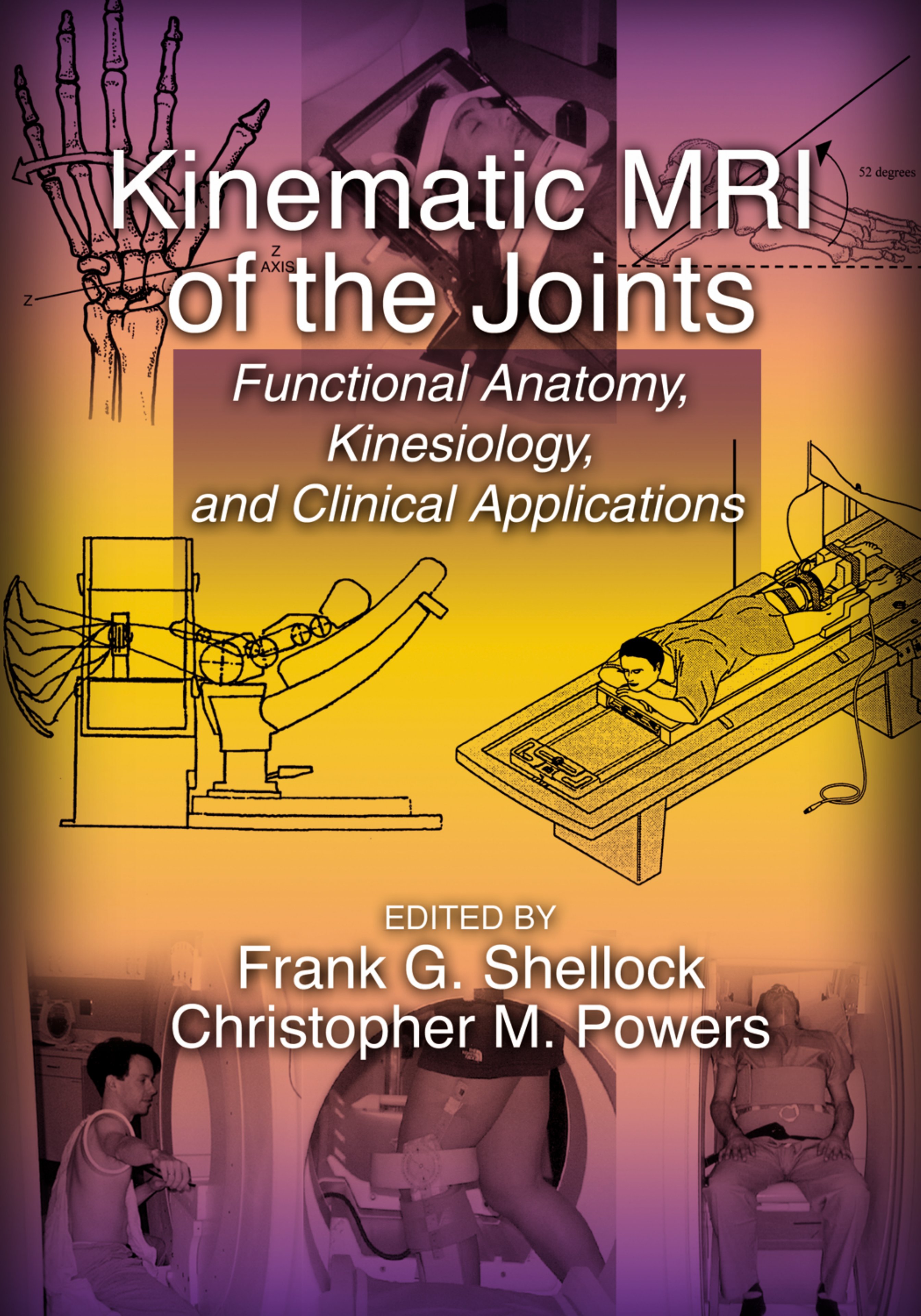
Kinematic MRI of the Joints

Functional Anatomy, Kinesiology, and Clinical Applications



EDITED BY

Frank G. Shellock
Christopher M. Powers

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Edited by
Frank G. Shellock, Ph.D.
Christopher M. Powers, Ph.D.

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Foreword

An impressive array of new imaging technologies revolutionized diagnostic medicine in the twentieth century. These advances culminated in the harnessing of proton magnetic resonance, and the breakneck speed of discovery and implementation is continuing into the twenty-first century.

This book is the first to comprehensively cover one of the most important of these rapidly advancing disciplines – functional imaging. The last century is known for developing static diagnostic imaging, but in neurologic and orthopedic medicine, functional impairments are the hallmark of disease. With static imaging we often use educated guesses to predict functional impairments, much like the physical examination allowed physicians to guess internal pathology. However, noninvasive visualization of internal pathology has largely replaced the physical examination in diagnosing and staging internal disease. Similarly, kinematic and dynamic imaging now give physicians tools to directly evaluate functional abnormalities.

Drs. Shellock and Powers have brought together an international team of experts to review the mechanics of the most commonly impaired joints. With each joint, they stress the clinical importance of biomechanics in determining the mechanism of injury, the nature and extent of pathology, and proper treatment. An accompanying chapter describes, in detail, magnetic resonance techniques and protocol used to image each joint, including kinematic and dynamic imaging, with and without stress. To my knowledge no other text contains this information under one cover.

The authors have performed a great service by compiling this information. Especially for radiologists, whose training does not traditionally include biomechanics, but also for physical therapists, orthopedic surgeons, osteopaths, sports medicine chiropractors, and sports-oriented physicians of all specialties, this book provides a rapid, thorough course in functional anatomy and pathology of joints. This book is valuable even for radiologists who do not commonly use motion-imaging sequences. Virtually all abnormalities seen with static imaging are caused by abnormal motion, and interpreters untrained in normal and abnormal joint motion may miss many of them. For example, shoulder impingement is caused by abnormal biomechanics, but with proper understanding the diagnosis can often be made on static images. This book is the first to describe joint mechanics in a clinically relevant way and correlate it with kinematic and dynamic magnetic resonance imaging (MRI).

I am certain the twenty-first century will witness great advancement in functional imaging. Two major impediments have hampered joint-motion imaging: the lack of understanding of the biomechanics of normal and abnormal joints and the complexity of magnetic resonance techniques in imaging motion. This book is one source that clearly explains both. With increasing sophistication of joint surgery and the availability of this book to empower dynamic MRI, it is likely that joint-motion imaging will become an increasingly important tool in pre- and post-surgical evaluation of a growing number of patients. This book is invaluable for all radiologists who interpret joint MRI and all clinicians using MRI for assessing their patients.

John V. Crues, III, M.D., F.A.C.R.
Medical Director
Radnet Management, Inc.
Los Angeles, California

Foreword

Kinematic magnetic resonance imaging (KMRI) is a new diagnostic science with great potential. The recently developed ability to rapidly record a sequence of images enables the investigator to document structural displacements and distortions of the soft tissues and articular surfaces as the joint moves. In the past, clinicians have attempted to glean such information by manually palpating the moving tissues or mentally imagining the reactions of the ligaments, tendons, capsule, and muscles based on their knowledge of static anatomy. But both the anatomy and the functional breadth of many joints are too complex for these subjective approaches to resolve the persistent diagnostic dilemmas.

