

Frederic Shapiro

Pediatric Orthopedic Deformities

Volume 1

Pathobiology and Treatment of
Dysplasias, Physeal Fractures,
Length Discrepancies, and
Epiphyseal and Joint Disorders

 Springer

Contents

1	Developmental Bone Biology	1
1.1	Overview of Bone Development.	1
1.1.1	Epiphysis.	2
1.1.2	Metaphysis.	2
1.1.3	Diaphysis.	3
1.1.4	Bone Tissue Formation	3
1.1.5	Perichondrial Ossification Groove of Ranvier	4
1.1.6	Cellular Components.	4
1.1.7	Gap Junctions Linking Bone Cells	5
1.2	Embryology of the Limbs	6
1.2.1	Timing and Staging of Human Limb Development	6
1.2.2	Outline of Embryonic Development of Long Bones	7
1.3	Early Scientific Understandings of Bone Growth	8
1.3.1	Theories of Embryogenesis. Preformationism and Epigenesis	9
1.3.2	Hales, Belchier.	9
1.3.3	Nesbitt	9
1.3.4	Duhamel	10
1.3.5	Hunter.	10
1.3.6	Howship	11
1.3.7	Flourens	11
1.4	Bone Development at the Light Microscopic Level Following Delineation of the Cell Theory and Advances in Microscopy and Histochemistry	12
1.4.1	Kolliker (1850).	12
1.4.2	Broca	12
1.4.3	Heinrich Mueller	14
1.4.4	Virchow (1860)	14
1.4.5	Gegenbaur (1864).	15
1.4.6	Ollier (1867)	15
1.4.7	Retterer (1900).	15
1.5	More Detailed Studies of Bone Formation	16
1.5.1	Overview of Bone Growth.	16
1.5.2	Histogenesis of Bone.	17
1.5.3	Chondrocyte Shape and Orientation in Epiphyseal and Physeal Cartilage; Cell, Matrix, Mineralization, and Vascularization in the Endochondral Sequence	17
1.6	Fate of the Hypertrophic Chondrocyte as Interpreted from Light Microscopic Studies	21
1.6.1	Chondrocyte Survival, Dedifferentiation, and Re-emergence to a Bone Forming Cell Line	21
1.6.2	Direct Transformation of Cartilage Cells to Bone Cells	21

1.6.3	Death of Cartilage Cells	22
1.6.4	Variable Responses	22
1.7	Structural Development of the Epiphyses, Metaphyses, and Diaphyses . . .	23
1.7.1	Epiphyses	23
1.7.2	Perichondrial Ossification Groove of Ranvier	43
1.7.3	Periosteum and its Relationship to the Epiphyses, Metaphyses, and Diaphyses	44
1.7.4	Cortical (Diaphyseal) Bone Formation	45
1.7.5	The Lacunar–Canalicular System	51
1.8	Development of Joints—General Description	52
1.8.1	Detailed Description of Joint Development.	53
1.9	The Blood Supply of Bone	54
1.9.1	Blood Supply of the Cortex	54
1.9.2	Epiphyseal Blood Supply.	55
1.10	Development of the Articular Cartilage	61
1.10.1	Stages in Articular Cartilage Development	61
1.10.2	Layers Within Articular Cartilage	61
1.10.3	Nutrition of Articular Cartilage	62
1.10.4	Bone and Articular Cartilage Formation in Metacarpals, Metatarsals, and Phalanges Where Only One End Has a Physis.	62
1.11	Summary of Coordinated Contributions of Cell and Tissue Regions to Bone Growth and Shaping.	63
1.12	Models and Patterns of Limb and Bone Development	63
1.12.1	Epigenesis, Epigenetics, and Development	63
1.12.2	Signaling Regions Which Affect the Patterns of Bone Development	66
1.12.3	Models of Tissue Patterning	67
1.12.4	Positional Information Mechanisms	67
1.12.5	Pre-pattern Mechanisms	68
1.12.6	Determination Wave Mechanisms	70
1.12.7	Rearrangement Mechanisms	71
1.12.8	Cell Lineage Mechanisms	71
1.12.9	Overview of Developmental Biology.	71
1.13	Gene and Molecular Controls of Limb Development.	72
1.13.1	Limb Bud Outgrowth	72
1.13.2	Apical Ectodermal Ridge	72
1.13.3	Progress Zone	72
1.13.4	Polarizing Region	88
1.13.5	Dorsal Non-ridge Ectoderm	88
1.13.6	Coordinating Multiaxial Development	88
1.14	Overview of Gene Controls of Limb Development	89
1.14.1	Hox Genes.	89
1.14.2	Retinoids.	93
1.14.3	Sox9.	94
1.14.4	Paired Box (PAX) Gene Pathway. Pax1, Pax9	94
1.14.5	Runx2.	95
1.14.6	Other Transcription Factors Involved in Cartilage and Bone Synthesis Include	95
1.14.7	Hedgehog Proteins. Sonic Hedgehog and Indian Hedgehog	95
1.14.8	Fibroblast Growth Factors (FGFs).	96
1.14.9	Wnt Family Proteins	97

