also relatively independent of fluctuations in hydration, as water excess or deficit has been shown to affect only the lean component – as it should. It allows for a rapid, non-invasive estimation of body fat with minimal radiation exposure (van der Ploeg et al. 2003) and has the advantage of a three-compartment model of body composition that quantifies fat, soft lean tissue and bone mineral.

Nevertheless, the validity of the method has remained subject to question, particularly with regard to concerns over tissue thickness and hydration levels (Laskey et al. 1992; Jebb et al. 1995; Pietrobelli et al. 1998; Wang et al. 1998; van der Ploeg et al. 2003), which will vary between individuals and groups of subjects. Furthermore, the method is confounded by the different manufacturers’ detection, calibration and analysis techniques, as well as type of beam and the specifics of the analysis software. Despite these difficulties, there is optimism among researchers that with continued improvement, DXA will at some point become the gold standard for body fat assessment.

Figure 1.5 Analysis of body composition of a female dual energy x-ray absorptiometry. Note that the sum of the individual predicted masses from the segments analyzed by the DXA equates very closely to the whole body mass of the subject – a factor which is essential for the validity of the technique.
1.5.3 Multi-component models for predicting body fat

Advances in in vivo measurement techniques has led to the development of multi-component models that estimate body fat by equations, which incorporate a number of measured variables (Heymsfield et al. 1996). This has allowed researchers to assess variations in hydration levels and bone mineral contents that are not possible to measure by hydrodensitometry alone. An example of a four-component chemical model might be fat, water, bone mineral and a residual component (i.e. all the fat-free, bone mineral-free, dry constituents). Adding measurements of total body water (by deuterium dilution), bone mineral density (by DXA), and whole-body density (by hydrodensitometry), allows the possibility to measure individual variances in mineral and water, and in theory, lead to more accurate measurement of per cent body fat (Peterson et al. 2003). The 4C model has been used as the criterion method in studies with children (Fields and Goran 2000), younger and middle-aged adults (Friedl et al. 1992; Withers et al. 1998), and the elderly (Baumgartner et al. 1991). Ryde et al. (1998) used a five compartment model of body composition comprising FFM, where FFM = water + protein + minerals + glycogen to calculate body fat changes in ten overweight women on a 10-week very low calorie diet. An example of using such a procedure is given in Practical 7, using the methods and data from the study by Withers et al. (1998).

1.5.4 Level III methods

The defining characteristic of a level III method is that it uses an equation that represents an empirically-derived mathematical relationship between its measured parameter and per cent fat by the level II method – almost always underwater weighing (though with the rise in acceptance of DXA, more DXA-based equations, e.g. Stewart et al. 2000, are likely to be published). This relationship is derived by regression analysis, and typically is a simple linear regression, linear regression of a logarithmic variable, or a quadratic curve fit. Thus all level II methods are doubly indirect, and as such, they are vulnerable to the errors and assumptions associated with underwater weighing, as well as those deriving from their own technique, whether this is skinfold callipers, bioelectrical impedance, infrared interactance or some other approach.

a) Skinfold thickness: There is good face validity to the idea that a representative measure of the greatest depot of body fat (i.e.
subcutaneous) might provide a reasonable estimate of total body fat. This notion becomes less tenable as a greater understanding emerges with respect to various patterns of subcutaneous fat depots and different proportions of fat in the four main storage areas. However, the fact that so many equations have been derived for estimating percent body fat from skinfold thickness suggests the need for caution, and an examination of the assumptions underlying the use of skinfold callipers reinforces this.

The skinfold method measures a double fold of skin and subcutaneous adipose by means of callipers, which apply a constant pressure over a range of thicknesses (Figure 1.6). In converting this linear distance into a percent fat value, various assumptions are required (Martin et al. 1985). Initially, one must accept that a compressed double layer of skin and subcutaneous adipose is representative of an uncompressed single layer of adipose tissue. This implies that the skin thickness is either negligible or constant and that adipose tissue compresses in a predictable manner. Clearly skin thickness will comprise a greater proportion of a thin skinfold compared to a thicker skinfold and its relationship cannot be regarded as constant. In addition it has been shown that skin thickness varies from individual to individual as well as from site to site, which suggests that it cannot be regarded as negligible (Martin et al. 1992).

With respect to compressibility, the evidence suggests that adipose tissue compressibility varies with such factors as age, gender, site, tissue hydration and cell size. The dynamic nature of compressibility is readily observed when callipers are applied to a skinfold and a rapid decline in the needle gauge occurs. The lipid fraction of adipose tissue must also be constant if skinfold thickness is to be indicative of total body lipid. Adipose tissue includes structures other than fat molecules; these include cell membranes, nuclei and organelles. In a relatively empty adipocyte the proportion of fat to other structures may be quite low while a relatively full adipocyte will occupy a proportionately greater volume. Orpin and Scott (1964) suggested that fat content of adipose tissue may range between 5.2% and 94.1% although Martin et al. (1994) suggested a general range of 60–85%.

The previous three assumptions relate to the measurement of a single skinfold. There remain two assumptions that must be considered with respect to the validity of skinfold thickness as a predictor of total body fat. The first deals with the assumption that a limited number of skinfold sites in some way represent the remaining subcutaneous adipose tissue; that is, the distribution of fat shows some regularity from one person to another. Despite the two general patterns of fat distribution, android (central predominance) and gynoid (gluteofemoral predominance), fat patterns are quite individual. The final assumption is that a limited number of subcutaneous sites are representative of fat deposited non-subcutaneously (omentum, viscera, bone marrow and interstices). While there is some evidence that internal fat increases with subcutaneous fat, this relationship is affected by many variables, particularly age.

The procedure for generating percent fat equations for level III methods can be illustrated by examining the classic approach of Durnin and Womersley (1974). They measured body density (D) by underwater weighing, as well as the sum of four skinfolds on 464 men and women, categorised by age and gender. The resulting plots showed a curvilinear shape, so they used the log10 of the sum of the four skinfolds to linearise the relationship and then carried out a linear regression to establish the constants of the equation. As an example, their equation for 20–29 year old men is:

\[ D = 1.1631 - 0.0632 \times \log_{10} \sum 4SF \]

Siri’s equation can then be used to calculate percent fat.

It is important to note that the slopes and intercepts were different for all their gender and age groups, demonstrating that
the relationship between body density and the sum of skinfolds differed. Put another way, people from different age and gender groups who have the same sum of skinfolds have different body densities. For a given sum of skinfolds, men have higher body density than women mainly because of higher bone density, greater muscularity and the women’s tendency to have more subcutaneous fat in the gluteo-femoral region which is not assessed by the four skinfolds that they chose. Similarly, for a given sum of skinfolds, older men have lower body density than young men because of increasing internalisation of fat, as well as a decline in muscle mass and bone density. There are other factors, such as skin thickness and skinfold compressibility whose variability potentially affects the relationship between skinfolds and body density.

In view of the complexity of per cent fat prediction from skinfold thickness, some guidelines are helpful when choosing an equation to estimate per cent fat in a particular subject. It is important to select an equation that has been derived from a sample whose characteristics (ethnicity, age, gender, athletic status, health status and so on) are similar to those of the subject to be measured. Equations with few skinfolds cannot detect deviations in fat patterning, so it is better to use equations with skinfold sites that include arm, leg and trunk. Not all equations are based on the same type of skinfold calliper, and since these give different readings for a given skinfold, the choice of calliper becomes important. Proper site location and correct technique will help minimise error.

An alternative approach to the use of skinfold measurement is the sum of a number of skinfold thicknesses to form a simple indicator of fatness. Use of this measure avoids many of the untenable assumptions that are inherent in the calculation of per cent fat from skinfold thickness. This approach can be useful when normative values for the sum of skinfolds are available, as the sum can then be converted into a percentile, showing an individual’s relative standing within a population.

**Importance of including lower limb skinfold measures as indicators of total body fatness**

Skinfolds or measures of adipose tissue thicknesses from the lower limb, both independently or in combination with selected upper-body skinfolds, explain significant variance in total body fat. This has been observed using several criterion methods; for example, hydrodensitometry (in adults (Jackson and Pollock 1978; Jackson et al. 1980; Eston et al. 1995); in children (Slaughter et al. 1988; Eston and Powell 2003); cadaver dissection (Martin et al. 1985; Clarys et al. 1987); ultrasound (Eston et al. 1994); DXA (Stewart and Hannan 2000; Eston et al. 2005) and a four-compartment model of body composition (van der Ploeg et al. 2003; Eston et al. 2005). The correlation between subcutaneous abdominal adipose tissue volume and thigh fat volume (assessed by magnetic resonance imaging) is also reported to be greater than the corresponding correlation for the sum of the biceps, triceps, subscapular and iliac crest (Eliakim et al. 1997). The importance of including the thigh and calf skinfolds to improve the estimation of body fat in adults has led to previous comment and discussion (Durnin 1997; Stewart and Eston 1997).

On the basis of the potential importance of the thigh skinfold as a predictor of total body fat, the steering group of the British Olympic Association (BOA) recommended that the anterior thigh skinfold should be added to the sum of the four skinfolds used in the equation of Durnin and Womersley (1974) to provide a more valid estimate of body fat in fit and healthy adults (Reilly et al. 1996). The value of adding the thigh skinfold to the sum of the four skinfolds has since been confirmed using DXA and a four compartment model as the criterion in young, healthy men and women (Eston et al. 2005). They also observed that the thigh and calf skinfolds explained the most variance in body fat. The lower limb skinfolds may be particularly useful predictors of running performance. In a longitudinal study on 37 top class runners, improvements in performance over 3 years
were consistently associated with a decrease in the lower limb skinfolds (Legaz and Eston 2005; Figure 1.7).

Validation of skinfold-thickness prediction equations with a four-compartment model

Three of the most widely used generalized skinfold thickness prediction equations are the equations developed by Durnin and Womersley (1974), Jackson and Pollock (1978) and Jackson et al. (1980). These equations were developed and validated by means of hydrodensitometry – a two-compartment model. As indicated above, the two-compartment model equation requires the assumption that the fat-free density (body hydration levels and bone mineral content) is stable. These assumptions are often violated because of significant variations in hydration levels and mineral content between groups of differing age, gender, race and training status. This will therefore lead to potentially large errors in estimates of per cent body fat. For these reasons, new equations have been developed from 681 healthy Caucasian adults using a four-compartment (4C) model as the criterion and compared against the above equations (Peterson et al. 2003). The final equations developed from this study included the sum of the triceps, subscapular, suprailiac and mid-thigh skinfolds for men and women. These equations, which are shown in Practical 2 (Section 1.10.2), were significantly more accurate than the three skinfold thickness methods based on hydrodensitometry.

b) Bioelectrical Impedance Analysis: BIA is a method of body composition analysis that has become increasingly popular for its ease, portability and moderate cost. The electrical properties, particularly impedance, of living tissue, have been used for more than 50 years to describe and measure certain tissue or organ functions. In recent years, bioelectrical impedance has been used to quantify the FFM allowing the proportion of body fat to be calculated. The method is based on the electrical properties of hydrous and anhydrous tissues and their electrolyte content. There have been a number of excellent reviews of BIA procedures and the various equations that have been derived from healthy subjects (Houtkooper et al. 1996; Kyle et al. 2004).

