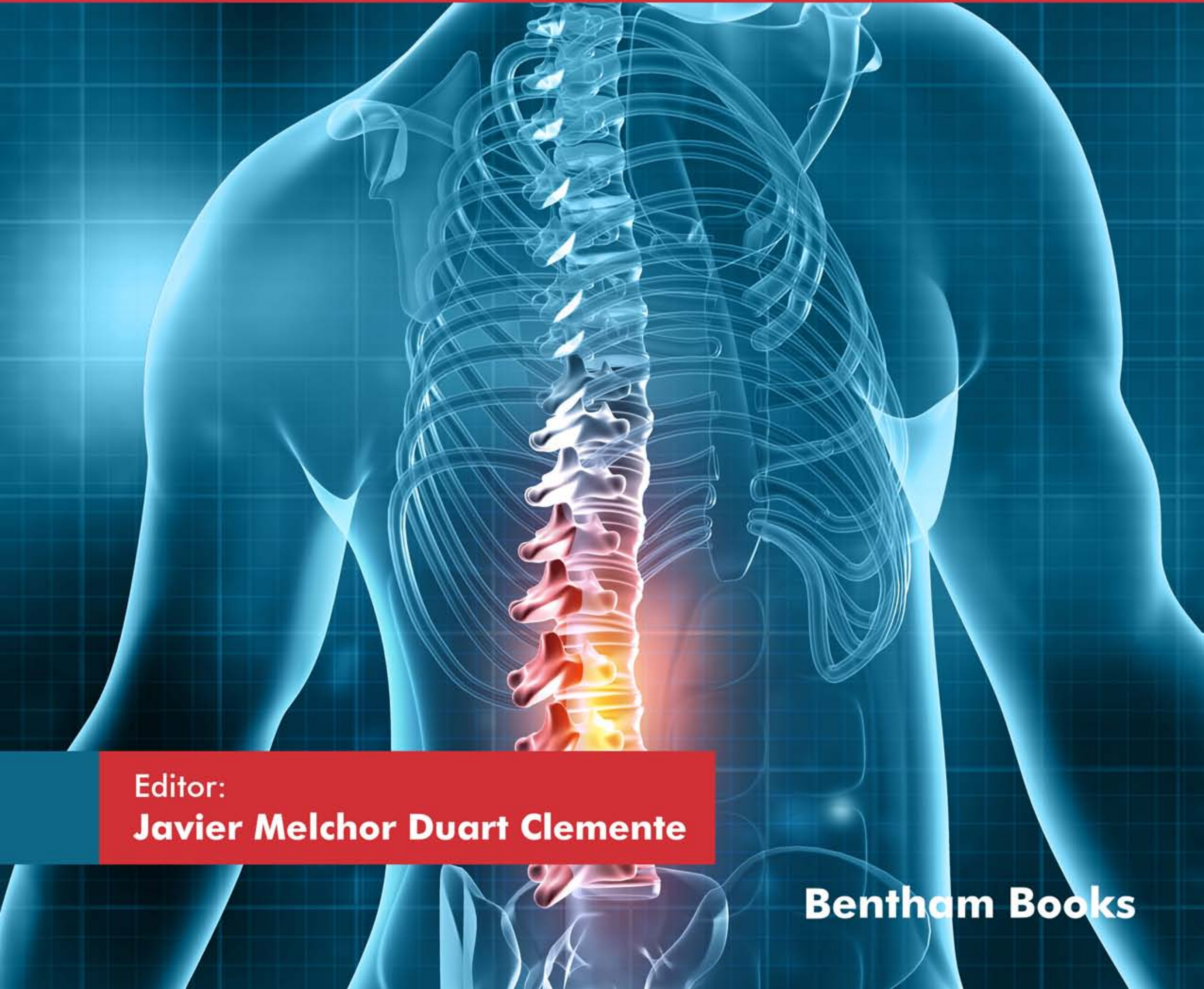
SPINAL SURGERY BIOMECHANICS: PRINCIPLES FOR RESIDENTS AND STUDENTS



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Spinal Surgery Biomechanics: Principles for Residents and Students

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FOREWORD

When I was challenged to write an introduction to this book, I did not hesitate in accepting it, since for me as a biomedical engineer who is an expert in the field of spinal biomechanics, it has always been a passion more than a job. For the last 30 years, I have studied the biomechanics of the spine and, based on that knowledge, developed new implants and spinal prostheses that respond to clinical problems that my medical colleagues have "suffered."

But I have not only found the passion in myself; the love of the authors for the spine and for the patients behind it and to whom we all owe ourselves, is evident in all the chapters of this book. I believe that in the vast world of medicine and biomedical engineering, few fields arouse as much interest and challenge as the biomechanics of the spine, which is why I believe that the existence of this type of publication is essential. As advances occur in the study of the biomechanics of the spine, a series of crucial questions arise to be addressed that are rigorously treated in this book, from the methods to evaluate the anchorage of pedicle screws to the different techniques of total lumbar disc replacement. In summary, the chapters of the book summarized below explore in detail the scientific and medical advances that have shaped this constantly evolving area of research.

The first chapter, "Biomechanical Testing of Pedicle Screw Anchorage", looks into the testing techniques that allow a rigorous evaluation of the anchorage capacity of pedicle screws. These components are essential for the stability of the spine and their understanding is essential for successful surgical procedures. This first chapter demonstrates how science and engineering come together in the search for surgical excellence.

In chapter two, the doors open to an in-depth debate on whether total lumbar disc replacement is an option that should continue to be worked on to achieve a disc prosthesis that truly maintains the biomechanics of the spine. In a world where surgical options are increasingly varied, the chapter explores the different types of available prostheses and immerses us in the biomechanical and clinical aspects that determine when this technique should be used and in what type of patients.

In contrast to the previous chapter in the third chapter, the focus is on the study of the different techniques to achieve intervertebral fusion with an interbody cage. Here, biomechanical and biological issues such as osseointegration or the movements of adjacent vertebrae are intertwined as we delve into the study of the different techniques that have been used to create an optimal environment for bone growth between the vertebrae using the concept of inter somatic cage.

