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EDITORIAL

In Memory of a Master

Prof. Dr. Emin Alıcı was born on March 1, 1947, in Adıyaman, Türkiye. He completed his primary, secondary, and high school education in Malatya and graduated from Ege University Faculty of Medicine in 1973 as a medical doctor. In the same year, he commenced his residency training in the Department of Orthopedics and Traumatology at Ege University Faculty of Medicine.

During his residency, he was awarded a scholarship that enabled him to gain experience in spinal surgery in Italy. He prepared his specialization thesis on spondylolisthesis and continued his academic career at Ege University. In 1982, he was promoted to Associate Professor with his thesis entitled "Spinal Biomechanics and Spinal Prosthesis". In 1988, he transferred to Dokuz Eylül University, where he attained the rank of Professor. While continuing his academic work there, Prof. Alıcı focused extensively on spinal deformities, spinal infections, and spinal tumors.

Throughout his academic career, he pioneered numerous innovations in spinal surgery. The "Alıcı Spinal System", named after him, became the first domestically produced spinal implant in Türkiye, marking a milestone in the country's medical history. Over the years, the system was further developed and came into widespread use nationwide. In addition to his significant contributions to healthcare, Prof. Alıcı's role as an educator stands out prominently. During his terms as Dean and Rector, he introduced the active learning model into medical education at the university level. By placing special emphasis on medical education, he institutionalized the concept of faculty development within medical schools.

Prof. Alıcı founded the first spinal surgery society in Türkiye and organized the first international spinal congress. In order to enhance the society's success and recognition, he played a leading role in organizing numerous national and international meetings. Even after stepping down from active duties, he continued to support the society. Through the dedicated efforts of subsequent administrations, the Turkish Spine Society has achieved its current level of success. The society's official journal, the Journal of Turkish Spinal Surgery, has continued its publication without interruption, demonstrating a steadily increasing trajectory of academic impact.

As one of the most significant cornerstones of spinal surgery in Türkiye, Prof. Dr. Emin Alıcı has served as a role model for all physicians devoted to spine care, both through his professional achievements and his identity as an educator. With a character firmly grounded in reason and science, he has secured a permanent place among the unforgettable figures of the Turkish scientific community. His cherished memory will continue to be kept alive by his students.

This special issue is dedicated to a great pioneer who inscribed his name in gold letters in the history of Turkish spinal surgery. The review articles were prepared by authors whose professional and personal paths frequently intersected with the life and career of Prof. Dr. Emin Alıcı. As a mark of respect for our senior colleague, the name of Prof. Dr. Emin Alıcı has been symbolically added as the final author to all manuscripts. It is our hope that his professional diligence and deep respect for humanity will continue to serve as an example for future generations.

Special Issue Contributor Editor

Ömer Akçalı, Prof. M.D.

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THE HISTORY OF SPINAL FUSION AND INSTRUMENTATION

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ABSTRACT

Spinal instrumentation techniques have evolved significantly to provide stability in the treatment of spinal deformities, trauma, tumors, and degenerative diseases. In earlier periods, external immobilization methods were used, whereas internal fixation and spinal fusion techniques began to be developed in the early 20th century. The modern era of spinal instrumentation, which started with Harrington rod systems, has advanced considerably with the introduction of pedicle screw systems, minimally invasive surgery, navigation technologies, and robot-assisted applications. This review discusses the historical development of spinal fusion and fixation techniques chronologically.

Keywords: Spinal instrumentation, spine surgery, pedicle screw, spinal fusion

INTRODUCTION

Approaches to the treatment of spinal disorders have evolved throughout history in line with differing medical concepts and technological advancements. The earliest records related to this field date back to the Edwin Smith Papyrus, described around 1550 BC[1]. Insufficient knowledge of the anatomical structure and functional characteristics of the spine led to persistently high morbidity rates associated with spinal injuries for a long period in history. During the Ancient Greek era, spinal anatomy began to be described more accurately. Although human dissection was prohibited in Greek society, anatomical knowledge was obtained through observation of athletes in gymnasiums and examination of cadavers on battlefields[2]. Early treatment approaches primarily consisted of recommending rest and applying wound dressings, whereas contemporary management has evolved into modern fusion surgeries. Naturally, the development of surgical techniques and instrumentation alone was not sufficient; Joseph Lister's development of antiseptic surgery and William Morton's pioneering work in anesthesia played a d ecisive role in advancing this process by significantly improving the safety of surgical procedures[3-5].

Pre-surgical Era

In the 5th century BC, Hippocrates was the first to describe the anatomy of the spine, its diseases, and deformities, and he published these observations along with treatment methods in his work On Joints[2]. He defined kyphosis as a deformity resulting from disease or injury. Hippocrates advocated that such deformities could be treated by applying pressure to the spine under traction using a wooden bench made of oak that he personally designed. This traction-based method continued to be used by many clinicians until the 15th century (Figure 1)[2]. Another Greek physician, Galen, in the 2nd century BC, introduced the terms scoliosis, kyphosis, and lordosis, and provided more detailed descriptions of spinal anatomy, particularly the spinal nerves[6,7]. He also argued that applying direct pressure under axial traction could be used to treat spinal deformities. Between the 5th and 11th centuries, during the Dark Ages, almost no progress was made[8].

In the 11th century, Avicenna (Ibn Sīnā), who lived in the Middle East, made substantial contributions to medicine and osteopathic approaches, and employed axial traction-based methods in his clinical practice. Nevertheless, the limited success of these treatments, and the development of paraplegia in many patients, led to a gradual decline in interest in mechanically correcting spinal deformities[8].

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In the 15th century, the Turkish physician Şerafeddin Sabuncuoğlu described the use of traction and cauterization methods for spinal injuries in his work *Cerrahiyetü'l-Haniyye*[9].

Approaching the Renaissance, in the 15th century, Leonardo da Vinci was the first to systematically elucidate the relationships between vertebrae and conducted highly valuable studies on spinal anatomy and biomechanics[10]. In the mid-16th century, Ambroise Paré described the first iron brace for the correction of scoliosis[11].

In the 17th century, Giovanni Alfonso Borelli, regarded as the father of spinal biomechanics, authored *De Motu Animalium*, considered one of the earliest works addressing biomechanical principles[10].

Surgical Era

Non-instrumented Fusion

While treatments based on corsets and non-surgical traction mechanisms were developing, in 1885, German physicist Wilhelm Roentgen discovered X-rays and introduced them to the medical world, resulting in extensive knowledge about the form and function of the human skeleton. These developments paved the way for surgeons to use materials such as metal and bone in fusion surgeries[12].

In 1891, Hadra[13] from Galveston successfully treated a case of cervical spine fracture-dislocation by using wires wrapped around adjacent spinous processes, an intervention that is considered the first attempt at spinal stabilization. Hadra modestly referenced Dr. W. Wilkins, who had previously performed a similar operation at the twelfth thoracic and first lumbar vertebrae. Fritz Lange[14] from Munich attempted to stabilize the spine in 1909 by first using silk, then steel wire, to attach celluloid rods and later steel rods to the sides of the spinous processes. These studies were conducted at a time when inert metals were not yet in use, and bone resorption occurred around internal fixation devices when metal was employed. Despite this limitation, Fritz Lange's concept of securing steel rods to the spine with wires interestingly served as an inspiration for modern fusion techniques used today[15].

Figure 1. Oak traction bench designed by Hippocrates

In 1900, Miller et al.[16] Hibbs focused on tuberculosis, a disease responsible for widespread mortality in Western societies, and established a center dedicated to treating patients with tuberculosis, particularly those with Pott's disease. In 1911, inspired by his previous knee arthrodesis procedures, he described interspinous arthrodesis using illustrative drawings[16]. This technique was initially applied in patients with Pott's disease who were rapidly developing deformities, and later in trauma patients. The method, which became known as the Hibbs technique, yielded favorable outcomes especially in pediatric patients. However, in adult patients, clinical outcomes deteriorated over time, with increased rates of pseudoarthrosis and loss of deformity correction. Many surgeons attempted to prevent these situations by including the iliac crests in spinal fusion, but they were not very successful, and the use of this method gradually declined[15].

In 1914, Albee[17] employed a similar technique but achieved spinal fusion by creating grooves in the spinous processes and inserting thin, rod-shaped autologous tibial grafts. He even designed a sterilizable saw specifically for harvesting tibial grafts and, for many years, did not use grafts from any other donor site[17].

This technique was modified by Watkins[18], who in his 1953 publication described a posterolateral incision to allow placement of bone grafts between the transverse processes. This spinal fusion method remains a viable option today, particularly for surgeons aiming to perform minimally invasive lumbar fusion procedures[19].

In 1932, Capener[20] described the treatment of patients by placing a bone dowel between L5 and the sacrum to help reduce anterior displacement of the L5 vertebra. During the same period, Burns[21] performed an anterior lumbar interbody fusion in a 14-year-old boy with traumatic spondylolisthesis, achieving fusion between L5 and the sacrum using a bone dowel harvested from the patient's tibia[22]. Rather than approaching the intervertebral disc space anteriorly, Briggs and Milligan[23] described a posterolateral approach to the disc space in 1944. To support the developing fusion mass, a bone peg was placed into the intervertebral disc space; this technique can be considered a precursor of modern posterior lumbar interbody fusion.

Parallel to these surgical advancements, John Cobb continued his nonoperative research and defined the types of coronal spinal deformities and their measurement methods on anteroposterior radiographs, which remain in use today[24].

In the mid-20th century, Risser[25] demonstrated the necessity of postoperative brace use to ensure immobilization following fusion procedures. During the same period, Walker Blount and Albert Schmidt developed the "Milwaukee Brace" an orthosis designed to minimize scoliosis progression in the postoperative period. This brace continues to be used in clinical practice today[26].

Until the mid-20th century, many surgeons attempted to develop their own techniques, but the length of the 6-9 month immobilization period required for spinal fusion, infections, failure of fusion, and loss of correction were the most common difficulties.