1.14.10	Transforming Growth Factors—Beta (TGF β) Superfamily	97
1.14.11	Bone Morphogenetic Proteins (BMPs).	98
1.14.12	Parathyroid Hormone (PTH), Parathyroid Hormone Receptor Protein (PTHrP), and PTH/PTHrP Receptor	98
1.14.13	Insulin-Like Growth Factor (IGF)	98
1.14.14	Vascular Endothelial Growth Factor (VEGF)	99
1.14.15	Growth/Differentiation Factor-5 (GDF-5)	99
1.14.16	Signal Transduction Pathways	99
1.15	Chemistry of the Extracellular Matrix of Epiphyseal Tissues	100
1.15.1	Collagen	100
1.15.2	Collagen Groups.	107
1.15.3	Detailed Review of Specific Cartilage Collagens.	108
1.15.4	Proteoglycans.	109
1.15.5	Glycoproteins, Non-collagenous Proteins	110
1.15.6	Cell Surface Proteoglycans.	112
1.15.7	Temporal and Spatial Changes in Specific Molecular Expression Within the Endochondral Sequence.	112
1.15.8	Matrix Metalloproteinases (MMPs) and Tissue Inhibitors of Matrix Metalloproteinases (TIMPs)	113
1.15.9	Matricryptins of Collagen	114
1.16	Mineralization	114
1.16.1	Vitamin D	114
1.16.2	Matrix Vesicles and the Collagen Matrix and Their Relationship to the Initiation of Mineralization	114
1.16.3	Mineralization of Cartilage in the Endochondral Sequence	115
1.16.4	Mineralization of Bone	117
1.16.5	Continuing Assessments of Biomineralization.	118
1.17	Epiphyseal Growth	119
1.17.1	Physeal Chondrocyte Metabolism	119
1.17.2	Studies of Cell Proliferation in Physeal Cartilage Using Tritiated Thymidine Autoradiography.	119
1.17.3	Kinetics of Epiphyseal Growth	120
1.17.4	Amount of Growth at Each Epiphyseal Plate	120
1.17.5	Growth Slowdown and Growth Arrest Lines (Harris Lines)	122
1.18	Responses of Developing Bones and Epiphyses to Mechanical Stresses.	122
1.18.1	Normal Responses to Mechanical Factors	122
1.18.2	Biophysical Effects Underlying Bone Development, Maintenance, and Repair. Mechanotransduction	124
1.18.3	Mechanical Stresses and Their Differences and Effects on Skeletal Development	128
1.18.4	Experimental Studies on the Mechanical Behavior of the Growth Plate.	130
1.18.5	Normal Relationship of Epiphyseal Plates to Compressive and Tensile Stresses	131
1.18.6	Responses of Physes to Abnormal Pressures. Pathogenesis of Creation and Correction of Deformity in Developing Bones.	133
1.18.7	The Effects of Pressure on Epiphyseal Growth	135
1.18.8	Mechanosensitive Genes During Skeletal Development	138