Each of the seven joints reviewed in this volume has unique anatomical complexity. The patellofemoral joint is a gliding contact track between the anterior musculo-retinacular sheath and the anterior articular surface of the knee. Localization of dysfunction in the cervical and lumbar spines is complicated by the fact that there are three joints at each intervertebral level: right and left facet joints and the interbody disc system. Structural differences between the upper and lower portion of the cervical spine add further diagnostic complexity. Ankle joint pathology is obscured by the biplane obliquity of its axis. In addition, interposition of the subtalar joint between the ankle joint and heel denies the examiner a direct grasp of the underside of the ankle joint. Further diagnostic complexity is created by the proximity of long tendons crossing the ankle area as they extend from the shank to the foot. Functional stability of the patella is challenged by the interactions of the fibrous tissue restraints, muscle balance, structural shape of the articular surfaces, and the knee's motion pattern. The diagnostic complexity of the shoulder (glenohumeral) joint lies in its extensive three-dimensional mobility (greatest in the body) and the multiple overlying tissue layers. With every motion the integrity of the near-vertical glenoid labile socket margins is threatened by exposure of the shear forces whenever muscular control is inadequate. Localization of the pathology is obscured by the significant displacement of the soft tissue layers (capsule, rotator cuff, and the deltoid) as the humerus rotates on its scapular base. The temporomandibular joint gains much of its expanded range from the mobility allowed by the fibrous disc which divides the joint into two functional articulations. Distortions of the interactive fibrous tissue structures containing the mandibular condyle are the basis of much of the functional pathology but difficult to identify. The wrist, with two rows of carpal bones as well as intercarpal mobility within the rows, is another area where multiplicity of joints obscures localization of the pathology.

The eleven chapters on KMRI included in this volume identify the current capability of this procedure to differentiate the multiple potential structural causes of dysfunction at the individual joints. With localization of the pathology clinicians can determine an appropriate therapeutic course.

To interpret the KMRI images, however, the analyst must have a comprehensive knowledge of normal static anatomy as a basis from which to identify the changes. As few clinicians are deeply versed in anatomical details, it is customary to seek a reference text in the nearest library. This diversion will not be needed as physical therapists with a strong biokinesiological background have provided an accompanying chapter for each KMRI topic which summarizes the critical reference material on static anatomy. Each chapter also is generously illustrated with very clear line drawings of the key material. This book will impart valuable information to orthopedic surgeons, rehabilitation specialists, and other physicians who are challenged to resolve the diagnostic dilemmas of the musculoskeletal system. Physical therapists and athletic trainers also will find this book a valuable guide for planning their therapeutic programs related to dysfunctional motion.

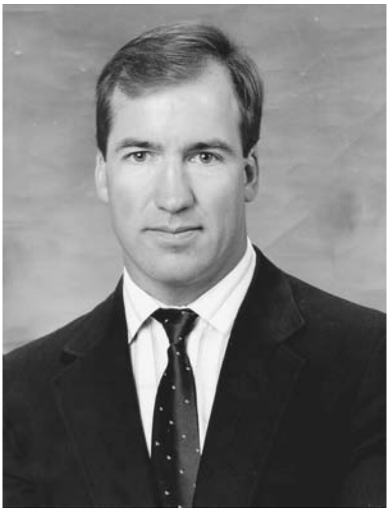
Jacquelin Perry, M.D., D.Sc. (Hon.)
Medical Consultant
Pathokinesiology Laboratory
Rancho Los Amigas Medical Center
and
Professor Emeritus
University of Southern California
Los Angeles, California

Editors

Frank G. Shellock, Ph.D. is a physiologist with more than 15 years of experience conducting laboratory and clinical investigations in the field of magnetic resonance imaging (MRI). He is an Adjunct Clinical Professor of Radiology at the University of Southern California School of Medicine, the President of Shellock R & D Services, and a Special Employee for the Food and Drug Administration. His primary research interests include investigations to develop kinematic MRI techniques for assessment of joint pathology, to identify and implement new clinical MRI applications, to evaluate electromagnetic field-related bioeffects, and to develop instruments and devices used for patient management and interventional MRI procedures.

Dr. Shellock is a member of the Committee for Standards and Accreditation of the Commission on Neuroradiology and MR for the American College of Radiology, the Safety Committee and the Educational Committee for the International Society for Magnetic Resonance Imaging, a former member of the Board of Directors of the Society for Magnetic Resonance Imaging, and a member of the Sub-Committee on MR Safety and Compatibility for the American Society for Testing and Materials. His memberships in professional societies include the American College of Radiology, the International Society for Magnetic Resonance in Medicine, and the Radiological Society of North America. He is a Fellow of the American College of Sports Medicine. Dr. Shellock is the recipient of a National Research Service Award from the National Institutes of Health, National Heart, Lung, and Blood Institute and has received numerous research grants from governmental agencies and private organizations. He is a frequently invited lecturer and visiting professor both in the United States and internationally.

Dr. Shellock has published five textbooks, over 50 book chapters, more than 150 peer-reviewed articles, and 180 scientific abstracts. He has served as a reviewing editor for 14 different medical and scientific journals. As a commitment to the field of MRI safety, Dr. Shellock developed and maintains the popular web site, *www.MRIsafety.com.*



Christopher M. Powers, Ph.D., P.T. is an Assistant Professor in the Department of Biokinesiology and Physical Therapy and Director of the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. He received a Bachelor's degree in Physical Education from the University of California, Santa Barbara; his Master's degree in Physical Therapy from Columbia University; and a Ph.D. in Biokinesiology from the University of Southern California. Dr. Powers currently teaches courses in biomechanics and the mechanics of human gait. He has been active in kinematic MRI research for the past 8 years, and he has focused on studying the pathomechanics of various orthopedic disorders. He has published over 25 articles and 50 abstracts in the field of orthopedic biomechanics, particularly in the area of patellofemoral joint dysfunction. In addition, Dr. Powers frequently lectures both nationally and internationally on topics related to kinematic MRI, kinesiology, and biomechanics.

Dr. Powers is an active member of the American Physical Therapy Association, the American College of Sports Medicine, the American Society for Testing and Materials, and the Society for Gait and Clinical Movement Analysis. He serves on the editorial board of the *Journal of Orthopaedic and Sports Physical Therapy* and as a reviewer for a number of other scholarly journals.

Acknowledgments

While the authors and editors get all the credit, many other people were responsible for this book. We would like to especially acknowledge our mentors, including the many radiologists, orthopedic surgeons, physiatrists, and other experts — John V. Crues, Jerrold H. Mink, Andrew L. Deutsch, James Fox, Michael Terk, Keith Feder, Richard Ferkel, Bert Mandelbaum, Clarence Shields, Jr., Kevin Stone, Todd Molnar, Joseph Horrigan, Helen Hislop, and Jaquelin Perry — who provided us with guidance, encouragement, support, and most importantly, friendship.

Finally, the excellent illustrations provided by our medical illustrator, Sandra Suycott, are a crucial part of this book.