Instrumented Fusion

Harrington Instrumentation System

In 1953, Paul Harrington began developing the rod system that bears his name, primarily for use in rapidly progressive neuromuscular scoliosis (Figure 2). The initial surgical approach included placement of facet screws to correct facet joint alignment. Although early postoperative outcomes were favorable, longer-term follow-up revealed that the results were not as satisfactory as initially expected[27].

In the subsequent period, Harrington enhanced his system by incorporating hooks and stainless steel rods to achieve a more rigid construct and successfully corrected scoliotic deformities using the concave distraction technique. Although early clinical outcomes appeared promising, long-term follow-up studies reported recurrence of the deformity, rod breakage, and the development of flat-back syndrome in these patients[28]. The Harrington rod instrumentation system provided a long and rigid construct; however, it had the potential to disrupt normal sagittal alignment in the thoracolumbar region and was insufficient in maintaining the required lordosis at the thoracolumbar junction or providing adequate rotational control[29].

Other complications associated with this system included hook dislodgement, hook-rod disengagement, and laminar fractures. Laminar fractures could also occur as a result of osteoporosis, extensive laminotomy, or excessive distraction[29]. Another notable complication was dural injury during placement of laminar hooks[29]. Harrington initially applied this system in cases of scoliosis and later expanded its use to the treatment of traumatic injuries, degenerative spinal diseases, and tumoral pathologies[29]. Despite the relatively high rate of complications, the Harrington rod represented a novel method for achieving thoracic stabilization. Patients treated with this system were followed postoperatively, and their outcomes were systematically analyzed. These studies demonstrated that, regardless of the skill and strength of the construct, thoracic stabilization without adjunctive fusion would inevitably result in implant (hardware) failure (Figure 2)[28].

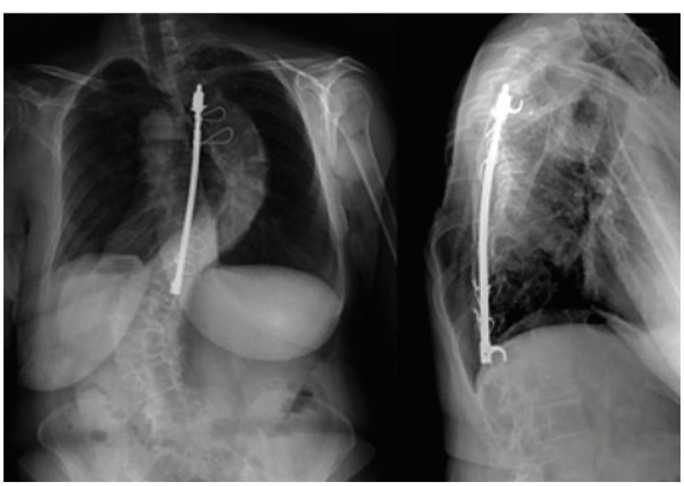

Figure 2. Harrington rod system

Luque (Segmental) Instrumentation System

In 1976, Eduardo Luque used more flexible rods and connected them to the vertebrae at multiple levels using 16-18 gauge wires passed sublaminarly. Following this technique, postoperative brace use was not required in many patients. By anchoring the rods at multiple points, this system achieved significantly higher fusion rates and better overall outcomes compared with the Harrington system. However, the risk of neurological injury during passage of the wires through the spinal canal was considerably high[29,30]. Approximately 10% of patients developed dysesthesia, and in some cases, paraplegia due to spinal cord ischemia occurred, necessitating reoperation for removal of the wires (Figure 3)[29].

As various instrumentation systems were being developed to increase fusion rates, Boucher HH[31] emphasized the strength of interpedicular fixation[32]. In the early 1970s, Roy-Camille et al.[33] was the first to describe screws placed through the facet joints or pedicles, followed by chromium-cobalt alloy plates used to connect these screws[32]. Similar systems supporting all three spinal columns are still in use today[34].

Cotrel-dubousset Instrumentation

In 1984, two French orthopedic surgeons, Yves Cotrel and Jean Dubousset, developed a contoured dual-rod system fixed to the

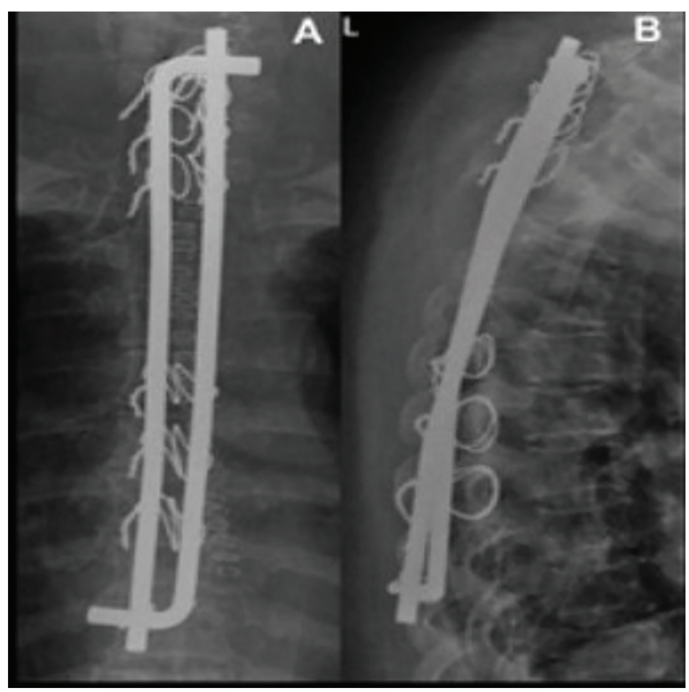

Figure 3. Luque segmental instrumentation system

spine using multiple hooks and screws. This system was the first to address the thoracic "rib hump" deformity associated with vertebral body rotation and paved the way for the development of modern fixation systems currently used in clinical practice[35].

Cervical Instrumentation

Posterior Approaches

Internal fixation of the cervical spine was first performed in 1891 by Hadra[13] using interspinous wiring in a patient with traumatic C6-C7 instability. He later applied the same technique to deformities caused by Pott's disease[13-36]. Over subsequent decades, various methods were developed to stabilize the cervical spine, including wiring techniques (interspinous, facet, interlaminar clamp), lateral mass screw-plate systems, lateral mass screw-rod systems, and ultimately cervical pedicle screw systems[36].

Wiring Techniques

In 1942, Rogers[37] utilized interspinous wiring for the treatment of post-traumatic injuries; in this technique, holes were drilled into the spinous processes, through which wires were passed and secured. Subsequently, McAfee[38] succeeded in stabilizing multiple levels using the triple-wire technique. Facet wiring was first described in 1977 by Callahan et al.[39] for use in cases where the spinous processes or laminae were not suitable. In this method, wires were passed through holes drilled in the lateral masses and secured to an autologous bone graft placed longitudinally over the lateral masses, thereby facilitating fusion. In 1983, Cahill et al.[40] described a new method in which the lateral masses and spinous processes could be wired together.

One of the most significant advances in wiring techniques was the replacement of monofilament rigid wires with multifilament wires that were more flexible, softer, and more durable[36]. This change reduced complications such as dural tears and spinal cord injury during sublaminar wire passage, while also providing stronger and longer-lasting stabilization with more durable materials[36].

Interlaminar Clamp

The interlaminar clamp was first used in 1975 for single-level C1-C2 stabilization. This technique required intact laminae, and the placement of sublaminar clamps carried a risk of neurological deficits, particularly in patients with a congenitally narrow spinal canal[41].

Lateral Mass Screws (Plate and Rod Systems)

Toward the late 1980s, following Roy-Camille's description of lateral mass screws and integrated plates, various modifications regarding screw entry points and trajectories were published by Magerl, Anderson, and An[36]. The use of plates was technically challenging in complex deformities or severe traumatic listhesis. With technological advances in screw systems, polyaxial screws and screw-rod constructs were developed, greatly facilitating posterior instrumentation in nearly all deformities and traumatic conditions.

Cervical Pedicle Screws

Based on animal models and human cadaver studies demonstrating greater stability and higher resistance to screw pullout compared with lateral mass screws, cervical pedicle screws were first used clinically by Abumi et al.[42] in 1991 in a patient with traumatic cervical instability. Similar to the thoracolumbar region, this method provided three-column stability; however, it presented several technical challenges. Accurate selection of the screw entry point was critical, a medial angulation of 25-45 degrees in the transverse plane was required, and pedicle diameters were relatively small. Consequently, there was a significant risk of vascular (vertebral artery) and neurological (nerve root or dural) injury during screw placement[36].

Anterior Approaches

The anterior approach to the cervical spine was first proposed by Leroy Abbott in 1952 during his visit to the clinic of Bailey and Badgley[43], and this approach was subsequently used on numerous occasions. Anterior cervical fusion was first described in the 1950s by Robinson and Smith[44]. This method, based on anterior fusion following removal of disc material and osteophytes, remains in use today with minor modifications. Cloward later modified the technique by recommending the use of a bone dowel for fusion[45]. Boni et al.[46] applied this technique at multiple levels and described anterior corpectomy with fusion using autologous grafts.

The earliest examples of anterior cervical plates were used by Orozco Delclos and Llovet Tapies[47] in 1970 in trauma patients. Caspar et al.[48] subsequently refined these plates and also applied them in traumatic cases. The addition of a plate to anterior cervical fusion provided rapid stabilization, prevented graft displacement and collapse, assisted in restoring sagittal alignment, and reduced both the duration of external immobilization and the need for supplemental posterior instrumentation[49]. The initially described plates required bicortical screw purchase; to eliminate this requirement, plate systems with screws that lock into the plate, still widely used today, were subsequently developed[50].

Acknowledgements

The authors wish to honor the memory of Prof. Dr. Emin Alıcı, whose invaluable contributions to the establishment and development of the Turkish Spine Society and the Journal of Turkish Spinal Surgery laid the foundation for scientific progress in our field. His leadership, mentorship, and dedication continue to guide future generations. This work is dedicated to his memory with deepest respect.

