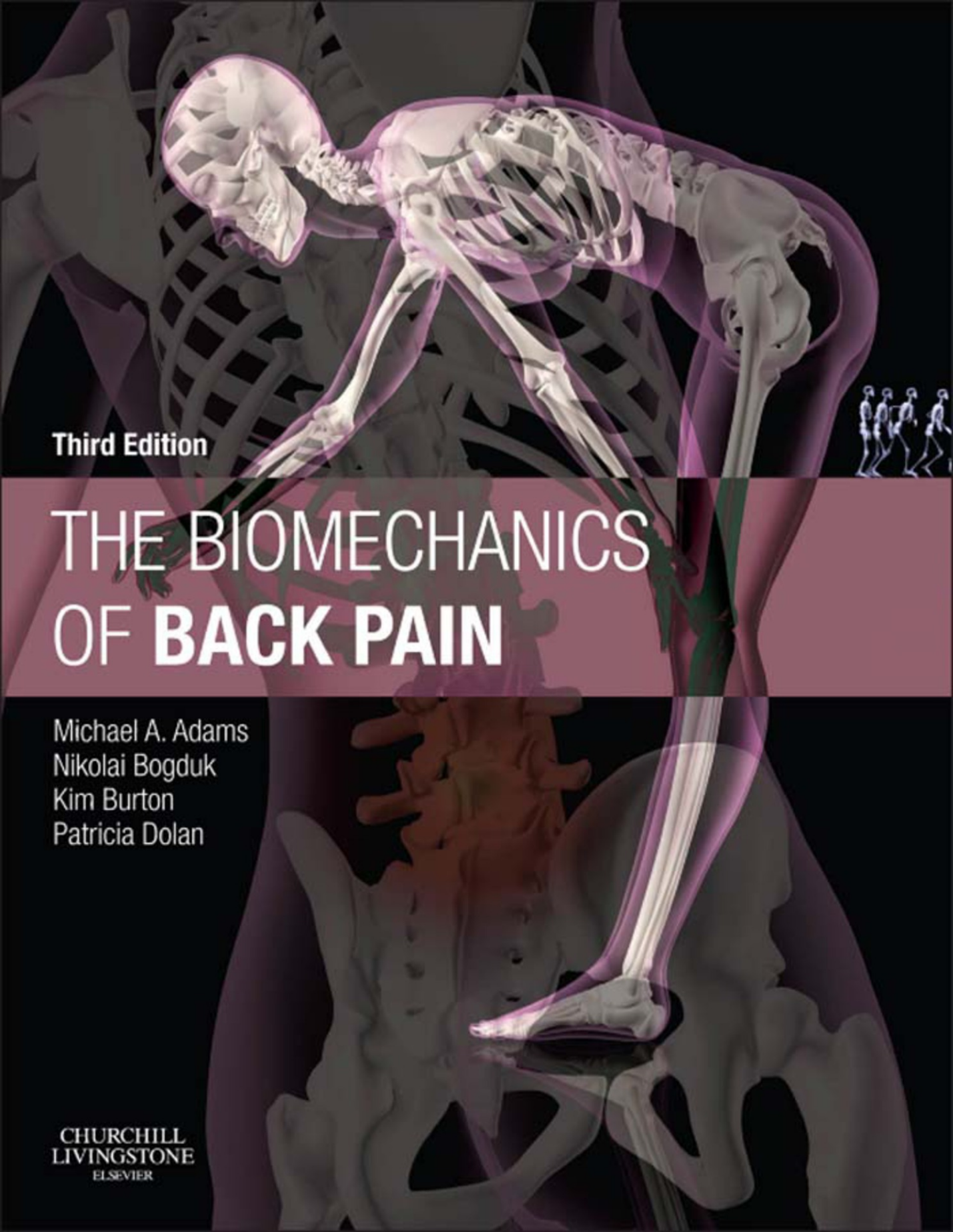


Third Edition

THE BIOMECHANICS OF **BACK PAIN**

Michael A. Adams
Nikolai Bogduk
Kim Burton
Patricia Dolan

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The Biomechanics of Back Pain

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The Biomechanics of Back Pain

Third Edition

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Preface

to the 3rd Edition

As the *Biomechanics of Back Pain* moves into its third edition, a prospective reader may wonder at the authors' motivation for carrying on. Do we have anything new to say? Are we creatures of habit? In fact we were uncertain of the value of a third edition until recent events helped us to make up our minds.

At long last, research into back pain seems to be paying off, with important clinically-relevant advances being reported in the last three years. For example, large population-based imaging studies now confirm beyond doubt that intervertebral disc degeneration has a strong association with severe and chronic back pain. The latest 'twins' studies show that genetic inheritance and environmental influences are equally important determinants of spinal pathology and pain, with some fascinating interactions. Other interesting and potentially useful therapeutic advances include an injection-based treatment for discogenic back pain with a 92% 'satisfaction' rating after two years, and a new generation of prosthetic intervertebral discs with highly encouraging short-term results. It remains to be seen if these apparent breakthroughs will stand the test of time, but certainly this is an invigorating period for back pain research.

These recent advances suggest a shift in perspective, from trying to understand and reverse age-related spinal degeneration, to tackling directly the tissue causes of pain. Securing perpetual youth for our backs may not be achievable, but we are learning how to identify and deal with the sensitised neurons which ultimately cause most back pain. This is the main reason for this new edition: to emphasise the new perspective, and to show how research is finally leading to clinical advances. This has required a complete re-writing of the final Summary chapter.

There are other reasons for carrying on. The book remains popular, and has been translated into several foreign languages, including Chinese. Although conceived as an undergraduate text, it has become accepted as an authoritative reference for teachers, researchers, clinicians, and those working in the medico-legal arena. With that comes a responsibility: it must be updated or replaced at regular intervals. Accordingly, every chapter and most paragraphs have been revised, and more than 350 new references incorporated. It was our intention to remove as much as we added, to keep the text concise, but we were equally concerned to preserve the best research from before the digital era, because access to this literature is often denied to young researchers. As a result, the book has grown slightly, but we suggest that the extra weight is 'meat' rather than 'fat'.

Other improvements include an all-colour format with many additional diagrams and photographs. Additional chapters are devoted to 'Sensorimotor Control' and 'Cervical Spine Biomechanics'. Not all of the material in these two chapters is new, but it should now be easier to find. The online content now allows the reader to download Figures, and to access PowerPoint slide shows summarising much of the core material. We hope that this new content will assist those who, like us, teach as well as learn.

Additional On-line Information

Besides the plethora of information found in the latest edition of *The Biomechanics of Back Pain*, this book comes with a bank of material which is available at www.biomechanicsofbackpain.com.

We have used this website for posting additional material which includes two extensive PowerPoint presentations which are suitable for senior undergraduate/post graduate teaching purposes – *Forces on the Spine* and *Back Pain*.

The site also includes instructive material about the *Psychosocial Flags Framework* and a short promotional video entitled *Get Back Active* [The Stationery Office, UK, 2009]. This DVD, which is based on *The Back Book*, was the winner of the 'Creative Excellence' award at the US International Film and Video Festival, and delivers evidence-based advice on overcoming back pain through a mixture of activities and positive thinking.

Finally, the now full-colour artwork program found within the book is available to download from the site and can be used for teaching purposes free of charge.

For full access to these additional resources on this website please register at www.biomechanicsofbackpain.com.

Chapter 1

Introduction

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Who should read this book? 2
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MECHANICAL LOADING AND BACK PAIN

Mechanical loading is good for your back. The bones, muscles, ligaments and discs of the spine are all capable of adapting to physical exercise by becoming stronger and this makes them less vulnerable to injury. Old notions concerning the harmful effects of physical exercise are gradually being discredited, as is the use of bed rest as a treatment for back pain. Instead, current research emphasises the importance of exercise in maintaining the health of the musculoskeletal system. The new threats to spinal health are considered to be genetic inheritance, which exerts a strong influence on the risk of spinal degeneration, and the human personality, which influences all aspects of back pain behaviour, including recovering from it. The 'back pain revolution' is how one leading expert has summarised these changes in attitudes.[1507]

However, it would be wrong to assume that genetic influences on spinal pathology somehow reduce the importance of mechanical or biochemical factors: on the contrary, genes exert their influence by affecting the mechanical, biochemical and metabolic properties of spinal tissues. Likewise it is a mistake to assume that psychosocial factors such as depressive tendencies and work dissatisfaction are important causes of back pain; infact they explain people's responses to pain rather than the pain itself. Recent pain provocation studies have not only located the anatomical origins of severe back pain, they have also confirmed that patients' characteristic back pain is often reproduced when the affected tissue is mechanically stimulated. These considerations have also been acknowledged[1507]: 'The balance of back pain research has perhaps swung too far towards these psychosocial issues, to the neglect of the physical. . . . Hopefully, the pendulum will swing back'.

PURPOSE OF THIS BOOK

The purpose of this book is not just to push the pendulum back again, but to help bring it to rest in a balanced position where all of the factors which influence back pain are given due attention. The title *The Biomechanics of Back Pain* does not imply a bias towards mechanical explanations of back pain; it merely reflects the fact that mechanical factors are the most obvious and preventable influences in a complex natural history which involves biological and psychological processes as well as mechanical ones (hence 'biomechanics'). The title is also intended to imply a mechanistic approach to back pain, in which our knowledge of the biological and physical sciences is applied to explaining the various chains of events which lead to back pain. Back pain is certainly a difficult and multifaceted problem, but it is not so difficult that we must abandon the normal scientific method in favour of some vague holistic approach. Back pain should be explained, not explained away. The varied background of the authors of

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this book reflects a desire by them, and by the publishers, to produce a balanced and integrated text which incorporates all of the recent scientific advances in our understanding of back pain.

THE AUTHORS

Mike Adams graduated in natural philosophy (physics) before studying for a PhD in spinal mechanics. Much of his research has involved mechanical testing of cadaveric spines and articular cartilage, but this strong biomechanics influence has been moderated by 20 years of teaching musculoskeletal biology to science students. His primary interest in back pain is to explain the interactions between mechanical and biological (cell-mediated) events which lead to degenerative changes within spinal tissues.

Nik Bogduk began studies into back pain while still an undergraduate medical student. He investigated the nerve supply of the lumbar spine with the view to establishing the possible sources of back pain. After graduating in medicine, he pursued a PhD in neurology in which he developed diagnostic procedures for back pain and for neck pain, based on his anatomical studies. His work subsequently progressed to apply those diagnostic procedures and others to determine the relative prevalence of different sources of back pain and neck pain, and to evaluate neuroablative surgical procedures for the treatment of pain. In the course of these clinical studies he continued to contribute to basic sciences on the anatomy of spinal muscles and the kinematics of spinal movement.

Kim Burton graduated as an osteopath before moving into research and undertaking a PhD in the biomechanics and epidemiology of back pain. Subsequent research involved epidemiological studies of different occupational groups, with a focus on the relative influence of psychosocial and ergonomic factors on disability due to back pain. More recently his research has been in the clinical environment, developing and testing interventions addressing psychosocial factors as obstacles to recovery. He has been involved in the development of the UK primary care and occupational health guidelines for the management of low-back pain, as well as the European guidelines on prevention in low-back pain. He is an Honorary Fellow of the Faculty of Occupational Medicine, and is the Editor-in-Chief of *Clinical Biomechanics*.

Trish Dolan graduated in biological sciences before concentrating on exercise and muscle physiology for her PhD. This was followed by postdoctoral experience in a biomechanics tissue-testing laboratory, and her subsequent research has continued to straddle the boundaries of physiology and biomechanics. Her primary research interests include the assessment of spinal loading in vivo, quantification and analysis of muscle function, sensorimotor control mechanisms and vertebral augmentation.

WHO SHOULD READ THIS BOOK?

The book has evolved from seminars in musculoskeletal tissues given by two of the authors (MA and TD) to final-year undergraduate students in anatomical science, and to postgraduate students of physiotherapy, orthopaedic surgery and ergonomics. This knowledge base has been augmented by the anatomical, epidemiological and clinical expertise of the other authors. The book is intended primarily for those who treat back pain, including physiotherapists, osteopaths, chiropractors, general practitioners, spine surgeons, occupational health professionals and nurses. It may also interest advanced undergraduate science students, ergonomists and those involved in personal injury litigation.

Very little previous knowledge of musculoskeletal tissue biology or biomechanics is required, because introductory chapters are included to explain the concepts and terminology used later in the book. However, in order to do justice to the many controversies regarding back pain, certain areas of the research literature have been analysed in more detail, and with more rigour, than is customary in undergraduate texts.

INTRODUCTION TO INDIVIDUAL CHAPTERS

Later sections of Chapter 1 define all biomechanical terminology used later in the book. Chapters 2–4 then describe the functional anatomy of the spine, including the overlying muscles and fascia. Structure and function are conveniently described together, but where a particular function is considered to be controversial or difficult to understand, reference is made to the relevant sections later in the book.

The provocative question 'where does back pain come from?' is tackled in Chapter 5. A satisfactory answer could be offered on the basis of pain provocation and pain-blocking studies alone, but additional sections in this and the previous chapter attempt to link back pain to the underlying neuroanatomy, and to common diagnostic syndromes. The evidence from this chapter justifies the emphasis placed on intervertebral discs in subsequent sections of the book.

Chapter 6 reviews the epidemiological evidence concerning the causes of spinal pathology, pain and disability. This information is essential to understand the relative importance of mechanical and other influences in the aetiology of back pain. It is a key chapter, which justifies the title and scope of the entire book.

The biology of spinal tissues is considered in Chapter 7. Some knowledge of the interactions between cell

metabolism and mechanical loading is required to appreciate why loading is sometimes beneficial to the spine, and sometimes harmful. This chapter also introduces concepts and terminology which are used in later sections on spinal growth, ageing and degeneration.

Chapter 8 describes how the spine develops before birth, grows to maturity and then declines into old age. Care is taken to discuss only those changes which are inevitable (and therefore 'constitutional') so that they might later be distinguished from spinal 'degeneration' (Ch. 15) which afflicts some people much more than others, usually in middle age.