Nyboer et al. (1943) demonstrated that electrical impedance could be used to determine biological volume. On application of a low voltage to a biological structure, a small alternating current flows through it, using the intra- and extra-cellular fluids as a
conductor and cell membranes as capacitors (condensers). The FFM, including the non-lipid components of adipose tissue, contain virtually all of the water and conducting electrolytes of the body and thus the FFM is almost totally responsible for conductance of an electrical current. Impedance to the flow of an electrical current is a function of the resistance and reactance of the conductor. The complex geometry and bioelectrical properties of the human body are confounding factors, but in principle, impedance may be used to estimate the bioelectrical volume of the FFM since it is related to the length and cross-sectional area of the conductor.

The impedance of biological structures can be measured with electrodes applied to the hands and feet, an excitation current of 800 µA at 50 kHz and a bioelectrical impedance analyzer that measures resistance and reactance. Some BIA instruments use other locations such as foot-to-foot (Jebb et al. 2000, Rowlands and Eston, 2001), or hand-to-hand electrodes. The resulting impedance value (though many systems use only the resistive component) is then entered into an appropriate equation.

Methods of bioelectrical impedance analysis include single frequency (SF-BIA), multi-frequency (MF-BIA), segmental BIA and localized BIA. Single frequency BIA is the most frequently applied method, which injects an excitation current of 800 µA at 50 kHz through surface electrodes, placed distally on the limbs. This technique estimates FFM and TBW, but it cannot determine differences in intra-cellular water (ICW). Multi-frequency BIA uses different frequencies (0, 1, 5, 50, 100, 200 to 500 kHz) to evaluate FFM, TBW, ICW and extra-cellular water (ECW). Segmental BIA, involving varied electrode placements on the limbs and trunk, has been used to determine fluid shifts and fluid distribution in some diseases. Although the trunk of the body represents as much as 50% of whole body mass, its large cross-sectional area contributes as little as 10% to whole-body impedance. Therefore, changes in whole-body impedance may be closely related to changes of the FFM (or muscle mass or body cell mass [BCM]) of the limbs and changes of the FFM of the trunk are probably not adequately described by whole body impedance measurements. Given that BIA measures various body segments and the validity of equations are therefore population-specific, localized BIA focuses on well defined body segments. For example, it has been used to determine local abdominal fat mass (Scharfetter et al. 2001).

Many equations have been published to predict the FFM from BIA for various healthy population subsets by age and gender. The most frequently occurring component in these equations is the resistive index, which is the square of stature, divided by resistance. Other variables that have been included in prediction equations include height, weight, gender, age, various limb circumferences, reactance, impedance, standing height, arm length and bone breadths. The reported R² values range between 0.80–0.988 with standard error of the estimate (SEE) ranging from 1.90 to 4.02 kg (approximately 2–3%). Slightly lower correlations (R² = 0.76 – 0.92) have been reported for the prediction of per cent fat with a prediction error (SEE) of 3–4%. Kyle et al. (2004) have provided a very useful summary of selected BIA equations published since 1990 for adults, which have been validated against a criterion measure for the variable of interest and which have involved at least 40 subjects. Given the vast array of equations available in the literature, Houtkooper et al. (1996) have suggested that the SEE of 2.0–2.5 kg and 1.5–1.8 kg in women and actual error of 0.0–1.8 kg is considered ideal. Prediction error of less than 3.0 kg for men and 2.3 kg for women would be considered to be very good. Three equations are presented in Practical 4 (Section 1.12.3) which satisfies these criteria.

Bioelectrical impedance is a safe, simple method of estimating the fat and fat-free masses, but some caution is needed. As “criterion” methods each have their limitations, these will be propagated into the BIA meas-
As with all level II methods, BIA equations tend to be population-specific with generally poor characteristics of fit for a large heterogeneous population. The measurement is influenced by electrode placement, dehydration, exercise, heat and cold exposure, and a conductive surface (Lukaski 1996), leading to the following recommendations for assessment procedures (Heyward 1991):

- no eating or drinking within 4 hours of the test
- no exercise within 12 hours of the test
- urinate within 30 minutes of the test
- no alcohol consumption within 48 hours of the test
- no diuretics within 7 days of the test.

Additionally,

- inaccuracies may be introduced during the pre-menstrual period for women (Gleichauf and Roe 1989);
- the changing pattern of water and mineral content of growing children suggests that a child-specific prediction equation should be used (Houtkooper et al. 1989; Eston et al. 1993; Bunc 2001; Rowlands and Eston 2001).

1.6 SIMPLE INDICES OF FATNESS, MUSCULARITY AND FAT DISTRIBUTION

1.6.1 Body mass index (BMI)

Body weight is often thought of as a measure of fatness, and this perception is reinforced by the use of height-weight tables as an indicator of health risk and life expectancy by the life insurance industry. Superficially it would appear that weight per unit of height is a convenient expression that reflects body build and body composition, and variations of this index have been a recurring theme in anthropometry for over 150 years following the pioneer work of Adolph Quetelet (1836). The simple ratio of weight to height may appear to be the most informative expression, but it expresses a three-dimensional measure (weight) in relation to a one-dimensional measure. Since three-dimensional measures vary as the cube of a linear measure, dimensional consistency may be better served by the expression of mass to the cube of height, a ratio known as the ponderal index. Since the objective of the ratio is to examine weight in relative independence of height, several authors have concluded that \( w/h^2 \) – with weight in kg and height in m – is the most appropriate index, and this has been termed the Body Mass Index (BMI), the inverse of which was previously known as the Quetelet Index.

Although the BMI is not ideal, it does have significant practical advantages. It is based on common measures of height and weight and it is familiar to most practitioners. The use of BMI measures to define adult obesity (BMI > 30 kg.m\(^{-2}\)) and adult overweight (BMI 25–30 kg.m\(^{-2}\)) is commonly accepted. According to the Association for the Study of Obesity (www.aso.org.uk), the ‘cut-offs’ for adults in each classification have been formalized by the World Health Organization and are:

<table>
<thead>
<tr>
<th>BMI (kg.m(^{-2})) Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;18.5</td>
<td>Underweight, thin</td>
</tr>
<tr>
<td>18.5–24.9</td>
<td>Healthy weight, healthy</td>
</tr>
<tr>
<td>25.0–29.9</td>
<td>Grade 1 obesity, overweight</td>
</tr>
<tr>
<td>30.0–39.9</td>
<td>Grade 2 obesity, obesity</td>
</tr>
<tr>
<td>&gt;40.0</td>
<td>Grade 3 obesity, morbid obesity</td>
</tr>
</tbody>
</table>

The above values are general guidelines. A female of average weight with the same height as an average-weight male, would normally have a lower BMI by one to two units. This is due to the greater proportion of fat-free mass in the male. Furthermore, these values apply to adults only as the cut-off values are significantly lower in children and vary significantly with age. The non-isometric changes in height, weight and shape occurring during growth are reflected in the huge variation in BMI in the growing years.
For example, at birth the median is as low as 13 kg.m\(^{-2}\), increasing to 17 kg.m\(^{-2}\) at 1 year, decreasing to 15.5 kg.m\(^{-2}\) at 6 years, and then increasing to 21 kg.m\(^{-2}\) at 20 years (Cole et al. 2000).

In order to quantify body weight in relation to obesity, reference values for children using BMI values, which are defined to pass through 25 kg.m\(^{-2}\) and 30 kg.m\(^{-2}\) at age 18, have been calculated for male and female children at six-monthly intervals from age 2 years, using data from large-scale surveys of childhood BMI in six different countries across several continents (Cole et al. 2000). This approach has been recommended by the International Obesity TaskForce (IOTF) for the comparison of child populations (Dietz and Bellizzi 1999).

The premise of using such an index is that body weight corrected for stature is correlated with obesity and adiposity (Ross et al. 1986). Indeed, the BMI has gained acceptance because in many epidemiological studies it shows a moderate correlation with estimates of body fat. Nevertheless, the widespread and often unquestioned application of the BMI to represent adiposity has attracted strong criticism (e.g. Garn et al. 1986; Ross et al. 1986, 1987, 1988). For such a premise to be true, a number of properties and assumptions need to be satisfied: a) the index should be highly correlated with weight and minimally correlated with height; and b) the difference in weight for a given height between individuals should be largely attributable to differences in body fat. With few exceptions, such as in the case of 66 world champion body builders (Ross et al. 1986; \(r = 0.41\)), and 1,112 children between 5 and 10 years (Garn et al. 1986; \(r = 0.30\)), BMI tends to be largely independent of height (Keys et al. 1972). With regard to b), the BMI is accepted because in many epidemiological studies it shows a moderate correlation with estimates of body fat (e.g. Keys et al. 1972). These same studies also show similar correlations between BMI and estimates of lean body mass or body density. As noted by others (Garn et al. 1986; Ross et al. 1986, 1987, 1988), the BMI reflects both the weight of lean tissue and the weight of fat tissue, and for some age groups, it may be a better measure of the amount of lean than of relative fatness (Garn et al. 1986). Unfortunately, the singular correlation values of BMI with body fat have been used to promote the use of the BMI for individual counselling with respect to health status, diet, weight loss and other fitness factors.

However, some of these studies also show very similar correlation values between BMI and estimates of lean body mass. In some populations the BMI is influenced to almost the same degree by the lean and fat compartments of the body, suggesting that it may be as much a measure of lean tissue as it is of fat. For example, in a study on 18,000 men and women aged 20–70 years to assess the predictive validity of the BMI as a means of estimating adiposity (Ross et al. 1988), the highest correlation of the BMI was with muscularity (\(r = 0.58\)), as assessed by the corrected arm girth technique. The correlation of BMI and adiposity was \(r = 0.50\).

The BMI may grossly underestimate the extent of lean tissue loss in certain diseases that are associated with sarcopenia (muscle wasting). For example, in a study on 97 rheumatoid arthritis patients in whom lean tissue loss exceeded fat loss, over half of the group were below the 10th percentile for muscularity, whereas only 13% were below the 5th percentile for BMI (Munro and Capell 1997). Similar observations are apparent in healthy men and women. In the large scale study by Ross et al. (1988) referred to above, 26% of those rated as extremely lean (BMI <20) had skinfolds above the 50th percentile and 16% of those rated as obese (BMI >27) had skinfolds below the 50th percentile.

Thus, for any individual, the use of BMI as a predictor of adiposity is seriously limited. On an individual basis, people of the same height will vary with respect to frame size, tissue densities and proportion of various tissues. A person may be heavy for his/her
height because of a large, dense skeleton and large muscle mass while another may be as heavy for his/her height because of excess adipose tissue. The proportion and density of tissue is dependent on gender, age, ethnicity, lifestyle and training – among other factors.