Footnotes

Authorship Contributions

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TRAUMATIC THORACOLUMBAR SPINE FRACTURES

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ABSTRACT

Traumatic thoracolumbar (TL) spine fractures are serious injuries that contribute substantially to morbidity and mortality. They remain relevant, particularly because the number of traffic accidents is increasing as motor vehicle use grows. Historically, we have observed that these injuries have been the subject of numerous scientific articles since the mid-1930s. Advances in technology undoubtedly affect many dynamics in the field of health. Therefore, the classification and treatment of these injuries have evolved. The purpose of this review is to present contemporary approaches to traumatic TL spine fractures and, in doing so, summarize their historical development for readers.
Keywords: Spine fractures, thoracolumbar, trauma

INTRODUCTION

Vertebral column injuries are serious injuries that occur after high-energy trauma. Approximately 75-90% of all spinal fractures occur in the thoracolumbar (TL) region, and about one-fourth of these are accompanied by neurological injury of varying severity[1,2]. The structure of the thoracic and lumbar spinal segments is more similar to each other than to the other segments, so they are classified together. The most common site for TL fractures is the TL junction. This region is vulnerable to trauma because it is the transition zone from the relatively immobile thoracic portion to the mobile lumbar portion. Although the rates vary in the literature, roughly 16% of injuries are observed between T1-T10, 52% between T11-L1, and 32% between L1-L5. The medullary canal is narrowest between T1 and T10. Therefore, fractures in the T1-T10 region are have sixfold higher risk of neurological deficits compared to fractures in other TL regions. On the other hand, the thoracic region is more stable than the lumbar region because it is located within the thoracic structure[3-5].Therefore, the thoracic region (except for the TL junction) should be considered among conservative treatment options for stable spinal fractures.

There are two important factors that make spinal injuries distinct and significant from other bone injuries. The first is undoubtedly its proximity to neural tissues. Spinal fractures and spinal cord injuries result in a decline in quality of life for 50 out of every million people each year[6]. The second factor is the difficulty in determining the extent of damage to the complex ligamentous structure after trauma. Historically, the importance of ligamentous structures in the vertebral column was first described by Nicoll[7]. Subsequently, in many classification systems, "demonstrated ligament injury" has been accepted as an important criterion.

Depending on the severity of the injury, more than 50% of spinal trauma cases are accompanied by additional injuries. Most of the accompanying injuries are intra-abdominal injuries resulting from distraction forces. Pulmonary injuries can be observed in 20% of cases, and intra-abdominal bleeding due to liver and spleen injuries can be observed in 10% of cases. In 6-15% of cases, other spinal fractures in adjacent or non-adjacent segments of the vertebral column may accompany the picture[5,8]. In TL fractures with neurological deficit, the likelihood of a second vertebral fracture, especially a cervical fracture, is 25%[9]. It should be remembered that lower extremity and pelvic fractures may accompany high-fall cases as well.

With the development of surgical techniques, imaging methods, and instrumentation techniques over time, the diagnosis, classification, and treatment of TL fractures have been revised to varying degrees but have always been a subject of debate. It would not be wrong to consider that with the developments in the last two decades, some issues related to diagnosis,

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classification, and treatment have reached a consensus. The aim of this review is to summarize the new developments in traumatic TL vertebral fractures, which are an important health problem, and to update the index review published in 2006[5].

Classification

History

The classification of TL spine fractures is an important issue in terms of organizing treatment, but it has been debated for many years. Many fracture classifications have been defined, but most now have only historical value. However, we observed significant progress in TL fracture classification over the last two decades. AOSpine has proposed a classification that actually encompasses previous classifications and can be more easily adapted for clinical use, and this has generally become established practice. We will discuss the details of this classification after a brief historical overview.

The fundamental question that classification of spinal fractures must answer is whether the fracture requires surgical treatment. Therefore, all classifications primarily question the concept of instability. According to the American Academy of Orthopaedic Surgeons definition, instability is the abnormal response of a spinal motion segment to load (a motion segment is a unit consisting of two vertebrae and an intervertebral disc). The main problem is that in a patient with a spinal injury, the concept of instability in the erect posture of the spine is usually evaluated using examinations performed in the supine position[10]. As a result, the evaluation of a spinal fracture in terms of instability cannot go beyond an estimation based on the data.

The history of classification in spinal fractures dates back to the 1930s. During these years, due to the limitations of radiological methods, classifications aimed at understanding the shape of the fracture. These classifications are termed morphological classifications (Figure 1). In Watson-Jones'[11] historical article, the definitions referred to as wedge fracture, communited fracture, and dislocation of the spine, over time, become known as compression fracture, burst fracture, and fracture-dislocations, respectively.

1980-2003

There are two fundamental characteristics that classifications should essentially cover. The first is that they should guide treatment, and the second is that they should be universally accepted. You will notice that the second is directly related to the first. As the descriptive characteristics of morphological classifications became insufficient over time, mechanistic classifications emerged alongside advances in imaging methods. These classifications introduced definitions of external load and the concept of columns to the literature, attempting to explain the mechanism of injury.

Earlier classifications defined two columns, anterior and posterior[12,13], while studies in the early 1980s defined three columns: anterior, middle, and posterior[8,14,15]. Accordingly, these classifications, which suggest surgical indications based on the affected columns regardless of the fracture mechanism, defined four fundamental injury mechanisms. The mechanisms are known according to their severity: volar flexion stress of the spine causing compression fractures, axial compression stress causing burst fractures, and vertebral tears (flexion-distraction) injuries involving flexion and distraction components. The final mechanism is multi-axial high-energy torsional forces causing fracture-dislocations. The mechanism associated with flexion-extension injuries is more common in flexion injuries occurring while wearing a seat belt, hence these fractures are referred to as seat-belt injuries. Interestingly, looking back at historical records, we see that this type of injury was described as early as 1948 by radiologist George Quentin Chance[16], predating all other classifications. Therefore, flexion-distraction injuries are also referred to as Chance fractures in textbooks. Among the classification systems of that period, the most widely accepted one was based on the three-column theory defined by Denis[8] in 1983, due to its ease of application. According to Denis[8], the TL vertebral column is divided into three columns. The anterior column includes the anterior longitudinal ligament and the anterior 2/3 of the vertebral body. The middle column includes the posterior third of the vertebral body, the posterior annulus fibrosus, and the posterior longitudinal ligament. The posterior column encompasses the posterior elements remaining posterior to the middle column. According to this definition, injuries involving all three columns should be operated on. The most recent classification of mechanistic injuries was published by Magerl et al.[17] in 1994. Known as the AO classification, it is based on the AO classification that had previously been used for orthopedic extremity injuries. The AO/Magerl classification

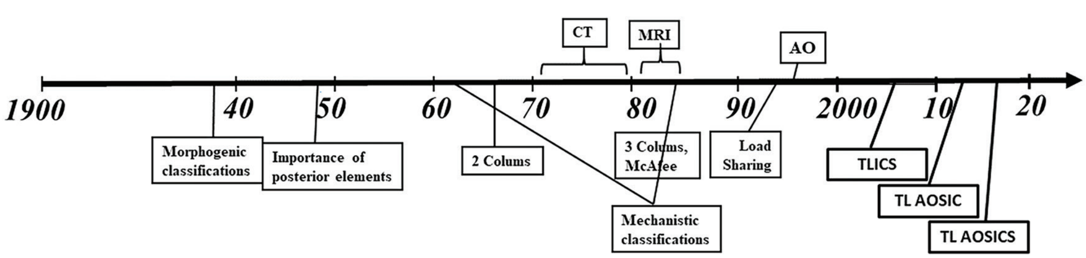

Figure 1. Historical development of the classification systems of spinal fractures (illustrative). CT: Computed tomography, MRI: Magnetic resonance imaging, TLICS: Thoracolumbar injury classification and severity score, TL AOSIC: Thoracolumbar AOSpine injury classification system

defines three major mechanisms of spinal injury-compression (A), distraction (B), and torsion (C). Although this classification, with its 53 subgroups, aims to cover more fracture types, it is considered a difficult classification in terms of memorability and reproducibility. Many spine surgeons therefore continued to use the Denis classification, finding it more practical. The "Load-sharing classification" published by McCormack in 1994 should be evaluated separately (Figure 1)[18]. This classification covers injuries requiring surgery. Among the controversial issues in spinal fractures is whether to treat with short segment (one segment above and one segment below) or long segment (two segments above and two segments below) instrumentation. This classification was created to assess the risk of failure in patients to be treated with short segment instrumentation. This classification is the first study to aim to directly guide surgery and to use a scoring system for the first time.

2005/TL Injury Classification and Severity Score (TLICS)

Mechanistic classifications had some fundamental limitations. For example, these systems were based on inferences about the mechanism of injury rather than an objective description of the morphology of the injury. More importantly, they did not take into account the patient's neurological status, which is critical in the medical decision-making process. Furthermore, particularly in terms of the AO classification, the comprehensive structure of its descriptors led to complexity, reduced reliability, and limited its usefulness in clinical and research settings. These classifications were designed for low-tech radiological examinations of their time. With the advancement of computed tomography (CT) and magnetic resonance imaging (MRI) technology, updating these classifications became a priority, and in 2005, the "Spine Trauma Study Group" published the "TLICS"[19]. The main purpose of this classification was to approach spinal trauma as a whole, rather than perceiving the injury solely as a morphological or anatomical disruption.

Among the innovations brought by this classification were its ease of application, its inclusion of the patient's neurological status in the assessment, and the examination of the integration of the posterior ligamentous complex with MRI. More importantly, it defined a scoring system and provided treatment recommendations based on the score obtained. The TLICS system quickly gained pupularity among older classifications, was widely adopted, and became the subject of numerous studies. The main drawback of the TLICS system was its requirement for MRI examination. Obtaining MRIs in trauma patients is not a very practical procedure, and access to MRIs was not equally easy in all healthcare centers; in fact, it was limited in most. This was considered the most significant handicap in the general acceptance of TLICS as a classification system.