Before considering how the spine responds to mechanical loading, it is necessary to consider the origins and magnitude of the forces applied to it during the activities of daily living. Spinal loading is analysed in Chapter 9.

The normal response of the thoracolumbar spine to non-damaging forces is described in Chapter 10. This indicates how each spinal structure has a specific job to do, and is a prerequisite to understanding mechanical dysfunction and failure. Wherever possible, qualitative descriptions are supported by experimental measurements, because it is generally true that you do not really understand a mechanism until you have measured it. To give an example, the observation that intervertebral discs bulge radially outwards when compressed may seem to be of some clinical interest – until, that is, you learn that the bulge is generally a small fraction of 1 mm, even when the compressive force is several times body weight!

Chapter 11 describes mechanisms of injury and fatigue failure in each spinal structure. It is the largest chapter, and primary focus of the book. Intervertebral disc failure is treated in particular detail, and numerous illustrations are included to give the reader a feel for normal and dysfunctional discs.

Cervical spine anatomy and biomechanics are considered briefly in Chapter 12. Much less is known about the cervical spine compared to the lumbar spine, so this chapter necessarily lacks detail. However, it is instructive to compare the two regions in order to give insight into cervical pathology and pain.

Many clinicians will require little convincing that back pain can arise in the apparent absence of injury or degenerative changes. Chapter 13 suggests that 'functional pathology' arises from high localised stresses within innervated tissues, and it shows how stress concentrations can be generated by small changes in posture, and intensified by time-dependent 'creep' loading.

The important and growing topic of sensorimotor control is introduced in Chapter 14. Muscles are required to move, stabilise and protect the underlying spine, but their function can be compromised by factors such as soft-tissue creep, muscle fatigue and pain.

Chapter 15 describes the various manifestations of spinal degeneration, including intervertebral disc degeneration, apophyseal joint osteoarthritis and osteoporosis. Attempts are made to explain the relative contributions of genetic inheritance, cell metabolism and mechanical loading to the key process of intervertebral disc degeneration, and how disc failure can lead on to a 'degenerative cascade' involving other spinal tissues.

This leads directly to possibilities for preventing back pain (Ch. 16) and for treating it conservatively (Ch. 17). The evidence from recent clinical and epidemiological research is shown to be consistent with the basic science presented in previous chapters. The old view that mechanical loading is always bad for the back is exposed as a fallacy, and the potential benefits of various physical, biological and psychosocial interventions are described, with detailed reference to the latest published international guidelines. As an antidote to the nihilism of the guidelines, Chapter 17 ends with some practical advice from the authors for preventing (and coping with) back pain.

The conceptual benefits and drawbacks of spinal surgery are outlined in Chapter 18, and a detailed review of current procedures is given in Chapter 19. This latter chapter has been contributed by a leading spine surgeon who is renowned for his willingness to submit surgical practice to scientific scrutiny.

Financial compensation and personal injury litigation are considered by some experts to be a natural consequence of chronic back pain coupled with ineffective treatment. Others view them as an important cause of back pain reporting, and subsequent disability. Chapter 20 shows that there is some truth in both points of view, but concludes nevertheless that certain spinal disorders, including disc prolapse, can often be attributed to mechanical loading of vulnerable tissues. The nature of tissue 'vulnerability', and its medicolegal implications, is a key issue in this chapter.

The concluding Chapter 21 summarises and emphasises the main themes of the book. It suggests that cell-mediated degenerative changes are often a consequence rather than a cause of tissue failure, and it attempts to explain why the links between spinal pathology and pain are so complex.

BIOMECHANICAL TERMS AND CONCEPTS

Certain words and concepts used later in the book are explained here for ease of reference. These notes are intended to provide helpful explanations for typical readers of the book, rather than rigorous definitions for the specialist.

Force

Force is an action exerted on a body which causes it to deform or to move. It is a **vector** quantity which has a magnitude (the size of the force) and a direction. The unit

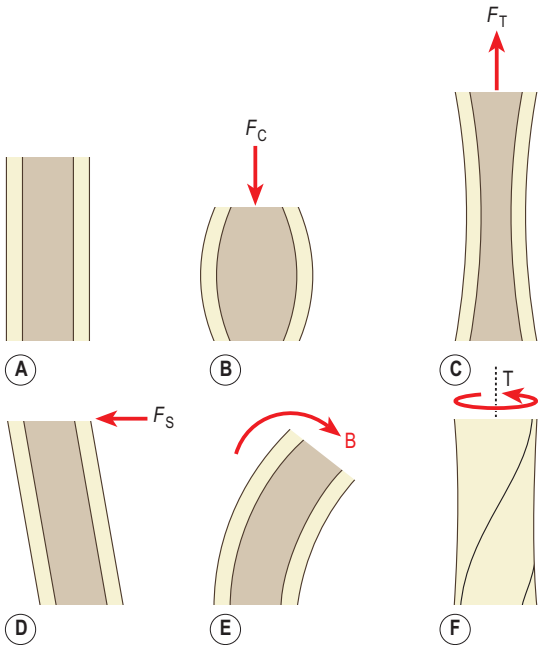


Figure 1.1 The effects of different types of forces acting on a solid object. (A) No forces acting; (B) compressive force, F_C; (C) tensile force, F_T, (D) shear force, F_S, (E) bending moment, *B*; (F) torsional moment, or torque, *T*.

of force is the newton (N). Approximately, 9.81 N = 1 kg = 2.2 lb.

A force is **compressive** if it compacts an object, **tensile** if it pulls it apart, and **shear** if it acts to deform the object without compacting or stretching it (Fig. 1.1).

A force can be represented (in two dimensions) by two **components** which act in convenient directions, usually at right angles to each other, as shown in Figure 1.2. 'Resolving' forces into components is a useful means of adding together two (or more) forces which act in different directions: the component forces can easily be summed, and then used to reconstruct the 'resultant' of the two original forces.

Mass

The mass of an object is the quantity of matter it contains, and represents the resistance of that body to being moved quickly (i.e. being accelerated). Mass simply has a magnitude, and so is a **scalar** quantity. The unit of mass is the kilogram (kg).

Weight

The weight of an object is the force exerted on it by the gravitational pull of the Earth. According to Newton's second law of motion:

$$\text{Force} = \text{mass} \times \text{acceleration} \quad [1]$$

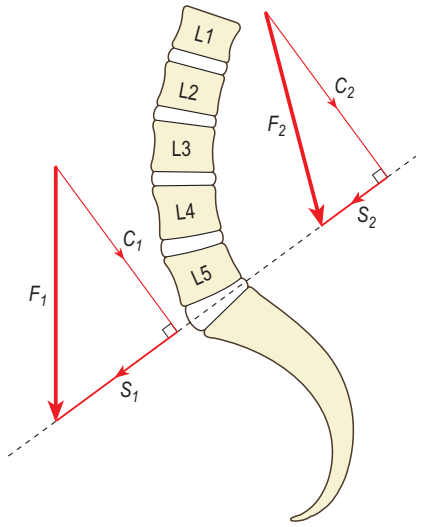


Figure 1.2 F_1 and F_2 represent the abdominal and back muscle forces acting on the lumbar spine. Because F_1 and F_2 act in slightly different directions, they cannot simply be added together to give the overall resultant force on the spine. To calculate the resultant, it is necessary to represent each force by two components, *C* and *S*, which act in two directions at 90° to each other. The components are added up to give the total force acting in these two directions (i.e. $C_1 + C_2$, and $S_1 + S_2$). Then the overall resultant force, *R* (not shown), acting on the L5–S1 disc, is given by: $R^2 = (C_1 + C_2)^2 + (S_1 + S_2)^2$. When adding forces in this manner, it is useful to calculate components in two meaningful directions, in this case, perpendicular to and parallel to the L5–S1 intervertebral disc.

so the weight of an object is given by $(m \times g)$, where m is its mass, and g the acceleration due to gravity. g depends on the height above sea level, falling to zero in outer space. Therefore, the weight of an object also diminishes with height above sea level. For this reason, weight should not be confused with mass. Equation [1] enables the unit of force (N) to be expressed in terms of the more familiar unit of mass (kg): 9.81 N = 1kg. This is approximate only, because the acceleration due to gravity is not exactly 9.81 m/s^2.

Stress

This is the intensity of loading, equal to the force exerted divided by the area over which it is applied. The unit of stress is the mega-pascal (MPa): 1 MPa = 1 N/mm^2. 1 MPa is equivalent to a 10-kg weight being applied to an area the size of a fingernail. A **shear stress** is equal to the shear force divided by the area over which it is applied.

Fluid

A fluid is a substance with such little rigidity that it deforms to take the shape of its container. In a fluid, shear stresses

are very small, so there is little resistance to the substance spreading out to equalise the pressure within it. In a static fluid, pressure does not vary with direction (e.g. vertically or horizontally) or with location.

Pressure (or hydrostatic pressure)

This is the intensity of loading within a fluid. It has the same units (MPa) as stress and so the two are often confused, but they should not be, because stress refers to solids and pressure to fluids. In a healthy intervertebral disc, the nucleus behaves like a fluid whereas most of the annulus behaves like a fibrous solid. Therefore the intensity of loading throughout the nucleus can be given by a single scalar quantity, the intradiscal pressure, whereas the intensity of loading within the annulus must be described by stresses which vary with location and direction.

Displacement

Displacement defines the location of one point relative to another. It is a vector quantity which has a magnitude (the **distance** between the two points) and a direction. Units are metres (m), millimetres (mm), micrometres (μm) or nanometres (nm). 1000 nm = 1 μm; 1000 μm = 1 mm; 1000 mm = 1 m. Approximately, 25.4 mm = 1 inch.

Velocity

This is the rate of change of displacement with time. Again, it is a vector quantity with a magnitude (the **speed**) and a direction. Units are metres/second (m/s).

Acceleration

This is the rate of change of velocity with time. It is another vector quantity with magnitude (acceleration) and a direction. Units are metres/second/second (m/s^2).

Strain

This is the amount an object deforms when a force is applied to it.

$$\text{Strain} = \text{change in length/original length} \quad [2]$$

Strain can be expressed as a fraction or as a percentage, so if the length of an object was increased by half, the strain would be 0.5 or 50%. Small deformations of stiff materials such as bone can be expressed in microstrains, where 10000 microstrains is equivalent to a strain of 1%.

Energy

Energy and **work** are essentially the same thing. If a force f is applied to an object in order to move it a distance d, then the work done is equal to $f \times d$. If the object is raised vertically against gravity, then it gains energy (in this case, potential energy) equal to the work done in moving it. If the object is allowed to fall, its potential energy is converted to energy of movement, or kinetic energy. (In fact, the kinetic energy of an object of mass m moving at a velocity v is equal to $\frac{1}{2}mv^2$.) Energy can transform itself into many other forms, including heat, and the unit of energy (the joule) is defined in terms of heat rather than forces and distances.

Momentum

Momentum is the mass of an object multiplied by its velocity. Bodies with a lot of momentum require a lot of stopping!

Bending moment

This is a measure of the turning or bending effect of a force which is applied to an object. It is equal to the size of the force (in newtons) multiplied by the lever arm (in metres) between the force and the chosen centre of rotation, so its units are newton metres (Nm). Note that any location can be chosen as the centre of rotation, and that the bending moment of a given force about each centre of rotation will be different (Fig. 1.3). For example, when a person bends forwards, the weight of the person's upper body (a force!) exerts a different bending moment about the centre of each of the intervertebral discs. A bending moment can be specified relative to the centre of rotation of the disc, or relative to its geometric centre, or indeed relative to any other point.

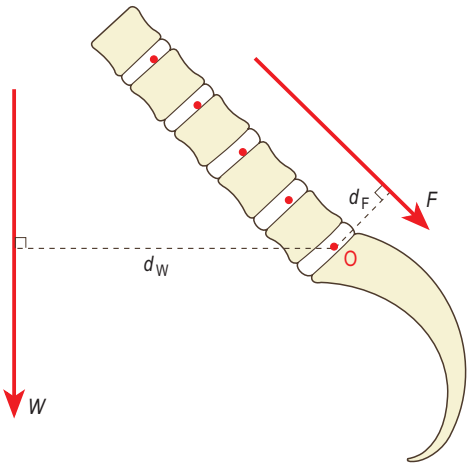


Figure 1.3 The moment generated by a force is equal to the magnitude of that force multiplied by the length of its lever arm. In this example, body weight W exerts a flexor moment of $W \times d_W$ about the centre of rotation O. No movement occurs if this is balanced by the extensor moment $F \times d_F$, generated by the back muscle force F. Moments can be calculated relative to any point whatsoever, but it is usual to select a point which coincides with a physical pivot, such as the centre of rotation within each intervertebral disc.

Torque

This is the equivalent to a bending moment except that the applied force acts to twist a body (Fig. 1.1) rather than to bend it. Its units are also newton metres (Nm).

Stiffness and strength

Stiffness is a measure of how strongly an object resists being deformed. It is normally measured as the deforming force (in newtons) divided by the deformation it causes (in millimetres) so a convenient unit of stiffness is the newton/millimetre (N/mm). If a biological tissue is referred to as being 'non-linear' it means that its stiffness increases as the applied load increases, so that a graph of deformation against applied force is curved, as shown in Figure 1.4. Stiffness is then measured as the gradient of the graph at any specified level of force (or deformation). Strength is the force (or stress) at which an object is damaged. Because the stiffness of most biological tissues depends on the force applied (Fig. 1.4), it cannot be used to predict strength, and stiffness and strength should not be confused.

Damage

Damage can be defined as a permanently impaired resistance to deformation, and is indicated on a force deformation graph by the first fall in stiffness (reduction in gradient). The point on the graph at which this occurs is the 'elastic limit' (Fig. 1.4). Any deformation occurring beyond the elastic limit is 'plastic' (non-recoverable) deformation which remains as a 'permanent set' when the object is unloaded. Sometimes, an 'ultimate strength' is defined as the force (or stress) at which the stiffness (gradient) not only reduces, but falls to zero. Warning! These concepts were developed to explain engineering materials, and 'permanent' changes can sometimes be reversed in living tissues.