1.19	Radiographic Characteristics in Development of Major Long Bone Epiphyses	139
1.19.1	General Information	139
1.19.2	Relationship of Proximal and Distal Tibial and Fibular Physes	145
1.19.3	Time and Pattern of Physeal Closure	145
1.19.4	Distal Tibial Growth Plate Closure	145
1.19.5	Proximal Femoral, Proximal Tibial, Metatarsal and Phalangeal, Growth Plate Closure	145
1.20	Why Epiphyses Form. Evolution of Epiphyses	146
	References	147
2	Overview of Deformities	159
2.1	Deformity	159
2.2	Orthopedics and Pediatric Orthopedics	159
2.3	Founders of the Discipline of Pediatric Orthopedics	159
2.3.1	Nicolas Andry (1658–1742)	159
2.3.2	Jean-Andre Venel (1740–1791)	160
2.3.3	Johann Georg Heine (1771–1838)	160
2.3.4	Jacques Delpech (1777–1832)	161
2.3.5	William John Little (1810–1894)	161
2.3.6	William Adams (1820–1900)	163
2.3.7	Léopold Ollier (1830–1900)	163
2.4	General Principles Regarding Pediatric Orthopedic Deformity	163
2.5	Terminology Describing Body Planes and Regions	166
2.6	Terminology Describing Extremity Deformities	167
2.6.1	Angular Deformity	167
2.6.2	Rotational Deformity	167
2.6.3	Translational Deformity	167
2.6.4	Length Deformity	167
2.6.5	Gigantism	168
2.6.6	Multiplanar Deformity	168
2.6.7	Primary Site of Limb Deformity	168
2.6.8	Joint Deformities	168
2.6.9	Lower Extremity Mechanical Axis Deformities	170
2.7	Deformities of the Spine	171
2.8	Spontaneous Correction of Deformities by Growth	172
2.9	Correction of Deformities by Non-operative Treatment	172
2.9.1	Stretching Exercises to Correct Deformities	172
2.9.2	Casting/Splinting/Bracing	172
2.9.3	Correction by Inducing Muscle Relaxation	173
2.9.4	Traction	173
2.9.5	Immobilization	173
2.9.6	Closed Reduction with Immobilization	173
2.10	Brief Overview of Correction of Deformities by Operative Treatment	173
2.10.1	Discoveries Greatly Enhancing Development of Surgical Procedures for Correction of Deformities	173
2.10.2	Subcutaneous Surgery	173
2.10.3	Antiseptic Surgery	174
2.11	Surgery on Tendons	174
2.11.1	Tenotomy	174
2.11.2	Tendon Lengthening	174

2.11.3	Tendon Shortening	174
2.11.4	Tendon Transfer	174
2.11.5	Lysis of Tendon Adhesions	175
2.12	Surgery on Joints	175
2.12.1	Capsulotomy. Arthrotomy	175
2.12.2	Open Reduction. Capsulorrhaphy	175
2.12.3	Capsular Release	175
2.12.4	Synovectomy	175
2.12.5	Intra-articular Repairs	175
2.12.6	Joint Arthrodesis.	175
2.12.7	Joint Debridement.	175
2.12.8	Arthroscopy. Arthroscopic Surgery	175
2.12.9	Arthroplasty	175
2.13	Surgery on Ligaments	176
2.14	Surgery on Bones. Osteotomy	176
2.14.1	Definition	176
2.14.2	Historical Background	176
2.14.3	Uni-planar and Multi-planar Deformities	176
2.14.4	Stabilization Post-Osteotomy	176
2.14.5	Osteotomy to Shorten or Lengthen Bones	177
2.15	Surgery on Growth Plates	178
2.15.1	Complete Epiphyseodesis.	178
2.15.2	Partial Epiphyseodesis	178
2.15.3	Growth Plate Transphyseal Bone Bridge Removal	178
2.15.4	Transphyseal Lengthening	178
2.15.5	Growth Plate Transplantation	178
2.16	Amputation	179
2.17	Mechanisms of Bone Development and Repair. The Role of Mesenchymal Osteoblasts and Surface Osteoblasts in Bone Development and Their Relation to Fracture and Osteotomy Repair	179
2.17.1	Bone Formation	179
2.17.2	Matrix Orientation	179
2.17.3	Osteoblasts.	179
2.17.4	The Molecular Biology of Developing Bone and of Fracture Repair.	179
2.17.5	Bone Repair.	181
2.17.6	Woven Bone and Lamellar Bone	182
2.17.7	Endochondral Bone Repair.	183
2.17.8	Bone Repair Terminology in Rigid Stable Environments (Primary and Direct)	184
2.17.9	Distraction Osteogenesis	195
2.17.10	Other Mechanisms of Bone Repair via Fibro-osseous and Chondro-osseous Tissue Accumulations.	196
2.17.11	Metaphyseal Bone Repair	196
2.17.12	Bone Repair Mechanisms in Clinical Settings. The Influence of Mechanical Stability	196
2.17.13	Abnormalities in Bone Repair	197
2.17.14	Biological Augmentation of Bone Repair.	198
2.18	Mechanisms of Cartilage Repair	200
2.18.1	Repair of Articular Cartilage	200
2.18.2	Repair of Physeal Cartilage	217
2.18.3	Meniscus Repair and Regeneration	221