F.G. Shellock
C.M. Powers

Contributors

Christopher F. Beaulieu, M.D., Ph.D.
Assistant Professor of Radiology
Stanford University Medical Center
Stanford, California

Barbro Danielson, M.D., Ph.D.
Assistant Professor and Senior Radiologist
Department of Radiology
Sahlgrenska University Hospital
Göteborg, Sweden

Marie Dufour, M.D.
Professor of Clinics
Quebec City University Hospital
and
Department of Radiology, Faculty of Medicine
Laval University
Hospital St-François d'Assise
Quebec City, Quebec
Canada

Wadi M.W. Gedroyc, M.B.B.S., M.R.C.P., F.R.C.R.
Consultant Radiologist and Medical Director, MRI
St. Mary's Hospital
London, United Kingdom

Garry E. Gold, M.D.
Assistant Professor of Radiology
Department of Radiology
Stanford University Medical Center
Stanford, California
and
Palo Alto Veterans Administration Medical Center
Palo Alto, California

Luc J. Hébert, M.Sc., P.T.
Doctoral Candidate
Department of Rehabilitation, Faculty of Medicine
Laval University and
Center for Interdisciplinary Research in Rehabilitation and Social Integration
Quebec City, Quebec
Canada

Sally Ho, D.P.T., M.S.
Adjunct Assistant Professor
Department of Biokinesiology and Physical Therapy
University of Southern California
Los Angeles, California

Juerg Hodler, M.D., M.B.A.
Professor of Radiology
Head, Department of Radiology
Orthopedic University Hospital Balgrist
University of Zurich
Zurich, Switzerland

Jari O. Karhu, M.D.
Department of Diagnostic Radiology
University of Turku and Turku University Hospital
Turku, Finland

Seppo K. Koskinen, M.D., Ph.D.
Radiologist-in-Chief
Department of Radiology
Töölö Hospital and
Helsinki University Central Hospital
Helsinki, Finland

Kornelia Kulig, Ph.D., P.T.
Associate Professor of Clinical Physical Therapy
Department of Biokinesiology and Physical Therapy
University of Southern California
Los Angeles, California

Susan Mais Requejo, D.P.T.
Lecturer, Department of Physical Therapy
Mount St. Mary's College
Los Angeles, California

Hélène Moffet, Ph.D., P.T.
Associate Professor and FRSQ
Research Scholar
Department of Rehabilitation, Faculty
of Medicine
Laval University
and
Center for Interdisciplinary Research
in Rehabilitation and Social Integration
Quebec City, Quebec
Canada

Christian Moisan, Ph.D.
Head, Interventional MRI Program
Quebec City University Hospital
Adjunct Professor
Department of Radiology
Laval University
Adjunct Professor
Department of Electrical
and Computer Engineering
Laval University
CHUQ-Hospital St-François d'Assise
Quebec City, Quebec
Canada

Christopher M. Powers, Ph.D., P.T.
Assistant Professor
Director, Musculoskeletal Biomechanics
Research Laboratory
Department of Biokinesiology
and Physical Therapy
University of Southern California
Los Angeles, California

John D. Reeder, M.D., F.A.C.R.
Chief, Musculoskeletal Imaging Division
Proscan Imaging
and
Assistant Professor
The Russell H. Morgan Department
of Radiology and Radiological Science
The Johns Hopkins University School
of Medicine
Baltimore, Maryland

Gretchen B. Salsich, Ph.D., P.T.
Post-Doctoral Fellow
Musculoskeletal Biomechanics
Research Laboratory
Department of Biokinesiology
and Physical Therapy
University of Southern California
Los Angeles, California

Marius R. Schmid, M.D.
Assistant Professor
Department of Radiology
Orthopedic University Hospital Balgrist
Zurich, Switzerland

Nils Schönström, M.D., Ph.D.
Assistant Professor and Senior Surgeon
Department of Orthopedics
Ryhov Hospital
Jönköping, Sweden

Frank G. Shellock, Ph.D., F.A.C.S.M.
Adjunct Clinical Professor of Radiology
University of Southern California
and
President
Shellock R & D Services, Inc.
Los Angeles, California

Elizabeth F. Souza, D.P.T., C.H.T.
Adjunct Clinical Faculty
Department of Biokinesiology
and Physical Therapy
University of Southern California
Los Angeles, California

Sandra Suycott, M.A.
Medical Illustrator
Monrovia, California

Michael R. Terk, M.D.
Assistant Professor of Clinical Radiology
Division Head, Musculoskeletal Imaging
Keck School of Medicine
University of Southern California
Los Angeles, California

Samuel R. Ward, P.T.
Doctoral Candidate
Musculoskeletal Biomechanics
Research Laboratory
Department of Biokinesiology
and Physical Therapy
University of Southern California
Los Angeles, California

Dominik Weishaupt, M.D.
Assistant Professor
Institute of Diagnostic Radiology
University Hospital Zurich
University of Zurich
Zurich, Switzerland

Simon Wildermuth, M.D.
Assistant Professor
Institute of Diagnostic Radiology
University Hospital Zurich
University of Zurich
Zurich, Switzerland

Jan Willén, M.D., Ph.D.
Associate Professor and Senior Spine Surgeon
Department of Orthopaedic Surgery
Sahlgrenska University Hospital
Göteborg, Sweden

Andrew Williams, M.B.B.S., F.R.C.S.
Consultant Orthopaedic Surgeon
Chelsea and Westminster Hospital
London, United Kingdom

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Preface

"Kinematics" is the branch of mechanics dealing with the study of motion. While traditional kinematic analyses (i.e., motion analysis systems that utilize external markers) form the cornerstone to the biomechanical assessment of joint function, interpretation of such data is limited with respect to identifying the internal factors contributing to abnormal joint motion (pathokinematics) and dysfunction. On the other hand, kinematic magnetic resonance imaging (MRI) provides a means by which the intricacies of joint function can be evaluated for both diagnostic and research purposes. The fact that images can be obtained during active motion provides the ability to thoroughly evaluate the interactions of osseous structures and the contribution of muscle action and other soft tissues to joint function.

Kinematic MRI techniques were developed in recognition of the fact that certain pathologic conditions that affect the joints are position-dependent and/or associated with stressed or "loaded" conditions. Information obtained using kinematic MRI procedures often serves to definitively identify and characterize the underlying abnormality or to supplement the information acquired with standard MRI techniques. Combining kinematic MRI with routine MRI views of the joint provides a means of conducting a more thorough examination and can improve the diagnostic yield of the imaging procedure.

The inspiration for this book came from our perceived need for a comprehensive text that would be the definitive resource on this topic. Because the development of most of the kinematic MRI techniques has been the result of the collaborative efforts of radiologists, biomechanists, physical therapists, orthopedic surgeons, and MR physicists, *Kinematic MRI of the Joints* was written by a carefully selected, international panel of leading experts in these various fields.

This book is organized into separate sections for each joint. The first chapter of each section provides information on pertinent functional anatomy and kinesiology, which serves as the foundation for understanding the abnormal conditions that may be assessed using kinematic MRI. Next, each section has one or more chapters devoted specifically to kinematic MRI, which describe the techniques and protocols, as well as a discussion of normal kinematics and pathokinematics seen using this imaging method. Notably, multiple case examples are provided to illustrate the usefulness of kinematic MRI for diagnosis or elucidation of pathologic conditions.

Kinematic MRI of the Joints was written primarily for two audiences: radiologists and clinicians. For the radiologist, this book is designed to be a reference text that guides the technical and practical aspects of performing and interpreting kinematic MRI examinations. For the clinician, this book provides a concise review of normal and abnormal joint function and describes how information obtained from kinematic MRI can be used to better interpret clinical findings and guide appropriate treatment of common orthopedic conditions. Additionally, we feel that orthopedic surgeons will find particular value in this book insofar as the use of MRI is a daily part of their clinical practice. Orthopedic surgeons should become familiar with the spectrum of kinematic MRI applications that exist, which will enable them to improve therapeutic decisions.