The BMI is positively associated with indicators of frame size. Garn et al. (1986) reported correlations of 0.50 overall between BMI and bony chest breadth in over 2,000 children and adults. Ross et al. (1988) also reported an overall correlation of 0.51 for BMI and the sum of humerus and femur breadths in over 18,000 Canadian men and women. Given the sample sizes in these studies, these values represent highly significant correlations.

This is not the end of the discussion however, because a further complicating factor arises since body shape changes as height increases (Ross et al. 1987). Whatever exponent for height is selected, human beings are not geometrically proportional. Changes in weight, and to some extent the change in shape, are dependent on the nature of the weight change, i.e. whether it is due to an increase in lean or fat mass. The measure assumes geometric proportionality and similarity in humans, but this assumption does not hold true for all measures. For example, the ratio of sitting height to stature (relative length of the trunk) is positively correlated with BMI. Children, adolescents, or adults with short legs for their height have higher BMI values (Garn et al. 1986). These authors indicated that short-legged individuals may have BMI values that are higher by as much as five units! It is notable that male weightlifters, gymnasts, judo players and Olympic wrestlers tend to have relatively short legs for their height (Norton et al. 1996), so it is likely that their BMI will be partly attributed to their body shape.

On an individual basis it is therefore erroneous to consider relative weight as a measure of obesity or fatness – the scientific evidence is not nearly strong enough to suggest a basis for individual health decisions (Garn et al. 1986, Keys et al. 1972). In summary, BMI is a good indicator of fatness in populations whose overweight individuals are overweight because of fatness, a condition which may hold for certain populations, such as all American adults, but not for others, such as specific groups of athletes for whom it is completely inappropriate.

1.6.2 Fat-Free Mass Index (FFMI) and Fat Mass Index (FMI)

The major limitation of the BMI is that the actual composition of body weight is not taken into account. A high BMI may be due to excess adipose tissue or muscle hypertrophy, both of which will be judged as ‘excess mass’ (Schutz et al. 2002). A low BMI may be due to a deficit in FFM (sarcopenia). The original idea of calculating the FFMI and FMI in analogy to the BMI was proposed by Van Itallie et al. (1990) as a means of indicating nutritional status in patients. The potential advantage of this technique is that only one component of body mass, i.e. FFM or FM, is related to \( \text{Ht}^2 \). Consequently, a preliminary attempt to derive FFMI and FMI reference standards has been conducted by Schutz et al. (2002) for Caucasian men and women, varying in age from 24 to 98 years. They used BIA to assess FFM and FM. They concluded that reference intervals of FMI vs FFMI could be used as indicative values for the evaluation of nutritional status (overnutrition and undernutrition) of apparently healthy subjects and can provide complementary information to the classical expression of body composition reference values (Pichard et al. 2000). Schutz et al. (2002) inferred that with reference to such values the FFMI is able to identify individuals with elevated BMI but without excess FM. Conversely, FMI can identify subjects with ‘normal’ BMI but who are at potential risk because of elevated FM. The percentile values for the men and women aged 18–54 years from their study are presented in Table 1.2

A modification of the FFMI was suggested
Table 1.2 Percentile values for FFM and FM index in men and women aged 18–54 years. Values taken from Schutz et al. (2002)

<table>
<thead>
<tr>
<th></th>
<th>P5</th>
<th>P10</th>
<th>P25</th>
<th>P50</th>
<th>P75</th>
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<tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>18–34 y</td>
<td>16.8</td>
<td>17.2</td>
<td>18.0</td>
<td>18.9</td>
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<td>17.6</td>
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<td>21.7</td>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>18–34 y</td>
<td>13.8</td>
<td>14.1</td>
<td>14.7</td>
<td>15.4</td>
<td>16.2</td>
<td>17.1</td>
<td>17.6</td>
</tr>
<tr>
<td>35–54 y</td>
<td>14.4</td>
<td>14.7</td>
<td>15.3</td>
<td>15.9</td>
<td>16.7</td>
<td>17.5</td>
<td>18.0</td>
</tr>
<tr>
<td>FMI</td>
<td></td>
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<td></td>
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<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18–34 y</td>
<td>2.2</td>
<td>2.5</td>
<td>3.2</td>
<td>4.0</td>
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</tr>
<tr>
<td>35–54 y</td>
<td>2.5</td>
<td>2.9</td>
<td>3.7</td>
<td>4.8</td>
<td>6.0</td>
<td>7.2</td>
<td>7.9</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18–34 y</td>
<td>3.5</td>
<td>3.9</td>
<td>4.6</td>
<td>5.5</td>
<td>6.6</td>
<td>7.8</td>
<td>8.7</td>
</tr>
<tr>
<td>35–54 y</td>
<td>3.4</td>
<td>3.9</td>
<td>4.8</td>
<td>5.9</td>
<td>7.3</td>
<td>8.8</td>
<td>9.9</td>
</tr>
</tbody>
</table>

* (N = 1,088 and 1,323 for 18–34 years and 35–54 years, respectively) + (N = 1,019 and 1,033 for 18–34 years and 35–54 years, respectively).

by Kouri et al. (1995) in a study of 157 male athletes. It was designed to assess whether an athlete’s musculature was within the naturally attainable range or was beyond that which could reasonably be expected without pharmacological assistance. The formula is:

\[
\text{FFMI} = \frac{\text{Mass (kg)} \times [(100 – \% \text{fat}/100)) + 6.1 \times (1.8 – \text{Height (m)})]}{\text{Height}^2}
\]

The correctional factor \((6.1 \times (1.8 – \text{Height}))\) is used only in calculations for males. According to Gruber et al. (2000) an FFMI of 18 kg.m\(^2\) indicates a slight build with low musculature; 20 – average musculature; 22 – distinctly muscular; above 22 – not normally achieved without weightlifting or similar activity; 25 – the upper limit of musculature that can be attained without use of pharmacological agents, whereby the FFMI could increase to 40! For women, a FFMI of 13 indicates low musculature; 15 – average; 17 – rather muscular; 22 – rarely achieved without using pharmacological agents (Gruber et al. 2000).

Similar FFMI techniques are applied in clinical populations to determine the extent of muscle wasting through disease.

1.6.3 Waist-to-hip ratio

The relationship between increasing body fat and health risk is generally accepted, even though two people with the same per cent fat may have very different risks for the cardiovascular-related diseases. This anomaly was addressed over 60 years ago by Vague (1947), who noted two general patterns of fat distribution on the body, which he designated as android and gynoid because of their predominance in males and females respectively. Greater health risk is associated with the android pattern of trunk deposition than the gynoid pattern of gluteofemoral deposition. The use of medical imaging techniques to quantify abdominal adiposity has demonstrated that it is the intra-abdominal adipose tissue that is associated with the highest health risk (Matsuzawa et al. 1995). Both magnetic resonance imaging (MRI)
and computerised tomography (CT) have been used successfully to measure adipose compartments of the abdomen. The full procedure is to take a series of consecutive scans that cover the whole abdominal region. Areas of subcutaneous and internal adipose tissue are determined from each scan and the corresponding volumes are generated since the distance between scans is known. However, a single scan at the level of the umbilicus shows a very high correlation ($r > 0.9$) with intra-abdominal adipose tissue volume (Abate et al. 1997). These methods are very expensive and are more use in research than in screening or individual evaluation.

The simplest approach to quantifying fat distribution is the use of waist circumference and the ratio of waist circumference to hip circumference (WHR). A waist circumference value of approximately 95 cm in both men and women, and WHR values of 0.94 for men and 0.88 for women have been found to correspond to a critical accumulation of visceral adipose tissue ($130$ cm$^2$) (Lemieux et al. 1996). Waist circumference is variously taken at the waist narrowing, the umbilicus, or other skeletally-determined locations, while hip circumference is taken at the maximum gluteal girth. Bjorntorp (1984) suggested that a ratio of $= 1.0$ in men is indicative of a significant elevation in the risk of ischaemic heart and cerebro-vascular disease. The corresponding value representing increased risk for women is $= 0.8$. The robustness of the association of WHR with health risk factors in large-scale epidemiological studies has been underscored by a substantial body of research that demonstrates important metabolic differences between abdominal and gluteofemoral adipose tissue. A tentative explanation for why women of reproductive age have great difficulty in reducing gynoid fat deposits is that gluteofemoral adiposity is an evolutionary adaptation to store fat for the energy-demanding lactational phase of childbearing; studies show that lipolysis in this region is facilitated by the endocrine environment of lactation. Though some women may want to reduce excess gluteofemoral fat, its presence is often more of an aesthetic issue than a health issue. As a general summary, this ratio appears to have some utility in the assessment of health risk although it should be used with caution.

1.7 THE ANATOMICAL MODEL

The anatomical model has been largely neglected since the rise of densitometry as the criterion method gave dominance to the chemical model. This is unfortunate since, for many applications, anatomical components are of major interest. Elite male athletes will show fat values that are typically in the range 6–12%, regardless of sport. However, measures of total and regional muscularity are considerably better at discriminating between athletes in different sports. Similarly, skeletal mass has been neglected and the chemical component, bone mineral content, has been the common measure of bone status. A strong argument can be made for the use of adipose tissue as a fatness measure since in lean people the amount of total body fat has almost no anatomical or physiological meaning. Despite the fact that, by their very nature, anatomical components have both anatomical and physiological significance, there are few proven techniques for estimating them.

1.7.1 Adipose Tissue

Surprisingly, there are no equations to estimate adipose tissue mass from skinfolds, BIA or any other level III method. The only current approach is the use of the medical imaging techniques such as CT, MRI or ultrasound. Though these methods depend on very different physical principles, from the viewpoint of body composition analysis, they are very similar. Each gives a cross-sectional view at a selected level of the body, from which areas of different tissues can be quantified. This quantification can be done with scan analysis software, or by scanning the resulting radiograph into a microcomputer...
for subsequent image analysis. A single scan is unable to yield adipose or any other tissue mass, however. It is at best an indicator of fatness in that region of the body. Adipose tissue volumes of a selected region, or of the whole body, can be calculated by geometric modelling of areas from a series of contiguous scans. A plot of adipose tissue area from each scan against the distance of the scan from one extremity of the body (foot) shows the distribution of adipose tissue along the body, and the area under this curve gives total adipose tissue volume; multiplying this by adipose tissue density gives adipose tissue mass. This approach has also used ultrasound imaging at measured points on the arm and thigh to estimate segmental fat and lean mass volumes (Eston et al. 1994). While medical imaging techniques could be used as a criterion measure against which level III methods may be calibrated – particularly skinfolds – this has yet to be done comprehensively as only a small number of subjects have been investigated in this manner. However, CT and MRI have proved very useful in the study of intra-abdominal adiposity, which is discussed in a later section.