2.19	Tendons	222
2.19.1	Brief Overview of the Anatomy, Histology, and Molecular Biology of Tendons	222
2.19.2	Surgical Approaches to Tendons to Correct Deformity	227
2.19.3	Tendon Transfer	231
2.19.4	Tissue Engineering for Tendon Repair	233
2.20	Ligaments	233
2.20.1	Terminology	233
2.20.2	Ligament Structure	233
2.20.3	Ligament Mechanical Function	234
2.20.4	The Biology of Ligament Repair	234
2.20.5	Specific Features of Ligament Injury and Repair in the Skeletally Immature Patient	234
2.21	Development and Structure of Normal Muscle	238
2.21.1	Normal Muscle Structure Defined by Muscle Biopsy	241
2.22	Muscle Tissue Repair	242
2.22.1	Muscle Satellite Cells in Muscle Repair	242
2.23	Peripheral Nerve Structure, Injury, and Repair	243
2.23.1	Anatomy of a Peripheral Nerve	243
2.23.2	Damage to Peripheral Nerves	243
2.23.3	Patterns of Nerve Degeneration	245
2.23.4	Nerve Regeneration	246
2.23.5	Molecular Aspects of Nerve Degeneration and Regeneration	246
2.23.6	Surgery on Nerves	247
2.23.7	Nerve Pressure Release	248
	References	248
3	Skeletal Dysplasias	255
3.1	Terminology	255
3.2	Classification Approaches	255
3.3	Prevalence of Skeletal Dysplasias	266
3.4	Diagnosis of Skeletal Dysplasias	266
3.4.1	Overview	266
3.4.2	Pre-natal Assessment	267
3.4.3	Clinical Examination	270
3.4.4	Radiographic Examinations	271
3.4.5	Laboratory Studies	272
3.5	Chromosome Abnormality Sites in Skeletal Dysplasias	272
3.6	Gene and Molecular Abnormalities in Skeletal Dysplasias	277
3.6.1	Mutation Families	277
3.6.2	Molecular Function Defects	281
3.6.3	Phase of the Developmental Cycle Where Abnormality Has Its Negative Effect	284
3.7	Lethal Perinatal Skeletal Dysplasias	285
3.7.1	Diagnostic Profile	285
3.7.2	Thanatophoric Dysplasia	287
3.7.3	Homozygous Achondroplasia	287
3.7.4	Osteogenesis Imperfecta	287
3.7.5	Achondrogenesis	287
3.7.6	Hypochondrogenesis	288
3.7.7	Atelosteogenesis	288
3.7.8	Chondrodysplasia Punctata, Rhizomelic Form	288