Modulus

Young's modulus is a measure of how stiff a material is, and is equal to applied stress divided by strain. Unlike stiffness, which describes an object, modulus is independent of specimen size.

Strain energy, hysteresis and toughness

The work done in deforming an object is indicated by the area under a force deformation graph (Fig. 1.5). This work

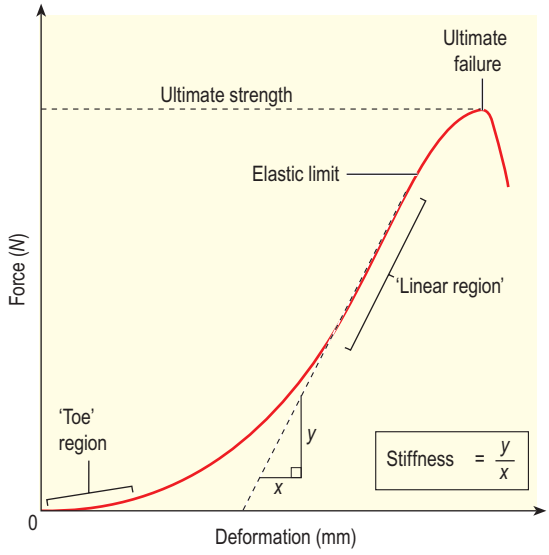


Figure 1.4 Typical force deformation graph obtained when stretching or compressing a biological tissue. In the toe region, deformation increases rapidly with increasing force, indicating that the stiffness of the specimen is low. (In some tissues, this region of low stiffness is attributable to straightening out the crimp structure of collagen fibres.) At higher loads, there is often a linear region in which the stiffness is approximately constant. The elastic limit marks the point where stiffness begins to fall, and this usually indicates that the specimen is starting to be damaged. Ultimate failure occurs when the stiffness falls to zero, and the force at this point is the (ultimate) strength of the specimen.

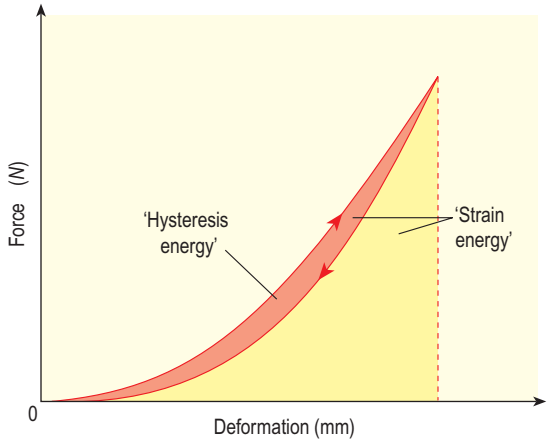


Figure 1.5 Typical force deformation graph for a biological tissue which is subjected to a non-damaging loading cycle. The unloading part of the curve (indicated by the downwards-pointing arrow) is below the loading curve, indicating that specimen deformation is greater for the same applied load. The area under the loading curve has units of energy (force × distance moved) and in fact this area represents the work done in deforming the specimen, or strain energy. Most of the strain energy is returned when the specimen is unloaded, but a small proportion is lost as heat. This small fraction is the hysteresis energy and is indicated by the hatched area between the loading and unloading curves.

is stored by the object as 'strain energy', and any body which can absorb a lot of strain energy before it is damaged is called 'tough'. A tin can is tough because it is strong and deformable, whereas a wine glass is the opposite ('brittle') because it cannot deform sufficiently to absorb much strain energy. When the deforming force is released, the object returns towards its original shape, and the strain energy is released. If the object is perfectly 'elastic', then the original shape is exactly regained, and all of the strain energy is recovered. However, many biological tissues exhibit a certain amount of inelastic deformation, in which some of the stored strain energy is lost as heat, and the original shape is not regained immediately. The non-recovered strain energy is referred to as 'hysteresis energy', and can be measured as the area between the loading and unloading curves (Fig. 1.5). Hysteresis energy is responsible for warming up any object that is repeatedly deformed and released: think of a squash ball after a hard game, or a small packet of butter after being squeezed repeatedly.

Creep

'Creep' is time-dependent deformation (or strain) under constant load (Fig. 1.6). In most soft biological materials, creep occurs because water is slowly expelled from the loaded tissue. However, other mechanisms of creep exist, and the lead on a church roof creeps over many years because of gradual relative slipping of adjacent atoms within the rigid material. Creep arising from fluid flow can usually be reversed: when the loading is reduced, the expelled fluid is sucked back in again, rapidly at first, but then slowing down later.

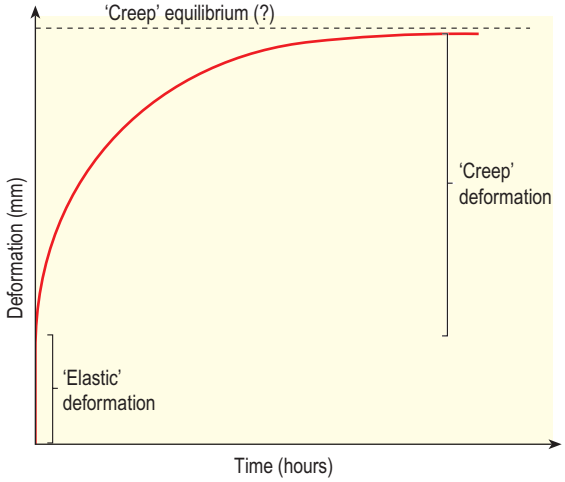


Figure 1.6 Creep curve for a typical biological specimen. When a constant force is initially applied, there is an immediate elastic deformation. If the force is not removed, then further creep deformation occurs as water is expelled from the specimen. Creep is rapid at first, but usually approaches an equilibrium as the water expulsion slows down. The word 'creep' can be used to denote the time-dependent deformation itself, or the process which causes it.

Tissues such as annulus fibrosus and articular cartilage are termed **poroelastic** because they can behave rather like an elastic body if they are loaded quickly (i.e. they spring back to shape as soon as the load is removed) but when loaded slowly, they creep, as fluid is expelled through tiny pores in the tissue. The term **biphasic** is also used to describe these tissues, because their fluid phase (water) is capable of moving relative to its solid phase (collagen and proteoglycans). Note, however, that articular cartilage and annulus fibrosus do not contain any macroscopic pores filled with fluid: the solid and liquid phases are mixed at the molecular level to form a fibrous solid, and the intensity of loading within these tissues must be characterised by stresses, not a pressure. Importantly, cells within these tissues do not simply experience a fluid pressure. On the contrary, they are deformed by unequal stresses acting in different directions.

Fatigue failure

A structure can be damaged by applying a high force to it once, or a smaller force to it many times. Small forces can create microscopic damage, perhaps in the form of tiny cracks, or a small plastic deformation, which would pass unnoticed if the force was applied and removed only once. However, after a large number of loading cycles, the microscopic damage can accumulate until the entire weakened structure fails, even though the applied loading remains relatively low. This is 'fatigue failure', and the process is often referred to as 'fatigue'. Fatigue failure can occur after only a few loading cycles if the applied load is greater than 60% of the strength of the structure, or it may require millions of loading cycles if the load is below 30% (Fig. 1.7). Sometimes a structure or material has a 'fatigue limit': a force below which fatigue failure never occurs, no matter how many loading cycles are applied. Fatigue explains how engine vibrations can eventually cause aeroplane wings to fall off, and why athletes can suffer so-called 'stress fractures' of bones during intense training or competition.

Cube-square law

If a solid object is scaled up in size, its volume (and therefore its weight) will increase approximately in proportion to its length cubed. However, its area or 'footprint' will increase in proportion to its length squared, so the compressive stress (weight per unit area) acting on the base of the object will steadily increase. If the scaling-up continues, the object will eventually crush itself. This general principle of scaling-up explains why polystyrene can be used to make a model bridge, but not a real bridge, and

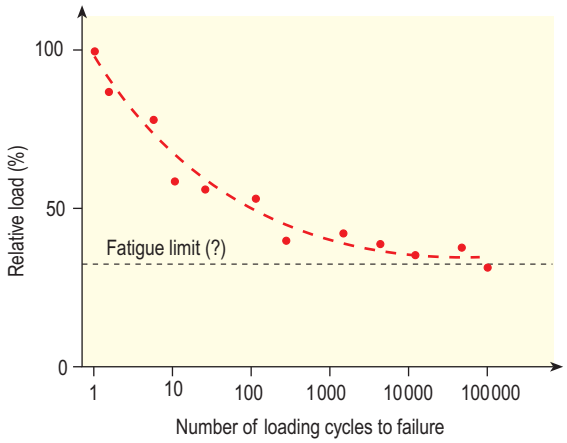


Figure 1.7 Typical fatigue curve showing how the strength of biological specimens decreases markedly with the number of loading cycles applied. The relative load (or stress) is the percentage of the load required to cause failure in a single loading cycle. In some (but not all) specimens there is a fatigue limit, which defines a threshold load below which fatigue failure never occurs, no matter how many loading cycles are applied.

why an elephant cannot fall as far as a mouse without hurting itself. The cube-square law is far from accurate, but it is often useful when attempting to interpret the significance of animal experiments to human beings. In general, large structures must be made from stronger materials than small structures.

Biomechanics and aesthetics

Biomechanical principles determine that the main bulk of each limb muscle should lie near the top of the limb or limb segment, so that the proximal tendon is much shorter than the distal (Fig. 1.8). The weight of the distal limb is therefore minimised, and so can be moved more quickly. This is why ballet shoes must be extremely light. A curious consequence of this principle is the widespread aesthetic judgement that slim ankles and wrists are desirable, whereas thighs and calves should have good shape. A well-tapered leg is best suited to rapid movements, to survival, and hence to attractiveness in a mate!

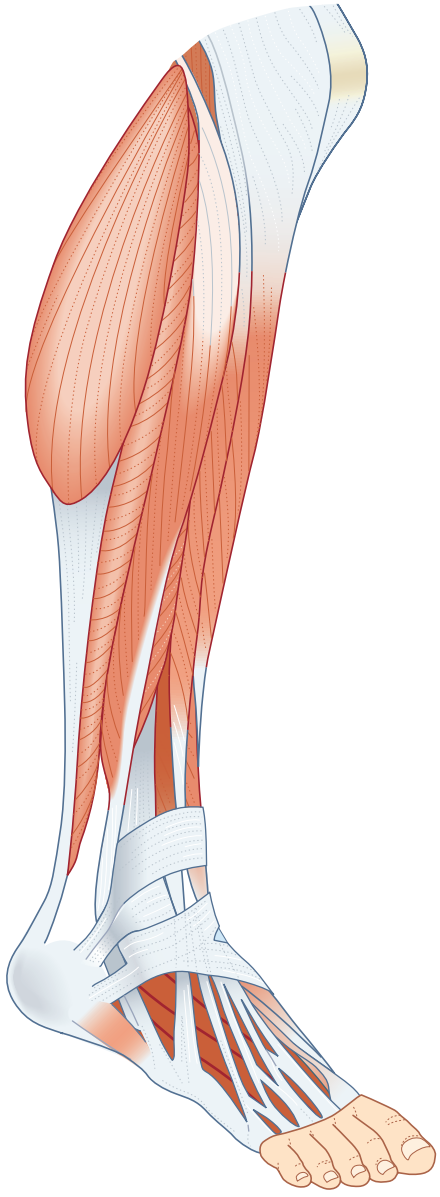


Figure 1.8 The calf muscle (gastrocnemius) has a long distal tendon (the Achilles tendon) but only a short proximal tendon, so most of the mucle bulk lies high up the leg, near the knee. Other limb muscles are similarly asymmetrical, ensuring that distal limb mass is minimised, so feet and hands can be moved more quickly. In this way, biomechanical benefits may provide a darwinian explanation for the widespread aesthetic appreciation of 'a shapely leg'!

Chapter 2

The vertebral column and adjacent structures

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When endowed with muscles and other surrounding tissues, the vertebral column is converted into a structure known as the spine. The vertebral column, therefore, constitutes the skeleton of the spine. The following account is based primarily on the thoracolumbar spine, but is mostly applicable to the cervical spine also. Some anatomical differences in the cervical spine are described in Chapter 12.

DESIGN FEATURES

In mechanical terms, the vertebral column is a device that:

- provides axial rigidity to the trunk
- enables certain movements between the skull and pelvis.

Secondarily, the vertebral column:

- affords an origin for muscles of the trunk and limbs.

The individual components of the vertebral column, in one way or another, are designed to contribute to one or other of these functions. Conversely, disorders of the spine may present with impairment of one or other of these functions. It is, therefore, pertinent to appreciate how the elements of the spine are designed to subserve their functions, not only to understand normal anatomy but also to understand the effects of pathology.

Rigidity

Axial rigidity is the cardinal feature that distinguishes vertebrates from soft-bodied molluscs. In biomechanical terms, rigidity means stiffness, or resistance to bending or collapse. This property is essential for the ability of humans to walk upright in the Earth's gravitational field.

In order to provide rigidity, the vertebral column consists largely of bone, in the form of vertebrae, named by number, from above downwards. If rigidity was its sole function, a single bone would suffice, acting as a strut between the skull and pelvis. A single bone, however, would not allow mobility. For that reason multiple bones form the skeleton of the spine.

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The notion of a single bone is, however, not totally absurd, because for a variety of reasons some individuals undergo surgical fusion of their spine, usually at one or two lumbar levels, but in some instances at up to five levels. Such patients effectively have their lumbar vertebral column converted to a single bone. Rigidity is maintained and, indeed, increased, but the cost is loss of mobility.