1.7.2 Muscle

The quantity and proportion of body fat have remained a focal point in body composition analysis because of the perceived negative relationship of fatness to health, fitness and sport performance. It is evident to many working with high-performance athletes that knowledge of the changing total and regional masses of muscle in an athlete is an equal or perhaps more significant factor in sport performance. Estimation of total and regional skeletal muscle mass (SM) has not received the same attention as estimation of fat mass although it could be argued that there is more variability among athletes in muscle mass than in body fat, and therefore a greater need to know. Anatomical (tissue based) models for estimating total muscle mass have been proposed by Matiegka (1921), Heymsfield et al. (1982), Drinkwater et al. (1986), and Martin et al. (1990). The early approach of Matiegka (1921) was based on the recognition that total muscle mass was in large part reflected by the size of muscles on the extremities. Thus, he proposed that muscle mass could be predicted by using skinfold-corrected diameters of muscle from the upper arm, forearm, thigh and calf multiplied by stature and an empirically derived constant. Drinkwater et al. (1986) attempted to validate Matiegka’s formula using the evidence of the Brussels Cadaver Study and proposed modifications to the original mathematical constant. Martin et al. (1990) published equations for the estimation of muscle mass in men based on cadaver evidence. Data from six unembalmed cadavers were used to derive a regression equation to predict total muscle mass. The proposed equation was subsequently validated by predicting the known muscle masses from a separate cohort of five embalmed cadavers ($R^2 = 0.93$, SEE 1.58 kg, approximately 0.5%) and comparing the results to estimates derived from the equations of Matiegka (1921) and Heymsfield et al. (1982). The equation recommended by Martin et al. (1990) was much better able to predict muscle mass than the other two equations, which substantially underestimated the muscle mass of what must be regarded as a limited sample. Martin et al. (1990) attempted to minimise the specificity of their equation by ensuring that the upper and lower body were both represented in the three circumference terms.

Several of the above methods are based on the geometric model of extremity girths describing a circle and a single skinfold as representative of a constant subcutaneous layer overlying a circular muscle mass. A simple formula predicts the skinfold corrected geometric properties of the combined muscle and bone tissue (Figure 1.8).

$$\text{muscle and bone area} = \pi \left( \frac{c}{2\pi} - \frac{SF}{2} \right)^2$$
where $c$ is girth measure (cm) and $SF$ is skinfold (cm).

Further, the volume of the segments of the limb have been predicted by use of the formula for a cone. The anthropometric/geometric model has been found consistently to overestimate muscle area when compared to areas measured from computed tomography and magnetic resonance images (de Koning et al. 1986; Baumgartner et al. 1992). Nevertheless, the correlation between anthropometrically derived areas and imaged areas has been shown to be very high $r > 0.9$.

More recently, the validity of the type of anthropometric procedures used in the above studies has been assessed in vivo on 244 non-obese adults ranging in age from 20 to 81 years (Lee et al. 2000). Using state-of-the-art whole-body multislice magnetic resonance imaging to measure skeletal mass, they assessed the predictive accuracy of the upper arm, calf and thigh circumferences (corrected for skinfold thickness), with height, race and gender as the other predictor variables. The final derived equation explained 91% of the variance in skeletal muscle mass with an SEE of 2.2 kg (refer to Practical 5, Section 1.13.2b). It is notable that of all the limb circumferences, corrected arm girth (CAG) had the highest correlation with total-body skeletal muscle mass ($R = 0.88$), which supports the frequent use of arm girth or arm muscle area as a measure of total-body SM and subject protein status.

The relationship of cross-sectional area of muscle to force output is well established (Ikai and Fukunaga 1968). Knowledge of the changing size of muscle resulting from particular training regimens is therefore important information for a coach evaluating the effect of the programme and for the motivation of the athlete (Hawes and Sovak, 1994). Size of muscle relative to body mass may provide information on a young athlete’s stage of development and readiness for certain categories of skill development; changing size of muscle may reflect the effectiveness of a particular exercise or activity; diminished size may reflect a lack of recovery time (over-training) or in-season response to changing patterns of training. In all instances regular feedback of results to the coach may provide early information for adjustment or enhancement of the training regimens.

### 1.7.3 Bone

The skeleton is a dynamic tissue responding to environmental and endocrine changes by altering its shape and its density. Nevertheless it is less volatile than either muscle or adipose tissue and its influence upon human performance has been largely neglected. Matiegka (1921) proposed that skeletal mass could be estimated from an equation that included stature, the maximum diameter of the humerus, wrist, femur and ankle and a mathematical constant. Drinkwater et al. (1986) attempted to validate the proposed equation against recent cadaver data and found that an adjustment to Matiegka’s constant produced a more accurate estimate in their sample of older, cadaveric persons. Drinkwater et al. (1986) commented that the true value of the coefficient probably lies between the original and their calculated values.
value. An estimation of bone mass within a prototypical model may provide insight into structural factors which contribute to athletic success. In a longitudinal study of high performance synchronized swimmers, Hawes and Sovak (1993) found that the world and Olympic champion had disproportionally narrow bony diameters compared with other synchronized swimmers competing at the international level. Since positive buoyancy contributes to the ease of performing exercises above water, a relatively small mass of the most dense body tissue might be construed as a morphological advantage in athletes of otherwise equal abilities.

1.8 OTHER CONSIDERATIONS

In this chapter, an overview of the issues surrounding the quantification of body composition in vivo has been presented. There are several issues in body composition that must be resolved before the field can advance to maturity. The most important is the absence of validation and the consequent lack of a true criterion method. While DXA is well placed to assume this role for per cent fat, some methodological improvements are needed before then. Considerable work has been done in recent years on multi-component models that estimate body fat by equations incorporating a number of measured variables, such as body density, total body water, and bone mineral content. In this way it is hoped that the improvement in prediction is not offset by the increased error inherent in the measurement of many variables. The second problem is the traditional focus on the chemical model, specifically fat. This has meant that sport scientists and others have few proven tools for quantifying body constituents that have physiological and anatomical meaning, particularly skeletal muscle. The advances in medical imaging discussed here may help to address this issue, but these methods are expensive and difficult for many to access.

In summary, care must be taken in applying body composition methods because of their sample specificity and poor validation. Because of this the best use of body composition techniques is probably for repeated measures in the same individuals over a period of time to investigate change due to growth, ageing or some intervention. The following laboratory exercises are designed to provide an introduction to a variety of body composition assessment procedures.

1.9 PRACTICAL 1: DENSITOMETRY

1.9.1 Purpose

- To determine body composition by densitometry

1.9.2 Methods

1. The subject should report to the laboratory several hours postprandial. A form-fitting swim suit is the most appropriate attire.
2. Height, body mass and age should be recorded using the methods specified in Practical 3.
3. Determination of total body density.

Facilities will vary from custom-built tanks to swimming pools. The following is an outline of the major procedures:
Determine the tare weight of the suspended seat or platform together with weight belt.

Record the water temperature and barometric pressure.

The subject should enter the tank and ensure that all air bubbles (clinging to hair or trapped in swim suit) are removed.

Subjects who may have difficulty in maintaining full submersion should attach a weight belt of approximately 3 kg.

The subject quietly submerges while sitting or squatting on the freely suspended platform and exhales to a maximum. Drawing the knees up to the chest will facilitate complete evacuation of the lungs. The subject remains as still as possible and the scale reading is recorded.

This procedure is repeated 4–5 times with the most consistent highest value accepted as the underwater weight.

4 Determination of residual volume (RV)

RV is the volume of air remaining in the lungs following a maximal exhalation.

RV may be measured by the O₂ dilution method or estimated from age and height.

If the RV is to be measured, there is evidence to suggest that the procedure should be completed with the subject submersed to the neck in order to approximate the pressure acting on the lungs in a fully submersed position.

The equipment used to determine RV will vary from laboratory to laboratory. The fundamental procedure is as follows:

- The gas analyzer should be calibrated according to manufacturer’s specifications.
- A three-way T valve is connected to a five-litre anaesthetic bag, a pure oxygen tank and a spirometer. The system (spirometer, bag, valve and tubing) should be flushed with oxygen three times. On the fourth occasion a measured quantity (approximately 5 l) of oxygen is introduced into the spirometer bell, the O₂ valve is closed and the T valve opened to permit the O₂ to pass into the anaesthetic bag. The bag is closed off with a spring clip and is removed from the system together with the T valve. A mouthpiece hose is attached to the T valve.
- The subject prepares by attaching a nose clip and immersing to the neck in the tank. The mouthpiece is inserted and the valve opened so that the subject is breathing room air. When comfortable the subject exhales maximally, drawing the knees to the chest in a similar posture to that adopted during underwater weighing, since RV is affected by posture (see Dangerfield, Chapter 4). At maximum exhalation the T valve is opened to the pure O₂ anaesthetic bag and the subject completes 5–6 regular inhalation-exhalation cycles. On the signal the subject again exhales maximally and the T valve to the anaesthetic bag is closed. The subject removes the mouthpiece and breathes normally. The anaesthetic bag is attached to the gas analyzers and values for the CO₂ and O₂ are recorded.
• Measurement of RV should be repeated several times to ensure consistent results.

1.9.3 Calculation of residual volume and density

(a) Measured residual volume (Wilmore et al. 1980)

\[ RV = \frac{V_O^2 \times F_{EN2}}{0.798 - F_{EN2}} - DS \times BTPS \]

where:
- \( V_O^2 \) is the volume of \( O_2 \) measured into the anaesthetic bag (~5 litres)
- \( F_{EN2} \) is the fraction of \( N_2 \) at the point where equilibrium of the gas analyzer occurred calculated as:

\[ \frac{[100\% - (\%O_2 + \%CO_2)]}{100} \]

- \( DS \) is the dead space of mouthpiece and breathing valve (calculated from specific situation)
- \( BTPS \), the body temperature pressure saturated, is the correction factor which corrects the volume of measured gas to ambient conditions of the lung according to the following Table 1.3

<table>
<thead>
<tr>
<th>Gas temp. (°C)</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>1.102</td>
</tr>
<tr>
<td>20.5</td>
<td>1.099</td>
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<tr>
<td>21.0</td>
<td>1.096</td>
</tr>
<tr>
<td>21.5</td>
<td>1.093</td>
</tr>
<tr>
<td>22.0</td>
<td>1.091</td>
</tr>
<tr>
<td>22.5</td>
<td>1.089</td>
</tr>
<tr>
<td>23.0</td>
<td>1.085</td>
</tr>
<tr>
<td>23.5</td>
<td>1.082</td>
</tr>
<tr>
<td>24.0</td>
<td>1.079</td>
</tr>
<tr>
<td>24.5</td>
<td>1.077</td>
</tr>
<tr>
<td>25.0</td>
<td>1.074</td>
</tr>
<tr>
<td>25.5</td>
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<tr>
<td>26.0</td>
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<td>26.5</td>
<td>1.065</td>
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<tr>
<td>27.0</td>
<td>1.062</td>
</tr>
<tr>
<td>27.5</td>
<td>1.060</td>
</tr>
</tbody>
</table>

(b) Predicted residual volume

Using the equations of Quanjer et al. (1993).

- Substitute 25 y in the equations for any adult under 25 y.