Continuing with the fourth chapter, "Management of Degenerative Spinal Conditions with Osteoporosis", what an osteoporotic vertebra is and the biomechanical behavior of an osteoporotic spine are analyzed. The above is essential to be able to understand which technique or set of surgical techniques are the most appropriate to restore the height and function of a fractured vertebra due to osteoporosis. The final part of the chapter explores the use of pedicle screws with cement, analyzing their advantages and possible complications that may appear when using these implants.

In the fifth chapter, we deal with the biomechanical causes that trigger spondylolisthesis, how they are classified, and finally how the body tries to mechanically compensate for this pathology. Finally, instructions are given on its treatment.

With chapters six and seven, our horizons on spinal biomechanics expand even further. In section six, interspinous devices are analyzed as an alternative for stabilization without fusion, making a classification of them and the consequences of their use on the biomechanics of the spine.

In the last chapter, the book immerses us in the definition of instability and in the different methodologies used throughout history to measure spinal instability, revealing how biomechanics is essential to understanding and classifying spinal injuries.

In summary, this book provides a detailed analysis of the complex biomechanical mechanisms that govern the human spine. From the evaluation of pedicle screw anchorage to innovative solutions for spinal stability, this book offers a comprehensive perspective that combines scientific research with clinical applications. Ultimately, it is a valuable source of knowledge for medical professionals, biomedical engineers, and students who wish to dig into the challenging field of spinal biomechanics and how different types of implants designed for the spine interact and restore function.

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PREFACE

Dear colleagues, we hope you enjoy this book you have now in your hands. It started spontaneously as a group of friends of spinal surgeons thought it would be useful for the coming generations to share and put at hand this useful knowledge based on our practical experience throughout the years to improve the clinical results of spinal surgery patients.

The spine is a complex structure both from the static or anatomic point of view, as it is composed of bone (vertebrae), intervertebral discs, muscles, and ligaments (that could be the reason why the less aggressive you are, the better the outcome. It is in this complex point of intersection of statism and dynamicity where biomechanics play an important role, helping us to understand both how the spine behaves in its intact fashion and more importantly after we apply surgical gestures either for decompression or stabilization.

Biomechanics is the study of mechanics of life, and in our case, the mechanics of the moving spine. Its knowledge is key to avoiding complications during and after spinal surgery and improving clinical results by striving to get enough bony fusion and achieving good sagittal balance. As important as which patient should be operated on and when, the answers of why and how are also important to achieve success. That is why it is so important to know and understand the basic concepts with the intent to try to best help our patients who need spinal surgery.

This book does not pretend to be extensive, but rather a start for our younger colleagues. It is focused on the lumbar spine, starting with a chapter on biomechanical testing of the pedicle screw, which is the cornerstone of instrumented lumbar fusion. Before dealing with different fusion techniques in the third chapter, the second chapter deals with the motion-sparing technique of disc replacement. Fixation in osteoporotic patients and interspinous stabilizers have also been discussed, playing a role in lumbar surgery. Finally, the last chapter deals with the biomechanical view of fracture classifications. We hope you enjoy it and find these few chapters useful. This content of the book will surely help in the care of spine health.

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CHAPTER 1

Biomechanical Testing of Pedicle Screw Anchorage

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Abstract: This chapter provides an overview of biomechanical *in vitro* testing of pedicle screws. Several aspects, such as specimen selection, test setup, and loading modalities for the investigation of screw anchorage are discussed. In general, cement augmentation is an effective technique to improve pedicle screw anchorage. However, in clinical practice, it should be considered that augmentation is most effective in the osteoporotic bone while in healthy bone, the improvement of screw anchorage is only marginal.

Keywords: Augmentation, Loading protocol, PMMA cement, Pedicle screws, Screw loosening, Screw failure.

INTRODUCTION

In the last decades, the use of pedicle screws has become standard for dorsal instrumentations in modern spine surgery for many pathologies. Different conditions in morphology and bone quality in degenerative, deformity, trauma and tumor surgery have led to adaptions and modifications of the traditional pedicle screw concept. To enhance pedicle screw anchorage and reduce the risk of loosening, augmentation techniques with PMMA cement and alternative materials were developed and established in clinical practice. Other options to increase pedicle screw anchorage without increasing the overall rigidity of the instrumentation are modifications in the screw design, such as adaption of the thread, screw core diameter, expandable screws, or osteointegrative coatings of the screws [1-5].

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In scoliotic deformities or hyperkyphotic spines, the research focus often shifts from the improvement of screw anchorage to the possibility of applying forces and moments with implanted pedicle screws to perform derotation, compression, and tension maneuvers to selected vertebrae, in order to correct the deformity. For this purpose, modified and long screw heads with reposition possibilities were developed.

In the implementation of design modifications and the development of novel pedicle screw designs, *in vitro* biomechanical investigation with cadaver specimens plays an important role in anticipating the effect and functionality of the implants and their later clinical performance. Therefore, *in vitro* biomechanical experiments are an important link between the development and clinical application of novel implants and surgical techniques.

The obvious advantages of biomechanical investigations prior to clinical trials are their relatively easy feasibility and the possibility of a direct comparison with current standard techniques using standardized protocols in a controlled lab environment with limited confounding factors. However, the clinical relevance of biomechanical *in vitro* investigations can vary with the experimental design and execution.

In the following lines, biomechanical testing methods for the evaluation of pedicle screw anchorage are briefly described and discussed. Additionally, selected studies investigating pedicle screw anchorage of various screw designs and augmentation techniques are presented, too.

MATERIALS

Specimens

Bone quality and donor characteristics such as age, sex, bone mineral density (osteoporotic, osteopenic or normal), and grade/state of degeneration can vary widely and may have a significant effect on the results. Therefore, selected specimens must be appropriate and suitable for the postulated hypothesis and study aim. Specimens of various origins as well as artificial bone surrogates or human cadaver tissue can be utilized for biomechanical testing. Due to the limited availability and legal handling requirements of human vertebral bodies, biomechanical testing is also conducted with ovine, bovine or porcine vertebral bodies. However, differences in the bone properties, anatomy, and morphology of animal specimens should be considered in the interpretation of the results and the transfer of the results to clinical practice [6].