Separation

The essential component of each vertebra is its vertebral body. This is a block of bone, rectangular in profile in a side view, with flat superior and inferior surfaces (Fig. 2.1A), and semicolumnar in top view, with curved anterior and lateral surfaces but a flat posterior surface (Fig. 2.1B). Because of the height of each vertebral body, the vertebral column is endowed with length, and thereby achieves separation of the skull from the pelvis. Separation is essential in order to provide space through which the skull can move relative to the pelvis. Without separation, the thoracic cage, for example, would clash against the pelvic brim and movement would be obstructed. The taller the vertebral bodies the greater the length of the spine, and the greater the possible range of movement.

Although the cervical, thoracic and lumbar regions of the vertebral column most commonly comprise seven, twelve and five vertebrae, respectively, variations do occur. For example, some individuals have four lumbar vertebrae; others have six. Changing the number of vertebrae changes the length of the lumbar spine and the potential mobility of the thorax. The clinical relevance of vertebral number lies in the naming of the last lumbar vertebra. Normally this is L5, but in a shorter lumbar spine it will be L4; in a longer lumbar spine it will be L6. In individuals with an abnormal number of lumbar vertebrae, disorders that normally befall L5 will affect L4 or L6 accordingly.

Compression

In fish, which live in a buoyant environment and are oblivious to the Earth's gravitational field, rigidity, separation and mobility are the only mechanical design requirements of the spine. However, any animal that ventures to be upright in the Earth's gravitational field inherits a liability resulting from the separation of the skull from the pelvis. Under the influence of gravity, the weight of the thorax, and of any load carried in the upper limbs, will exert a compression load on the vertebral column. Moreover, these loads are amplified by the contraction of the back muscles that control the position of the upright spine (Chs 3 and 9). Consequently, the vertebrae are designed to sustain axial compression loads.

Each vertebral body consists of an outer shell of cortical bone, much like a box (Fig. 2.2). Although strong, this shell is not strong enough to sustain the axial loads that are habitually exerted on the spine. Therefore, the vertebral bodies are reinforced internally by narrow struts of bone called trabeculae (Fig. 2.2). Basically, these are arranged in vertical and horizontal arrays (Fig. 2.3). The vertical trabeculae act like columns that transmit compression loads from the upper surface of the vertebral body to its

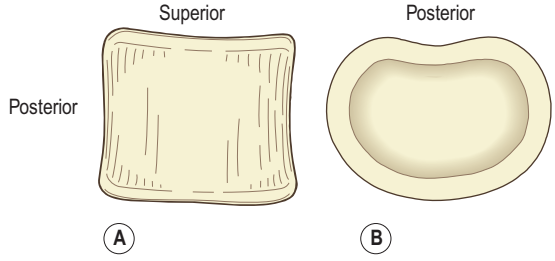


Figure 2.1 Side view (A) and top view (B) of a lumbar vertebral body.

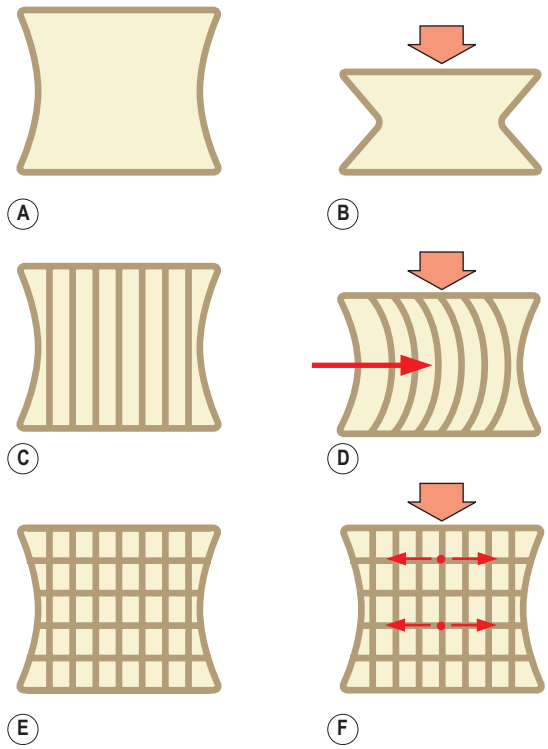


Figure 2.2 Reconstruction of the internal architecture of the vertebral body. (A) With just a shell of cortical bone, a vertebral body is like a box, and collapses (B) when a load is applied. (C, D) Internal vertical struts brace the box. (E) Transverse connections prevent the vertical struts from bowing, and increase the load-bearing capacity of the box. (F) Loads are resisted by tension in the transverse connections. *(From Bogduk (1997), with permission.)*

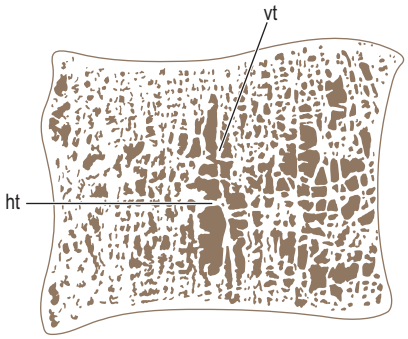


Figure 2.3 A sketch of a sagittal section through a lumbar vertebral body showing the appearance of its vertical (vt) and horizontal (ht) trabeculae.

lower surface. The horizontal trabeculae serve to reinforce the vertical trabeculae by preventing them from buckling sideways under large compression loads.

Absence of horizontal trabeculae weakens the vertebral body. Under load, the vertical trabeculae buckle and can fracture. Lacking the support of the vertical trabeculae, the cortical shell and, therefore, the entire vertebral body can subsequently be easily crushed. This phenomenon is of particular relevance to the condition of spinal osteoporosis (Fig. 8.7).

Mobility

In order to be mobile, the spine requires joints. The principal joints occur between the vertebral bodies. These joints have no formal name (other than 'the intervertebral amphiarthroses', which few people use), but they can be conveniently referred to as the interbody joints. They occur between the inferior surface of one vertebral body and the superior surface of the next. Each is a secondary cartilaginous joint, in which the vertebral bodies are separated by an intervertebral disc. The structure of these joints is such that they allow bending, twisting and sliding movements between vertebral bodies, and the total mobility of the spine is the sum of the mobilities of its joints.

INTERVERTEBRAL DISCS

The intervertebral discs are designed to separate consecutive vertebrae, thereby producing a potential space between them into which the vertebral bodies can dip and execute bending movements. In order to separate the vertebral bodies, each intervertebral disc must have height, but in order to allow movement, the tissue of the disc must be pliable. Meanwhile, the tissue must also be stiff and strong in order to sustain the compression loads between the vertebral bodies.

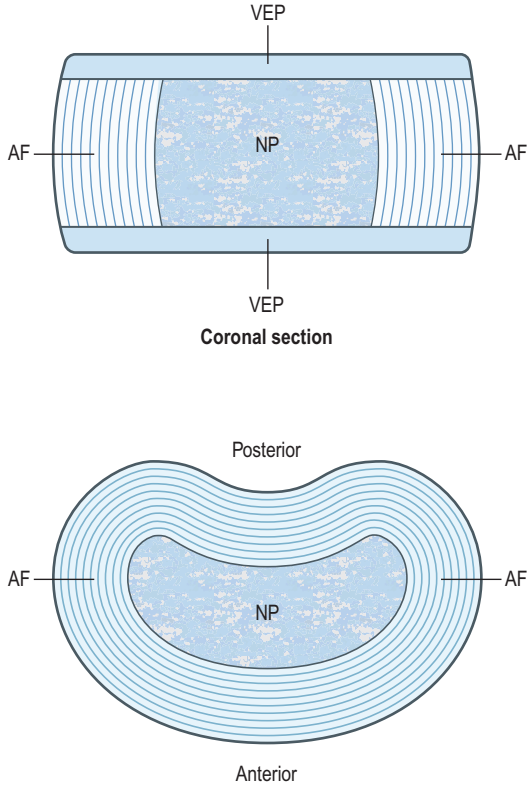


Figure 2.4 The basic structure of a lumbar intervertebral disc. The disc consists of a nucleus pulposus (NP) surrounded by an annulus fibrosus (AF), both sandwiched between two cartilaginous vertebral endplates (VEP). *(From Bogduk (1997), with permission.)*

The essential component of the intervertebral disc is the annulus fibrosus. This consists of some 10–20 sheets of collagen, called lamellae, tightly packed together in a circumferential fashion around the periphery of the disc (Fig. 2.4). While packed tightly together, these lamellae are stiff, and can sustain considerable compression loads. A suitable analogy is the stiffness of a telephone directory that is wrapped into a cylindrical shape and stood end-on. Nevertheless, being collagenous, the annulus fibrosus is sufficiently pliable that it can deform and thereby enable bending movements between vertebral bodies. However, herein lies the liability of the annulus fibrosus. If it buckles it loses its stiffness, and is less able to sustain compression loads. To prevent this, the annulus fibrosus requires the second component of the intervertebral disc – the nucleus pulposus.

The nucleus pulposus is a hydrated gel located in the centre of each disc (Fig. 2.4). When compressed, this

semifluid mass expands in a radial fashion. On the one hand this radial expansion is resisted by the surrounding annulus fibrosus, but on the other hand, the expansion braces the annulus fibrosus from the inside, thereby preventing it from buckling inwards and losing its stiffness. Cooperatively, the nucleus pulposus and annulus fibrosus maintain the stiffness of the disc against compression loading, but both tissues are sufficiently compliant that they allow some degree of movement between vertebral bodies.

The third components of the intervertebral disc are the superior and inferior vertebral endplates. These are plates of hyaline cartilage that cover the superior and inferior aspects of the disc, and bind the disc to their respective vertebral bodies (Fig. 2.4). Each endplate covers almost the entire surface of the adjacent vertebral body; only a narrow rim of bone, called the ring apophysis, around the perimeter of the vertebral body is left uncovered by cartilage.

That portion of the vertebral body to which the cartilaginous vertebral endplate is applied lacks a formal name, but can be referred to as the subchondral bone (of the vertebral body) or the bony vertebral endplate. It is, however, a component of the vertebral body and not a component of the disc, as is the cartilaginous vertebral endplate. Notwithstanding this distinction in nomenclature, mechanical disorders that affect the region of the endplate typically involve both the osseous and cartilaginous endplates simultaneously.

In addition to enabling bending movements between vertebral bodies, the intervertebral disc allows for twisting and sliding movements of small amplitude. These are resisted by tension developed in the collagen fibres of the annulus fibrosus, and their amplitude is a function of the elasticity and tensile stiffness of the annulus.

Microstructure

The annulus fibrosus consists mostly of type I and type II collagen. The concentration of type I collagen is greater towards the periphery of the annulus, while that of type II collagen is reciprocally greater towards the centre of the disc. This distribution of type I collagen matches the greater tensile role of the outer annulus fibrosus.

Within each lamella of the annulus fibrosus, the collagen fibres are arranged in parallel. They pass obliquely from one vertebral body to the next, at an angle of about 65° to the sagittal plane. However, as a rule, the fibres in each successive lamella are oriented in an opposite sense, with one layer inclined to the left, the next layer inclined to the right, and so on (Fig. 2.5). This alternating arrangement precludes any cleavage plane developing through the annulus, through which nuclear material might seep or burst, and is critical to the integrity of the disc. Moreover, the alternating orientation allows the annulus to resist tension in a variety of directions.

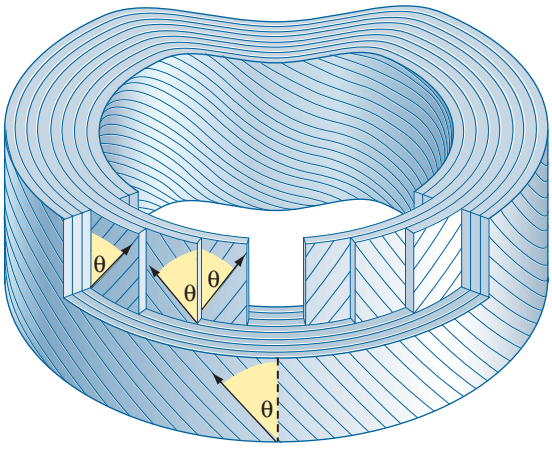


Figure 2.5 The architecture of the annulus fibrosus. Collagen fibres are arranged in 10–20 concentric, circumferential lamellae. The orientation of fibres alternates in successive lamellae, but their orientation with respect to the vertical (θ) is approximately the same, and measures about 65°. *(From Bogduk (1997), with permission.)*

Sliding movements between the vertebral bodies will be resisted by all those collagen fibres that are inclined in the direction of movement (Fig. 2.6A). Similarly, twisting movements will be resisted by those fibres inclined in the direction of movement (Fig. 2.6B). All fibres will contribute to resisting separation of the vertebral bodies (Fig. 2.6C).

In this regard, it is the outermost fibres of the annulus fibrosus that contribute most to resisting these movements. To that end, they are attached directly to bone, around the ring apophysis, and for that reason they are referred to as the ligamentous portion of the annulus fibrosus (Fig. 2.7). The inner fibres of the annulus do not attach to bone but insert into the vertebral endplate. Within the endplate they can be traced forming a continuous envelope around the nucleus pulposus. For this reason they are, at times, referred to as the capsular portion of the annulus fibrosus.

The nucleus pulposus consists largely of proteoglycans, which are large molecules consisting of complex sugars and protein (Fig. 7.13). They have the valuable property of being able to imbibe and retain large amounts of water. It is this property that endows the nucleus pulposus with its hydrodynamic properties. If the nucleus loses its proteoglycans, it can no longer hold its water, and the nucleus can no longer properly brace the annulus fibrosus. If that function is lost, the disc can no longer resist compression loads, and will be progressively compressed and narrowed under the loads of daily living.