2013/AOSpine TLICS

In order to create a more universal classification, the same team published another study in 2013[20]. In this survey study, 40 cases were sent to members of the "Spine Trauma Study Group" to determine consensus on the classification, and the results were published. This study defined a total of nine injury patterns, including the three injury type and all its subgroups. CT examination was required for the injury patterns, but this was not a difficult imaging modality to obtain with today's emergency protocols and advanced multislice machines. Ultimately, the 53 subgroups in the old AO/Magerl classification evolved into nine subgroups in the current AO TLICS classification (Figure 2). This new classification includes six neurological modifiers, as in the 2005 TLICS. N0 is neurologically intact, N1 is a patient with transient minor neurological findings that have resolved, N2 is a patient with radiculopathy, N3 is a patient with incomplete spinal cord or cauda equina findings, N4 is a patient with complete spinal cord or cauda equina findings, and NX is recorded as unevaluable. In addition, two newly added patient-specific modifiers are denoted by the letter M. These modifiers are intended to provide information about the current status regarding whether the patient will undergo surgery or not. M1 indicates that the presence of a PLC injury cannot be confirmed by examination or imaging methods. M2 indicates that the patient has comorbidities such as ankylosing spondylitis, rheumatoid arthritis, osteoporosis, or burn scar in the surgical area. The most reliable aspect of this new classification, whose criteria are summarized in Table 1, is that it is based on Delphi

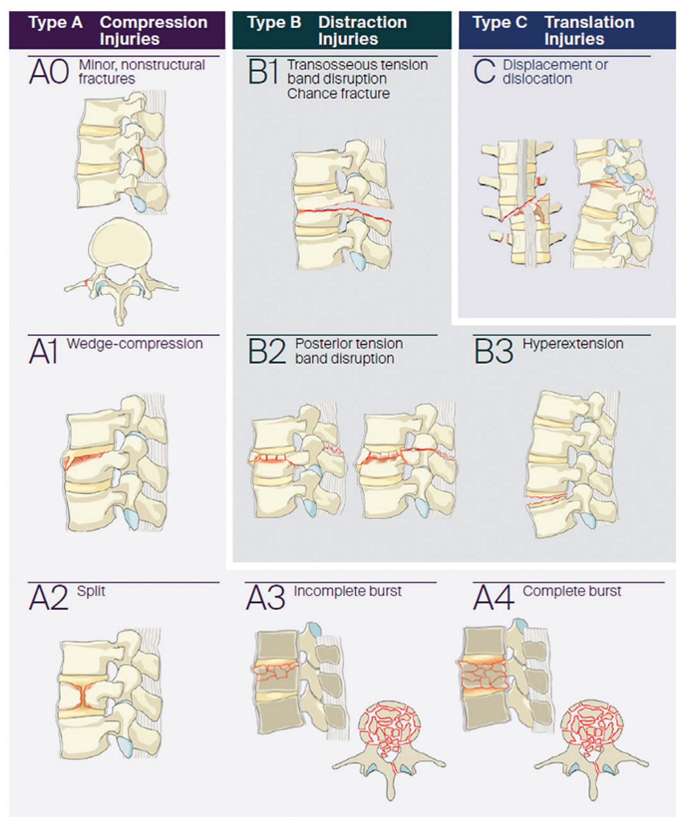

Figure 2. Nine different fracture types, along with their subgroups in the current classification (https://www.aofoundation.org/spine/clinical-library-and-tools/aospine-classification-systems)

analyses using data obtained from a pool of spine surgeons worldwide. When the classification was first published, it did not include scoring.

TL AOSpine Spinal Injury Score (TL AOSIS)

The TL AOSIS and TL AOSIS surgical algorithm were published in 2015 and 2016[21,22]. This scoring system was developed based on the evaluation of spine surgeons in a large survey. The TL AOSIS surgical algorithm uses an integer scoring system similar to that used in the AO TLICS (Table 1). According to the algorithm, conservative treatment is recommended for injuries with TL AOSIS <4. Early surgical treatment is recommended for injuries with TL AOSIS >5. Injuries with TL AOSIS 4 or 5 can be treated surgically or nonoperatively, depending on patient variables and the surgeon's preference (Table 2).

Treatment

The main goals in treating spinal column injuries are to protect the integrity of the spinal column, decompress neural tissues, and achieve a stable column with the appropriate contour when the spine is in an upright posture. Spinal fracture treatment has evolved around certain controversial issues in the history of spinal surgery. The primary point of debate has been whether fractures should be treated conservatively or surgically. The fundamental goal in all classifications is to make this distinction. Conservative treatment includes bed rest (for minor fractures), hyperextension splints, three-point contact hyperextension braces, or TL-sacral orthosis style full-contact orthoses. However, over time, these treatment methods have become less commonly used by spine surgeons. This is primarily due to the improvement in imaging techniques, which allow for better assessment of fracture morphology, and the advancement of implantation technology. The increase in surgical practice and the associated surgical experience has also made the surgical treatment of these types of injuries less of a feared prospect.

Another much-debated topic in historical development concerns surgical technique. Anterior surgery performed via thoracotomy and lumbotomy was a popular approach for a time. It was fundamentally believed that adequate decompression and optimal restoration of compromised anterior support could only be achieved through this method. Although this is a valid concept, the additional morbidity associated with anterior surgery has led to the greater popularity of posterior approaches today. Of course, the technical advancement of anterior cord decompression performed via the posterior approach has also contributed to this. Anterior surgery still has a place in patients with apparent cord compression and neurological deficit.

The number of vertebrae to be included in the fixation has also been a topic of debate, with short segment and long segment approaches. A short segment refers to the vertebrae one level above and below the fractured vertebra (3 vertebrae), while a long segment refers to the vertebrae two levels above and below (5 vertebrae). We may say, theoretically, the concept that a short segment is sufficient in patients accompanied anterior surgery, while fixation of two segments above and two segments below is required in those undergoing posterior surgery alone, remains valid today. Therefore "posterior-only" surgeries, which involve applying a long segment from the back, have become the standard for surgeons. If decompression is necessary, anterior cord decompression from the posterior can also be added to the procedure. The current development regarding whether the segment should be long or short concerns the application of screws to fractured vertebrae. This technique, known as intermediate screw application, was actually defined by Dick et al.[23]. It has gained popularity over the past 15 years and is now increasingly applied. The intermediate pedicle

Table 1. AOSpine thoracolumbar spine injury classification system[20]

Fracture morphology	**A: Compression injury**	A0: No fracture, insignificant spinous or transverse process fractures	
		A1: Single endplate, no posterior wall involvement	
		A2: Both endplates, no posterior wall involvement	
		A3: Single endplate and no posterior wall involvement	
		A4: Both endplates and no posterior wall involvement	
	B: Tension band injury	B1: Monosegmental osseous failure of posterior tendon band, extending into vertebral body	
		B2: Disruption of posterior tension band w/ or w/o osseous involvement	
		B3: Disruption of anterior tension band, intact post	
	C: Displacement/translational injury		
Neurological status	N0: Neurologically intact	Case-specific modifiers	M1: Fractures with indeterminate injury to tension band (based on MRI or clinical examination)
	N1: Transient neurological deficit, resolved		
	N2: Symptoms or signs of radiculopathy		
	N3: Incomplete spinal cord injury or cauda equina injury		M2: Patient-specific comorbidity affecting surgical decision
	N4: Complete spinal cord injury		
	N5: Patient cannot provide reliable examination		

MRI: Magnetic resonance imaging

Table 2. Thoracolumbar AOSpine injury score

A0	0
A1	1
A2	2
A3	3
A4	5
B1	5
B2	6
B3	7
C	8
Neurological status	
N0	0
N1	1
N2	2
N3	4
N4	4
NX	3
Case-specific modifiers	
M1	1
M2	0

Conservative treatment is recommended for injuries with TL AOSIS <4. Early surgical treatment is recommended for injuries with TL AOSIS >5. TL AOSIS 4 or 5 can be treated surgically or non-operatively. TL AOSIS: The AOSpine spinal injury score

screw significantly increases the stability of the construct[24-26] and therefore allows for short segment (3 vertebrae) fixation in posterior approaches[25]. Some authors have also noted its positive effect on kyphosis correction and endplate restoration. Bleeding may increase slightly when placing screws in an fractured level, but no other complications, including surgery time, have been observed that would be detrimental to the technique[27,28].

Another fixation technique that has entered practice in the last two decades is percutaneous transpedicular instrumentation. Placement of transpedicular screws with small incisions on the skin by reducing soft tissue damage is a technique that has a long history. In the external fixation concept, a percutaneous vertebral pedicle fixation was first reported by Magerl[29]. Since the beginning of the 2000s, percutaneous pedicle screw fixation (PPSF) has come into common use as an internal fixation method in spinal surgery in the direction of increased usage of pedicle screws in surgical procedures and the developments in implant technology[30]. The indications for this application have expanded over time due to the advantages of less invasiveness[31]. All type A fractures without neurological deficit and not suitable for conservative treatment are candidates for PPSF. In addition, depending on the surgeon's experience, it can also be applied in type B and C fractures, provided there is no neurological deficit[32]. There are numerous studies on PPSF, both biomechanical and clinical. Their positive outcomes have supported the widespread adoption of the procedure.

In conclusion, we have observed significant changes in the diagnosis and treatment of TL injuries in recent decades. These developments have also significantly influenced our practical applications. Looking ahead, it seems inevitable that new innovations, along with advances in navigation, imaging, and implant technology, will change our practice and routines.

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We extend our deepest gratitude to Professor Emin Alıcı, who made significant contributions to the advancement of spinal surgery in our country, and to his cherished memory.

Footnotes

Authorship Contributions

Surgical and Medical Practises: E.A., Concept: E.K., Design: E.K., Data Collection or Processing: E.K., A.Ç., Literature Search: E.K., A.Ç., Writing: E.K.