With the use of human specimens, ethical considerations and specimen handling must be clarified and settled with the local ethical institutional review board prior to the start of testing [7]. Another relevant point to be considered with the use of human specimens is specimen preservation. It must be distinguished between fresh frozen and embalmed (*e.g*. Alcohol-Glycerin, formalin, Thiel fixated, *etc*.) specimens. In a study comparing the biomechanical properties of formalin-fixed and fresh frozen functional spinal units (FSU), it was reported that embalmed specimens do not resemble *in vivo* features and show significantly different biomechanical properties than fresh frozen specimens [8]. Regarding the effect of preservation methods on bone tissue, Unger *et al.* compared three preservation methods with fresh frozen bone tissue and concluded that embalming significantly alters the mechanical properties of bone tissue, and the use of embalmed specimens should be restricted to pilot tests [9]. In the literature, fresh frozen specimens are considered the gold standard. After slow thawing, they should be kept wet with saline solution during testing, and at room temperature. Also, test duration should be kept constant for reliable and reproducible results of the biomechanical experiments [10].

For clamping and fixation of the specimens in the test setup to enable mechanical loading, specimens are usually embedded in plastics (*e.g*. Poly-methyl-methacrylate (PMMA) or Epoxy -resin). The rigidity of the embedding on the tested structure as well as the stiffness of the embedding material should also be considered in the evaluation and interpretation of the measured physical parameters.

Biomechanical Testing

In the last decades, biomechanical test methods were continuously refined and adapted to implement new insights and knowledge in the engineering of material testing, *in vivo* measurements, and anatomy. This allowed a more realistic simulation of clinical conditions and to investigate relevant research questions as physiologically as feasible. In the following, two test methods to investigate pedicle screw anchorage are described.

Test Setups for Pedicle Screw Pull-Out Tests

Initial, simple, and quick experimental comparisons of varying screw designs or augmentation techniques of pedicle screws are often conducted with axial pull-out tests. They are carried out by applying an axial load with a displacement vector co-axial to the long screw axis while the vertebral body is fixed in the test setup (Fig. **1**). After the complete pullout of the pedicle screw, the force-displacement curve is analyzed and a drop in the force plot (*e.g*. 25% of maximal force) is considered a failure of the screw anchorage.

CHAPTER 2

Lumbar Total Disc Replacement (TDR), is it Worth it?

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Abstract: Low back pain is a prevalent medical condition. Although most patients improve conservative treatments, some need surgery. The traditional procedure, the spinal arthrodesis, fixes a spinal segment, forcing the adjacent ones to undergo an extra load and a mobility excess that is the cause of middle and long-term discal degeneration and zygapophyseal joint arthritis changes. All this can be the source of further low back pain and require a new surgical procedure with a new spinal fusion in an average of ten years.

Joint mobility preservation is a must in all areas of surgery, and the spine is no exception. Disc arthroplasty has provided better results than spinal arthrodesis, particularly in patients under 50 with discal degeneration and no concurrent zygapophyseal joint arthritic changes. The patient selection must be accurate to get adequate results. No zygapophyseal joint damage must be present as otherwise, low back pain is common after disc arthroplasty.

The surgical technique must concentrate on every detail. The retroperitoneal approach is challenging even in the best hands. In this respect, the assistance of an access vascular surgeon is of particular help. The prosthetic disc's final position inside the discal must be no more than 2mm from the midline and 4 mm from the posterior aspect of the vertebral body. The anterior longitudinal ligament and annulus fibrosus removal induce an excess of mobility not controlled by the commercially available discal prosthesis. It is an area that still needs improvement.

The choice of which discal prosthesis to use depends on the surgeon's preferences, and new designs steadily improve the features, results, and complication rate of the previously existing ones. But there is still plenty of room for further improvement.

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Keywords: Anterior lumbar approach, Disc prosthesis, Total disc replacement.

INTRODUCTION

Chronic low back pain is frequent in the population [1 - 4] and a highly prevalent cause of temporary sick leave [5 - 7] and permanent disability [8 - 10]. Its causes include all spine components, supporting structures, ligaments, and muscles [11 - 13].

A significant percentage of these patients are young people [14] under 50 years of age [15], in whom this type of pain causes substantial negative consequences for their quality of life [16] and work opportunities [17 - 19].

Although degenerative disc disease is not always painful, and many cases are asymptomatic [20, 21], it can be pretty disabling [22, 23]. It affects mainly men 25-45 years old [14, 15], with axial back pain that worsens when leaning forward, lifting weights, and getting in and out of the car [24, 25].

When medical treatments are ineffective [26 - 30], surgery may be helpful [31, 32]. The standard treatment, lumbar arthrodesis (fusion) [31, 33], can be performed through anterior or posterior approaches [31, 34 - 38]. On the one hand, posterior lumbar fusion disrupts paraspinal musculature [39 - 42], causing chronic pain and functional impairment [40, 43]. On the other hand, anterior lumbar arthrodesis avoids paraspinal muscle damage [42] but risks abdominal vessel injury and retrograde ejaculation [44 - 46].

Moreover, lumbar fusion can induce pseudoarthrosis [47, 48], adjoining level overloading [49, 50] with facet joint arthritis [51, 52], and disc degeneration [53 - 55]. Consequently, a reoperation to extend the arthrodesis is not uncommon [50, 56] in a term that varies depending on the number of fused levels [35, 50, 51, 57].

Schellnäck and Büttner-Janz [58] in the 1980s implanted the first total lumbar disc prosthesis, but the first implants had many problems [59 - 61], minimized through a continuous improvement (Charitè) [62] and the introduction of new designs [63] (Prodisc™ [64, 65], Activ-L™ [66, 67], Maverick-L™ [68, 69], Cadisc-L™ [70], Baguera-L™ [71], M6-L™ [72]).

Many studies comparing lumbar arthrodesis *versus* arthroplasty [73 - 82] report that with the latter, there is a higher percentage of return to the same job post [75, 83], a better quality of life [84, 85], a lower incidence of the adjoining level syndrome [73, 74, 77, 86] and a lower number of reoperations [80]. However, total disc prosthesis induces facet joint arthritis of the operated [87 - 89] and the supra-adjoining levels [88, 90 - 92] with chronic low back pain [93]. This degenerative process correlates with the excessive mobility of the total disc prostheses [94 - 96]. It is more evident in those with a greater motion range (Charitè) [97, 98] and when the rotation center is not in the posterior third of the intervertebral disc (Prodisc™ [99], Activ-L™ [100]).