3.7.9	Campomelic Dysplasia	290
3.7.10	Hypophosphatasia	290
3.7.11	Short-Rib Syndromes	291
3.7.12	Asphyxiating Thoracic Dystrophy (Jeune)	291
3.7.13	Metatropic Dysplasia Lethal Variants	291
3.8	Microstructural–Morphologic Abnormalities of the Epiphyses and Metaphyses in Skeletal Dysplasias	292
3.8.1	General Considerations	292
3.8.2	Histopathologic Classification of Skeletal Dysplasias	292
3.8.3	Interpretation of the Pathogenesis of Skeletal Dysplasias in Relation to the Structural Approach	298
3.9	Histopathologic Changes in Specific Chondrodysplasias	299
3.9.1	Lethal Chondrodysplasias	299
3.9.2	Histopathologic Changes in Non-lethal Chondrodysplasias	302
3.10	Orthopedic Deformities in Skeletal Dysplasias: Regional Abnormalities and Their Relation to Clinically Significant Deformity	307
3.10.1	Overview	307
3.10.2	Cervical Spine Abnormalities	308
3.10.3	Thoracolumbar Spine Abnormalities: Scoliosis, Kyphosis, and Kyphoscoliosis	310
3.10.4	Lumbar Spinal Stenosis and Lumbar Lordosis	312
3.10.5	Abnormalities of the Skull	313
3.10.6	Abnormalities of the Clavicles	314
3.10.7	Abnormalities of the Extremities	314
3.10.8	Abnormalities of the Hip Region	316
3.10.9	Knee Abnormalities	319
3.10.10	Ankle Abnormalities	322
3.10.11	Foot Abnormalities	322
3.10.12	Abnormalities of the Upper Extremities	322
3.11	Limb Lengthening	322
3.12	Review of Specific Skeletal Dysplasias: Pathobiology, Clinical and Radiographic Characteristics, Orthopedic Management	324
3.12.1	Achondroplasia	324
3.12.2	Hypochondroplasia	330
3.12.3	Multiple Epiphyseal Dysplasias	331
3.12.4	Dysplasia Epiphysealis Hemimelica	333
3.12.5	Metatropic Dysplasia	334
3.12.6	Kniest Dysplasia	334
3.12.7	Chondrodysplasia Punctata	334
3.12.8	Spondyloepimetaphyseal Dysplasia	335
3.12.9	Diastrophic Dysplasia	335
3.12.10	Spondyloepiphyseal Dysplasia	338
3.12.11	Dyggve–Melchior–Claussen Dysplasia; Smith–McCort Dysplasia	339
3.12.12	Pseudoachondroplasia	339
3.12.13	Mucopolysaccharidoses	339
3.12.14	Metaphyseal Dysplasia	343
3.12.15	Spondylometaphyseal Dysplasia	343
3.12.16	Cleidocranial Dysplasia	343
3.12.17	Hereditary Progressive Arthro-Ophthalmopathy (Stickler Syndrome)	344
3.12.18	Dyschondrosteosis	345

3.12.19	Other Mesomelic Dysplasias	346
3.12.20	Acromesomelic Dysplasia	346
3.12.21	Acromelic Syndromes (Acrodysplasias)	346
3.12.22	Larsen Syndrome	347
3.12.23	Ollier's Disease	349
3.12.24	Maffucci Syndrome.	353
3.12.25	Hereditary Multiple Exostoses: (Hereditary) Multiple Osteochondromas.	353
3.12.26	Clinical Problems in Hereditary Multiple Exostoses.	360
3.12.27	Metachondromatosis	366
3.12.28	Osteopetrosis	367
3.12.29	Pycnodysostosis	377
3.12.30	Osteogenesis Imperfecta.	378
3.13	Anesthetic Implications in the Skeletal Dysplasias	397
3.13.1	Occipital and Cervical Structural Abnormalities in Skeletal Dysplasia Patients	397
3.13.2	Airway Abnormalities	397
3.13.3	Pulmonary Abnormalities.	397
3.13.4	Neurologic Abnormalities	397
	References	398
4	Bone and Joint Deformity in Metabolic, Inflammatory, Neoplastic, Infectious, and Hematologic Disorders.	411
4.1	Rickets	411
4.1.1	Terminology	411
4.1.2	Pathogenesis of Rickets	411
4.1.3	Experimental Models of Rickets	411
4.1.4	Pathology of Human Nutritional Vitamin D Deficiency Rickets	413
4.1.5	Classification of Types of Rickets.	415
4.2	Inflammatory Disorders.	433
4.2.1	Juvenile Rheumatoid Arthritis.	433
4.2.2	Pigmented Villonodular Synovitis	441
4.3	Neoplastic Disorders of Epiphyses	441
4.3.1	Primary Involvement of Epiphyseal Regions	441
4.3.2	Secondary Involvement of Epiphyseal Regions from Primary Metaphyseal Foci of Benign and Malignant Disorders	444
4.4	Osteomyelitis and Septic Arthritis.	447
4.4.1	Primary Subacute/Chronic Epiphyseal Osteomyelitis	447
4.4.2	Epiphyseal Osteomyelitis Secondary to Transphyseal Spread from Subacute or Chronic Metaphyseal Foci	448
4.4.3	Acute Neonatal/Infantile Osteomyelitis and Its Damaging Effects on Epiphyses.	449
4.4.4	Summary of Effects of Epiphyseal and Metaphyseal Infection on Epiphyseal Growth	460
4.4.5	Transient Synovitis of the Hip in Children and Its Differentiation from Septic Arthritis	461
4.4.6	Overview of Findings in Childhood Hip Pain and Limping Re "Arthritis"	463