The final section of this book describes unique and emerging applications of kinematic MRI (Chapter 17, Kinematic MRI of the Knee: Preliminary Experience Using the Upright, Weight-Bearing Technique and Chapter 18, The Extremity MR System: Kinematic MRI of the Patellofemoral Joint). Finally, we included a Glossary that provides definitions of common terms from the fields of biomechanics and radiology used in this book.

We hope that this book serves to expand the clinical use of kinematic MRI procedures and to stimulate additional research and development that will further contribute to the understanding of normal and pathological joint function.

Frank G. Shellock, Ph.D., F.A.C.S.M.
Christopher M. Powers, Ph.D., P.T.

Dedication

To my loving wife and best friend, Jaana

F. G. Shellock

To my parents and grandparents for their continued support and encouragement during my educational and professional pursuits

C. M. Powers

Part I

Lumbar Spine

1 The Lumbar Spine: Functional Anatomy and Kinesiology

Kornelia Kulig

CONTENTS

I. INTRODUCTION

The lumbar spine provides a stable, yet adaptable musculoskeletal support for the trunk and upper extremities. In addition to the stability requirements, the lumbar spine serves to transfer weight and resist the resulting bending moments of the upper trunk and motion of the upper extremities. Finally, the lumbar spine protects the spinal cord and cauda equina from excessive physiological movements and trauma.

This chapter discusses the lumbar spine with regard to functional anatomy, normal kinesiology, and pathokinesiology. The material in this chapter has been divided into five sections. The functional anatomy section focuses on structures relevant to description of motion and common pathologies. The section on kinesiology analyzes the lumbar spine as a mechanical structure with controlled articulations by levers (vertebrae), pivots (facets and discs), passive restraints (ligaments), and activators (muscles). Section IV presents pathological conditions and their relationship to structure, function, and motion of the lumbar region.

II. FUNCTIONAL ANATOMY

A. Osseous Structures and Articulating Surfaces

There are common aspects of the osseous structures for the five most caudal vertebrae referred to as the lumbar spine (Figure 1.1). The lumbar region serves as a transition between the trunk and pelvis. Structurally, there are three distinct components to each of the lumbar vertebrae: the vertebral body, the pedicles, and the posterior elements (Figure 1.2). Functionally, the lumbar region consists of five functional spinal units (FSU) with L1-L2 being most cranial and L5-S1 most caudal. The FSU is made up of two neighboring vertebrae and the interconnecting soft tissue, devoid of musculature.

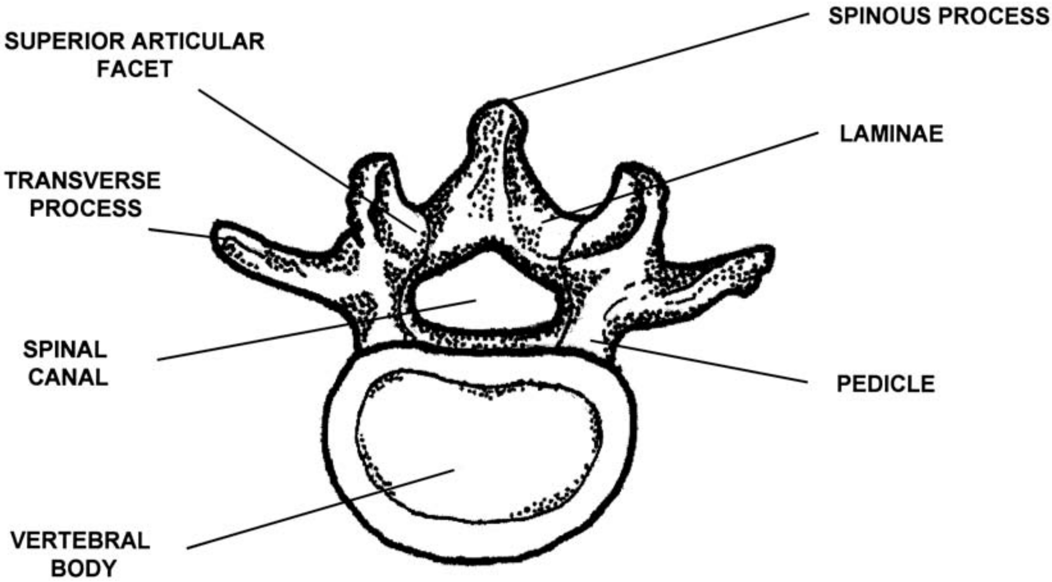

FIGURE 1.1 Typical lumbar vertebra (superior view).

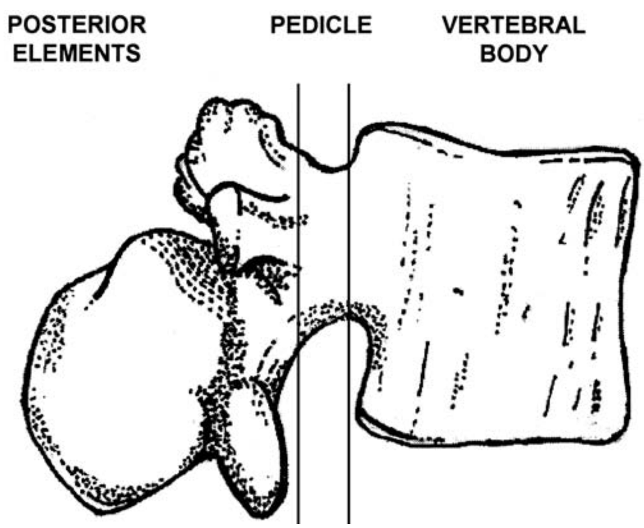

FIGURE 1.2 Typical lumbar vertebra (lateral view). The three functional components of the vertebral body, pedicles, and posterior elements are identified.

The lumbar vertebral body is a box-like structure, oval in the transverse plane, with flat superior and inferior surfaces. The lateral surfaces become slightly concave with age. The posterior surface has visible foramina serving as entry sites for arteries and veins. The main role of the vertebral body is axial load, weight-bearing. The dynamic weight-bearing capabilities of the vertebral body are enhanced by its internal structure of vertical and transverse trabeculae enveloped by a cortical shell.

The lumbar pedicles, two osseous structures projecting posteriorly from the lateral aspect of the vertebral body, are the connectors between the anterior and posterior elements (Figure 1.1). The superior and inferior borders of the pedicle form two neighboring intervertebral foramen. The pedicles are structures well suited to resist tension and bending forces. If fractured due to an excessive extension torque, spondylolisthesis may result.

The posterior elements of a vertebra are the transverse processes, laminae, articular processes, and the spinous process (Figure 1.2). The posterior elements serve as sites of muscle attachment and as structures resisting rotatory and fore-aft forces. The transverse processes project laterally at the level of the inferior vertebral body.

Posterior to each transverse process are superior and inferior articular processes. The medial aspect of the superior articular process has a facet serving as an articular surface with the inferior articular surfaces of the superior vertebrae (zygapophyseal joint). Posterior to the articular processes there is a hemi-lamina, which also serves as a muscle attachment site and protects the neural canal. The right and left hemi-laminas join posteriorly to form a spinous process. The lumbar spinous process is relatively wide, long, and high, providing a long lever for the attaching muscles.