Symptoms that make a Total Disc Prosthesis an Option

The usual complaints are low back pain radiating anteriorly to the groin and genital area at times, affecting one or both sides [101]. When there is also nerve root compression, patients may complain of leg pain [102], but waist pain is usually the most prevalent [103]. Low back pain worsens when bending forward, standing up from leaning forward, and lifting weights. Therefore, a total lumbar disc prosthesis is an option if the dominant feature is back pain with this clinical characteristic [104].

Not all patients are susceptible to a lumbar disc prosthesis. Solid bones are generally required, so osteoporosis is a contraindication. Otherwise, the prosthesis may sink into the vertebral body.

If there is facet joint arthritis, the disc prosthesis is not indicated because motion preservation will be at the price of significant lower back pain.

Inclusion Criteria

• Patients should be included between 18 and 50 years of age since, above that age, there is usually facet joint arthritis.

• Chronic lower back pain with or without leg pain originating from degenerated discs and with no signs of lumbar facet joint arthritis.

• Discogenic lower back pain that worsens in flexion but not in extension and has a truncal distribution with possible anterior irradiation towards the groins or genital area.

• MRI findings compatible with lumbar disc disease.

• No vertebral instability or listhesis of the levels in plain X-ray studies.

• No response to 6 weeks of conservative, non-surgical treatment or symptom progression.

• No previous treatment, such as microdiscectomy, laminectomy, or lumbar arthrodesis.

CHAPTER 3

Lumbar Interbody Fusion: Different Approaches and Biomechanical Issues

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Abstract: Fusion is frequently considered when planning for a spinal surgery procedure; nowadays, such a fusion is preferred between the intervertebral bodies (so-called *interbody fusion*) because there is a bigger surface for the bone to grow and make contact (increasing fusion rates), improving also overall spine alignment (trying to get a balanced spine), which in turn protects the adjacent segment, as there is also less wobbling at the fused space and mechanic aspects are less deleterious.

From a mechanical point of view, a fusion is an ankylosing procedure that eliminates any movement between vertebral bodies, so the Functional Spine Unit (FSU) is abolished; both kinetics (forces at stake), kinematics (displacements caused by those forces) and stiffness (deformations by those same forces) within FSU should be considered.

Keywords: ALIF, Lumbar interbody fusion, OLIF, PLIF, TLIF, XLIF.

INTRODUCTION

Nowadays, a fusion of vertebral bodies is one of the most common surgical procedures performed worldwide. It implies bridging the selected vertebrae with bone tissue without a gap between them. Anatomically, that bridge may form in the posterior elements (laminae, facets, transverse apophyses) or in between the endplates of vertebral bodies: it is in this situation that we talk about interbody fusion, packing bone in the intervertebral disc space after removing the cartilaginous endplates. Some annulus fibrosus is kept in place as a safety measure to avoid either over distraction or intracanal migration of the graft or implants placed. It is important to highlight this point on graft, as fusion requires

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bone tissue formation, not just an implant set between endplates to stabilize them (nevertheless, as any rule has exceptions, something that safely anchors to both endplates and incorporates into both vertebral bodies might pose such an exception), such as porous metallic blocks or cages.

So once established that we need to form a stable composite capable of withstanding physiological forces between vertebral bodies, two more issues should be addressed: a) how do we get there?; and b) how do we create a favorable environment for the bony bridge to grow, both from a mechanical and a biological viewpoint?

How do we Get there? The Surgical Approach

There are several acronyms regarding interbody approach fusion. To ease understanding, a root, and a prefix may help the reader to understand this. The root word is -LIF, which stands for *Lumbar Interbody Fusion* (LIF). We may extend the L to the Thoracic spine, with two core differences: a) the rib cage and the thoracic cavity, which makes the thoracic spine less mobile than the lumbar spine, and b) the anterior approaches have to deal with the pleural cavities, which are physiologically different to the peritoneum; for instance, they have a negative pressure during inspiration, suctioning every loose matter (this can be avoided access the spine through a retropleural approach). The cervical spine has considerations that go way beyond this chapter.

Let us think about a transverse anatomical slice at the level of a lumbar disc in a supine patient, the standard CT or MRI axial cuts. If we go around the clock, then we have several approaches: a)ALIF (anterior, straight from the front, at 12:00, either -mostly- retroperitoneal or else transperitoneal), b)OLIF (oblique) between the great vessels and the psoas, c)XLIF (*extreme lateral*) through the psoas -by splitting fibers, at 3:00-: d)TLIF (*transforaminal*, approximately at 5:00), through the foramen, but lateral to the dural sac (with its variation e-TLIF, extreme-transforaminal, from the back but quite lateral from the facets); and e)PLIF (posterior, at 6:00), retracting the dural sac to the midline to create the approach.

They all have pros and cons, and some anatomical specificities make the surgeon choose one over another when planning a LIF technique. The anatomy of the great vessels and the nerve roots have a bearing on the anterior approaches: while on the one hand, the L5-S1 level is easily accessible through ALIF, the L4-L5 level is the big puzzle, as the aortic and iliac bifurcations usually lie there, with a gross lumbar vein tying the great vessels (making it almost mandatory to ligate it in case mobilization is needed). The psoas has up to 80% of the cross-sectional area with a nerve root in the way of a direct lateral approach -the percentage of which progressively decreases at the more cranial levels-; thus the Oblique

(OLIF) might be a choice if the vascular anatomy allows for it (there must be a corridor between the great vessels and the psoas muscle). On the downside of the OLIF, the interbody implant insertion needs a rotation of 30º that the iliac crest may hamper. Among the posterior approaches, the TLIF leaves the dural sac untouched and protected by the ligamentum flavum, and the sac needs no retraction.

Should an Implant be Placed in the Interbody Space?

Although increasing the overall cost and lengthening the surgical time, there are several reasons for this:

a) Higher Fusion Rate

Higher fusion rate anterior structural support adds stability. A recent meta-analysis confirms this assertion [1]. The optimal conditions for an interbody fusion (graft incorporation) are as follows:

1) Forces and stresses acting at the graft-host interface should not exceed its failure limits;

2) The stresses´ average (stress, by definition, being a load that causes a deformation) should not sum up to zero, because bone growth is enhanced by loads; and

3) Cyclic variations in stress are beneficial unless motion (mostly shear) occurs at the graft-host interface.