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CURRENT CONCEPTS IN THE MANAGEMENT OF SPONDYLOLYSIS AND SPONDYLOLISTHESIS

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ABSTRACT

Spondylolysis and spondylolisthesis encompass a heterogeneous group of spinal disorders with varying etiologies, age distributions, clinical presentations, and management strategies. This narrative review was prepared in memory of Prof. Dr. Emin Alıcı, whose residency thesis and subsequent academic career were devoted to spondylolysis and spondylolisthesis, and whose early work significantly influenced the understanding and surgical management of these conditions in our institution. By integrating his foundational concepts with contemporary evidence, this review traces the evolution of knowledge from classical principles to current practice. Clinical manifestations range from mechanical low back pain to radiculopathy and neurogenic claudication, highlighting the importance of a careful clinical evaluation, supported by appropriate imaging. Standing radiographs remain essential for assessing slip severity, sagittal alignment, and pelvic parameters, while computed tomography and magnetic resonance imaging provide detailed evaluation of morphology. Traditional classification systems, such as Meyerding and Wiltse, remain widely used because of their simplicity, but they are limited in prognostic value and in guiding treatment. More recent systems, including those proposed by the French Society for spine surgery, clinical and radiographic degenerative spondylolisthesis classification, and the University of California San Francisco degenerative spondylolisthesis classification, incorporate sagittal balance, instability, and clinical symptoms, offering a more comprehensive framework for individualized treatment planning. This shift toward biomechanically informed and patient-specific assessment reflects principles emphasized in Prof. Dr. Emin Alıcı's early work. Management strategies differ substantially between pediatric and adult populations. Conservative treatment is the first-line approach for most cases of spondylolysis and low-grade spondylolisthesis. Surgical intervention is reserved for patients with persistent pain, neurological deficits, progressive deformity, or high-grade slips. Spondylolysis and spondylolisthesis require individualized evaluation and management, grounded in an understanding of the biomechanics, natural history, and clinical presentation. This review summarizes current evidence while honoring the lasting academic legacy of Prof. Dr. Emin Alıcı, whose contributions continue to shape modern approaches to these complex spinal disorders.

Keywords: Spondylolisthesis, spondylolysis, posterior surgery

INTRODUCTION

Spondylolisthesis is a general term used to describe anterior displacement of a vertebral body along with the vertebral column above it over the vertebra below. Spondylolisthesis may be caused by different clinical entities. Congenital dysplasia of posterior elements of vertebra, a defect or elongation of isthmus (pars interarticularis), degenerative changes of intervertebral disc or facet joints, traumatic fractures of vertebra, pathologies such as neoplasms or infection, and posterior decompression surgeries with no stabilisation are among different clinical scenarios which may cause spondylolisthesis. Spondylolysis is a defect or elongation of pars interarticularis. Spondylolysis may be unilateral or bilateral. Spondylolysis or spondylolisthesis may be seen in different age groups, spondylolyis being commonly encountered in active adolescents, whereas degenerative spondylolisthesis is mostly seen in elderly age group. Clinical presentation may vary from mild low back pain to neurological claudication or neurological deficisits depending on etiology. There are many classification systems, relying on displacement percentage (Meyerding) or causative etiology (Wiltse), or relatively newly described classification taking sagittal alignment and/or instability into consideration such as French Society for spine surgery (FSSS) and clinical and radiographic degenerative spondylolisthesis classification (CARDS). Conservative methods (non-steroidal anti-inflammatory drug, physical thearpy, bracing) are usually

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firstline treatment for patients with mild symptoms[1]. Patients with segmental instability, persisting pain and neurologic deficits often require surgical treatment varying from fusion, reduction, decompression and/or fusion with instrumentation.

Epidemiology and Natural history

Spondylolisthesis and spondylolysis are disorders of bipedals, and have not been reported newborns or in non-ambulants[2,3,4]. Lumbar spondylolysis is seen radiologically in 4.4% percent of 6 year old children and 6% of young adults[3]. Children who are actively involved in sports activities that require repetative spine flexion-extension and rotation such as gymnastics, volleyball, wrestling and diving are more prone to develop spondylolysis. Wimberly and Lauerman[5] reported the incidence of spondylolysis to be up to 50% among athletes engaged in high-risk sports with persistent back pain. Pelvic geometry, increased pelvic incidence and related larger lumbar lordosis are reported to increase the risk of pars interarticularis stress fracture[6]. Most of pars interarticularis fractures develop on lower lumbar levels. A magnetic resonance imaging (MRI) study by Kriz et al.[7] revealed that 65% of pars fracture occured at L5, 24% at L4, 8.4% at L3, and only 7.1% at or above L3. The incidence of spondylolysis is estimated to be 3-8%, with a prevalence of approximately 11.5%[8]. Unilateral spondylolysis or stress reaction in isthmus detected by MRI without a fracture is a self-limiting condition and has been reported to heal at a mean of 14 weeks[9,10]. A computed tomography study revealed fusion of acute partial or complete isthmus fracture in 67% of of patients after activity restriction of 4 months[11]. Progression to spondylolisthesis was encountered in 25% of patients with bilateral spondylolysis in a 2 year follow-up study[11]. Healing and fusion of spondylolytic defect depends on anatomical features and more likely with unilateral defect or defect in L4, whereas non-healing or progression to spondylolysis is more common in patients with a trapezoidal L5, rounding of sacral dome, and more than 5% spondylolisthesis, whereas union is not expected to occur with sclerotic and round fracture lines (Figures 1 and 2)[12]. 80% of patients with spondylolysis return to sport activities and remain pain-free but persistent low back pain may develop in 20%[13]. Increased incidence of spondylolysis among first degree relatives are reported and genetic predispostion such as seen in Alaska Natives as well as sagittal and coronal plane vertebral deformities may predispose to development of spondylolysis[11,14,15].

Spondylolisthesis can be seen in approximately 6% of general population[3]. Progression of spondylolisthesis depends on the etiology. Degenerative spondylolistesis is mostly seen in adults, frequently associated with aging, with predominance in females (two to six times more common), possibly related to increased laxity and hormonal factors, with prevelance of 24-43% in women over 65 years of age[16,17,18]. Most cases of degenerative spondylolisthesis are low-grade and do not progress beyond Meyerding grade I or II. Dysplastic (low or high-grade) sponylolisthesis tend to progress and may present with pain and neurologic deficits and may progress to Meyerding grades III, IV or even to spondyloptosis (Figure 3). Rate of progression is reported to be 34% in degenerative spondylolisthesis, 32% in isthmic spondylolisthesis, and 45 in traumatic cases[19].

Clinical Features

Although not all patients develop clinical symptoms, main presenting symptom of patients with spondylolysis or spondylolisthesis is low back pain. The low back pain has typical mechanical characteristics, worsening when transitioning from supine to erect and flexion or extension of the spine[16,20]. With aging, especially in degenerative spondylolisthesis cases,

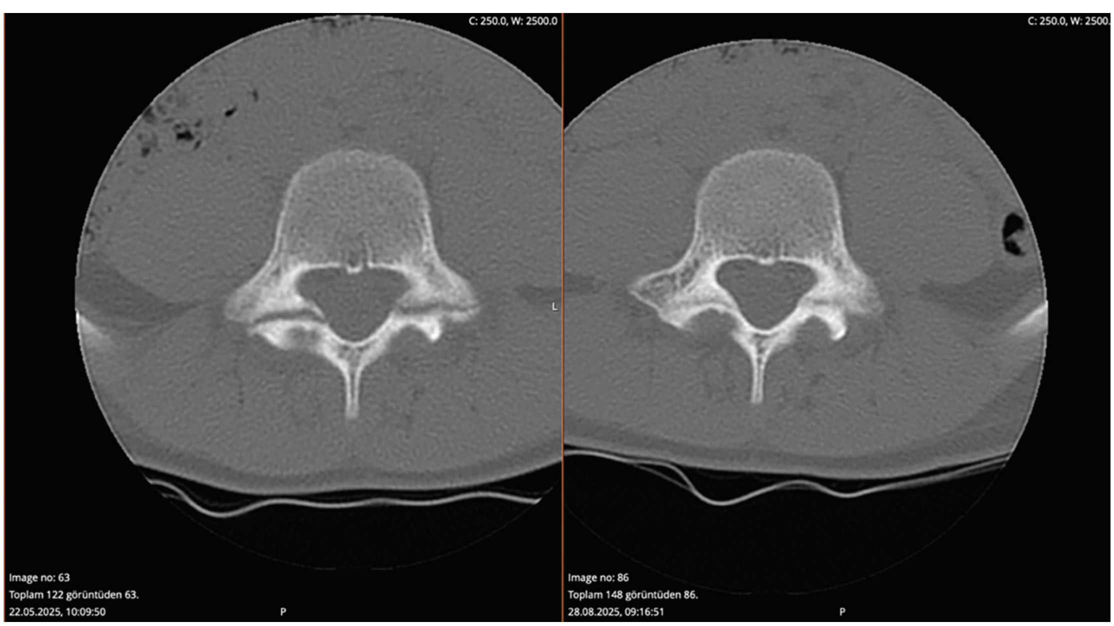

Figure 1. Fused pars defect after 3 months of conservative treatment

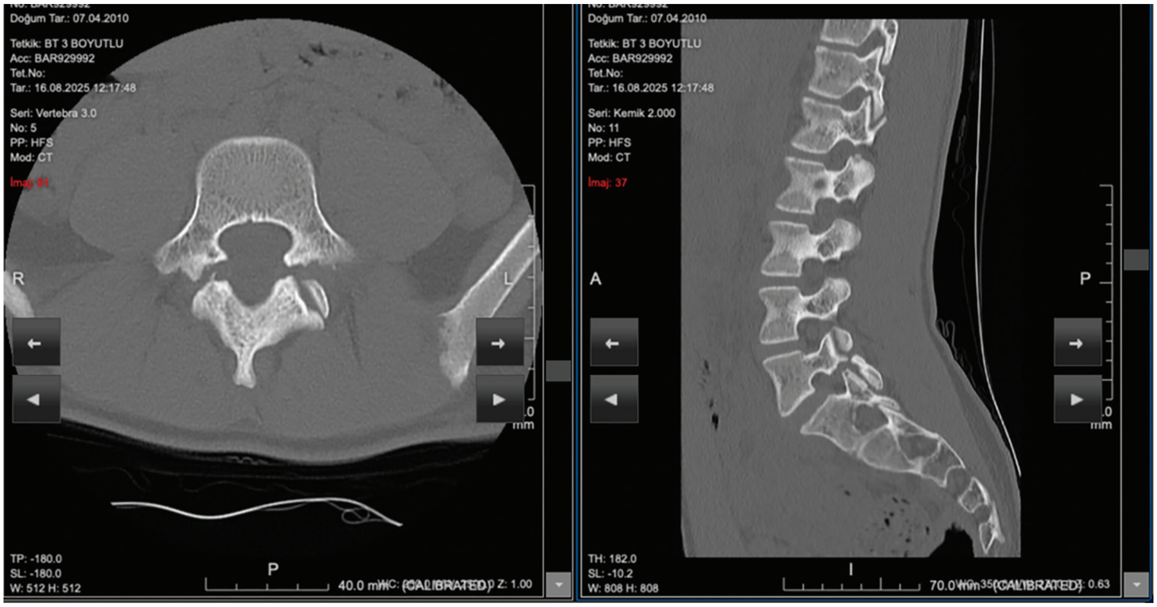

Figure 2. Chronic, non-union of pars defect in 14 years old female gymnast. CT: Computed tomography