Men: \( RV = (1.31 \times \text{height (m)}) - (0.022 \times \text{age (y)}) - 1.23 \)

Women: \( RV = (1.81 \times \text{height (m)}) + (0.016 \times \text{age (y)}) - 2.00 \)

1.9.4 Body density calculations

Total body volume (l) = (Mass in air – mass in water)/Density of water corrected for water temperature
Total body density (kg l⁻¹) = (Mass in air)/(Total body volume (L) – trapped air)
where: trapped air = residual lung volume + tubing dead space + 100 ml
(100 ml is the conventional allowance for gastro-intestinal gases) and correction for
water temperature is according to Table 1.5:

<table>
<thead>
<tr>
<th>Water temp (°C)</th>
<th>Density of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>0.997</td>
</tr>
<tr>
<td>28.0</td>
<td>0.996</td>
</tr>
<tr>
<td>31.0</td>
<td>0.995</td>
</tr>
<tr>
<td>35.0</td>
<td>0.994</td>
</tr>
<tr>
<td>38.0</td>
<td>0.993</td>
</tr>
</tbody>
</table>

% Fat according to Siri (1956) = [(4.95 / body density) – 4.50] × 100
% Fat according to Brozek et al. (1963) = [(4.57/ body density) – 4.142] × 100

**Effect of changes in assumed density of the fat-free body**

You can compare the estimations of per cent body fat in the following hypothetical
pairs of individuals (who have identical hydrodensitometric values) when the %fat is
calculated by the Siri equation and when it is calculated from an equation which is
derived from respective assumed population-specific densities of the fat free body (FFB)
(see Table 1.5). Assume the temperature of the water is 35 degrees C.

It can be noted from these values, that when the density of the fat free body is above
the assumed value of 1.10 kg.l⁻¹, the per cent fat is underestimated when calculated using
the Siri equation. When the density of the fat free body is below the assumed value of
1.10 kg.l⁻¹, the per cent fat is overestimated when calculated using the Siri equation.

### Table 1.5 Effects of changes in the assumed density of the fat-free body on per cent body fat

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Adult male A</th>
<th>Adult male B</th>
<th>Adult female A</th>
<th>Adult female B</th>
<th>Male child A</th>
<th>Female child A</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>1.80</td>
<td>1.80</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.60</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>90.0</td>
<td>90.0</td>
<td>63.0</td>
<td>63.0</td>
<td>70.0</td>
<td>55.0</td>
</tr>
<tr>
<td>RV (L)</td>
<td>1.80</td>
<td>1.80</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
<td>1.05</td>
</tr>
<tr>
<td>Assumed GIG</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>Mass in water (kg)</td>
<td>4.4</td>
<td>4.4</td>
<td>2.3</td>
<td>2.3</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Body volume (l)</td>
<td>86.1</td>
<td>86.1</td>
<td>59.9</td>
<td>59.9</td>
<td>65.8</td>
<td>51.9</td>
</tr>
<tr>
<td>Body density (kg.l⁻¹)</td>
<td>1.0689</td>
<td>1.0689</td>
<td>1.0517</td>
<td>1.0517</td>
<td>1.0638</td>
<td>1.059</td>
</tr>
<tr>
<td>Density of FFB (kg.l⁻¹)</td>
<td>1.100</td>
<td>1.113</td>
<td>1.097</td>
<td>1.106</td>
<td>1.094</td>
<td>1.093</td>
</tr>
<tr>
<td>% Fat (Siri)</td>
<td>13.1</td>
<td>13.1</td>
<td>20.6</td>
<td>20.6</td>
<td>15.3</td>
<td>17.4</td>
</tr>
<tr>
<td>% Fat from FFB density</td>
<td>13.1</td>
<td>17.7</td>
<td>19.4</td>
<td>22.2</td>
<td>12.6</td>
<td>15.6</td>
</tr>
</tbody>
</table>
1.10 PRACTICAL 2: MEASUREMENT OF SKINFOLDS

1.10.1 Purpose

- To develop the technique of measuring skinfolds.
- To compare various methods of computing estimates of proportionate fatness.

1.10.2 Methods

A well-organized and established set of procedures will ensure that test sessions go smoothly and that there can be no implication of impropriety when measuring subjects. The procedures should include:

- prior preparation of equipment and recording forms;
- arrangements for a suitable space which is clean, warm and quiet;
- securing the assistance of an individual who will record values;
- forewarning the subjects that testing will occur at a given time and place;
- ensuring that females bring a bikini-style swim suit to facilitate measurement in the abdominal region and that males wear loose-fitting shorts or speed swim suit;
- ensuring that the measurer’s technique includes recognition and respect for the notion of personal space and sensitive areas;
- taking great care in the consistent location of measurement sites as defined in Figures 1.10–1.15 and section 1.10.3;
- recognition that the data are very powerful in both a positive and negative sense. Young adolescents in particular are very sensitive about their body image and making public specific or implied information on body composition values may have a negative effect on an individual.

(a) Skinfold measurements – general technique

- During measurement the subject should stand erect but relaxed through the shoulders and arms. A warm room and easy atmosphere will help the subject to relax, which will help the measurer to manipulate the skinfold.
- Ideally, but not essentially, the site should be marked with a washable felt pen.
- The objective is to raise a double fold of skin and subcutaneous adipose leaving the underlying muscle undisturbed.
- All skinfolds are measured on the right side of the body.

Measurements should be made in series – moving from one site to the next until the entire protocol is complete.

- The measurer takes the fold between thumb and forefinger of the left hand following the natural cleavage lines of the skin.
- The calliper is held in the right hand and the pressure plates of the calliper are applied perpendicular to the fold and 1 cm below or to the right of the fingers, depending on the direction of the raised skinfold. (see Figure 1.9 for examples at various sites).
The calliper is held in position for 2 s prior to recording the measurement to the nearest 0.2 mm. The grasp is maintained throughout the measurement. In the case of large skinfolds, the needle is likely to be moving at this time, but the value is recorded nevertheless (Stewart and Eston 2006).

- The mean of duplicate or the median of triplicate measures (when the first two measures differ by more than 5%) is recommended.

(b) Secondary computation of fatness

There are over 100 equations for predicting fatness from skinfold measurements. The fact that these equations sometimes predict quite different values for the same individual leads to the conclusion that the equations are population-specific, i.e. the equation only accurately predicts the criterion value (usually densitometrically determined) for the specific population in the validation study. When applied to other populations the equation loses its validity. This diversity will be illustrated if estimates of per cent fat are computed from the following frequently used equations. It should be observed that while inter-individual comparisons of per cent fat may not be valid for many of the reasons previously discussed, intra-individual comparisons of repeated measurements may provide useful information. The summation of skinfold values will also provide comparative values avoiding some of the assumptions associated with estimates of proportionate fatness.

Figure 1.9 Skinfold calliper technique showing correct two-handed method and with calliper aligned to natural cleavage lines of the skin. Sites shown are supraspinale, pectoral, thigh, calf, triceps and subscapular.
(c) Per cent fat equations (skinfold sites shown in Table 1.6)

Parizkova (1978) – ten sites

\[
\text{%Fat} = 39.572 \log \Sigma 10 - 61.25 \quad (\text{females 17–45 y.})
\]
\[
\text{%Fat} = 22.320 \log \Sigma 10 - 29.00 \quad (\text{males 17–45 y.})
\]

where \( \Sigma 10 \) = 10 skinfolds as specified (mm)

Durnin and Womersley (1974) – four sites

\[
\begin{align*}
\text{body density} &= 1.1610 - 0.0632 \log \Sigma 4 \quad (\text{men}) \\
\text{body density} &= 1.1581 - 0.0720 \log \Sigma 4 \quad (\text{women}) \\
\text{body density} &= 1.1533 - 0.0643 \log \Sigma 4 \quad (\text{boys}) \\
\text{body density} &= 1.1369 - 0.0598 \log \Sigma 4 \quad (\text{girls})
\end{align*}
\]

\ [%F \ (\text{Siri, 1956}) = [(4.95 / \text{Body Density}) - 4.5] \times 100
\]

where \( \Sigma 4 = \Sigma 4 \) skinfolds as specified (mm)

Jackson and Pollock (1978) – three sites (males)

\[
\begin{align*}
\text{body density of males} &= 1.1093800 - 0.0008267 (\Sigma 3_M) + 0.0000016 (\Sigma 3_M)^2 \\
& \quad - 0.0002574 (\text{age y})
\end{align*}
\]

Jackson et al. (1980) – three sites (females)

\[
\begin{align*}
\text{body density of females} &= 1.099421 - 0.0009929 (\Sigma 3_F) + 0.0000023 (\Sigma 3_F)^2 \\
& \quad - 0.0001392 (\text{age y})
\end{align*}
\]

\ [%F \ (\text{Siri, 1956}) = [(4.95 / \text{Body Density}) - 4.5] \times 100
\]

where \( \Sigma 3_M = \Sigma 3 \) skinfolds (mm) as specified for males
\( \Sigma 3_F = \Sigma 3 \) skinfolds (mm) as specified for females

Jackson and Pollock (1978) – seven sites

\[
\begin{align*}
\text{body density of males} &= 1.112 - 0.00043499 (\Sigma 7) + 0.00000055 (\Sigma 7)^2 \\
& \quad - 0.00028826 (\text{age y})
\end{align*}
\]

Jackson et al. (1980) – seven sites

\[
\begin{align*}
\text{body density of females} &= 1.097 - 0.00046971 (\Sigma 7) + 0.00000056 (\Sigma 7)^2 \\
& \quad - 0.00012828 (\text{age y})
\end{align*}
\]

\ [%F \ (\text{Siri, 1956}) = [(4.95 / \text{Body Density}) - 4.5] \times 100
\]

where \( \Sigma 7 = \Sigma 7 \) skinfolds as specified (mm)
Peterson et al. (2003) – four sites
For men:
\[
\%\text{Fat} = 20.94878 + (\text{age} \times 0.1166) - (\text{Ht} \times 0.1166) + (\Sigma 4 \times 0.42696) - (\Sigma 4^2 \times 0.00159)
\]

For women:
\[
\%\text{Fat} = 22.18945 + (\text{age} \times 0.06368) + (\text{BMI} \times 0.60404) - (\text{Ht} \times 0.14520) + (\Sigma 4 \times 0.30919) - (\Sigma 4^2 \times 0.00099562)
\]

Where Ht is in cm and $\Sigma 4$ = the sum of skinfolds as specified

Table 1.6 Summary of skinfold sites used in selected equations for prediction of per cent fat

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Sum of skinfolds</td>
<td>$\Sigma 10$</td>
<td>$\Sigma 3$</td>
<td>$\Sigma 3$</td>
<td>$\Sigma 7$</td>
<td>$\Sigma 4$</td>
<td></td>
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<td>$\Sigma 4$</td>
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<tr>
<td>Population</td>
<td>M &amp; F female</td>
<td>male</td>
<td>female</td>
<td>male</td>
<td>male</td>
<td>M &amp; F male</td>
<td>male</td>
<td>female</td>
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<tr>
<td>BMI</td>
<td>*</td>
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<tr>
<td>Age (y)</td>
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<tr>
<td>Height (cm)</td>
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<tr>
<td>Skinfold Site</td>
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<tr>
<td>Cheek</td>
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<tr>
<td>Chin</td>
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<tr>
<td>Pectoral (chest 1)</td>
<td>*</td>
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<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
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<tr>
<td>Axilla (midaxillary)</td>
<td>*</td>
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<td>*</td>
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<tr>
<td>Chest 2</td>
<td>*</td>
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<td></td>
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<tr>
<td>Iliocristale</td>
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<td></td>
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<tr>
<td>Abdomen</td>
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<td></td>
</tr>
<tr>
<td>Abdominal</td>
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<td>*</td>
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<td>*</td>
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<tr>
<td>Iliac Crest*</td>
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<td></td>
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<td>Suprailium</td>
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<td></td>
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<tr>
<td>Subscapular</td>
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<td>*</td>
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<td>*</td>
<td>*</td>
<td>*</td>
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<tr>
<td>Triceps</td>
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<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<tr>
<td>Biceps</td>
<td>*</td>
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<td>*</td>
<td>*</td>
<td>*</td>
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<td></td>
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<tr>
<td>Patella</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Mid-thigh</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal calf</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Referred to as ‘suprailiac’ by Durnin and Womersley (1974) and ‘iliocristale’ by Parizkova (1978).
1.10.3 Locations of skinfold sites

All measurements are taken on the right side of the body.