Historically, two models have been proposed [2]:

1) The tripod: anterior cancellous graft and posterior distraction.

2) The flagpole: anterior interbody distraction with a block and posterior compression.

Due to global spinal alignment reasons, only the second has stood the test of time; the tripod had built a flat back and imbalanced the spine.

b) Alignment of the Sagittal Plane

Alignment of the sagittal plane by increasing segmental lordosis, hence the importance of something structural to withstand axial forces at the intervertebral space until the bone bridges become strong enough by themselves at the anterior column and in the posterior one (in the midline, facets or intertransverse area).

CHAPTER 4

Management of Degenerative Spinal Conditions with Osteoporosis

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Abstract: Osteoporosis is the most frequent metabolic bone disease, affecting particularly women. Due to the progressive ageing of the population, the number of patients with this condition requiring spine surgery is increasing, while new techniques and implants are in development to help this particular population: apart from percutaneous augmentation techniques (such as vertebroplasty and kyphoplasty), fenestrated pedicle screws which can be cemented have changed the spinal management of these patients.

Keywords: Bone cement, Degenerative spine, Fenestrated screws, Osteoporosis.

INTRODUCTION

Osteoporosis is the most frequent metabolic bone disease, which is characterized by a decrease in bone mass, a rate of bone resorption greater than synthesis, and microarchitectural deterioration [1]. This entails a decrease in the mechanical resistance of the bone and bone fragility and, consequently, an increased risk of fracture. Therefore, it is both a quantitative and qualitative alteration of the bone tissue.

The diagnosis is based on densitometry (DEXA) score: normal (T-score > -1 SD), osteopenia (T-score between -1 and -2,5 SD), and osteoporosis (T-score < -2,5 SD).

Epidemiology

This disease affects around 6% of men and 21% of women between the ages of 50 and 84 years in Europe n the European Union, around 27 million people

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currently suffer from osteoporosis. It is estimated that in the next 10 years, the cases of this disease will increase by 23% [2].

It is estimated that 1 in 3 women over the age of 50 experience an osteoporosis-related fracture. Men have a lower risk of osteoporotic fracture but nevertheless, it is not trivial, reaching the maximum risk 10 years after women. Apart from age and gender, there are other risks factors, which can be found in Table **1**.

Table 1. Osteoporosis risks factors (modifiable and non-modifiable).

Non-modifiable factors	-Caucasian race -Thin constitution -Early menopause, amenorrhea -White skin and hair
Modifiable factors	-Smoker -Inactivity -Excessive alcohol consumption -Exercise-induced amenorrhea -Malnutrition and anorexia -Caffeine - High-fiber diet -Medications: glucocorticoids, thyroid hormones, diuretics, antiepileptics (phenytoin), benzodiazepines, antidepressants, heparin, methotrexate, *etc*.

Classification

Primary osteoporosis

Its cause is unknown.

Idiopathic or juvenile primary

It is detected in patients aged 8-14 years with osteopenia, growth retardation, and osteoarticular pain. Multiple microfractures can be seen in the vertebral bodies. Spontaneous resolution occurs 2-4 years after puberty.

Involutionary of the adult: There are 2 subtypes.

Postmenopausal (Type I)

It affects women with a frequency 6 times greater than men, aged 55-75 years. It is characterized by a rapid phase of osteoclast-mediated bone loss. It mainly affects cancellous bone and is associated with vertebral and distal radius fractures. Analytically, a decrease in PTH function and an increase in urinary calcium can be observed (frank hypercalciuria is detected in 20% of patients).

Senile (Type II)

It is related to aging (in women > 70 years and in men > 80 years). It affects women twice as often as men. It is produced by a decrease in osteoblastic activity and affects trabecular and cortical bone. It is characterized by vertebral and hip fractures.

Secondary osteoporosis

Its cause is known. There are several types:

• Drugs: heparin, antiestrogens, corticosteroids, methotrexate.

• Endocrine and metabolic diseases: hypogonadism, hyperparathyroidism, Cushing's disease, hyperthyroidism.

• Hematological: myeloma.

• Genetics: osteogenesis imperfecta, homocystinuria, Ehler-Danlos syndrome, and Marfan disease.

• Others: prolonged immobilization, mast cells, scurvy, malnutrition, alcoholism.

Clinical Presentation

It is usually asymptomatic until low energy or fragility fractures occur, being vertebral fractures the most frequent, specially located in the lumbar area. They produce sharp back pain that sometimes radiates to the abdomen, which intensifies when sitting down when standing up, and with the Valsalva maneuver. From a radiological point of view, there is an anterior collapse of the vertebral body that produces a decrease in height, dorsal kyphosis, and limited mobility of the spine.

Other common locations for osteoporotic fractures are the hip, distal forearm, and proximal humerus.

Diagnosis

It is based on densitometry (DEXA) and risk factors; there are no uniform diagnostic criteria in the world. Densitometry is the gold standard test. According to the WHO, osteoporosis is defined as a disease characterized by having a bone mineral density > 2.5 standard deviations below the maximum bone mass of a young person [3].

CHAPTER 5

Degenerative Spondylolisthesis: Why Does it Occur and How the Body Reacts?

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Abstract: Degenerative spondylolisthesis (DS) is a common entity in the fifth-sixth decade of life, and it is assumed that there is a biomechanical rationale behind the pathogeny as it will not develop in all individuals. There are several causes that could initiate its natural history: strong lumbopelvic anatomical fixations, ligamentous laxity, sarcopenia, spinopelvic parameters, *etc*. In the end, it will stabilize by itself due to the Kirkaldy-Willis cycle. The issue arises when it becomes symptomatic because of the facet deformity and hypertrophy together with the endplate spondylotic osteophytes - even with small displacements-, producing a central and lateral stenosis with a concomitant pluriradicular involvement. The biomechanical background is analyzed to provide clues to understand the natural history of DS and set the rationale for treatment.

Keywords: Pelvic incidence, Spondylolisthesis, Spondylolysis, Spinal balance.