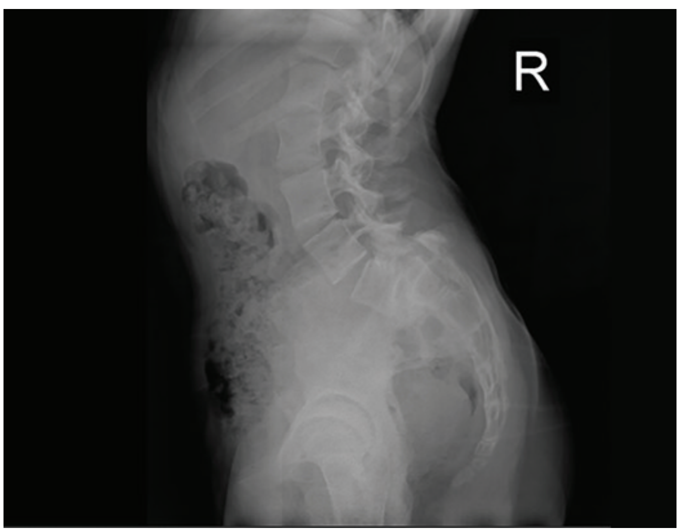

Figure 3. High-grade spondylolisthesis

degenerative changes develop at the functional segmental unit and leg pain, neurological claudication, radiculopathy become more dominant[21]. In the spine patient outcomes research trial study, only 7% of patients had instability, whereas 34% had pain radiating to legs, 26% back pain and 40% had both leg and back pain[2]. Symptoms become more apparent with higher grade spondylolisthesis (grade III-IV), 55% to 91% back pain, 44% to 55% radicular symptoms and up to 50% activity limitation[17,22,23]. Physical examination requires detailed assessment of posture, lumbar lordosis, gait (for Phalen Dickson sign), spinal mobility at flexion and extension, neurological status, and motor and sensory deficits. Palpation of spinous processes may delineate instability which is usually pathognomonic for bilateral pars defects and step-off sign for spondylolisthesis. Stork test (patient extends spine while standing on one leg) is also helpful for detecting pars defects. Hamstring tightness and pain at lower back and thigh on spinal extension indicates isthmic spondylolisthesis.

Imaging

First-line imaging modality for patients suspected of spondylolysis or spondylolisthesis is standing anterior-posterior and lateral X-rays. Standing lumbosacral vertebral xray is valuable for detecting bilteral pars defects, spondylolisthesis grade (percentage of slippage), slip angle, and lumbar lordosis. Supine X-rays should be avoided as this position allows listhesis to reduce into its normal position (Figure 4). Full vertebral scoliosis X-rays are importand and must be obtained whenever possible, to detect sagittal and coronal plane deformities and pelvic parameters (pelvic incidence) which are important for development and may be a predisposing factor for spondylolisthesis[6]. Dynamic lateral flexion and extension X-rays taken supine are valuable in detecting segmental instability. Segmental instability must be suspected when translation is more than 3mm and change in disc angle is more than 10 degrees[24]. Right and left oblique X-rays to detect pars defects are no longer recommended as they do not improve diagnostic accuracy[25,26].

Computerised tomography provides valuable information about the presence and status of pars defects, whether the fracture is acute, or chronic with sclerotic round edges[27]. MRI is also valuable in detecting pre-fracture stress reaction in pars interarticularis or edema in pedicle[28]. MRI is also valuable for diagnosis in case of neurologic deficits, however, it must be remembered that MRI takes 20 min lying down in supine position, therefore is not accurate for diagnosing spondylolisthesis.

Classification

One of the most commonly used classification for spondylolisthesis is Meyerding classification. First described in 1932, it basically defines the percentage of slip on lower vertebra on lateral X-ray. The upper end-plate of caudal vertebra is divided into 4 parts, and the location of the posterior end of cranial vertebral corpus determines the grade (Table 1). Grade 1 indicates up to 25%, grade 2 up to 50%, grade 3 up to %75, and grade 4 up to %75 slippage. Grade 5, although was not in the original classification indicates 100% displacement and often reffered as spondyloptosis. Although Meyerding a is well-known and used classification, this system can not differentiate between low and high-risk patients for slippage. Also many patients with severe degerative changes and clinical finding may be classified as grade 1 or 2. Therefore, although widely used and easily describes the amount of slip, Meyerding classification lacks the accuracy to guide treatment and predict prognosis.

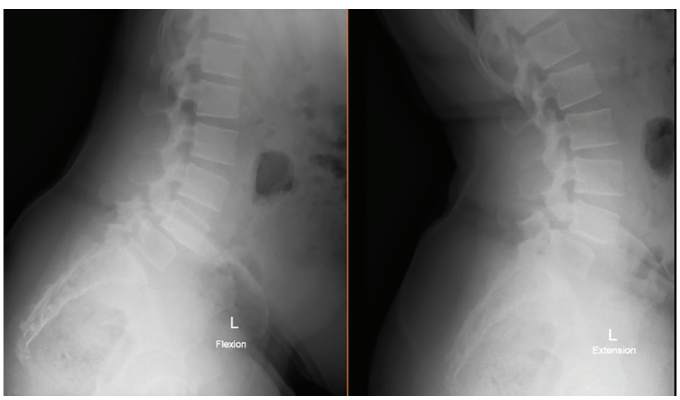

Figure 4. Flexion-extension dynamic X-rays

Wiltse et al.[29] proposed a classification based on etiology and causative mechanism in 1976: dysplastic (type I), isthmic (type II), degenerative (type III), traumatic (type IV), pathologic (type V) (Table 2). Type I is the result of dysplasia of posterior elements of L5. Type II corresponds to a defect in isthmus and further divided into type IIA, stress fracture of pars interarticularis and type IIB, elongated pars interarticularis resulting from repeated fractures and healing. Type III is caused by degeneration of intervertabral disc, facet joints and ligament. Type IV, traumatic type is fractures caused by fractures due to high energy trauma. Type V is caused by pathologies such as neoplasms or metabolic bone diseases. Type IV is added to the classification later which is iatrogenic, and caused by wide decompressions during surgery with no stabilisation. Although Wiltse classification clearly distinguishes the etiology of spondylolisthesis, it can not describe the severity of listhesis, nor risk for progression of slip.

Marchetti and Bartolozzi, in an effort to take into account the natural history and risk of progression, described their classification as developmental and acquired, and further divided developmental group into low dysplastic and high displastic groups (Table 3). However, as Lan et al.[30] pointed out in their review, this system lacks the ability to accurately describe the degree of slippage, describe and predict disease severity and prognosis, and surgical treatment methods. Many classification systems have been described recently to accomplish the insufficiencies of these widely used classification, like FSSS and CARDS[31,32]. The FSSS classification take into account the lumbar lordosis, pelvic incidence, sagittal vertical axis and pelvic tilt and reccommend surgery accordingly (Table 4). CARDS classification system takes into account 3 radiographic and 1 clinical parameters, as intervertebral disk height preservation, segmental angle, vertebral translation

Table 1. Meyerding classification

Grade	Percentage of slip	Definition
Grade I	**0-25%**	Mild anterior translation of the vertebral body.
Grade II	**26-50%**	Moderate slip with partial forward displacement.
Grade III	**51-75%**	Advanced slip; significant anterior translation.
Grade IV	**76-100%**	Severe displacement approaching complete dislocation.
Grade V (spondyloptosis)	**>100%**	Complete anterior dislocation; vertebral body fully translated beyond sacrum.

Table 2. Wiltse-Newman-Macnab classification

Type	Name	Definition
I	Dysplastic	Congenital deficiency of L5-S1 facets or sacral anatomy leading to slip.
II	Isthmic	Pars interarticularis defect; includes stress fracture (IIA), pars elongation (IIB), and acute fracture (IIC).
III	Degenerative	Slip due to facet joint degeneration with intact pars; typical in older adults.
IV	Traumatic	Slip caused by fracture of posterior elements other than the pars.
V	Pathologic	Slip due to bone-weakening disease (tumor, infection, metabolic disorder).
VI*	Iatrogenic	Post-surgical instability (e.g., after wide laminectomy). Not in original* Wiltse.

IIA: Type II A, IIB: Type II B, IIC: Type II C and presence and bilaterality of leg pain (Table 5). In 2024, Rangwalla et al.[33] proposed a novel classification for degenerative spondylolisthesis, University of California San Francisco degenerative spondylolisthesis classification, which includes four components; 1) segmental dynamic instability, 2) location of spinal stenosis, 3) sagittal alignment, and 4) primary clinical presentation (Table 6).

Classifications based primarily on etiology or slip percentage are inadequate for prediction of prognosis or guiding the treatment plan. Recently described classifications which include sagittal parameters and clinical findings may ameliorate the process of classification and decision making in lumbar spondylolisthesis.