There are four facet surfaces on each lumbar vertebra, two superior (concave medially) and two inferior (convex laterally). Consequently, an FSU has two facet (zygapophyseal) joints. The joint planes transition from the sagittal plane at L1-L2 to almost frontal plane at the L5-S1 FSU (Figure 1.3). Therefore, the L1-L2 FSU has less sagittal motion than L5-S1. In general, the orientation of the lumbar joint surfaces restricts axial rotation at a lumbar FSU.

The role of the facet joint is to direct and restrict motion. Asymmetry of the right and left facet joints is observed in the lumbar spine more frequently than in other regions. This asymmetry may cause aberration of segmental motion. Facet joint surfaces are covered by 2 mm of articular cartilage.

An intervertebral disc is present between each vertebra of the lumbar spine region (Figure 1.4). The disc has a discal joint with both neighboring vertebrae. The primary role of the disc is to distribute weight across the entire vertebral body. The secondary role is to dictate mobility of the FSU (i.e., the higher the disc the more mobile the FSU).

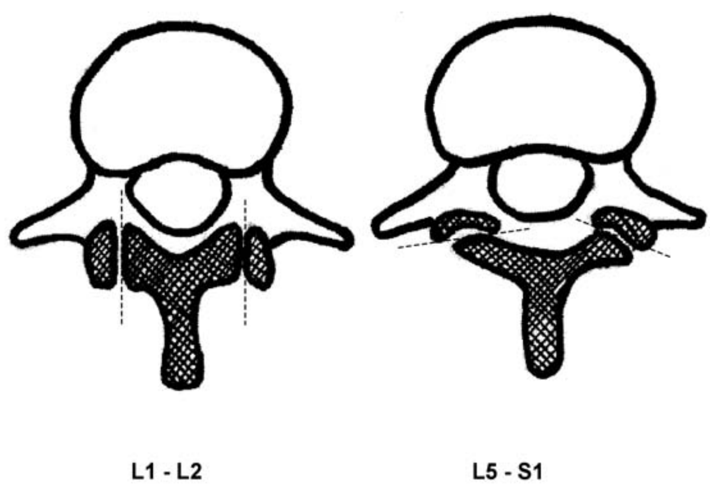

FIGURE 1.3 Variability of lumbar facet orientation: L1-L2 and L5-S1.

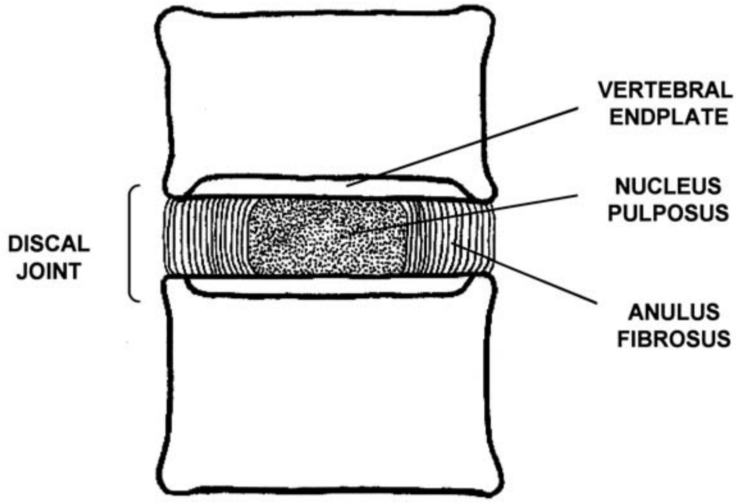

FIGURE 1.4 Frontal view of a lumbar intervertebral disc and neighboring vertebral endplates.

The two distinct components of the disc, the nucleus pulposus and the anulus fibrosus (Figure 1.4), have different roles but can meet these demands only when functioning cooperatively. The nucleus is designed to sustain and transmit pressure with the assistance of the external ring of the anulus. The anulus fibrosus acts like a ligament to restrain movement and to stabilize the FSU. An FSU with a ruptured anulus often presents as being hypermobile (i.e., excessive translatory motion).

B. Ligaments and Joint Capsule

From posterior to anterior there are six ligaments in the lumbar spine, which interconnect the vertebral bodies and are common to the ligaments running from cervical and thoracic regions. The common ligaments (shown in Figure 1.5) are the supraspinous ligament, interspinous ligament, intertransverse ligament (not pictured), ligamentum flavum, apophyseal joint capsular ligaments (not pictured), posterior longitudinal ligament, and anterior longitudinal ligament (Figure 1.5).

In the neutral position, the ligaments are lax. In the sagittal plane, the ligament located anterior to the axis of rotation is taut in extension (anterior longitudinal ligament) and ligaments posterior to the axis of rotation are taut during flexion (the remaining six of the above listed ligaments). During sidebending, the ligaments opposite to the side of sidebending are taut and in rotation all are taut.

The zygapophyseal joint is covered by a joint capsule consisting of transversely oriented collagen fibers at the posterior, superior, and inferior margins of the joint. Anteriorly, the joint capsule is replaced by ligamentum flavum. Posteriorly, the capsule is reinforced by the multifidus muscle. The superior and inferior aspects of the joint capsule are enlarged and contain a small foramen for infiltration of fat into the joint. Intraarticular fat contributes to distribution of articular compression present at end range rotation.

There are additional ligaments unique to the lumbar region: the iliolumbar and false ligaments. The iliolumbar ligaments connect the ipsilateral iliac crest with the transverse processes of L5 and in some cases L4. Its main role is to provide support for L5 and restrict it from anterior translation on the sacrum. The spatial orientation of the iliolumbar ligament, in its five multidirectional parts, provides additional support from excessive flexion, extension, sidebending, and rotation.

The false ligaments (i.e., intertransverse, transforaminal, and mamillo-accessory) are a unique feature of the lumbar spine. However, the false ligaments do not fully meet the criteria of a ligament, that is, a collagenous structure that functions to limit motion between the two bones it connects. The false ligaments either attach to the same bone (mamillo-accessory and transforaminal ligaments)

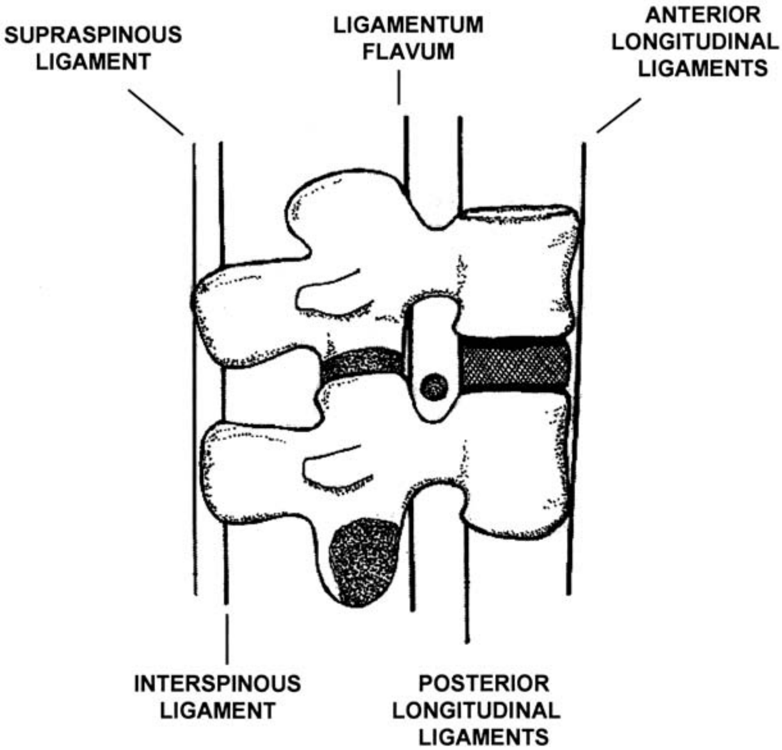

FIGURE 1.5 Ligaments of the lumbar spine.

or appear more membranous than collagenous (intertransverse ligament). The false ligaments play a negligible role in segmental stability.