INTRODUCTION

Degenerative spondylolisthesis (DS) is diagnosed when there is a ventral displacement of one vertebra over the adjacent one without affecting the integrity of the posterior structures. It could be understood as a rupture or insufficiency of the spine in two when it fails due to a concentration of stresses at this level that results in the anterior sliding of (most frequently) L4 over L5, due to instability in the lumbar segment; this concentration of tensions is due to the fixation of L5 to the pelvis by strong iliotransverse ligaments, transmitting the anterior shearing tensions in the flexion-extension movements to the immediately superior disc (L4-L5).

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This fact has promoted the study of possible causes that may explain the beginning of this particular displacement, among them:

1. Lack of ligamentous laxity, supported mainly by the fact that it is more frequent in women (1:3 ratio in the Framingham Heart Study) of middle age with estrogen deficiency; patients with estrogen receptor alpha deficiency have a higher prevalence of DS [1].
2. Degenerative disc disease (DDD). The loss of hydrostatic pressure of the disk causes a loss of height and a loss of resistance to displacement with shearing. The start of the degenerative cascade in the intervertebral disc and posterior articular facets causes instability of the mobile vertebral segment that can lead to the development of DDD (one study shows the disease of several disc segments in the context of DS) [2]. The vertebral segment in which this lesion most frequently occurs is L4-L5 and there are certain anatomical conditions at that level that can facilitate the onset and development of this pathology, among them the inclination of the upper vertebral plate of L4 at more than 10º with respect to the horizontal or the sagittal orientation of the articular facets, with interfacetal angles greater than 60º (although this association is not clear whether it may be a cause or a consequence) [3].
3. The morphology of the distal segments of the vertebral spine and their relationship to the pelvis, including the strong iliotransverse ligaments. Biomechanical factors would be especially relevant including all those that facilitate an anterior displacement of the center of gravity, such as obesity [4]. In this line, it would be worth studying the distribution of shapes of the spine (following Roussouly) [5] with the two arches of lumbar lordosis, divided precisely by the upper plate of L4, which is assumed to be parallel to the ground.

ETIOPATHOGENESIS

The cause of DS is currently unknown, and many etiological factors have been implicated, so the general opinion is that its cause is multifactorial.

Both local anatomical factors and others of a more general nature that favor the degenerative displacement of one vertebra over another could be taken into account. Among these local factors, it has been found that there is a molding towards the sagittalization in the arrangement of the articular facets of the L4-L5 joint secondary to destabilization due to disc degeneration and the concentration of shear stresses at that level. In this situation, they would offer less resistance to the anterior displacement of one vertebral body over another, to which ligamentous laxity would also help. On the other hand, there are more general factors mainly of a biomechanical nature that favor this displacement, including a greater inclination of the L4 vertebral body and the different values of spinopelvic parameters in patients suffering from DDD in relation to the healthy population.

In the L4-L5 segment, two important biomechanical situations are combined so that it is precisely at this point where the pathology develops: a) it is the most mobile segment of the lumbar spine, and therefore, more susceptible to becoming unstable; and b) the total lordosis of the lumbar spine is considered to be formed by two arches, an upper one (related to thoracic kyphosis) and a lower one -in which two-thirds of the global lordosis are located- and that the inflection point of those arches happens to meet at the L4 superior vertebral endplate, which presupposes that the facet joints at that level possibly bear relevant stress forces. Together with this, there is a more “stable” disposition of L5 due to its embedded position in the pelvis, fixed by powerful iliolumbar ligaments and by its posterior articulations with S1, generally oriented in the coronal plane. Thus, we speak of “deeply seated” L5 vertebrae, as a predisposing factor to DS.

The influence of the force vectors that -as noted above- affect this segment, can facilitate its instability and the progression towards DS. Therefore, it is pertinent to study the relationship of the lumbar region with the pelvis, through the spinopelvic parameters. A more inclined glide plane will favor the ventral displacement of the L4 vertebral body over that of L5. This “favorable” condition is typically found in those spines with a lordosis of greater magnitude both in its absolute value and in the number of segments involved in it, with which the inflection point, in this case, the transition from lumbar lordosis to thoracic kyphosis migrates cranially. On the other hand, the relationship between lumbar lordosis and pelvic incidence is also known, so both values should not differ by more than 10 degrees. With all this, the spines with a profile of lumbar lordosis and high pelvic incidence will be prone to the development of DS.

CLASSIFICATIONS

There are several classification systems, which we now introduce to the reader.

Wiltse classifies DS according to their anatomical/pathological origin (see Table **1**). Marchetti and Bartolozzi in their 1990 classification differentiated spondylolisthesis from acquired or developmental origin. Their main contribution was to identify high-grade spondylolisthesis with certain specific characteristics, such as S1 endplate insufficiency, L5 trapezoidal index, verticality of the sacrum, and lumbosacral kyphosis (see Table **2**). Then, Meyerding in this classification -which is the most frequently used-, spondylolisthesis is categorized by measuring the percentage of anterior displacement of the cranial vertebra over the caudal one. Grade I would correspond to a displacement between 0 and 25%, in grade II, the displacement would be between 26% and 50%, grade III corresponds between

CHAPTER 6

Biomechanics of Interspinous Devices: The Option to Stabilize without Fusion

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Abstract: Several interspinous devices have been incorporated into the spinal implant market. There have been several reasons for their wide use, including that they can be implanted using a minimally invasive approach even under local anesthesia. This chapter reviews the biomechanical studies about interspinous devices to allow the reader a better comprehension of the effects of these devices, not only on the treated segment but also on the adjacent segments of the spine. Unfortunately, the use of these implants is often not associated with a thorough understanding of their biomechanical behaviour, which is useful to address both indications and contraindications for this procedure.

Keywords: Dynamic spinal stabilization, Interspinous devices, Motion preservation devices.

INTRODUCTION

Interspinous devices (ISD) are implants that are inserted between the spinous processes of two neighboring vertebrae in order to maintain distraction. These devices are constructed using various materials, including titanium, polyetheretherketone (PEEK), and elastomeric compounds [1]. Initially, ISD implantation was primarily indicated for lumbar stenosis, especially in cases where symptoms improved with flexion. However, its applications have expanded to include other surgical indications, such as grade I degenerative spondylolisthesis, discogenic low back pain, non-traumatic instability, and facet syndrome [2, 3]. It is important to note that ISDs do not play a role in preventing disc reherniation. Additionally, these devices are utilized to prevent adjacent segment disease. Even in the surgical treatment of occupational low back pain, the

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use of interspinous spacers offers advantages such as reduced invasiveness and morbidity, increased range of motion, decreased overload on adjacent levels, comparable clinical outcomes, and improved work results when compared to arthrodesis.