4.4.7	Tuberculosis	463
4.5	Hematologic Disorders	467
4.5.1	Hemophilia	467
4.5.2	Von Willebrand Disease	489
4.5.3	Hemoglobinopathies: Sickle-Cell Anemia and Thalassemia	490
	References	495
5	Epiphyseal Growth Plate Fracture-Separations	505
5.1	Introduction	505
5.2	Clinical and Experimental Investigations of Growth Plate Fracture-Separations in the Preradiographic Era	505
5.2.1	Early Clinical Descriptions	505
5.2.2	Important Studies Establishing the Validity of the Entity of Epiphyseal Growth Plate Fracture-Separations	506
5.2.3	Relatively Slow Acceptance by Many of the Existence of Epiphyseal Fractures	508
5.2.4	Pathoanatomic Studies of Epiphyseal Growth Plate Fracture-Separations	509
5.2.5	The Level of Transphyseal Fracture	514
5.2.6	Mechanisms of Injury	514
5.2.7	Epiphyseal Fracture-Separations Accompanying Traumatic Births	514
5.2.8	Understanding of Growth Plate Fracture-Separations at the End of the Preradiographic Era	515
5.2.9	Early Surgical Efforts in Relation to Growth Plate Injuries	517
5.3	Clinical Approaches to Growth Plate Fracture-Separations in the Radiographic Era	517
5.3.1	Pathoanatomic Classifications	517
5.3.2	Mechanistic Considerations	523
5.3.3	Negative Sequelae of a Growth Plate Fracture-Separation	526
5.4	Pathophysiologic Approaches to Growth Plate Fracture-Separations	526
5.4.1	Pathophysiologic Classification—Shapiro	526
5.4.2	Experimental Approaches to Growth Plate Structure, Blood Supply, and Function in Relation to Growth Plate Fracture-Separations	528
5.4.3	Pathogenesis of Growth Deformity	537
5.4.4	MR Imaging in Assessment of Growth Plate Fracture-Separations	539
5.4.5	Clinical Use of the Pathophysiologic Approach	546
5.5	General Clinical Profile of Growth Plate Fracture-Separations	548
5.5.1	Overview	548
5.5.2	Distribution of Physeal and Non-physeal Fractures in Childhood	549
5.5.3	Incidence of Epiphyseal Growth Plate Fracture-Separations in Males and Females	549
5.5.4	Incidence of Epiphyseal Growth Plate Fracture-Separations at Specific Epiphyses	549
5.5.5	Age at Occurrence of Physeal Fractures	550
5.5.6	Distribution of Specific Salter–Harris Types Per Long Bone Region	551
5.5.7	Epiphyseal Fracture-Separations with Difficult Births	551

5.6	Clinical Features of Acute Epiphyseal Fracture-Separations	552
5.6.1	General Principles of Management	552
5.7	Management of Growth Plate Fracture-Separations at Specific Epiphyses	553
5.7.1	Proximal Humerus	553
5.7.2	Distal Humerus.	555
5.7.3	Proximal Radius	562
5.7.4	Distal Radius	563
5.7.5	Distal Ulna	567
5.7.6	Metacarpals and Phalanges.	569
5.7.7	Clavicle.	569
5.7.8	Triradiate Acetabular Cartilage	570
5.7.9	Proximal Femur	570
5.7.10	Distal Femur	575
5.7.11	Proximal Tibia	581
5.7.12	Distal Tibia	586
5.7.13	Proximal and Distal Fibula.	594
5.7.14	Growth Patterns Following Distal Tibial and Fibular Growth Plate Fracture-Separations Using Roentgen Stereophotogrammetry	594
5.7.15	Ligament Damage Following Distal Femoral and Proximal Tibial Physeal Fractures.	596
5.8	Traumatic Damage to Growth Plates by Pathologic, Chronic Repetitive, and Indirect Effects.	596
5.8.1	Pathologic Epiphyseal Growth Plate Fracture-Separations.	596
5.9	Management of Negative Sequelae of Growth Plate Fracture-Separations	601
5.9.1	General Considerations	601
5.9.2	Management of Early Bone Bridge Formation	602
5.9.3	Management of Late Sequelae of Bone Bridges. Bone Bridge Excision, Physeal Interposition Materials and Transphyseal Chondrodiasis.	602
	References	603
6	Lower Extremity Length Discrepancies	613
6.1	Terminology	613
6.2	Clinically Significant Length Discrepancies	613
6.2.1	General Guidelines Concerning Extent of Clinically Significant Length Discrepancies	613
6.2.2	Percentage of Individuals with Equal Limb Lengths	613
6.2.3	Clinical Effects of Lower Extremity Length Discrepancies	614
6.3	Limb Length Determination.	618
6.3.1	Clinical Measurements.	618
6.3.2	Segments to Be Considered in Assessing Lower Extremity Length Discrepancies	619
6.3.3	Radiographic and Other Imaging Documentation of Lower Extremity Length Discrepancies	619
6.4	Causes of Lower Extremity Length Discrepancies.	620
6.5	Developmental Patterns in Lower Extremity Length Discrepancies	621
6.5.1	Patient Population.	621
6.5.2	Classification of Developmental Patterns in Lower Extremity Length Discrepancies	621