Cheek: horizontal skinfold raised at the midpoint of the line connecting the tragus (cartilaginous projection anterior to the external opening of the ear) and the nostrils (Figure 1.10).

Chin: vertical skinfold raised above the hyoid bone: the head is slightly lifted but the skin of the neck must stay loose (Figure 1.10).

Pectoral (chest 1): oblique skinfold raised along the borderline of the m. pectoralis major between the anterior axillary fold and the nipple (Figure 1.9b and 1.11).

Females: measurement is taken at 1/3 of the distance between anterior axillary fold and nipple.

Males: measurement is taken at one-half of the distance between anterior axillary fold and nipple (Figure 1.9a and 1.11).

Axilla: vertical skinfold raised at the level of the xipho-sternal junction (midaxillary) on the mid-axillary line (Figure 1.12).

Chest 2: horizontal skinfold raised on the chest above the 10th rib at the point of intersection with the anterior axillary line—slight angle along the ribs (Figure 1.12).

Abdomen: horizontal fold raised 3 cm lateral and 1 cm inferior to the umbilicus (Figure 1.13).

Abdominal: vertical fold raised at a lateral distance of approximately 2 cm from the umbilicus (Figure 1.13).

Iliac crest: diagonal fold raised immediately above the crest of the ilium on a vertical line from the mid-axilla. This skinfold was
referred to as the ‘suprailiac’ by Durnin and Womersley (1974) and ‘iliochristale’ by Parizkova (1978) (Figure 1.14).

Supraspinale: *diagonal* fold raised immediately above the crest of the ilium on a vertical line from the anterior axillary fold.

Subscapular: *oblique* skinfold raised 1 cm below the inferior angle of the scapula at approximately 45° to the horizontal plane following the natural cleavage lines of the skin (Figure 1.9f and 1.15).

Triceps: *vertical* skinfold raised on the posterior aspect of the m. triceps, exactly halfway between the olecranon process and the acromion process when the hand is supinated (Figure 1.9e and 1.15).

Biceps: *vertical* skinfold raised on the anterior aspect of the biceps, at the same horizontal level as the triceps skinfold (Figure 1.15).

Patella: *vertical* skinfold in the mid sagittal plane raised 2 cm above the proximal edge of the patella. The subject should bend the knee slightly (Figure 1.16).

Mid-thigh: *vertical* skinfold raised on the anterior aspect of the thigh midway between the inguinal crease and the proximal border of the patella (Figure 1.9c and 1.16).

A preferred method is to flex the knee slightly with the subject in the standing position with the heel of the foot resting on the other foot (as shown in Figure 1.8). An alternative method is to flex the knee at an angle of 90 degrees with the subject in a seated position, or the subject could stand with the foot placed on a box.
1.11 PRACTICAL 3: SIMPLE INDICES OF BODY FAT DISTRIBUTION

1.11.1 Purpose

- to evaluate body mass index;
- to evaluate the fat-free mass index;
- to evaluate waist to hip ratio as a measure of fat patterning.

1.11.2 Method: body mass index (BMI)

- BMI = body mass (kg) / stature² (m);
- describes weight for height;
- often used in epidemiological studies as a measure of obesity;
- a high BMI means proportionately high weight for height.

(a) Stature

- As height is variable throughout the day the measurement should be performed at the same time for each test session. (Height may still vary due to activities causing compression of the intervertebral discs, i.e. running.)
- All stature measurements should be taken with the subject barefoot.
- The Frankfort Plane refers to the position of the head when the line joining the orbitale (lower margin of eye socket) to the tragion (notch above tragus of the ear) is horizontal.
- There are several techniques for measuring height which yield slightly different values.

The following technique is recommended:

(b) Stature against a wall

- The subject stands erect, feet together against a wall on a flat surface at a right angle to the wall mounted stadiometer.
- The stadiometer consists of a vertical board with an attached metric rule and a horizontal headboard that slides to contact the vertex.

Proximal calf: *vertical* skinfold raised on the posterior aspect of the calf in the mid-saggital plane 5 cm inferior to the fossa poplitea (Figure 1.17).

Medial calf: *vertical* skinfold raised on the medial aspect of the calf at the level of the maximal circumference. The subject may be sitting or have the foot placed on a box (Figure 1.9d and 1.17).
The heels, buttocks, upper back and (if possible) cranium should touch the wall. The subject’s head should be in the Frankfort Plane; arms relaxed at sides. The subject is instructed to inhale and stretch up. The measurer slides the headboard of the stadiometer down to the vertex and records the measurement to the nearest 0.1 cm.

(c) Body mass
- Use a calibrated beam-type balance.
- The subject should be weighed without shoes and in minimal clothing.
- For best results, repeated measurements should be taken at the same time of day, in the same state of hydration and nourishment after voiding (preferably first thing in the morning – 12 hours after ingesting food).
- The measurement should be recorded to the nearest 0.1 kg.

(d) Interpretation
Values should be interpreted according to previous discussion (Section 1.6.1).

1.11.3 Method: fat free mass index (FFMI)
The FFMI has been used to assess whether an athlete’s musculature is within the naturally attainable range or is beyond that which could reasonably be expected without pharmacological assistance.

The correctional factor \[6.1 \times (1.8 – \text{height (m)})\] is based on data from the study of Kouri et al. (1995) and is used only in calculations for males.

Insert the height, mass and per cent fat values into the following equation:

\[
\text{FFMI} = \frac{\text{Mass (kg)} \times \left(\frac{100 - \%\text{fat}}{100}\right) + 6.1 \times (1.8 - \text{Height (m)})}{\text{Height}^2}
\]

Interpretation: Refer to Table 1.2 for percentile values.

MEN
18 = slight build low musculature; 20 = young man of average muscularity; 22 = distinctly muscular; 25 = upper limit that can be attained without use of anabolic steroids.

WOMEN
13 = low musculature; 15 = young woman of average muscularity; 17 = muscular woman; 22 = upper limit than can be used without use of anabolic steroids.

1.11.3 Method: waist-to-hip ratio (WHR)
- WHR = waist girth / hip girth.
- WHR may be used in conjunction with trunk skinfolds to determine whether excess fat is being carried in the trunk region.
- A high WHR combined with high trunk skinfolds has been shown to be associated
with increased morbidity; glucose intolerance, hyperinsulinaemia, blood lipid disorders and mortality.

- A high WHR with low skinfolds may be associated with high trunk muscle development.

(a) **Tape technique (cross-handed technique)**
- The metal case is held in the right hand and the stub end is controlled by the left hand.
- Girths are measured with the tape at right angles to the long axis of the bone.
- The tape is pulled out of its case and around the body segment by the left hand; the two hands are crossed intersecting the tape at the zero mark.
- The aim is to obtain the circumference of the part with the tape in contact with, but not depressing, the fleshy contour.

(b) **Waist girth**
- The subject stands erect with abdomen relaxed, arms at sides and feet together.
- The measurer stands facing subject and places a steel tape measure around the subject’s natural waist (the obvious narrowing between the rib and the iliac crest).
- If there is no obvious waist, find the smallest horizontal circumference in this region.
- Measurement is taken at the end of a normal expiration to the nearest 0.1 cm.

(c) **Hip girth**
- The subject stands erect with buttocks relaxed, feet together and preferably wearing underwear or a swimsuit.
- The measurer stands to one side of the subject and places steel tape measure around the hips at the horizontal level of greatest gluteal protuberance (usually at the level of the symphysis pubis).
- Check that the tape is not compressing the skin and record to the nearest 0.1 cm.

(d) **Interpretation**
- Values of = 0.90 (males) and = 0.80 (females) are considered to place an individual in health risk zones according to morbidity and mortality data for males and females aged 20–70 years. These values should be considered within the context of the discussion presented previously.

1.12 PRACTICAL 4: BIOELECTRICAL IMPEDANCE ANALYSIS (BIA)

- BIA is based on the electrical conductance characteristics of hydrous (fat free) and anhydrous (fat component) tissues.
- The impedance to the flow of an electrical current is a function of resistance and reactance and is related to length and cross-sectional area of the conductor (the hydrous or fat free tissue).
- Electrical resistance (Ω) is most commonly used to represent impedance.
1.12.1 Test conditions

Prior to testing the subject should:

- not have had anything to eat or drink in the previous 4 hours;
- not have exercised within the previous 12 hours;
- not have consumed alcohol within the previous 48 hours;
- not have used diuretics within the previous 7 days;
- have urinated within the previous 30 minutes.

1.12.2 Anthropometric procedures

- as defined by the manufacturer (if using the pre-programmed function of the unit) or according to the equation of choice;
- subject should lie supine on a table with the legs slightly apart and the right hand and foot bare;
- four electrodes are prepared with electro-conducting gel and attached at the following sites (or as per manufacturer’s instructions):
  - just proximal to the dorsal surface of the 3rd metacarpal-phalangeal joint on the right hand
  - on the dorsal surface of the right wrist adjacent to the head of the ulna
  - on the dorsal surface of the right foot just proximal to the 2nd metatarsal-phalangeal joint
  - on the anterior surface of the right ankle between the medial and lateral malleoli
- the subject should lie quietly while the analyzer is turned on and off;
- the subject should lie quietly for 5 minutes before repeating the procedure.