These devices have been created with the purpose of opening the spinal canal, restoring foraminal height, and relieving pressure on the facet joints. They offer sufficient stability, particularly during extension, while still allowing movement in the treated area [4]. By preserving the range of motion in the implanted segment, these devices prevent or minimize the risk of overloading and premature degeneration in the adjacent segments, which is in contrast to the effects of fusion [5]. In addition to these motion-preserving devices, another type of interspinous device has been developed to promote the fusion of the interspinous space [6], as explained further below.

This chapter provides an overview of the biomechanical research conducted on interspinous devices, aiming to enhance the reader's understanding of the impact of these devices. It not only focuses on the treated segment but also examines the influence on the neighboring segments of the spine. Regrettably, the utilization of these implants frequently occurs without a comprehensive comprehension of their biomechanical characteristics, which is crucial for determining the appropriate indications and contraindications for this procedure.

CLASSIFICATION OF INTERSPINOUS DEVICES

The interspinous devices currently in the market could be classified into two main groups: motion preservation devices and devices that fuse the interspinous space.

Motion Preservation Devices

These were the initial interspinous devices developed for the treatment of spinal stenosis, by blocking extension, which in turn can be achieved either in a rigid or a flexible manner. The former –also called static- devices consist of non-compressible materials of different biomechanical properties with the same mechanism of action, providing a wedge between the spinous processes causing a fixed distraction during extension. On the other hand, flexible or dynamic devices –which are different due to their material and/or to their shape- offer a higher level of elasticity that allows their deformation during extension of the segment in which they have been implanted, acting as a rear shock absorber. While rigid devices may be compared to a stone preventing a door from opening, flexible devices may be compared to a rubber stopper.

Fusion Devices

These kinds of devices merged as an evolution of the mobile ones in order to overcome their lack of stability in axial rotation; they may have paired plates with teeth or maybe U-shaped devices with wings that are attached to the spinous process. They are supposed, when used with interbody fusion, to be an alternative to pedicle screws -rod constructs to aid in the stabilization of the spine, being less invasive and with fewer risks than pedicle (or facet) screws.

BIOMECHANICAL EFFECTS OF INTERSPINOUS DEVICES

Biomechanics Effects of Nonfusion Interspinous Devices

From the review of the studies on the biomechanics of non-fusion interspinous devices available in the literature, we have focused our attention on the analysis of the following biomechanical effects:

1. Influence on the range of movement (ROM) of the treated segment and of the adjacent segments;
2. Influence on the size of the spinal canal area and foraminal canal area;
3. Effects on the intradiscal pressure, disc load, and facet load;
4. Influence on the segmental tilt and instantaneous axis of rotation (IAR) of the treated segment.

Influence on the Range of Movement (ROM) of the Treated Segment and the Adjacent Segments

New interspinous devices have undergone testing and comparison to determine if their implantation affects the movement characteristics of the involved vertebrae in different clinical scenarios, such as intact and destabilized conditions. The impact of these devices on not only the instrumented level but also the adjacent levels has been extensively studied using cadaveric specimens and Finite Element Modelling. In a study by Lindsey [7], the X-Stop device was found to only reduce the range of motion (ROM) in flexion-extension at the implanted levels, without affecting the other vertebral functional units, despite a slight decrease in lordosis (2º). However, when considering decompressive procedures commonly performed in spinal surgeries, the biomechanical outcomes may vary. Phillips [8] investigated the effect of partial facetectomy and discectomy and found that the insertion of a different interspinous spacer, the DIAM device, improved certain values after destabilization caused by discectomy. Although the DIAM device restored postdiscectomy motion in flexion extension to levels below intact values, it did not have the same effect on other movement modalities. In lateral bending,

CHAPTER 7

Biomechanical Basis of Spinal Stability and Instability Scores

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Abstract: It is critical for any doctor dealing with spinal trauma cases to be able to reliably and quickly determine the stability of traumatic injuries throughout the sub-axial spine. Ultimately, the stability of the spine is dependent on numerous, complex biomechanical relationships between bone, ligament, disc, and muscle. There have been many attempts at classifying different traumatic injuries in the spine based on mechanism, morphology, and a combination of the two, which are presented for review along with two commonly used systems in modern practice.

Keywords: Posttraumatic instability, Vertebral fracture.

INTRODUCTION

Evaluating traumatic injuries in the thoracic and lumbar spine is a large part of neurosurgical practice. To do this properly, an understanding of the biomechanics of the thoracolumbar spine is needed. The end goal of evaluating a patient with traumatic thoracolumbar injuries is to determine if said injuries result in mechanical instability of the spine, as these patients may require surgical fixation. Throughout the years, our understanding of the biomechanics of the thoracolumbar spine has been advanced through clinical observations, cadaveric studies, and computerized models of the spine. This chapter will briefly present the anatomy responsible for spinal stability and the evolution of different thoracolumbar trauma classification systems that have been developed to determine if a fracture results in spinal instability.

BIOMECHANICAL ROLE OF THORACOLUMBAR SPINAL ANATOMY

Stability of the spine refers to the ability of the spine to maintain posture, function, and neurological integrity of the contained spinal cord and cauda equina.

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The mechanical stability and properties of the thoracolumbar spine are the result of a complex interplay of skeleton, ligaments, and muscles. In its entirety, the spine provides dynamic stability, which confers strength for upright position, and protection of neural elements, while allowing a finite amount of movement in all 3 planes: axial rotation, flexion and extension, and lateral bending [1].