6.6	Lower Extremity Length Discrepancies in Specific Disease Entities: Pathoanatomy, Pathophysiology, Developmental Patterns, Ranges of Discrepancies	625
6.6.1	Terminology of Congenital Limb Deficiencies	625
6.6.2	Congenital Abnormalities of the Femur	627
6.6.3	Congenital Developmental Abnormalities of the Fibula; Fibular Hemimelia	630
6.6.4	Congenital Abnormalities of the Tibia	633
6.6.5	Skeletal Dysplasias with Asymmetric Involvement	635
6.6.6	Destroyed Physes	637
6.6.7	Abnormal Growth Following Use of Neonatal Umbilical or Femoral Catheters	638
6.6.8	Poliomyelitis	638
6.6.9	Hemiparetic Cerebral Palsy	640
6.6.10	Septic Arthritis of the Hip	640
6.6.11	Tuberculosis	642
6.6.12	Premature Epiphyseal Fusion at the Knee Complicating Prolonged Lower Extremity Immobilization	643
6.6.13	Osteomyelitis	644
6.6.14	Meningococemia	645
6.6.15	Physeal Damage Following Irradiation for Childhood Tumors	646
6.6.16	Fractured Femoral Diaphysis	647
6.6.17	Fractured Tibial Diaphysis	655
6.6.18	Overgrowth Syndromes and Lower Extremity Length Discrepancies	656
6.6.19	Congenital Vascular Malformations Associated with Lower Extremity Length Discrepancies	659
6.6.20	Neurofibromatosis	668
6.6.21	Juvenile Rheumatoid Arthritis	669
6.6.22	Thalassemia	671
6.6.23	Hemophilia	671
6.6.24	Synovial Hemangioma of the Knee Joint	672
6.6.25	Legg–Calve–Perthes Disease	672
6.6.26	Slipped Capital Femoral Epiphysis	672
6.6.27	Infantile Cortical Hyperostosis: Caffey’s Disease	672
6.6.28	Limb Length Discrepancies Due to External Causes	673
6.7	Projection of Limb Length Discrepancies by the Time Skeletal Maturity is Reached	673
6.7.1	Percentages of Growth at Each End of Major Long Bones	674
6.7.2	Systems for Assessing Skeletal Development and Maturation	674
6.7.3	Systems for Projecting Limb Length Discrepancy at Skeletal Maturation	675
6.7.4	Discussion of Methods Used	683
6.8	Use of the Developmental Pattern Classification in Projecting Limb Length Discrepancies	686
6.9	Management of Lower Extremity Length Discrepancies	687
6.9.1	General Considerations	687
6.9.2	Procedures to Shorten the Longer Limb	688
6.9.3	Procedures to Lengthen the Shorter Limb	703

6.10	Direct Operation on Epiphyses to Enhance Growth Potential by Removing Focal Transphyseal Tethers	742
6.10.1	Bone Bridge Resection	742
6.11	Treatment of Premature Partial Physeal Closure by Means of Growth Plate Transplantation	745
6.11.1	Free Autogenous Iliac Crest Physeal Grafts—Focal Defects	745
6.11.2	Vascularized Autogenous Epiphyseal and Iliac Crest Grafts	750
6.11.3	Physeal Reconstruction Using Tissue from Fetal and Early Postnatal Epiphyses	751
6.11.4	Cell-Based Therapy for Focal Growth Plate Cartilage Repair . . .	752
6.11.5	Transplantation of Entire Physes and Epiphyses	752
	References	757
Index	773