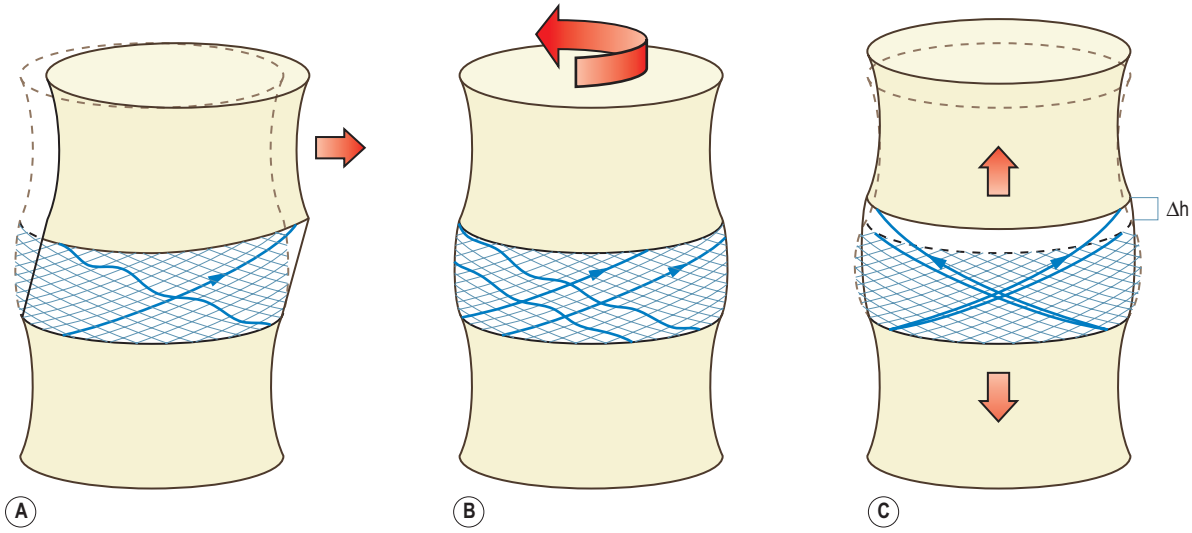


Figure 2.6 Mechanics of the annulus fibrosus. (A) Sliding movements between vertebral bodies are resisted by tension developing in those fibres of the annulus that are inclined in the direction of movement. Other fibres are relaxed by the displacement. (B) Twisting movements are resisted by those fibres lengthened by the movement. Other fibres are relaxed. (C) Separation of the vertebral bodies (Δ*h*) is resisted by all fibres, regardless of their orientation. *(From Bogduk (1997), with permission.)*

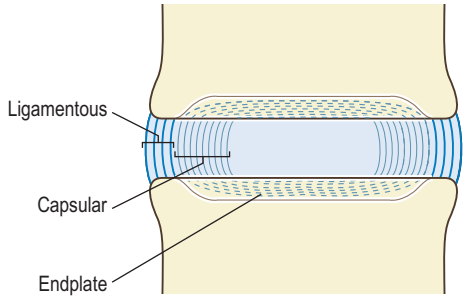


Figure 2.7 Detailed structure of the annulus fibrosus. The peripheral fibres attach to the ring apophysis and constitute the tensile, ligamentous portion of the annulus. The inner fibres surround the nucleus pulposus and constitute the capsular portion. They can be traced into the cartilage of the vertebral endplate, thereby forming a complete envelope around the nucleus. Because of these fibres the superficial parts of the endplate are fibrocartilage. The deeper parts are hyaline cartilage.

Disc height

Each lumbar intervertebral disc is 5–10 mm in height. Thoracic discs are somewhat narrower. Collectively, the intervertebral discs contribute approximately 25% to the length of the spine. During activities of daily living, when an individual is upright, water is squeezed out of the discs, and they each lose height. After rest in a recumbent position this height is restored, as water is re-imbibed. Disc height is fully restored at night, during sleep.

Disc height is preserved with age. Discs do not narrow because of age. Discs of the elderly have even been reported to be slightly higher than average,[1445] although this refers to the nucleus pulposus, which can sink into adjacent vertebrae if they are osteoporotic. However, disc narrowing can occur in certain disorders of the disc. Any disorder that disrupts or degrades the proteoglycans of the nucleus pulposus will impair their water-binding capacity, and compromise the ability of the disc to restore and maintain its height.

THE ESSENTIAL LUMBAR VERTEBRAL COLUMN

Five vertebral bodies and their respective discs constitute the essential components of the lumbar vertebral column (Fig. 2.8). From above downwards, the five vertebral bodies are named numerically as lumbar one to five, i.e. L1, L2, L3, L4 and L5. The intervertebral discs are numbered according to the vertebral bodies that each separates, i.e. L1–2, L2–3, L3–4, L4–5, and the last disc is known as the lumbosacral disc, or L5–S1.

Collectively the vertebral bodies and discs form a column that provides rigidity and length, and permits movements. The vertebral bodies and intervertebral discs strongly resist compression, and easily bear the loads of the thorax and upper limbs. Forward bending is achieved by each intervertebral disc being compressed slightly,

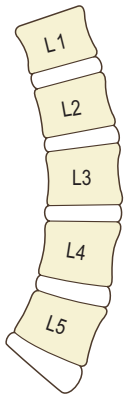


Figure 2.8 The essential lumbar vertebral column consists of the five lumbar vertebral bodies and their intervertebral discs.

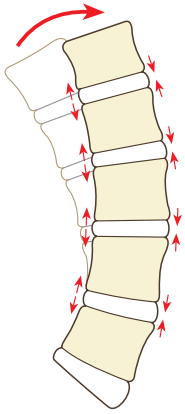


Figure 2.9 Forward bending of the vertebral column is achieved by compression of the anterior ends of the intervertebral discs, and resisted by tension in the posterior annulus fibrosus.

anteriorly, and is resisted by tension developed in the posterior annulus fibrosus (Fig. 2.9). Extension and lateral flexion are achieved by corresponding events in the opposite direction and in the coronal plane, respectively. Rotation of the lumbar spine is achieved by each disc allowing a small degree of twist, and is resisted by tension developed in the annulus fibrosus.

However, the vertebral bodies and discs are not the complete structure of the lumbar vertebral column. Alone these structures are relatively unstable and susceptible to injury. The annulus fibrosus is not strong enough, on its own, to resist excessive torsion of the lumbar spine without being damaged. Nor can the vertebral bodies and discs alone maintain a straight, or upright, posture; the discs are sufficiently compliant that the slightest axial load will tend to bend the column. In order to maintain stability, and to afford control of movements, the essential lumbar vertebral column requires additional elements. These are the posterior elements of the lumbar vertebrae.



Figure 2.10 A typical lumbar vertebra, comprising the vertebral body (VB) and the neural arch (NA).

POSTERIOR ELEMENTS

The posterior elements of the lumbar vertebrae (Fig. 2.10) are designed to control the position of the vertebral bodies. Forces may be exerted directly by muscles acting on the posterior elements, or indirectly by loads on the thorax trying to bend or twist the lumbar spine.

Towards the upper end of its posterior surface, each lumbar vertebral body is endowed with a pair of stout pillars of bone called the pedicles (Fig. 2.11B). These support the posterior elements, and transmit forces from them to the vertebral body, and vice versa.

From each pedicle, a plate of bone, called the lamina, projects towards the midline, in the manner of a sloping roof (Fig. 2.11D). At the midline, the two laminae fuse seamlessly. In a top view, the pedicles and laminae can be perceived as forming an arch, known as the neural arch, which together with the posterior surface of the vertebral body encloses a space and channel, behind the vertebral body, known as the vertebral foramen (Fig. 2.11E). By convention, the laminae are perceived to form the roof of the foramen, and the vertebral body to form the floor.

At the junction of its two laminae in the midline, each lumbar vertebra bears a spinous process which projects dorsally in the shape of the blade of an axe (Fig. 2.11A). Projecting laterally from the junction of the pedicle with its lamina on each side is a long, rectangular, flattened bar of bone called the transverse process (Fig. 2.11C). On its posterior surface, near its root, each transverse process bears a thick but narrow spike of bone called the accessory process (Fig. 2.11D). These several processes serve as sites of attachment for muscles that control the lumbar vertebral column, and endow these muscles with lever arms.

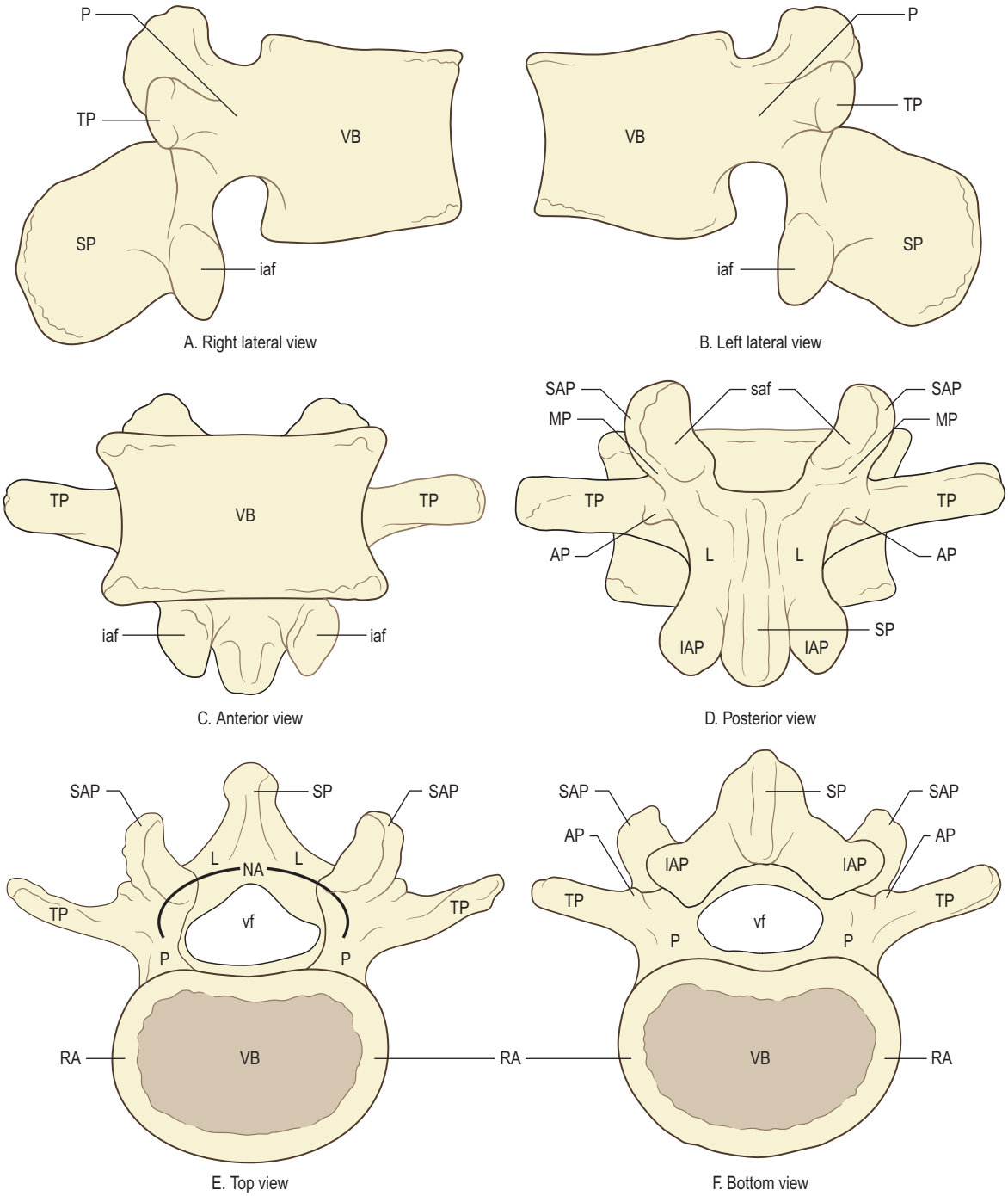


Figure 2.11 (A–F) The parts of a typical lumbar vertebra. VB, vertebral body; P, pedicle; TP, transverse process; SP, spinous process; L, lamina; SAP, superior articular process; IAP, inferior articular process; saf, superior articular facet; iaf, inferior articular facet; MP, mamillary process; AP, accessory process; vf, vertebral foramen; RA, ring apophysis; NA, neural arch. *(From Bogduk (1997), with permission.)*

From its superior, lateral corner, the lamina gives rise to an extension of bone called the superior articular process (Fig. 2.11E). On its medial surface, the superior articular process presents an articular facet that is covered by articular cartilage. On its dorsal surface, each superior articular process bears a small bump, known as the mamillary process, which serves as a site for muscle attachments.

From its inferior, lateral corner, the lamina gives rise to an inferior articular process that bears an articular facet on its lateral surface (Fig. 2.11B). The superior articular processes of one vertebra receive the inferior articular processes of the vertebra above to form synovial joints known as the zygapophyseal joints. These joints serve to enable certain movements of the lumbar vertebral column but to limit or prevent others.

THE COMPLETE LUMBAR VERTEBRAL COLUMN

When the posterior elements of the lumbar vertebrae are added to the essential vertebral column, they provide a series of interlocking bony elements behind the vertebral bodies and discs (Fig. 2.12). The laminae of consecutive vertebrae are separated from one another by a short interval, but consecutive vertebrae are articulated through the zygapophyseal joints. The complete lumbar vertebral column sits on the sacrum, articulating with it anteriorly through the L5–S1 intervertebral discs, and posteriorly through the lumbosacral (L5–S1) zygapophyseal joints.

When the vertebral foramina of the five lumbar vertebrae are longitudinally aligned, they form a series of arcades surrounding what can be perceived as a canal running behind the vertebral bodies and discs. This is known as the vertebral canal. Amongst other elements, the vertebral canal transmits the lower end of the spinal cord and the roots of the lumbar, sacral and coccygeal nerves (see Ch. 4). Routes of access to the vertebral canal occur in the form of passages between consecutive pedicles, behind each intervertebral disc and in front of the zygapophyseal joints at each level. These passages are called the intervertebral foramina (Fig. 2.12).

The resting shape of the intact lumbar vertebral column is a curve concave posteriorly. The basis for this curve is tension in the joints of the vertebral column and the ligaments that bind the lumbar vertebrae together.