The bony elements of the spine include the vertebral body, neural arch, spinous process, and facet processes. Anteriorly, the vertebral body is a large cylinder that provides much of the axial strength of the spine, forming a large column where the axial load is eventually transmitted to the pelvis. Additionally, the posterior portion of the vertebral body forms the anterior wall of the spinal canal. The neural arch, comprised of the pedicles, facets, and lamina, forms the lateral and posterior aspects of the spinal canal, enclosing the spinal cord and nerve roots within the bone, thereby protecting these delicate structures. The spinous process extends posteriorly off the lamina in the midline, serving as an attachment point for various muscles and ligaments of the spine, but it does not add to the bony support of the spine. Each vertebra includes two superior, and two inferior articulating facets connected by the pars interarticularis. The facet processes themselves provide strength in opposing excessive movement of the spine, providing strength in flexion and extension, opposing excessive rotation, lateral bending, and translation of one vertebra on another. Iatrogenic excision of facets, or their disruption by trauma or disease results in instability, deformity, and potential neurologic deficit [2]. The facets are necessary for preventing the translation of one vertebra into another. In the adult spine, a fracture of facets is necessary for an injury to result in translation or dislocation. Based on the orientation of the facet joints, it is easy to see why dislocation occurs most easily in the cervical spine due to the most horizontally oriented joint line, whereas dislocation in the thoracic spine is rare due to nearly vertical orientation, and translation in this segment of the spine almost always requires fracture of the facets (Fig. **1**).

The pedicles are robust bony bridges that connect the bodies to the neural arch. Congenital absence of pedicles or disruption through trauma or tumor impairs stability and alignment. In addition, pedicles are important anchors for spinal instrumentation when stability has been disrupted by trauma, tumor, or infection.

Stability of the thoracic spine is further enhanced by the rib cage which has been demonstrated in numerous cadaveric as well as computerized models. The intact rib cage further stiffens the thoracic spine, reducing motion in all planes compared to the mobile cervical and lumbar spines. It would take removal of several ribs or disarticulation of the sternum to destabilize the thoracic spine [4 - 6].

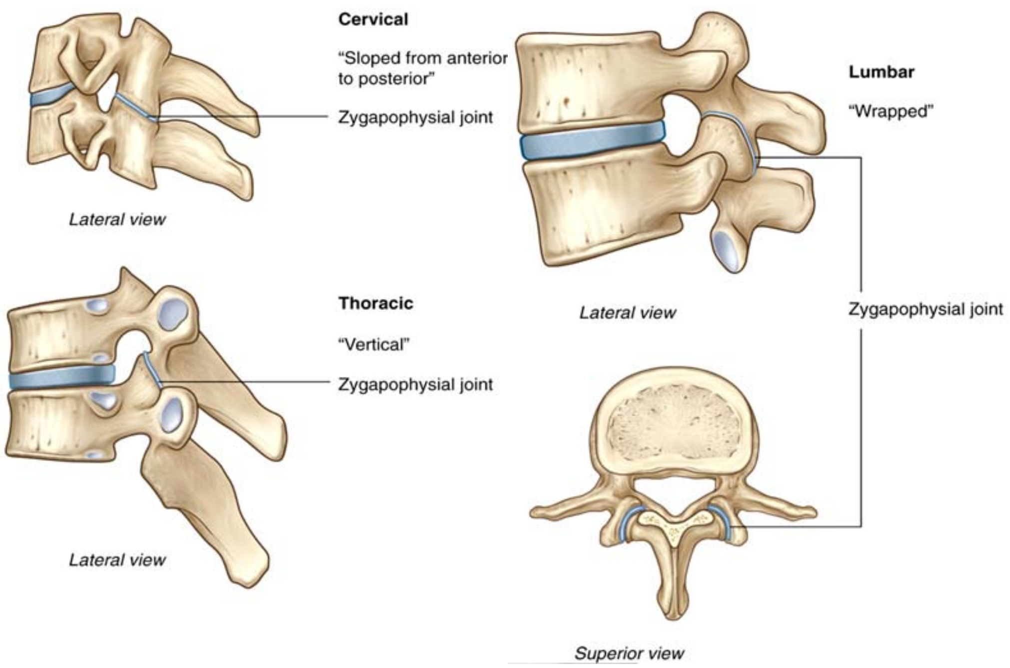

Fig. (1). Diagram comparing anatomy and orientation of cervical (least vertically oriented), thoracic (most vertically oriented), and lumbar (vertical and angled in the axial plane) facet joints. Courtesy of Drake RL, Vogl W, Mitchell AWM, Gray H. Gray's anatomy for students. Fourth edition [3].

The vertebral bodies of adjacent vertebrae are separated by and connected to each other *via* an intervertebral disc. The disc is composed of two parts, the fibrous, exterior limiting structure called the *annulus fibrosus* which contains the inner gel-like material termed *nucleus pulposus*. The *annulus fibrosus* is made of collagenous fibers arranged in laminated bands, which are oriented 90 degrees to the adjacent band. At the bony interface, the *annulus* attaches to the cartilaginous end plate of the vertebral body as well as the cortical surface of the body. The *annulus* confers resistance to rotation, tensile, and shear stresses, which helps prevent excessive movement in any plane or rotation between two adjacent vertebral bodies. The *nucleus pulposus* is made of mucopolysaccharides, mucoprotein, and water forming a gel that forms a viscoelastic material whose mechanical properties change with changing rates at an applied load. The slower a load is applied, the greater the *nucleus pulposus* can deform, and *vice versa*, which helps provide motion to the spine with purposeful movement but can fail under severe traumatic impacts. Additionally, in the axial load, the nucleus acts to absorb shock, cushioning the spine.

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Javier Melchor Duart Clemente

Prof. Javier Melchor Duart Clemente completed medicine in 1999, and then did the residency first in orthopedics, and then neurosurgery, meanwhile he did spinal fellowship with Dr. Mayer, Beisse and Korge at Orthozentrum München February in 2010, in minimally invasive approaches (including thoracoscopy) and disc replacement surgery, and other advanced skills. Then he became attending surgeon and a spinal consultant both in Orthopedics and Neurosurgery Departments. In 2014, he became senior spinal fellow both at Royal London Hospital and at the Centre for spinal studies and surgery in Nottingham (UK). He completed doctoral thesis on biomechanics of dynamic cervical plates in 2023. His areas of special interest are: - spinal surgery, including minimally-invasive and endoscopic approaches (such as thoracoscopy) - spinal cord injury: benefit from early surgery and regeneration by autologous adult stem cell - spinal implants: design and biomechanical testing. He presented at spinal international congresses such as Spine-week, Global Spine Congress, Asia Pacific Cervical Spine Meeting and Eurospine. He has a number of publications to his credit.