C. The Vertebral Canal and the Intervertebral Foramen

The consecutive vertebral foramina form the vertebral canal containing the spinal cord (at the L1-L2 level) and the cauda equina (caudally to the terminal end of the spinal cord). Anteriorly, the vertebral canal is formed by the posterior vertebral bodies, discs, and most intimately, by the posterior longitudinal ligament. Posteriorly, the canal is embraced by the ligamentum flavum and the vertebral laminae. Laterally, the vertebral canal is defined by the pedicles, which are intercepted by the intervertebral foramens.

The size of the vertebral canal can be lessened by encroachment of osseous outgrowths, expansion of discal material, buckling of ligamentum flavum, or the presence of developmental anomalies. This narrowing is clinically referred to as spinal stenosis. The pathogenesis of the symptoms related to spinal stenosis will be described later in this chapter.

The lumbar intervertebral foramen is oval shaped and its dimensions have been reported to be 108 mm^2.[1] The size of the intervertebral foramen increases with flexion (24%) and decreases with extension (20%). The intervertebral foramen contains the nerve root with its dural sleeve, radicular vein, radicular artery, and fat. Several structures can decrease the lumen of the intervertebral foramen (i.e., disc, ligamentum flavum, and osseous spurring).

An injury to the intervertebral disc decreases the distance between the vertebral bodies and consequently decreases the size of the intervertebral foramen. Arthrosis of the zygapophyseal joint may result in its enlargement and a decrease of the space defined by the intervertebral foramen. The presence of transforaminal ligaments may contribute to a decrease in size of the intervertebral foramen. These changes may or may not be associated with clinical signs and symptoms.

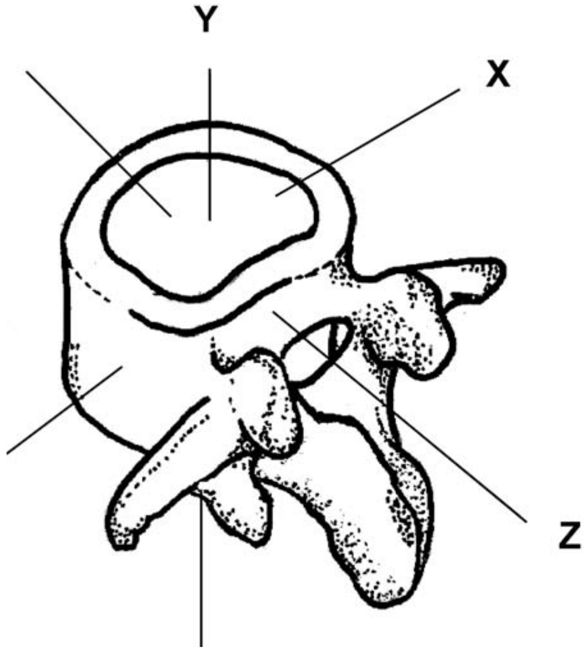

FIGURE 1.6 Orientation of the reference axes.

III. NORMAL JOINT KINESIOLOGY

A. Osteokinematic and Arthrokinematic Motions

In "neutral" the lumbar spine is positioned in lordosis (a posterior concavity of the lumbar curvature). Movement into lumbar flexion results in relative straightening from the lordotic position. In some cases there is a reversal of the lordotic curve as a whole or its selected segments. During extension of the lumbar spine the lordosis is accentuated. To reach that position, the cranial FSU (e.g., L1-L2) extends and the caudal (e.g., L5-S1) may be required to flex.

Sidebending of the lumbar spine creates a concavity on the side of sidebending. The osseous structure of the lumbar spine produces rotation in association with sidebending. This concomitant rotation varies with the position of the lumbar spine in the sagittal plane, that is, when the spine is flexed the anterior aspect of the vertebral body rotates to the same direction as the sidebending, and to the opposite side when it is extended. Axial rotation is available, but it is quite limited, primarily due to the orientation of the zygapophyseal joints.

By convention, the direction of motion is identified by the position of the anterior aspect of the superior vertebral body. For example, if the description of the position is "L1-L2 is in right rotation," it occurred either by the anterior vertebral body of L1 rotating right or the anterior vertebral body of L2 rotating left. If a motion of a bone at a joint takes place around or along two or more axes, it is referred to as "coupled motion."[2]

Each lumbar FSU has 6 degrees of freedom. The osteokinematic degrees of freedom will be quantified and described in relationship to their axes of rotation. The described motion will be flexion, extension (x-axis), sidebending (z-axis), and rotation (y-axis) (Figure 1.6). Muscles responsible for the movement in each plane and their lever arm will be presented. Additionally, uniplanar and multiplanar motion will be identified.

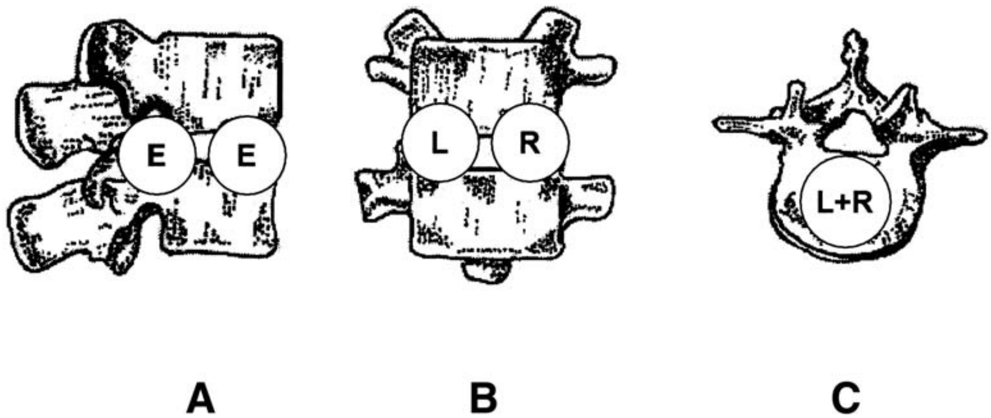

FIGURE 1.7 Approximate locations of the instantaneous axes of rotation in the sagittal (A), frontal (B), and transverse (C) planes at a lumbar functional spinal unit. E, extension; L, left; R, right. (From White, A. A. and Panjabi, M. M., Spinal kinematics, in *The Research Status of Spinal Manipulative Therapy,* NNCDS Monograph, no. 15, U.S. Department of Health, Education and Welfare, Washington, D.C., 1975, p. 93.)

1. Flexion and Extension

Flexion and extension occur in the sagittal plane. These rotatory (osteokinematic) motions are coupled with linear (arthokinematic) motions. The linear motions occur at the discal and facet joints. During flexion, the superior vertebra rotates anteriorly. There is a coupled anterior translation of the superior vertebra on the inferior vertebra of the FSU at the discal joint.[3]

Additionally, due to the presence of the disc, there is a superior and posterior motion of the inferior articular facets in relationship to the superior articular facets. The combination of these motions is referred to as "rocking." Ultimately, the superior facet surfaces glide anteriorly, which results in the anterior translation of the superior vertebra. The shape of the facet joints will dictate the distribution of joint loading. That is, a planar surface will promote even distribution and a joint with a curved articular surface will have more loading anteriorly (see Figure 1.3).