Treatment

Treatment of Pediatric Spondylolysis and Spondylolisthesis

Pediatric spondylolysis and spondylolisthesis is addressed seperately from adult spondylolisthesis as degenerative type is the most common type in adults where clinical symptoms are usually caused by secondary changes in the spinal segment in addition to instability. As acute pediatric spondylolysis usually has a favorable prognosis and has a chance of fracture healing, conservative treatment is the first-line treatment. Restriction of high-risk activities including flexion-extension or rotation, core muscle strengthening for 4 months usually increases the likelihood of fusion[34]. Immobilisation or brace

Table 3. Marchetti Bartolozzi classification

Main type	Subtype	Definition
Type I-developmental	Ia-high dysplastic	Severe congenital lumbosacral dysplasia with high-risk of progression.
	Ib-low dysplastic	Mild–moderate congenital dysplasia with limited progression potential.
	IIa-isthmic (lytic)	True pars interarticularis defect caused by stress or fatigue fracture.
	IIb-isthmic (elongation)	Pars elongation due to chronic repetitive stress without complete defect.
Type II-acquired (secondary)	IIIa-postsurgical (iatrogenic)	Slip associated with posterior arch insufficiency after spinal surgery.
	IIIb-posttraumatic	Slip due to fractures of posterior elements other than the pars.
	IVa-degenerative	Slip secondary to facet joint arthrosis or segmental degeneration with intact pars.
	IVb-pathologic	Slip resulting from bone-weakening diseases such as tumor, infection, or metabolic disorders.

Table 4. FSSS classification

Type	Subtype	Radiographic criteria	Description
Type 1	**1A**	PI-LL <10°; SL >5°	Normal global sagittal alignment with preserved segmental lordosis
	1B	PI-LL <10°; SL <5°	Normal global sagittal alignment with loss of segmental lordosis
Type 2	**2A**	PI-LL >10°; PT <25°	Compensated malalignment without pelvic compensation
	2B	PI-LL >10°; PT >25°	Compensated malalignment with pelvic compensation
Type 3	**-**	SVA >4 cm	Global sagittal malalignment

FSSS: French Society for spine surgery, PI: Pelvic incidence, LL: Lumbar lordosis, SVA: Sagittal vertical axis, SL: Segmental lordosis, PT: Pelvic tilt

Table 5. CARDS classification

Type	Radiographic criteria	Definition
Type A	Advanced disc collapse; no segmental kyphosis	Collapsed disc space with preserved segmental lordosis
Type B	Disc height partially preserved; translation ≤5 mm	Mild slip with maintained alignment
Type C	Disc height partially preserved; translation >5 mm	Significant slip with progressive instability
Type D	Segmental kyphosis present	Kyphotic alignment at the affected motion segment

CARDS: Clinical and radiographic degenerative spondylolisthesis classification treatment does not improve results[11]. Patients that do not respond to conservative treatment may benefit from surgery. Many methods have been described for surgical treatment of symptomatic spondylolysis refractory to conservative which can be grouped as direct repair or spinal segmental fusion. Spinal segmental fusion is rarely indicated in spondylolysis without spondylolisthesis. Direct repair techniques are contraindicated in spondylolysis cases with more than Meyerding grade I, facet joint arthrosis, severe disc degeneration. Conservative treatment of spondylolysis is the first-line treatment for unilateral pars interarticularis defect, patients with high signal intensity on MRI, and acute bilateral defects. Conservative treatment includes 4 months of activity restriction, isometric trunk muscle strenthening exercises (core stability) and limiting trunk flexion and extension. Spondylolysis patients with unresolved clinical findings, bilateral defects with sclerotic edges indicating non-union may benefit from pars repair techniques. Many methods have been described for direct pars repair, including Buck screw, Scott wiring, Morscher screw, pedicle screw-hook-rod and V-rod (Figure 5)[35]. Resection and grafting of defect is followed by a stabilisation in these thechniques. Buck screw and Scott wiring are not practical and do not provide adequate stability[36]. Pedicle-screw-hook-rod and V-rod techniques are most popular methods for direct pars repair in patients with spondylolysis[37].

Surgical Management

Surgical treatment is usually indicated when conservative treatment fails and patients continue to experience persistent back pain or neurologic symptoms like radiculopathy or neurogenic claudication that affects their quality of life. High-grade spondylolisthesis due to dysplasia and segmental degenerative changes in degenerative spondylolisthesis are two different and main etiologies and indications requiring surgical intervention. Dysplastic spondylolisthesis and degenerative spondylolisthesis are two distinct entities with different treatment strategies, therefore will be discussed seperately.

High-grade Spondylolisthesis

High-grade (more than Meyerding grade II) spondylolisthesis usually develops in L5 with dysplasia of posterior elements. High pelvic incidence and sacral slope causes shear forces, therefore patients with this pelvic morphology are more prone to develop high-grade spondylolisthesis. Surgical treatment methods for high-grade spondylolisthesis include *in-situ* fusion, reduction and fusion, and reduction and instrumented fusion.

In-situ Fusion

In-situ fusion can be posterolateral, interbody and circumferential. Posterolateral *in-situ* fusion via muscle splitting Wiltse approach between L4 and S1 is a safe method but has more than 20% risk of non-union and progression of slip[38]. Interbody fusion has the advantage of creating a fusion between vertebral bodies of L5 and S1, thus obtaining a wider fusion area when combined with posterolateral fusion. Interbody fusion can be obtained with a fibular strut graft (Bohlman technique), pedicle screws or transsacral interbody cage[39,40]. Bohlman method is a popular method. In this method in which a fibular strut graft is inserted into a bony tunnel from posterior body of S1 to anterior body of L5 after wide laminectomies of L5 and S1, then augmented with posterolateral grafting between L4 and S1. Alıcı, in 1991, decribed methods used for *in-situ* fixation of spondylolisthesis (Figures 6-8)[41].

Table 6. UCSF DS classification

Category	Subcategory	Definition
1. Segmental dynamic instability	**<3 mm translation**	Stable segment with minimal motion
	3-5 mm translation	Moderate dynamic instability
	>5 mm translation	Marked dynamic instability
2. Location of spinal stenosis	**Central/lateral recess stenosis only**	Stenosis limited to central canal or lateral recess
	Foraminal stenosis without up/down stenosis	Foraminal narrowing without pedicle-on-pedicle compression
	Foraminal stenosis with up/down stenosis	Foraminal stenosis involving superior/inferior compression (pedicle or osteophyte impingement)
3. Sagittal alignment	**Maintained segmental lordosis**	Normal local alignment at the involved segment
	Segmental neutral or kyphotic alignment	Loss of local lordosis or segmental kyphosis
	Global sagittal malalignment	SVA >5 cm or PT >30°
4. Primary clinical presentation	**Primarily leg pain**	Leg pain VAS ≥4; back pain <4
	Both leg and back pain	Leg pain VAS ≥4 and back pain VAS ≥4
	Primarily back pain	Back pain VAS ≥4; leg pain <4

UCSF DS: University of California San Francisco degenerative spondylolisthesis, SVA: Sagittal vertical axis, PT: Pelvic tilt, VAS: Visual analog scale

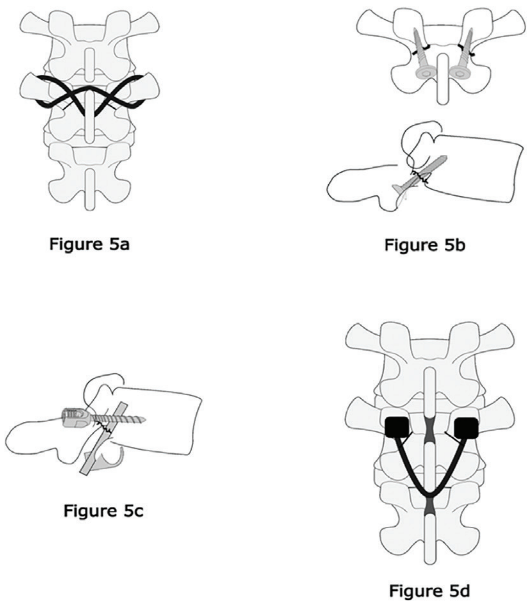

Figure 5. Direct repair techniques. **a)** Scott wiring, **b)** Buck screw, **c)** Screw-hook, **d)** V-rod

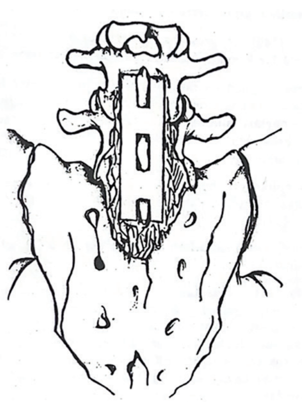

Figure 6. Bosworth-Sicard method

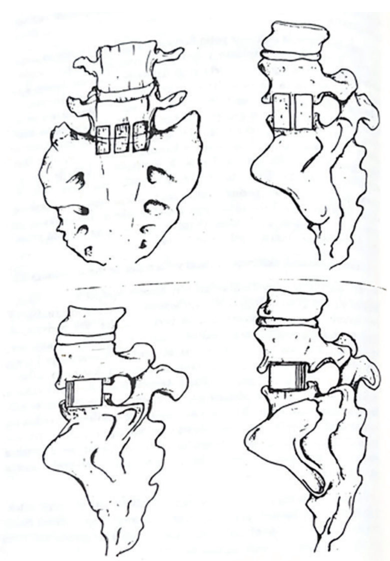

Figure 7. Wilterberger method

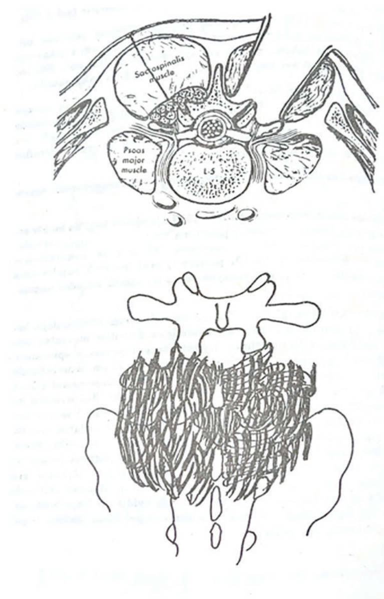

Figure 8. Wiltse and Hibbs method

Reduction and Fusion

Sagittal balance is generally disturbed in high-grade spondylolisthesis. Reduction of slip aids in restoration of sagittal balance, global spinopelvic balance and also increases fusion rates[42]. Alıcı[41], in his 1991 textbook described Scaglietti maneouvre for closed reduction of high-grade spondylolisthesis. Instrumented reduction and fusion techniques are generally indicated in patients with high slip angle or severe sagittal imbalance, high-grade spondylolisthesis, high-grade dysplastic spondylolisthesis, hyper-mobility of L5-S1 segment, and anatomic factors such as small transverse processes, sacral dysplasia, trapezoidal L5 vertebral body, and rounding of the sacrum[43]. L5 nerve stretch is a potential complication during reduction of a long standing slip of L5 over S1 vertebra. Therefore wide decompression of posterior elements of L5 is mandatory. Sacral dome osteotomy aids in reducing L5 nerve stretch and increasing fusion. Extension of instrumentation and fusion to L4 is usually recommended[44]. In rare cases like spondyloptosis L5 vertebrectomy or transsacral *in-situ* fusion are options.