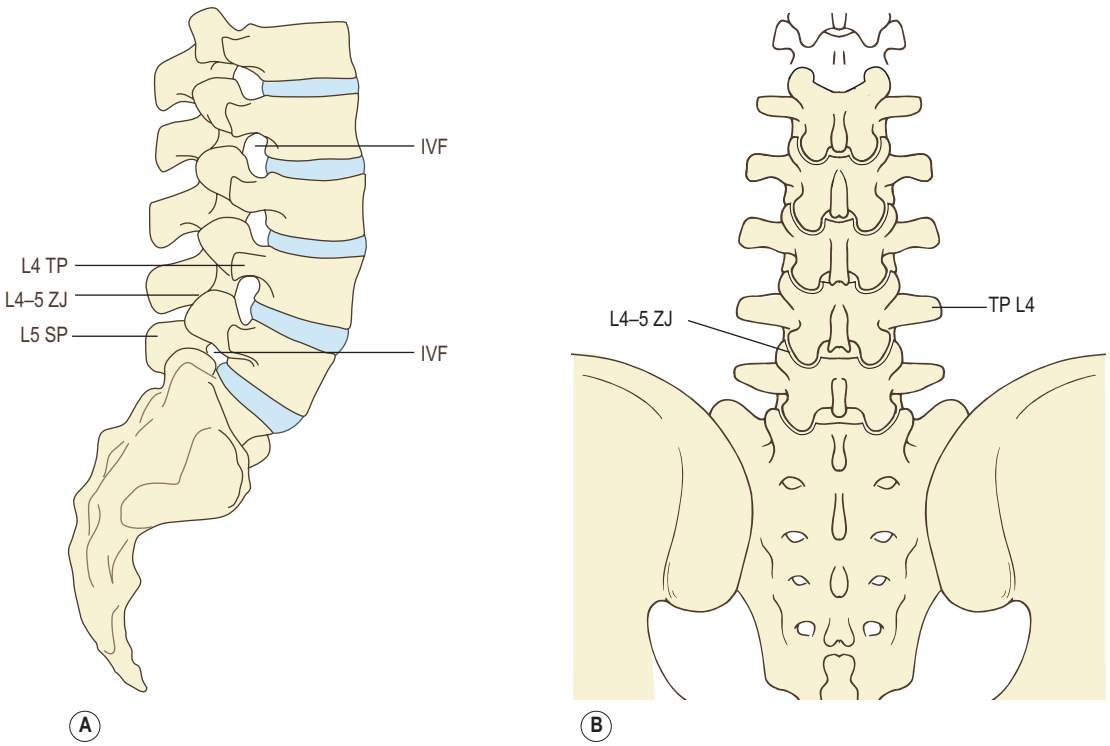


Figure 2.12 The complete lumbar vertebral column. (A) Side view; (B) rear view. TP, transverse process; SP, spinous process; ZJ, zygapophyseal joint; IVF, intervertebral foramen.

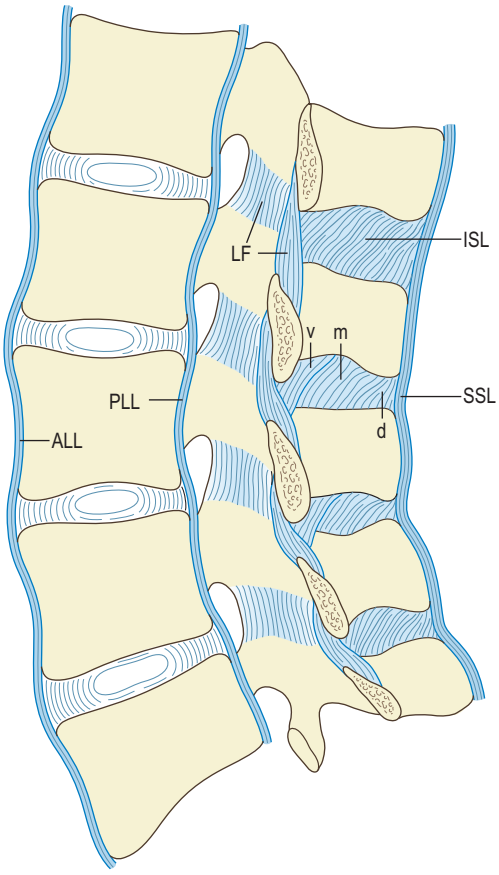


Figure 2.13 A median sagittal section of the lumbar spine to show its various ligaments. ALL, anterior longitudinal ligament; PLL, posterior longitudinal ligament; SSL, supraspinous ligament; ISL, interspinous ligament; v, ventral part; m, middle part; d, dorsal part; LF, ligamentum flavum, viewed from within the vertebral canal, and in sagittal section at the midline. *(From Bogduk (1997), with permission.)*

LIGAMENTS

Many of the structures called ligaments in the lumbar spine are not truly ligaments. Either they do not connect two bones, or they are too feeble to serve as ligaments.

The most definitive ligament is the ligamentum flavum (Fig. 2.13). It consists of fibres of elastin that connect the lower end of the internal surface of one lamina to the upper end of the external surface of the lamina below, and closes the gap between consecutive laminae. This is a very extensible ligament that stretches when the lumbar vertebral column bends forwards. It consists of elastin in order that, upon resumption of the neutral posture of the lumbar spine after flexion, the fibres of the ligamentum flavum can recoil and shorten without buckling. A ligament made of collagen could just as well resist flexion as does the ligamentum flavum, but it could not shorten. As a result it would buckle inwards towards the neural elements within the vertebral canal, with the risk of compressing them. The virtue of an elastic ligamentum flavum is that it ensures that the neural elements are always presented with a smooth flat surface.

The transverse processes are connected by thin sheets of collagen fibres. Although called the intertransverse ligaments, these structures are too insubstantive to function as ligaments. Rather, they constitute membranes that separate the ventral muscle compartment of the lumbar spine from its dorsal muscle compartment (Ch. 3).

The opposing edges of spinous processes are connected by collagen fibres referred to as the interspinous ligaments (Fig. 2.13). Although the ventral portions of these ligaments are distinctly ligamentous, their dorsal portions actually constitute tendinous fibres of the erector spinae muscle (Ch. 3).

A supraspinous ligament has traditionally been recognised, but this structure is not a ligament. It consists of tendinous fibres of various muscles (Ch. 3), and is lacking below L3.

In addition to the ligaments of the posterior elements, the lumbar vertebral column is reinforced by ligaments that connect the vertebral bodies. The posterior longitudinal ligament covers the floor of the vertebral canal (Fig. 2.13). Its fibres are attached to the posterior aspects of the lumbar vertebral bodies and to the intervertebral discs. It has short fibres that span consecutive vertebra, and longer fibres that span several vertebrae. The anterior longitudinal ligament covers the anterior aspects of the vertebral bodies and discs (Fig. 2.13). Its fibres are attached to the edges of the vertebral bodies. Many of its fibres, however, are not truly ligamentous, but constitute the prolonged tendons of the crura of the diaphragm.

The strongest ligament attached to the lumbar vertebral column is the iliolumbar ligament. Its fibres arise from the tip and borders of the transverse process of the fifth lumbar vertebra, and pass backwards and laterally to the ilium. They serve to anchor the L5 vertebra on the pelvic girdle, to prevent it from sliding forwards and from rotating.

ZYGAPOPHYSEAL JOINTS

The zygapophyseal joints provide an important locking mechanism between consecutive lumbar vertebrae. They are designed to block axial rotation and forward sliding of the lumbar vertebrae. By blocking axial rotation the joints protect the intervertebral discs from excessive torsion. By blocking forward slide they prevent the vertebral bodies from dislocating under the weight of the trunk when the spine is flexed forwards.

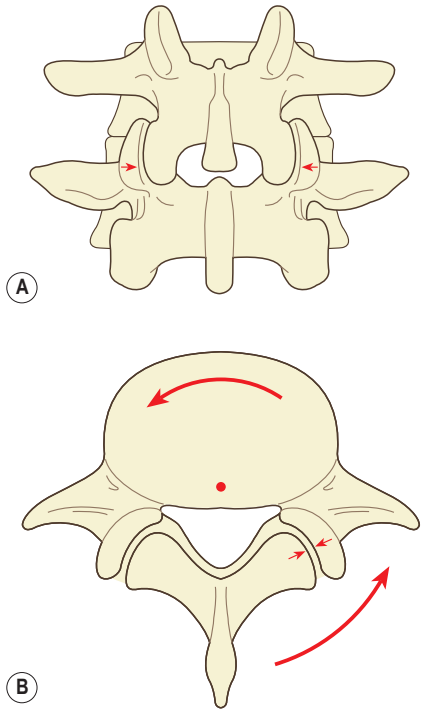


Figure 2.14 (A) A sketch of a posterior view of a lumbar zygapophyseal joint showing how the superior articular processes clasp the inferior articular processes laterally. (B) A top view showing how the superior articular processes block rotation of the inferior articular processes.

Axial rotation of the lumbar vertebrae occurs around a longitudinal axis that passes through the posterior third or so of the vertebral bodies and intervertebral discs. When rotation occurs about this axis, the posterior elements of the moving vertebra swing laterally, in a direction opposite to that of the rotation. To block this rotation, the zygapophyseal joints are arranged in such a way as to block the lateral displacement of the posterior elements.

Each pair of superior articular processes clasps the inferior articular processes of the vertebra above (Fig. 2.14A). The flat, medially facing facet of each superior articular process apposes the laterally facing facet of the inferior articular process. If the upper vertebra attempts to rotate to the left, its right inferior articular process will ram into the apposing superior articular process (Fig. 2.14B). This locking mechanism limits axial rotation at each intervertebral joint, and protects the intervertebral disc from torsion (Fig. 11.10).

In order to prevent forward slide, the inferior articular processes act as hooks. Projecting downwards from the pedicles, the inferior articular processes extend below the bottom of the vertebral body and engage the superior articular processes of the vertebra below, from behind (Fig. 2.15A). Consequently, if the upper vertebra attempts to slide forwards, its inferior articular processes hook on to the superior articular processes which oppose the motion and thereby prevent forward sliding. In order to exert resistance to the inferior articular processes, the superior articular processes have to face backwards to some extent. This is achieved in one of several ways.

When examined in a top view, the superior articular processes exhibit one of three basic shapes. Their articular facets may be flat, C-shaped or J-shaped. Flat facets afford resistance to axial rotation and to forward sliding by being obliquely oriented, such that they face backwards as well as medially (Fig. 2.15B). C-shaped and J-shaped facets offer a posterior end that faces medially and opposes axial rotation, and an anterior end that faces posteriorly and opposes forward slide (Fig. 2.15C and D).

Notwithstanding their shape in top view, the superior articular facets are flat in a longitudinal sense, as are the apposing inferior articular facets. This shape allows for unrestricted gliding movement between the facets in a superoinferior direction. This gliding allows the inferior articular processes freely to lift upwards as its vertebral body flexes on the one below (Fig. 2.16). Thus, whereas the zygapophyseal joints restrict axial rotation and forward slide, they permit flexion between their vertebrae. Extension is permitted in the same way but is limited in range as the tips of the inferior articular processes impact the lamina of the vertebra below (Fig. 2.16).

To facilitate the gliding movement between the articular processes, the facets of the zygapophyseal joints are covered by articular cartilage, which in turn is lubricated by a film of synovial fluid. The fluid is retained by a synovial membrane that attaches to the edges of the articular cartilage, and the membrane is supported by a joint capsule (Fig. 2.17). Posteriorly the joint capsule is fibrous, with short, tight fibres running transversely between the articular processes. Superiorly and inferiorly the fibrous capsule is lax in order to accommodate the displacement of the articular processes during flexion and extension movements. Anteriorly the fibrous capsule is replaced by the most lateral fibres of the ligamentum flavum.

As the inferior articular process in a zygapophyseal joint slides across the apposing superior articular facet during flexion, it subluxates, i.e. while the lower half of its articular facet remains in contact with the facet of the superior articular process, its upper half loses contact, and is effectively exposed. Similarly, the lower half of the superior articular facet is exposed. In order to protect these exposed surfaces, and to maintain a film of synovial fluid over their articular cartilages, the zygapophyseal joints are endowed with intra-articular meniscoids. These fibroadipose structures are crescentic wedges, located at the superior and inferior poles of the joint, with a base attached to the joint capsule, and a tapering apex that projects into the joint cavity (Fig. 2.17). In the neutral position of the joint, the meniscoids project between the articular cartilages. As the inferior articular process slides upwards across the

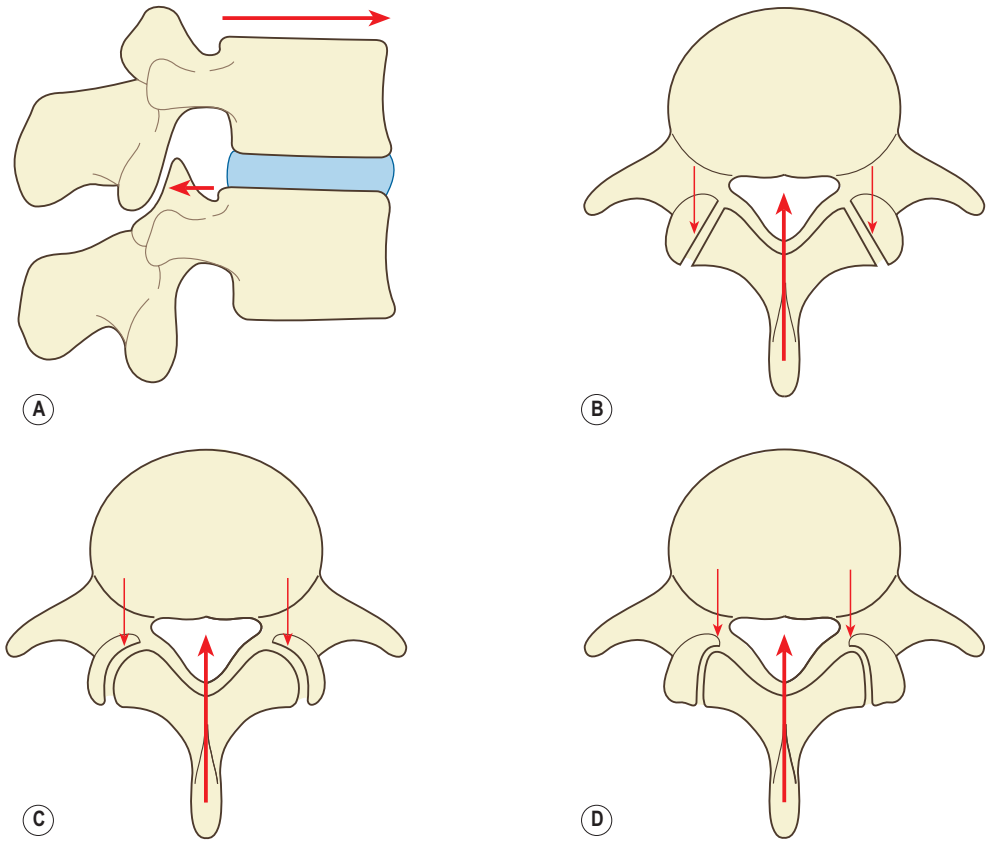


Figure 2.15 (A) A sketch of a lateral view of a lumbar zygapophyseal joint showing how the inferior articular processes hook behind the superior articular processes. The external surface of the superior articular process has been cut away in order to reveal the internal features of the joint. (B) A top view of a flat zygapophyseal joint showing how it resists forward sliding of the inferior articular processes. (C) A top view of a C-shaped zygapophyseal joint showing how its anterior end resists forward sliding of the inferior articular processes. (D) A top view of a J-shaped zygapophyseal joint showing how its narrow anterior end resists forward sliding of the inferior articular processes.

superior articular process, it leaves the inferior meniscoid applied to the exposed surface of the superior articular facet, and takes the superior meniscoid with it to protect its own exposed surface.