1.12.3 Calculations

- as per manufacturer instructions, or

For prediction of fat-free mass in adults:

i) Kyle et al. (2001) (derived from 343 healthy adults aged 18–94 years using DXA as the criterion)

\[
\text{FFM (kg) = (0.518 \times Ht^2/R) + (0.231 \times \text{body mass}) + (0.130 \times Xc) + (4.229 \times \text{gender}) - 4.104}
\]

\[R^2 = 0.97; \text{SEE} = 1.8 \text{ kg}\]

ii) Deurenburg et al. (1991) (derived from 661 healthy adults using a multicomponent model and hydrodensitometry as the criterion)

\[
\text{FFM (kg) = (0.34 \times Ht^2/R) + (0.1534 \times Ht) + (0.273 \times \text{body mass}) - (0.127 \times \text{age}) + (4.56 \times \text{gender}) - 12.44}
\]

\[R^2 = 0.93 \text{ SEE} = 2.6 \text{ kg}\]
1.13 PRACTICAL 5: ESTIMATION OF MUSCLE MASS AND REGIONAL MUSCULARITY USING IN VITRO- AND IN VIVO- DERIVED EQUATIONS

1.13.1 Purpose

- to develop the technique required to estimate total and regional muscularity

1.13.2 Methods

a) In vitro-derived equations

Matiegka (1921) – males and females

\[
M (kg) = \left( \frac{(CDU + CDF + CDT + CDC)}{8} \right) \times ht (cm) \times 6.5 \times 0.001
\]

\[
M \% = \left( \frac{M \text{ kg}}{\text{body mass}} \right) \times 100
\]

where:

\[
CDU = \frac{\text{max upper arm girth}}{\pi} - \text{triceps SF (cm)}
\]

For prediction of fat-free mass in children:

i) Houtkooper et al. (1989) (derived from 94 North American children aged 10–14 years using a multicomponent model using hydrodensitometry and TBW as the criterion)

\[
FFM (kg) = 2.69 + (0.58 \times \frac{Ht^2}{R}) + (0.24 \times \text{body mass})
\]

\[
R^2 = 0.96 \text{ SEE} = 2.00 \text{ kg}
\]

ii) Eston et al. (1993) (derived from 94 Hong Kong Chinese children aged 11–17 years using a children’s skinfold equation as the criterion)

\[
FFM (kg) = 3.25 + (0.52 \times \frac{Ht^2}{R}) + (0.28 \times \text{body mass})
\]

\[
R^2 = 0.93 \text{ SEE} = 2.20 \text{ kg}
\]

For prediction of skeletal muscle (SM) mass in adults:

\[
\text{SM mass (kg)} = (Ht^2/R \times 0.401) + (\text{gender} \times 3.825) + (\text{age} \times 0.071) + 5.102
\]

(Janssen et al. 2000)

where \(ht = \text{height (cm)}; R = \text{resistance (}\Omega\); \(M = \text{mass (kg)}; \text{gender for males} = 1, \text{females} = 0; \text{age in years}\)
\[ \text{CDF} = \frac{(\text{max forearm girth})}{\pi} - \frac{\text{forearm SF 1(cm)} + \text{forearm SF 2(cm)}}{2} \]

\[ \text{CDT} = \frac{(\text{mid thigh girth})}{\pi} - \text{mid thigh skinfold (cm)} \]

\[ \text{CDT} = \frac{(\text{max calf girth})}{\pi} - \text{mid calf skinfold (cm)} \]

- \( \text{ht} \) is stature in cm;
- variables for computing corrected diameters are defined on the following pages;
- CD is corrected diameter of \( U = \) upper arm, \( F = \) forearm, \( T = \) thigh, \( C = \) calf;
- note that skinfolds should be expressed in cm, i.e. caliper reading/10.

**Martin et al. (1990) – males only**

\[ M (\text{kg}) = [\text{ht} \times (0.0553 \text{CTG}^2 + 0.0987 \text{FG}^2 + 0.0331 \text{CCG}^2) - 2445] \times 0.001 \]

\[ M \% = \left( \frac{M \text{ kg}}{\text{body mass}} \right) \times 100 \]

where:

\[ R^2 = 0.97, \ \text{SEE} = 1.53 \text{ kg} \]

\( \text{ht} \) is stature in cm

\( \text{CTG} \) is corrected thigh girth = thigh girth \(-\pi\) (front thigh SF/10)

\( \text{FG} \) is maximum forearm girth

\( \text{CCG} \) is corrected calf girth = calf girth \(-\pi\) (medial calf SF/10)

**b) In vivo-derived equations**

**Lee et al. (2000) males and females** (derived from 244 men and women aged 20–81 years using MRI as the criterion)

**i) Skinfold-circumference model**

\[ \text{SM (kg)} = \text{Ht (cm)} \times (0.00744 \times \text{CAG}^2) + (0.00088 \times \text{CTG}^2) + (0.00441 \times \text{CCG}^2) + (2.4 \times \text{gender}) \times (0.048 \times \text{age}) + \text{race} + 7.8, \]

where:

\[ R^2 = 0.91, \ P < 0.0001, \ \text{and SEE} = 2.2 \text{ kg}; \]

\( \text{CAG} \) = corrected arm girth (cm) using the triceps skinfold

Corrected circumference = limb circumference \(-\pi \times \text{skinfold}\)

\( \text{CTG} \) = corrected thigh girth (cm) using the mid-thigh skinfold

\( \text{CCG} \) = corrected calf girth (cm) using medial calf skinfold

\( \text{gender} = 0 \) for female and 1 for male,

\( \text{race} = -2.0 \) for Asian, 1.1 for African American, and 0 for white and Hispanic
ii) Body weight and height model

\[
SM (kg) = (0.244 \times \text{body mass (kg)}) + (7.80 \times \text{Ht (cm)}) - (0.098 \times \text{age}) + (6.6 \times \text{gender}) + \text{race} - 3.3
\]

where

\[R^2 = 0.86, \ P < 0.0001, \ \text{and SEE} = 2.8 \text{ kg};\]

\[\text{gender} = 0 \text{ for female and 1 for male,}\]

\[\text{race} = -1.2 \text{ for Asian, 1.4 for African American, and 0 for white and Hispanic}\]

1.13.3 Determination of variables related to estimation of muscle mass

Stature (ht) as before (Practical 3)

Maximum upper arm girth (cm)
- the girth measurement of the upper arm at the insertion of the deltoid muscle;
- subject stands erect with the arm abducted to the horizontal, measurer stands behind the arm of the subjects, marks the insertion of the deltoid muscle and measures the girth perpendicular to the long axis of the arm.

Maximum forearm girth (cm)
- the maximum circumference at the proximal part of the forearm (usually within 5 cm of the elbow);
- subject stands erect with the arm extended in the horizontal plane with the hand supinated; measurer stands behind the subject’s arm and moves the tape up and down the forearm (perpendicular to the long axis) until the maximum circumference of the forearm is located.

Mid-thigh girth (cm)
- the girth taken at the midpoint between the trochanterion and the tibiale laterale;
- subject stands erect, feet 10 cm apart and weight evenly distributed, measurer crouches to the right side, palpates and marks the trochanterion and the tibiale laterale. The midpoint is found using a tape or anthropometer;
- the girth is taken at this level, perpendicular to the long axis of the thigh.

Maximum calf girth (cm)
- subject stands erect, feet 10 cm apart and weight evenly distributed; measurer crouches to the right side and moves the tape up and down the calf perpendicular to the long axis until the greatest circumference is located.

Triceps skinfold (cm)
- as before (Practical 2)

Mid-thigh skinfold (cm)
- as before (Practical 2)
1.14 PRACTICAL 6: ESTIMATION OF SKELETAL MASS

- an indication of skeletal robustness that correlates highly with bone breadths at the elbow, wrist, knee and ankle

1.14.1 Purpose

- to develop the technique required to estimate skeletal mass by anthropometry

1.14.2 Methods

*Matiegka* (1921) – males and females.

\[ S \ (kg) = \left( \frac{HB + WB + FB + AB}{4} \right)^2 \times ht \times 1.2 \ kg \times 0.001 \]

\[ S \ % = \left( \frac{S \ kg}{body \ mass} \right) \times 100 \]

where: HB is biepicondylar humerus, WB is bistyloideus, FB is biepicondylar femur, AB is bimalleolar, ht is height in cm.

*Drinkwater et al.* (1986) – males and females

\[ S \ (kg) = \left( \frac{HB + WB + FB + AB}{4} \right)^2 \times ht \times 0.92 \ kg \times 0.001 \]

\[ S \ % = \left( \frac{kg \ S}{body \ mass} \right) \times 100 \]

where variables are as defined previously.

---

Mid-calf skinfold (cm)
- as before (Practical 2)

Medial calf skinfold (cm)
- A vertical skinfold is taken on the medial aspect of the calf at the level of maximum calf girth; the subject stands with the right foot on a platform, flexing the knee and hip to 90°.

Forearm 1 (lateralis) (cm)
- A vertical skinfold is taken at the level of maximum forearm girth on the lateral aspect of the forearm with the hand supinated.

Forearm 2 (volaris) (cm)
- A vertical skinfold is taken at the level of maximum forearm girth taken on the anterior aspect of the forearm with the hand supinated.
1.14.3 Determination of variables related to estimation of skeletal mass

- Landmarks for bone breadth measurements should be palpated with the fingers, and then the anthropometer is applied firmly to the bone, compressing soft tissue when necessary.

Stature (ht) as before (Practical 3)

Biepicondylar humerus breadth
- the distance between medial and lateral epicondyles of the humerus when the shoulder and elbow are flexed;
- the measurer palpates the epicondyles and applies the blades of an anthropometer or small spreading calliper at a slight upward angle while firmly pressing the blades to the bone.

Bistyloideus breadth
- the distance between the most prominent aspects of the styloid processes of the ulna and radius;
- the subject flexes the elbow and the hand is pronated so that the wrist is horizontal;
- the styloid processes are palpated and the anthropometer is applied firmly to the bone.

Biepicondylar femur breadth
- This is the distance between the most medial and lateral aspects of the femoral condyles (epicondyles).
- The subject stands with the weight on the left leg and the right knee flexed (the foot may rest on a raised surface or the subject may sit with the leg hanging).
- The measurer crouches in front of the subject, palpates the femoral condyles and applies the anthropometer at a slight downward angle while firmly pressing to the bone.

Bimalleolar breadth
- This is the maximum distance between the most medial and lateral extensions of the malleoli.
- The subject stands erect with the weight evenly distributed over both feet.
- The measurer palpates the malleoli and applies the anthropometer firmly to the bone.
- A horizontal distance is measured, but the plane between the malleoli is oblique.
1.15 PRACTICAL 7: EXAMPLE OF A MULTICOMPONENT (4C) MODEL OF BODY COMPOSITION ASSESSMENT USING THE MEAN DATA FROM WITHERS ET AL. (1998)

Withers et al. (1998) compared the accuracy of predicting per cent body fat from the two-component model of hydrodensitometry against a four-component model of body composition. The following practical uses the mean data from the group of 12 trained men in that study to exemplify how the prediction of per cent fat from hydrodensitometry tends to underestimate the true value when this is calculated from a model that can account for the various components of the fat-free body.

The mean values for the trained men in their study are:

Age = 22.3 ± 5.1 years, height = 175.2 ± 5.7, mass = 67.87 ± 5.30 kg, body density(D) = 1.0767 ± 0.0083 kg.l⁻¹, total body water (TBW) = 43.23 ± 3.59 L, total body bone mineral mass (BMM) = 3.40 ± 0.33 kg

The 4C Model used in the study was:

\[
\%\text{fat} = \left(\frac{251.3}{D}\right) - 73.9 \left(\frac{TBW}{\text{Mass}}\right) + 94.7 \left(\frac{BMM}{\text{mass}}\right) - 179
\]

Insertion of the average values into the above formula provides a close approximation of the reported mean \%fat value for the trained group:

\[
\%\text{fat} = \left(\frac{251.3}{1.0767}\right) - 73.9 \left(\frac{43.23}{67.87}\right) + 94.7 \left(\frac{3.40}{67.87}\right) - 179
\]

The above 4C model prediction of \%fat = 12.1%. The reported mean value was 12.1 ± 2.8 \%fat.