During extension, the superior vertebra rotates posteriorly. Posterior translation of the superior vertebra on the inferior vertebra of the FSU occurs at the discal joint. Conjointly, the superior facet surfaces glide inferiorly and posteriorly along the plane of the facet joints. Extension can be limited by the following: contact of the neighboring spinous processes, inferior articular processes, laminae, and tension of the anterior anulus of the disc.

The axis of rotation for the lumbar FSU is at the level of the intervertebral disc. The axis for flexion is at the posterior aspect of the vertebral body and the axis for extension is at the anterior aspect of the vertebral body (Figure 1.7). For flexion and extension, there is a caudal decrease in the quantity of motion in the sagittal plane (Table 1.1). The quantity of osteokinematic motion at the lumbar spine is the highest in the sagittal plane, followed by sidebending and rotation. The segments with the highest mobility (L4-L5 and L5-S1) are also those with the highest incidence of disc injury.

The arthrokinematic motion of translation is a part of normal spinal mobility and takes place in the three planes. However, if excessive (exceeding 4.5 mm in the sagittal plane), it is considered a measure of clinical instability.[2] Translation for the lumbar spine is typically measured in flexion and extension using x-rays.

2. Sidebending

Sidebending takes place in the frontal plane. This rotatory motion (osteokinematic) is coupled with osteokinematic motion (i.e., rotation) and linear (arthokinematic) motions. The linear motions occur

TABLE 1.1
Representative Values of Segmental Range of Motion in the Lumbar Spine

FSU	Combined Flexion/Extension (degrees)	Lateral Bending (One Side) (degrees)	Axial Rotation (One Side) (degrees)
L1–L2	12	6	2
L2–L3	14	6	2
L3–L4	15	8	2
L4–L5	16	6	2
L5–S1	17	3	1

FSU, functional spinal unit.

Data adapted from White and Panjabi.[2]

at the discal and facet joints. The coupled sidebending and rotation occur as a result of the alignment of the facet joints guiding motion at the FSU. For example, when a motion is initiated with right sidebending and the spine is flexed, right rotation of the superior vertebra will follow. However, when the same right sidebending is initiated with the segment extended, a left rotation will follow.

During sidebending to the right (in extension), the superior vertebra glides right at the discal joint. The right inferior facet of the superior vertebra glides inferiorly while the left glides superiorly along the facet joint surface, thereby causing rotation. Approximation occurs at the zygapophyseal joint, leading to left rotation and separation of the left zygapophyseal joint. These are coupled motions at the lumbar spine.

The axis of rotation for sidebending at the lumbar spine passes from anterior to posterior at the intervertebral disc of an FSU (Figure 1.7). The amount of unilateral sidebending is nearly constant throughout the lumbar spine (5 to 8 degrees), with the exception of the L5-S1 segment, which has the least amount of sidebending (3 degrees). Representative values of segmental range of motion for the lumbar spine are show in Table 1.1.

3. Rotation

Rotation takes place in the transverse plane. Rotation, if initiated in flexion, is coupled with ipsilateral sidebending. If the rotation is taking place to the right, the left facet joint surfaces approximate and consequently the right facet joint surfaces separate. This motion is followed by sidebending if the superior vertebra is rotated to the right. Further sidebending results from superior glide at the left facet joint and inferior glide at the right facet joint.

The axis of rotation for axial rotation at the lumbar spine passes vertically through the center of the vertebral body (Figure 1.7). The amount of unilateral rotation is 2 to 3 degrees, with the least amount of motion at the L5-S1 segment. This pattern of motion reflects the orientation of the facet joints, which are transitioning from a sagittal orientation to an almost frontal orientation.

4. Axial Approximation and Distraction

Axial approximation and distraction for the lumbar spine occur along the vertical axis. Axial approximation (compression) is caused by gravity, external loads, and the forces created by muscle contraction. Consequently, compression is part of all upright positions and most activities. As vertebral bodies approximate, discal height decreases.[4] The vertebral body is able to withstand 3 to 12 kN of compression[5] and its strength is directly related to bone density.[6] Excessive axial loading may cause fracture of the central aspect of the endplate.[7]

The zygapophyseal joints may bear up to 20 to 40% of an applied vertical load.[8,9] The loading on the zygapophyseal joints is dependent on the status of the disc. An FSU with a healthy disc transfers less weight to the zygapophyseal joints, while an FSU with an injured disc would rely more on the zygapophyseal joints for load bearing.

Functionally, axial distraction of the lumbar spine happens much less frequently than axial approximation. However, axial distraction of the lumbar spine is used therapeutically (i.e., "pelvic traction"). Twomey[10] studied the entire cadaveric lumbar spine during sustained axial traction to mimic the clinical procedure and found that traction of 18 lb caused a 7.5 mm lengthening of the entire spine (i.e., 40% of lengthening resulted from flattening of the lumbar lordosis; 60% was due to distraction of the vertebral bodies).

B. Muscles and their Functions

The lumbar muscles protect the spine, interconnect and move the lumbar FSUs, and connect and move the lumbar, thoracic, and pelvic regions. Muscles with direct attachments to the lumbar spine will be discussed first. Then muscles that do not attach to the lumbar spine, but strongly impact on the lumbar spine due to their long lever arms, will be reviewed.

The muscles with direct attachments to the lumbar spine are posterior, lateral, and anterior. The posterior elements of the lumbar spine are covered by the lumbar back muscles, the lateral aspect by the intertransversarii and quadratus lumborum, and the anterior portion is covered by the psoas major muscle (Figure 1.8). Most muscles of the lumbar region are capable of contributing to multidirectional motions. However, each muscle seems to have a dominant lever arm for one type of motion.

The lumbar back muscles include short intersegmental muscles and the polysegmental muscles. The short intersegmental muscles are interspinales and intertransversarii mediales. These muscles are short and small and lie close to the axis of rotation. Therefore, they are not powerful activators. Bogduk[11] states that the value of the intersegmental muscles lies not in the force they can exert, but in the muscle spindles they contain, offering a system of proprioception.