THE SACRUM

The sacrum is a block of bone that supports the lumbar vertebral column. However, it is also an integral component of the pelvic girdle, and thereby serves to transmit forces between the vertebral column and the lower limbs.

In front and rear views the sacrum is triangular in shape, with a broad upper end tapering to a blunt point inferiorly (Figs 2.18 and 2.19). In profile the sacrum is curved, with a smooth, concave anterior surface and a rough, convex posterior surface (Fig. 2.20). Superiorly it presents features designed to receive the lumbar vertebral column. Laterally, it is designed to articulate with the ilium on each side.

Intrinsically the sacrum consists of five segments that are fused together, each representing a rudimentary vertebra. On the anterior surface of the sacrum the superior and inferior edges of the vertebral bodies are represented as transverse ridges (Fig. 2.18). Between these ridges a narrow block of bone replaces what might have been an intervertebral disc. In longitudinal sections of the sacrum (Fig. 2.20), rudimentary discs may be found deep within the substance of the bone, particularly between the first and second sacral segments.

Projecting laterally from the vertebral bodies are the lateral masses of the sacral segments (Fig. 2.18). These represent the transverse processes, but instead of remaining separate, the tips of these transverse processes are fused together laterally to form a single mass of bone. However, fusion does not occur more medially where between

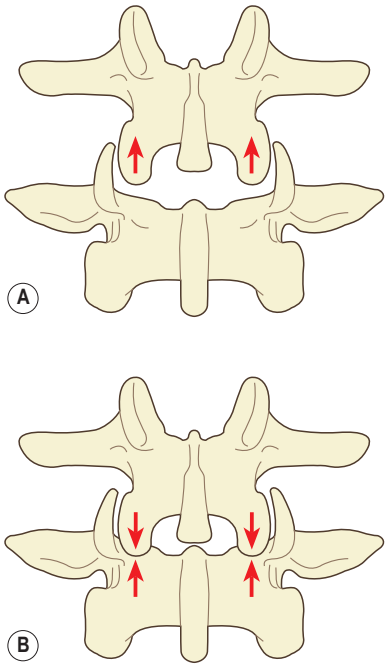


Figure 2.16 Posterior views of a lumbar zygapophyseal joint. (A) During flexion the inferior articular processes are free to glide upwards across the superior articular processes. (B) During extension the inferior articular processes glide downwards across the superior articular processes but are arrested by impaction against the lamina below.

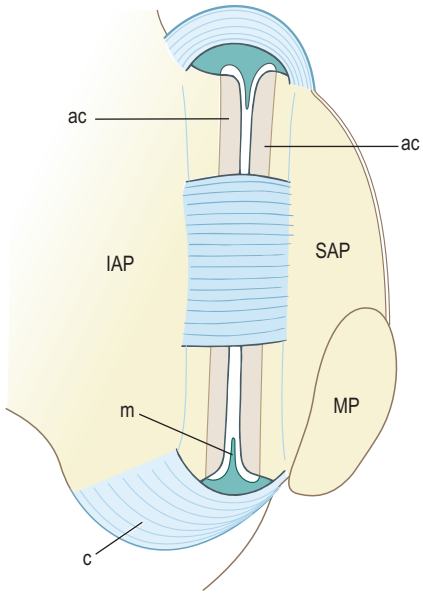


Figure 2.17 A posterior view of the components of a right, lumbar zygapophyseal joint. The facets of the superior articular process (SAP) and inferior articular process (IAP) are covered by articular cartilage (ac). The capsule (c) is loose and abundant at the superior and inferior poles of the joint. Dorsally it consists of transverse fibres. These have been resected superiorly and inferiorly to reveal the fibroadipose meniscoids (m) that lie between the articular cartilages at the superior and inferior poles.

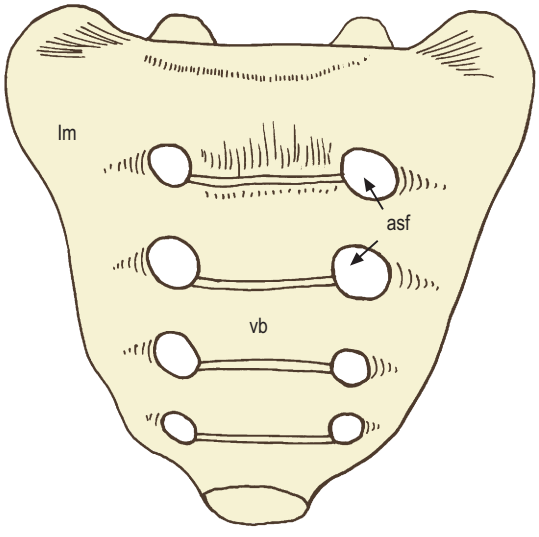


Figure 2.18 An anterior view of the sacrum. vb, vertebral body; lm, lateral mass; asf, anterior sacral foramina. *(From Bogduk (1997), with permission.)*

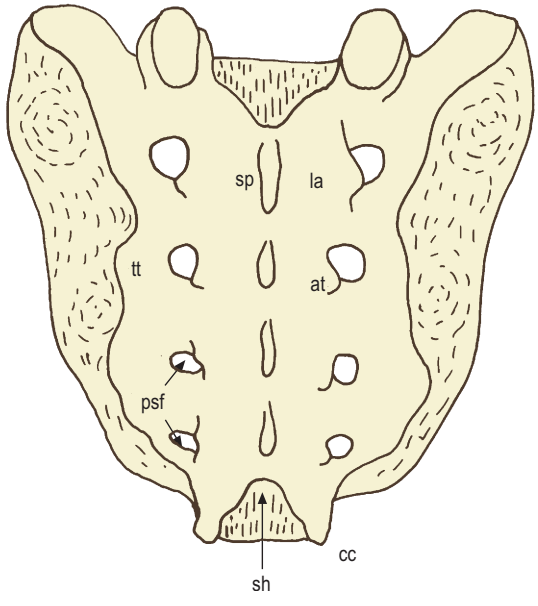


Figure 2.19 A posterior view of the sacrum. sp, spinous process; la, lamina; tt, transverse tubercle; psf, posterior sacral foramen; at, articular tubercle; sh, sacral hiatus; c, cornu. *(From Bogduk (1997), with permission.)*

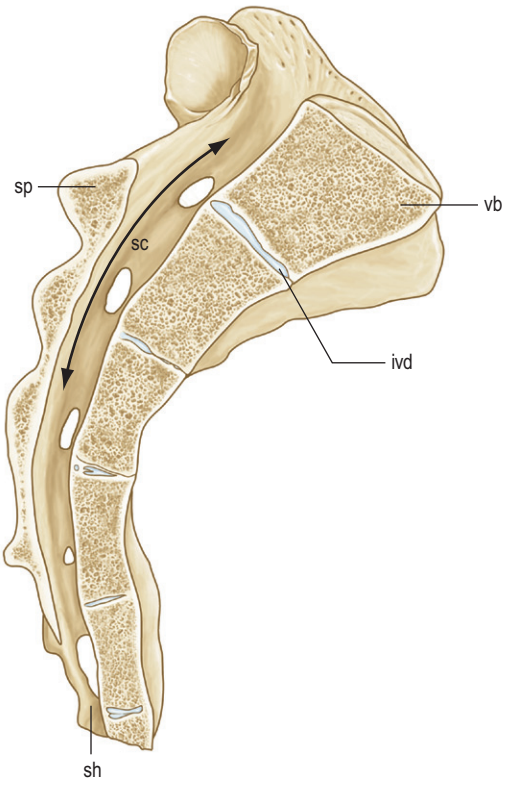


Figure 2.20 A longitudinal section through the sacrum. sc, sacral canal; sh, sacral hiatus; sp, spinous process; vb, vertebral bodies; ivd, remnant of an intervertebral disc. *(From Bogduk (1997), with permission.)*

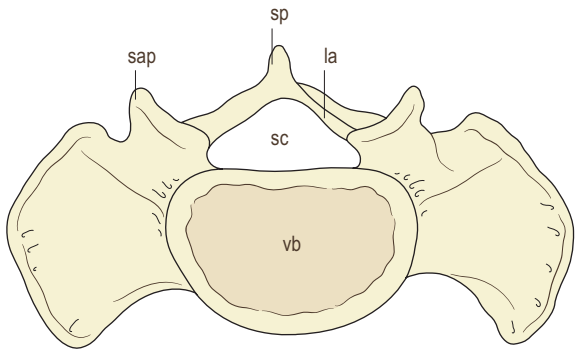


Figure 2.21 A superior view of the sacrum. vb, vertebral body; sap, superior articular process; sp, spinous process; la, lamina; sc, sacral canal. *(From Bogduk (1997), with permission.)*

consecutive transverse processes foramina are formed. The foramina seen on the anterior surface of the sacrum transmit the anterior rami of the sacral spinal nerves, and are known as the anterior sacral foramina.

Posteriorly, each of the sacral segments exhibits components homologous to the posterior elements of the lumbar vertebrae. Prominent in the midline are the spinous processes (Fig. 2.19). Beside these are the laminae, which are fused between consecutive segments. A lamina and spinous process are lacking from the fifth sacral segment, leaving a hole, known as the sacral hiatus. This hiatus constitutes the inferior opening of the sacral canal, which passes longitudinally through the sacrum, and represents the continuation of the lumbar vertebral canal. Laterally, the transverse processes of the sacral segments are fused and surround the posterior sacral foramina, which transmit the posterior rami of the sacral spinal nerves. The tip of each transverse process is marked by a small prominence, each known as a transverse tubercle. Medial to each posterior sacral foramen is a small bump that represents what might have been a zygapophyseal joint, for which reason the bump is known as the articular tubercle. The fifth sacral segment presents a pair of definitive articular processes which articulate with the coccyx. They flank the sacral hiatus like horns, for which reason they are known as the sacral cornua.

The superior end of the sacrum presents a central surface that resembles the superior surface of a lumbar vertebral body (Fig. 2.21). It receives the L5–S1 intervertebral disc. Laterally, the transverse process is long and thick, and is known as the ala (wing) of the sacrum. From its posterior surface on each side projects a superior articular process which receives the inferior articular process of the L5 vertebra.

In the upright position, the sacrum is inclined forwards, such that its upper surface slopes below horizontal at an angle of about 50° (Fig. 2.22). This orientation compromises the base for the lumbar vertebral column, for it invites the lumbar vertebral column to slip forwards and downwards across the sloping superior surface of the sacrum. Three design features militate against this tendency. First, the L5–S1 intervertebral disc is wedge-shaped, by about 16°, so as to lessen the angle between the top of the sacrum and the bottom of the L5 vertebral body. Secondly, the superior articular processes of the sacrum face backwards, at between 45° and 90° to the sagittal plane. As a result, the inferior articular processes of L5 hook securely on to the sacrum, and prevent the lumbar vertebral column from sliding forwards. Finally, the L5 transverse processes are strongly secured to the ilium on each side by the iliolumbar ligaments. These large ligaments prevent forward displacement of the L5 vertebra in relation to the sacrum and pelvis.

The lateral surface of the sacrum presents a large ear-shaped articular surface, known either as the articular surface or the auricular surface, and a roughened

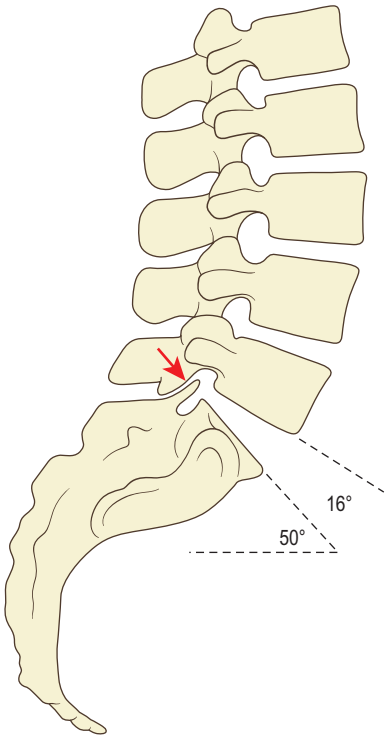


Figure 2.22 A side view of the lumbosacral junction in the upright standing position. The superior surface of the sacrum slopes downwards at about 50° below horizontal. The L5–S1 intervertebral disc is wedge-shaped. The inferior articular processes of L5 hook behind the superior articular processes of the sacrum, so as to prevent slipping of the L5 vertebra on the sloping surface of the sacrum.