The prediction of \%fat using the Siri equation with the whole-body density value (1.0767) = 9.7% (\(P<0.01\)). Using these techniques, the density of the fat-free body was calculated to be greater (1.06360.005 (range 1.0974–1.1137) than the assumed value of 1.100 in the equation of Siri. When this value is used it underestimates \%fat in the trained men.

1.16 ANTHROPOMETRIC LANDMARKS AND MEASUREMENT DEFINITIONS

These definitions are aligned with those of the International Society for the Advancement of Kinanthropometry, and are used here by permission of Turnpike Electronic Publications from whose CD-ROM, Anthropometry Illustrated, they are abridged.

1.16.1 Landmark definitions

Vertex (V): The vertex is the most superior point in the mid-sagittal plane on the skull when the head is held in the Frankfort Plane.

Gnathion (GN): The gnathion is the most inferior border of the mandible in the mid-sagittal plane.

Suprasternale (SST): The suprasternal notch is located at the superior border of the sternal notch (or incisura jugularis) in the mid-sagittal plane.

Mesosternale (MST): The mesosternale is the point located on the corpus sterni at the intersection of the mid-sagittal plane and the transverse plane at the mid-level of the 4th chondrosternal articulation.
Epigastrale (EG): The epigastrale is the point on the anterior surface of the trunk at the intersection of the mid-sagittal plane and the transverse plane through the most inferior point of the 10th rib.

Thelion (TH): The thelion is the breast nipple.

Omphalion (OM): The omphalion is the mid-point of the navel or umbilicus.

Symphysion (SY): The symphysis forms the superior border of the symphysis pubis at the mid-sagittal plane.

Acromiale (A): The acromiale is the point located at the superior and external border of the acromion process when the subject is standing erect with relaxed arms.

Radiale (R): The radiale is the point at the proximal and lateral border of the head of the radius.

Stylion (STY): The stylion is the most distal point on the styloid process of the radius. The stylion radiale is located in the so-called anatomical snuffbox (the triangular area formed when the thumb is extended at the 1st carpal-metacarpal joint, the area being defined by the raised tendons of the abductor pollicus longus, the external pollicus brevis and the extensor pollicus longus). It is the most distal point of the styloid process of the radius.

Dactylion (DA): The dactylion is the tip of the middle finger (3rd digit). It is the most distal point on the hand. The tips of the other digits are designated as the 1st, 2nd, 4th and 5th dactylions (the thumb being the 1st digit).

Metacarpale Radiale (MR): The metacarpal radiale is the most lateral point on the distal head of the 2nd metacarpal of the hand (located either on the outstretched hand or when gripping a dowel or pencil).

Metacarpale Ulnare (MU): The metacarpal ulnare is the most medial point on the distal head of the 5th metacarpal of the hand (located either on the outstretched hand or when gripping a dowel or pencil).

Iliocristale (IC): The iliocristale (or supracristale) is the most lateral point on the iliac crest. This is the site for locating the iliac crest skinfold that is immediately superior.

Iliospinale (IS): The iliospinale is the inferior aspect of the anterior superior iliac spine. The iliospinale is the undermost tip of the anterior superior iliac spine, not the most anterior curved aspect.

Spinale (SPI): The spinale is a less exact term for the iliospinale.

Trochanterion (TRO): The trochanterion is the most superior point on the greater trochanter of the femur, not the most lateral point.

Tibiale Mediale (TM): The tibiale mediale (or tibiale internum) is the most superior point on the margo glenoidalis of the medial border of the head of the tibia.

Tibiale Laterale (TL): The tibiale laterale (or tibiale externum) corresponds to the previously defined tibiale mediale, but is located on the lateral border of the head of the tibia (not to be confused with the more inferior capitum fibulare).

Sphyrion Laterale (SPH): The sphyrion laterale is on the malleolare mediale (or internum). It is the most distal tip of the malleolare mediale (or tibiale). It can be palpated most easily from beneath and dorsally (it is the distal tip, not the outermost point of the malleolare).

Sphyrion Fibulare (SPH F): The sphyrion fibulare is the most distal tip of the malleolare laterale (or externum) of the fibula. It is more distal than the sphyrion tibiale.

Pternion (PTE): The pternion is the most posterior point on the heel of the foot when the subject is standing.

Acropodion (AP): The acropodion is the most anterior, distal point on the longest phalange of the foot when the subject is standing. The subject’s toenail may be clipped to locate this landmark when measuring.

Metatarsale Tibiale (MT T): The metatarsal tibiale is the most medial point on the head of the 1st metatarsal of the foot when the subject is standing.

Metatarsale Fibulare (MT F): The metatarsal fibulare is the most lateral point on the
head of the 5th metatarsal of the foot when the subject is standing.

Cervicale (C): The cervicale is the most posterior point on the spinous process of the 7th cervical vertebra.

Gluteale (GA): The gluteale is the distal point in the mid-sagittal plane at the arch of the sacro-coccygeal fusion.

**Measurement definitions**

**Stretch Stature:** The maximum distance from the floor to the vertex of the head, when the head is held in the Frankfort Plane and a gentle traction force is applied.

**Sitting Height:** Stretch Sitting Height is the distance from the vertex of the head to the base of the sitting surface when the seated subject is instructed to sit tall and when gentle traction is applied to the mandible.

**Body Weight:** The force of gravity acting on the mass of the body.

**Armspan:** The distance from the left to the right dactylion of the hands when the palms are facing forward on the wall and the outstretched arms are abducted to the horizontal with the shoulders.

**Lengths**

**Acromiale-Radiale Length (arm):** The distance from the acromiale to the radiale.

**Radiale-Stylion Length (forearm):** The distance from the radiale to the styliion.

**Mid-stylion-Dactylion Length (hand):** The shortest distance from the mid-stylion line to the dactylion III.

**Iliospinale Height (obtained height plus box height):** Projected height from the box or tabletop to the iliospinale landmark.

**Trochanterion Height (obtained height plus box height):** Projected height from the box or tabletop to the trochanterion landmark.

**Trochanterion-Tibiale Laterale Length (thigh):** The distance from the trochanterion to the tibiale laterale.

**Tibiale Laterale Height (leg):** Distance from the box to the tibiale laterale landmark.

**Tibiale Mediale-Sphytrion Tibiale (tibia length):** Direct length from tibiale mediale to sphytrion tibiale.

**Foot length:** The distance between the acropodion and pternion (i.e. the most distal toe and posterior surface of the heel).

**Breadths**

**Biacromial Breadth:** The distance between the most lateral points on the acromion processes when the subject stands erect with the arms hanging loosely at the sides.

**Biiliocristal Breadth:** The distance between the most lateral points on the superior border of the iliac crest.

**Transverse Chest Breadth:** The distance between the most lateral aspects of the thorax at the mesosternale level.

**Anterior-Posterior Chest Depth:** The depth of the chest at the mesosternale level obtained with spreading calliper or anthropometer with recurved branches used as a sliding calliper.

**Biepicondylar Humerus Breadth:** Distance between medial and lateral epicondyles of the humerus when the arm is raised forward to the horizontal and the forearm is flexed to a right angle at the elbow.

**Wrist Breadth:** The bistyloid breadth when the right forearm is resting on a table or the subject’s thigh and the hand flexed at the wrist to an angle of about 90º.

**Hand Breadth:** The distance between the metacarpale laterale and metacarpale mediale when the subject firmly grasps a pencil.

**Biepicondylar Femur Breadth:** The distance between medial and lateral epicondyles of the femur when the subject is seated and the leg is flexed at the knee to form a right angle with the thigh.

**Ankle Breadth:** The distance between the maximum protrusions of the medial tibial malleolus and the lateral fibular malleolus.

**Foot Breadth:** The distance between the metatarsale fibulare and the metatarsale tibiale.

**Girths**

**Head Girth:** The maximum perimeter of the
head when the tape is located immediately superior to the glabellar point (mid-point between brow ridges).

Neck Girth: The perimeter of the neck taken immediately superior to the larynx (Adam's apple).

Arm Girth (relaxed): The perimeter distance of the right arm parallel to the long axis of the humerus when the subject is standing erect and the relaxed arm is hanging by the sides.

Arm Girth (flexed and tensed): The maximum circumference of the flexed and tensed right arm raised to the horizontal position.

Forearm Girth: The maximal girth of the right forearm when the hand is held palm up and relaxed.

Wrist Girth: The perimeter of the right wrist taken distal to the styloid processes.

Chest Girth: The end-tidal perimeter of the chest at mesosternale level.

Waist Girth: The perimeter at the level of the noticeable waist narrowing located approximately half way between the costal border and iliac crest.

Omphalion Girth (abdominal): The perimeter distance at the level of the omphalion or mid-point of the umbilicus or navel.

Gluteal Girth (hip): The perimeter at the level of the greatest posterior protuberance and at approximately the symphysis pubis level anteriorly.

Thigh Girth (upper): The perimeter of the right thigh which is measured when the subject stands erect, weight equally distributed on both feet, and assisting by holding clothing out of the way.

Mid-Thigh Girth: The perimeter distance of the right thigh perpendicular to the long axis of the femur at the marked mid-trochanterion-tibiale level.

Calf Girth: The maximum perimeter of the calf when the subject stands with weight equally distributed on both feet.

Ankle Girth: The perimeter of the narrowest part of the lower leg superior to the sphyron tibiale.

**Skinfold Thicknesses**
See descriptions in Practical 2.

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**FURTHER READING**

**Books/CD/DVD**


**Websites**

http://www.nutrition.uvm.edu/bodycomp/
Department of Nutrition and Food Sciences, University of Vermont, USA. This website provides very useful interactive tutorials on hydrodensitometry, dual energy x-ray absorptiometry and bioelectrical impedance analysis techniques described in this chapter.

http://www.isakonline.com/
International Society for the Advancement of Kinanthropometry. This site contains a great deal of useful information and lots of useful links.

http://www.rosscraft.ca/
Rosscraft Incorporated (publishers of Anthropometry Illustrated) is a Canadian-based anthropometric instrument design, manufacturing and marketing company. This website contains a range of useful resources.
The health tools page of the Canadian-based Preventdisease.com is an excellent website, which includes dedicated programmes to calculate body fat from skinfolds, BMI, waist to hip ratios, etc.

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7 CHAPTER 7 ASSESSMENT OF PERFORMANCE IN TEAM GAMES


8 CHAPTER 8 SPECIAL CONSIDERATIONS FOR ASSESSING PERFORMANCE IN YOUNG PEOPLE


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11 CHAPTER 11 SCALING: ADJUSTING FOR DIFFERENCES IN BODY SIZE