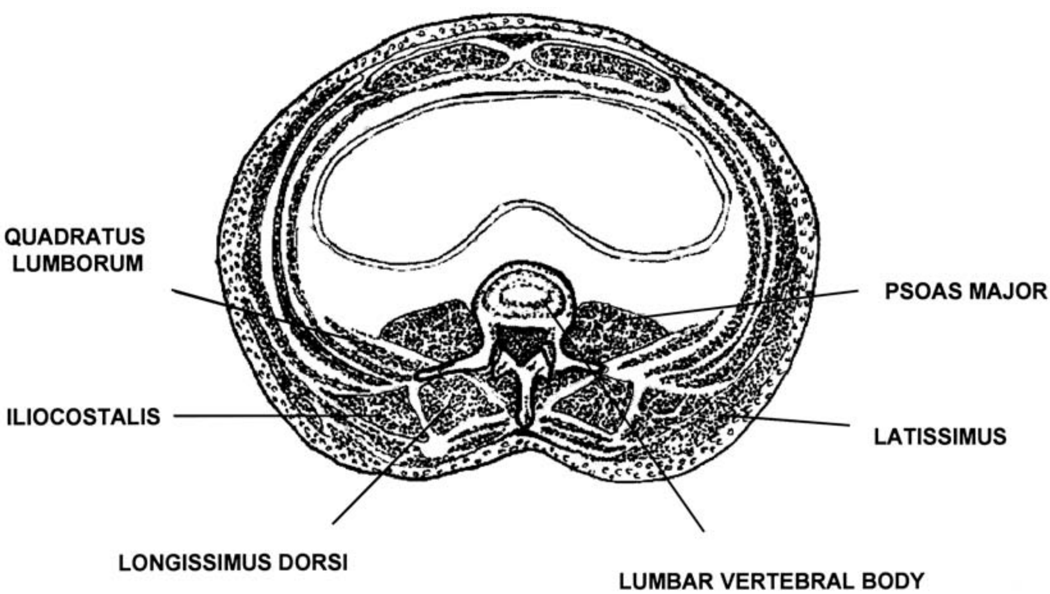

FIGURE 1.8 Transverse view of the muscles of the lumbar spine. (From White, A. A. and Panjabi, M.M., *Clinical Biomechanics of the Spine*, J.B. Lippincott, Philadelphia, 1990. With permission.)

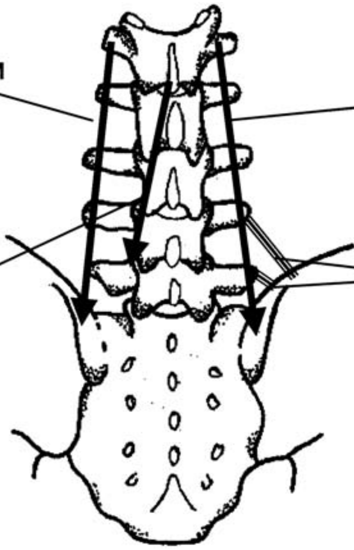

FIGURE 1.9 Line of action of the multifidus and of the lumbar components of the longissimus and iliocostalis. (Adapted from Bogduk, N., *Clinical Anatomy of the Lumbar Spine and Sacrum,* 2nd edition, Churchill Livingstone, New York, 1997, p. 107.)

The polysegmental muscles are the multifidus and lumbar components of the longissimus and iliocostalis (lumbar erector spinae). Multifidus, true to its name, is formed by a large number of independent fascicles and is the most medially located lumbar muscle. There are two distinct components of the multifidus, fibers attaching to the lamina and those attaching to the spinous processes. Both types of fibers attach to the mamillary processes at the posterior aspect of the superior articular process. The laminar component attaches two levels below (i.e., L1 to L3) the iliac crest and sacrum and the spinous process component attaches three levels below (i.e., L1 to L4). The line of action of this muscle is caudal and lateral (Figure 1.9). The vertical component is longer than the horizontal, indicating that multifidus is predominantly an extensor. The horizontal component serves as a stabilizer for rotation.[12]

The lumbar erector spinae, composed of two muscles (longissimus and iliocostalis), lies laterally to the multifidus. The longissimus thoracis pars lumborum runs from the accessory process and transverse process of each lumbar vertebra to the medial aspect of the posterior superior iliac spine. The line of action of this muscle is caudal and lateral, which is similar to that of the multifidus (Figure 1.9). The difference is in the depth of the horizontal component; the longissimus has a longer anterior-posterior component, contributing to a slight advantage as a rotator.

Finally, the iliocostalis lumborum runs from the tip of the transverse process to the iliac crest. Of the three polysegmental muscles, the iliocostalis lumborum has the greatest advantage to produce axial rotation (Figure 1.9).

The intertransversarii and quadratus lumborum are the lateral muscles of the lumbar spine. The intertransversarii medialis connects the mamillary processes of two neighboring vertebrae and, therefore, has a short lever arm for sidebending and extension. This low mechanical advantage coupled with small size categorizes this muscle as an accessory muscle for stabilization. Quadratus lumborum is a rectangularly shaped muscle with its attachments to the iliolumbar ligament posterior iliac crest, the 12th rib, and the transverse processes of L1-L4. This muscle depresses the last rib and if acting unilaterally, it sidebends the lumbar spine.

Anterior to the lumbar spine is the psoas major. It attaches to the transverse processes, the discs, and vertebral margins with the discs of T12 though L5. Its distal attachment is to the lesser trochanter of the femur. The psoas major is able to extend the upper lumbar segments and flex the lower lumbar segments; however, the lever arm for sagittal plane motion is small. Alternately, the psoas is a strong compressor of the lumbar discs.[13]

IV. PATHOKINESIOLOGY: CLINICAL RELEVANCE AND IMPLICATIONS

A. Lumbar Spondylosis

Lumbar spondylosis is a degenerative process of activity and age-related changes of the lumbar spine leading to mechanical low back pain. It is thought that the process begins at the intervertebral disc. Subsequently, changes in other structures may follow (deformation of the zygapophyseal joints, osteophytes at the vertebral bodies, ossification of the posterior longitudinal ligament, hypotonic ligamentum flavum). The degenerative process may become symptomatic at any stage.

The symptoms may be placed in one of four categories: back pain, back pain with proximal referral, radicular pain, and myelopathy. Back pain, back pain with proximal referral, and lower extremity radicular pain can be caused by several lumbar structures containing nociceptors, including the disc, nerve root sleeve, facet joints, and ligaments.

In lumbar spondylitic myelopathy, the cauda equina is compromised within the spinal canal. As a result there are degenerative changes of the lumbar spine. Narrowing of the spinal canal, also referred to as spinal stenosis, is another form of spondylosis.

B. Stenosis

Stenosis is defined as narrowing of the spinal canal. Schonstrom[14] lists seven forms of lumbar stenosis: congenital, developmental, degenerative, metabolic, iatrogenic, post-traumatic, and "miscellaneous." In absolute stenosis, the antero-posterior diameter of the spinal canal is 10 mm or less. Spatially, the spinal stenosis can be central or lateral. Spinal stenosis usually has gradual onset and is seen greatly in persons more than 60 years of age. The main components of a patient's presentation are lower extremity symptoms such as numbness, paresthesia, weakness, and neurogenic claudication. Neurogenic claudication is associated with lower extremity symptoms during walking. Sitting relieves these symptoms. Additionally, walking uphill is easier than on flat surfaces. The management of patients with lumbar stenosis is most often with conservative treatment, but occasionally it requires surgical intervention.

C. Spondylolytic Instability

Spondylolytic instability is most often associated with bilateral spondylolysis. Spondylolysis is associated with a fracture of the pars interarticularis (pedicle). If the vertebra translates forward, the condition will become a spondylolisthesis. A spondylolisthesis can be associated with hypermobility or instability. The symptoms of a patient with instability may include localized low back pain, leg pain, or weakness.

D. Facet Subluxation

Facet subluxation is most commonly of traumatic origin. However, degenerative changes leading to weakening of passive restraints and muscles may also cause subluxation. The patient may present with a painful movement pattern or restriction during an attempt to move the lumbar spine. The management of patients with facet subluxation requires conservative rehabilitation.

V. SUMMARY AND CONCLUSIONS

The lumbar region consists of five FSUs. Its stability depends on the vertebral structure, including the facet joints, and the integrity of the disc, ligaments, and muscles. The lumbar spine exhibits