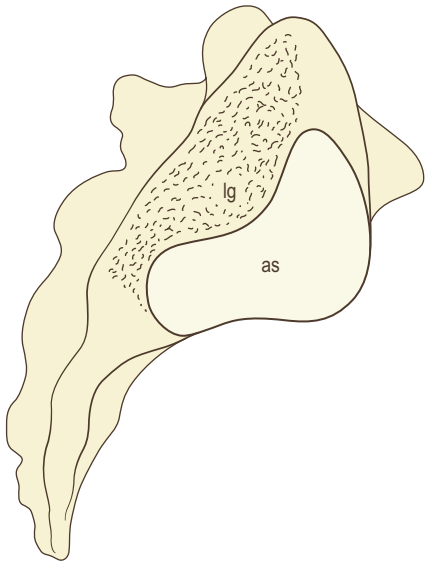


Figure 2.23 A lateral view of the sacrum. as, auricular surface; lg, ligamentous surface. *(From Bogduk (1997), with permission.)*

ligamentous area behind it (Fig. 2.23). These are designed to lock the sacrum into the pelvic ring through the sacroiliac joint.

SACROILIAC JOINT

Unlike the typical joints of the limbs, or even those of the lumbar vertebral column, the sacroiliac joint is not designed to accommodate substantial ranges of movement. Indeed, its mobility is limited to about 2°. Moreover, there are no muscles that act to produce active physiological movements of this joint. Rather, the sacroiliac joint is designed to act as a stress-relieving joint in the pelvic girdle.

During gait, the pelvic girdle is subjected to complex twisting forces, the nature of which can be likened to the effect of taking a ring and twisting it towards the shape of a figure of eight. The stresses applied to the pelvic girdle are such that if it were a solid ring of bone, it would crack. Intriguingly, this phenomenon occurs in elderly individuals in whom the sacroiliac joints are fused as a result of age changes or disease. If they remain mobile, their pelvic girdle fails by fractures that develop parallel to the line of the sacroiliac joints. By having sacroiliac joints, the pelvic girdle avoids cracking. For this purpose the sacroiliac joint is endowed with strong ligaments that absorb the stresses applied to the pelvic girdle during gait.

The sacroiliac joint is a synovial joint between the auricular surface of the sacrum and the articular surface of the ilium. The auricular surface of the sacrum is not flat, but presents a depression opposite the second sacral segment, and prominences opposite the first and third segments. These undulations articulate with reciprocal surfaces on the ilium, such that the sacrum is locked between the two ilia of the pelvic girdle (Fig. 2.24). Provided the ilia are kept pressed against the sacrum, the sacrum is prevented by the locking mechanism from being driven downwards by the weight of the trunk, or from rotating forwards. The ilia are attached to the sacrum by the interosseous sacroiliac ligament.

This ligament is short but thick. It arises from the ligamentous area of the sacrum and inserts into an opposing area of the ilium (Fig. 2.25). Tension within the ligaments on both sides keeps the ilia pressed against the sacrum. Injuries that tear this ligament, or conditions that slacken it, such as pregnancy, can compromise the integrity of the sacroiliac joint by relaxing the pressure of the ilium against the sacrum.

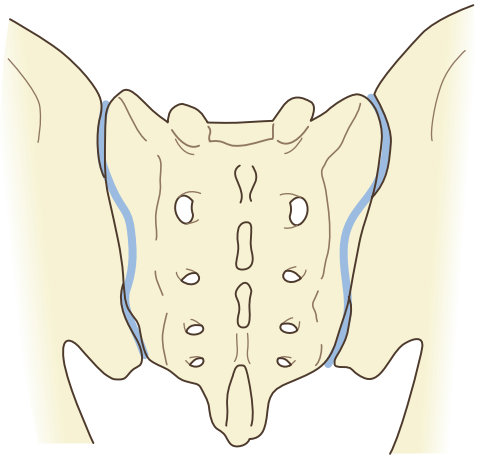


Figure 2.24 A posterior view of the sacroiliac joints, showing the sinuous shape of the joint space, and how the undulating surface of the sacrum locks into reciprocal surfaces of the ilium. *(From Bogduk (1997), with permission.)*

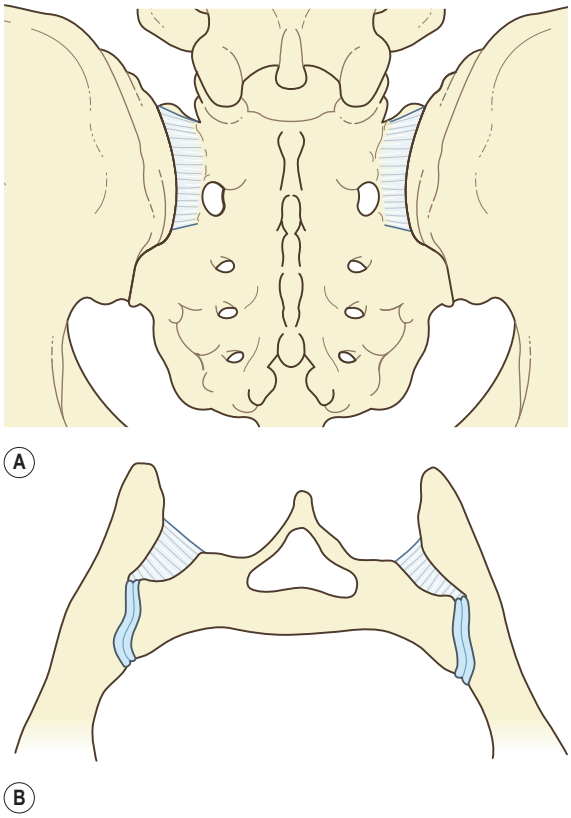


Figure 2.25 The interosseous sacroiliac ligament. (A) Posterior view. (B) Axial view. *(From Bogduk (1997), with permission.)*

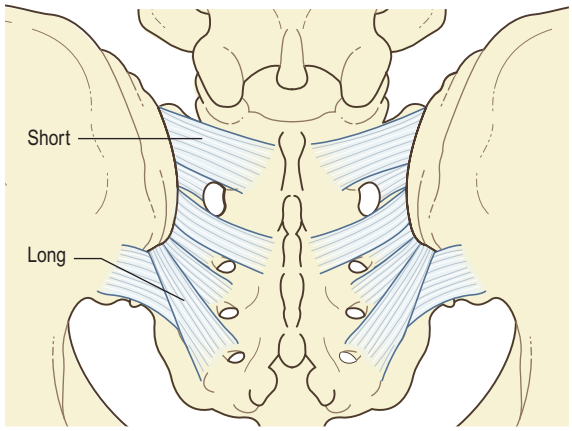


Figure 2.26 The posterior sacroiliac ligaments. *(From Bogduk (1997), with permission.)*

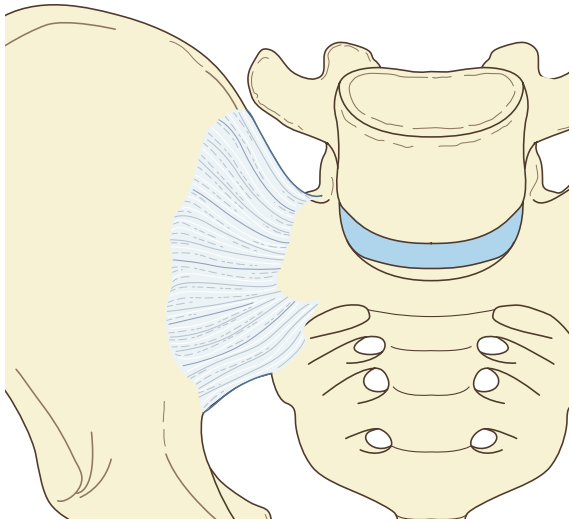


Figure 2.27 The anterior sacroiliac ligaments. *(From Bogduk (1997), with permission.)*

Additional ligaments reinforce the sacroiliac joint. Posteriorly, the long and short posterior sacroiliac ligaments connect the ilium to the posterior surface of the sacrum (Fig. 2.26). Anteriorly, the capsule of the joint is thickened to form the anterior sacroiliac ligament (Fig. 2.27). It serves to prevent the anterior edges of the sacrum and ilium from separating. Remote from the sacroiliac joint, the sacrospinous and sacrotuberous ligaments anchor the sacrum to the spine of the ischium and the tuberosity of the ischium, respectively. They serve to prevent forward rotation of the sacrum.

THORACIC SPINE

The thoracic spine consists of the thoracic vertebral column, the ribs and the sternum. It is pertinent to the function of the lumbar spine in so far as:

- loads from the upper trunk are transmitted to the lumbar spine from the thoracic spine
- muscles that act on the lumbar spine reach into the thoracic region and attach to thoracic vertebrae and ribs
- abdominal muscles, which act on the lumbar spine, arise from the ribs.

Thoracic vertebral column

In general terms, the thoracic vertebrae resemble lumbar vertebrae (Fig. 2.28). When stacked, the thoracic vertebrae form a curve that is concave forwards, and this is known as thoracic kyphosis. A concave curve increases the antero-posterior diameter and, therefore, the volume of the thoracic cavity.

At most thoracic levels, the thoracic zygapophyseal joints are oriented close to the coronal plane, such that their superior articular processes face backwards; but at lower levels the joints exhibit a gradual transition towards a more lumbar orientation, towards the sagittal plane. This arrangement prevents axial rotation at lower thoracic levels but allows it at middle and upper levels.

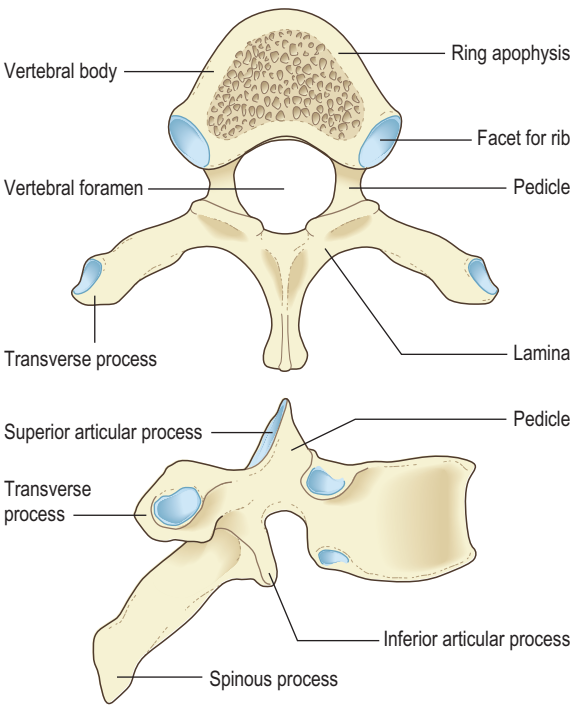


Figure 2.28 Typical thoracic vertebra in the transverse (upper) and sagittal planes. *(Adapted from Bogduk N In: Rheumatology, 4th edn. Hochberg et al. (eds) Elsevier.)*

Sternum

The sternum is a long but narrow and flat bar of bone located in the middle of the front of the chest. Along its lateral edges it bears facets that receive connections form the upper seven ribs. Its upper lateral corners are expanded and thickened to receive the medial end of the clavicle. Through the sternoclavicular joint, certain loads are transmitted from the upper limb to the thorax and then through the ribs to the vertebral column.

Ribs

The ribs form the skeleton of the thoracic cage. They are narrow curved bones of different lengths. They are short at upper levels; become progressively longer to middle levels; and then progressively shorter at lower levels of the thorax.

At its medial end each rib is expanded to form a head. A short distance laterally along its shaft each typical rib bears a bump known as the tubercle. That portion of the rib between its head and its tubercle is known as the neck of the rib. A short distance laterally beyond the tubercle the rib changes its curvature. This point is known as the angle. In effect, that region medial to the angle belongs to the back, and is involved in spinal functions, whereas the remainder of the rib, laterally, pertains to respiratory functions.

At its anterior end each rib is prolonged by a shaft of cartilage known as the costal cartilage. The costal cartilages of the upper seven ribs reach the sternum, with which they form sternocostal joints. The costal cartilages of the eighth, ninth and 10th ribs join the costal cartilages above. The tips of the 11th and 12th ribs float freely, without forming any articulations.

Medially, a typical rib articulates with the thoracic vertebral column through two joints. The head of the rib forms a costovertebral joint with the posterior corner of the intervertebral disc and facets on the adjacent corners of the two vertebral bodies joined by the disc (Fig. 2.28). The tubercle of the rib articulates with a facet on the anterior surface of the tip of the transverse process, to form a costotransverse joint. Various ligaments bind the head, neck and costal tubercles of the rib to the vertebral bodies and transverse process.

The first rib differs in that its head articulates exclusively with the first thoracic vertebra. The 11th and 12th ribs differ in that their tubercles form rudimentary or no joints with their transverse processes.

Muscle surface

When fully articulated, the thoracic vertebral column and ribs present a posterior surface on to which various muscles attach. Intrinsic muscles of the thoracic spine attach between the spinous processes in the roots of the transverse processes. Certain respiratory muscles suspend each rib to the transverse process above. Certain muscles of the neck take root on upper thoracic transverse processes.

Otherwise, various muscles descend from thoracic levels to act on the lumbar spine. These arise from:

- the posterior surface of the lateral end of each transverse process
- the adjacent surface of each lateral to the tubercle
- the posterior surface of the angle of each rib.

Additionally, various abdominal muscles arise from the external and internal surfaces of the lower six ribs or their costal cartilages.

FURTHER READING

Bogduk N. Clinical anatomy of the lumbar spine and sacrum. 3rd ed. Edinburgh: Churchill Livingstone; 1997.