Degenerative Spondylolisthesis

Degenerative changes in the vertebral segment that take place during stabilisation phase in the unstable vertebral segment frequently cause facet joint arthritis and hypertrophy of malfunctioning ligaments thus cause lumbar spinal stenosis. Furthermore, segmental instability in degenerative spondiylolisthesis is not as common as it is isthmic or dysplastic spondylolisthesis. Studies demonstrate substantially greater improvement of pain and function with surgical methods compared to conservative treatment in degenerative spondylolisthesis[45,46]. Decompression alone and decompression with instrumented fusion are two surgical methods widely used in spondylolisthesis. Decompression of hypertrophic facet joint osteophytes and ligamentum flavum without creating instability is a safe and less invasive method for relief of symptoms in degenerative spondylolisthesis. However, in the presence of instability on flexion extension lateral X-rays fusion is generally recommended to decrease the risk of progression of slip after decompression. Decompression with fusion became widely considered standart treatment with support from studies indicating increased instability after decompression alone[47,48]. There is an ongoing debate on whether fusion should be added to decompression. Recent meta-analysis and systematic review studies demonstrated no significant advantages of fusion in terms of pain relief, patient reported outcomes and reoperation rates, rather reported increased operative time and surgical complications[49,50]. Fusion in degenerative spondylolisthesis can be performed by posterior only with pedicle screws, or interbody fusion either by anterior, posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF). PLIF is performed through posterior approach and involves extensive exposure, nerve retraction which may increase neurological complication and greater blood loss[51]. TLIF is performed unilaterally, requires less nerve retraction decreasing neurological complications[52]. Both TLIF and PLIF help correcting lordosis and sagittal balance and increasing fusion rates. In a systematic review of studies comparing TLIF and PLIF by Zhang et al.[53] demonstrated increased complication rates and operative time with PLIF with no difference in fusion rates, patient reported outcomes and functional results.The decision to add fusion and to perform fusion either posterior or anterior with TLIF or PLIF during decompression surgery for degenerative spondylolisthesis must be individualised based on presence of instability, severity of sympomts and requirement of correction of sagittal profile.

CONCLUSION

Spondylolisthesis and spondylolysis are two different entities. Spondylolisthesis is an anterior displacement of a vertebral body, and spondylolysis is a defect or elongation of pars interarticularis. There are different classifications of spondylolisthesis, based on etiology, grade of slip, and recent classifications taking sagittal profile, clinical symptoms or instability into consideration. While spondylolysis is common among adolescent athletes, spondylolisthesis can be encountered in different age groups depending on etiology. Conservative treatment is the first-line treatment for spondylolysis and spondylolisthesis. In patients inresponsive to constervative treatment or with progressive neurological and clinical symptoms surgical methods can be performed. Defect repair and monosegmental fixation must be the surgical method of choice for spondylolysis with minimal slip. Decompression and fixation and/or reduction is generally required spondylolisthesis cases, depending on neurologic deficits, clinical symptoms and sagittal deformity.

Footnotes

Authorship Contributions

Concept: M.C.K., Design: R.H.B., Data Collection or Processing: M.C.K., E.Ak., Analysis or Interpretation: E.Ak., Literature Search: E.Ak., Writing: M.C.K.

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THE HISTORY AND EVOLUTION OF SURGICAL DEFORMITY CORRECTION IN ADOLESCENT IDIOPATHIC SCOLIOSIS

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ABSTRACT

The surgical correction of adolescent idiopathic scoliosis (AIS) has transitioned from long, coronal-focused distraction constructs to more sophisticated three-dimensional (3D) strategies that prioritize physiologic alignment, shorter fusions, and reliable recovery. The Harrington era demonstrated that internal fixation could safely control deformity on a large scale, yet experience with thoracic hypokyphosis and limited axial control exposed the need for constructs that address rotation and the sagittal profile. Cotrel-Dubousset instrumentation reframed AIS as a rotational deformity and introduced deliberate 3D correction; comparative series subsequently documented improved sagittal restoration and reduced reliance on postoperative external immobilization compared with earlier systems. The widespread adoption of thoracic pedicle-screw constructs-and later, direct vertebral rotation-made strong multiplanar correction routine while allowing more selective, shorter fusions guided by the Lenke classification. Current decision-making fine-tunes implant strategy and perioperative care, rather than seeking a single "best" construct. Enhanced recovery pathways consistently shorten hospital stays and reduce blood loss without increasing complications, supporting broader implementation alongside modern anesthetic and analgesic techniques. Posterior minimally invasive scoliosis surgery can decrease blood loss and length of stay compared with open posterior spinal fusion, though operative time may be longer and radiographic outcomes may be similar, underscoring the role of case selection and surgeon experience. Image guidance and robotics may improve pedicle-screw accuracy, but large contemporary datasets warn of higher radiation exposure and modeled lifetime cancer risk with routine navigation in AIS, supporting selective use rather than default adoption. Recently, for skeletally immature patients who fail bracing, vertebral body tethering offers a motion-preserving, non-fusion alternative with meaningful correction but a non-trivial risk of reoperation, requiring careful counseling and follow-up.

Keywords: Adolescent idiopathic surgery, deformity correction, posterior surgery

INTRODUCTION

What surgeons mean by a "good" scoliosis correction has changed with each generation of implants. Early internal fixation proved that large curves could be controlled safely and reproducibly, but it also taught hard lessons about what happens when we straighten the coronal plane without safeguarding rotation and thoracic kyphosis.

The field then pivoted from "making it straight" to "making it balanced." A common language-the Lenke classification-helped surgeons decide which curves truly require fusion and how far to extend it[1]. At the same time, thoracic pedicle-screw constructs offered us reliable control over three columns, making multiplanar correction a standard practice rather than a goal to strive for. In practice, this combination of classification and segmental screws enabled shorter, more selective fusions while maintaining alignment[2].

Today the central question is not whether to correct in three planes, but how to individualize that correction for a specific teenager in front of us. Perioperative bundles such as enhanced recovery after surgery (ERAS) can shorten hospital stay and reduce blood loss without worsening complications[3]. While guidance technologies can enhance the precision of screw

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placement, recent data indicate that routine navigation in adolescent idiopathic scoliosis (AIS) may lead to increased radiation exposure. Therefore, it is often more sensible to employ these technologies selectively rather than universally. For patients who are still growing and do not respond to bracing, vertebral body tethering offers a renewed chance to maintain spinal motion, though it comes with a reoperation risk that requires meticulous planning[4]. This review presents a journey from historical milestones to present-day choices-to offer pragmatic, classification-aligned guidance for individualized AIS correction.

Early Concepts and the Harrington Era

Recognition of spinal deformity dates to antiquity. Hippocratic descriptions emphasized forceful traction and suspension, while Renaissance and early-modern care remained largely mechanical-splints, corsets (e.g., Ambroise Paré's steel corset), and prolonged traction-aimed at containment rather than durable correction In the 19th century, Jules Guérin's myotomy marked the first purposeful surgical attempt at deformity release, and by 1911 Albee and Hibbs had introduced spinal fusion as a means to stabilize progressive curves; however, early fusion attempts were plagued by high nonunion rates and lengthy immobilization[5]. Mid-20th-century work on controlled spinal osteotomy clarified technique, dangers, and safeguards, framing the risk-benefit calculus that still informs corrective surgery[6].

The step-change came with Harrington's rod-and-hook system. His 1962 report established internal distraction/compression as a reproducible method to control deformity at scale, and the subsequent 1973 series of 578 cases cemented its feasibility and safety in routine practice[7]. Yet the lessons were equally formative: distraction constructs prioritized coronal straightening at the expense of axial derotation and physiologic sagittal contour. Loss of thoracic kyphosis and lumbar lordosis-the "flat-back" tendency-along with the need for prolonged postoperative immobilization (often months in a cast or brace) highlighted the limits of first-generation systems and set the stage for segmental, three-dimensional (3D) solutions.

The First-generation: The Reign of Distraction

The first widely adopted internal fixation for AIS arrived in 1962 with Paul Harrington's rod-and-hook construct, which applied distraction/compression across the curve and rapidly became the global standard for two decades[7,8]. Contemporary series documented substantial immediate coronal straightening, but limited control of axial rotation and thoracic kyphosis, with some loss of correction over time-limitations that would shape the next-generation of systems[5].

Standard postoperative care in the Harrington era commonly included prolonged external immobilization to protect fusion-often a body cast for weeks followed by bracing for a total of roughly 6-9 months-reflecting the biomechanics of single-rod distraction and fusion techniques of the time[9,10]. With longer follow-up, the characteristic complication profile of distraction constructs also emerged; most notably, flat-back sagittal imbalance from loss of lumbar lordosis frequently required later revision surgery[11].

Experience during this period likewise sharpened awareness of neurological risk from over-distraction. Surgeons adopted "wake-up test" as an intraoperative safeguard, a practice that later gave way to multimodal neurophysiologic monitoring as technology matured[12,13].

Segmental Constructs and Anterior Systems

By the 1970s, the field recognized the need for greater segmental control; Eduardo Luque's segmental spinal instrumentation used sublaminar wires at each level to anchor pre-bent rods and formalized translation of the spine toward the rod, enhancing coronal control while better preserving sagittal contour[14]. These constructs frequently reduced or eliminated the need for postoperative plaster immobilization compared with Harrington-era protocols[2]. Nevertheless, neurologic risk inherent to passing sublaminar wires limited universal adoption; a British Scoliosis Society survey reported neurologic complications of roughly 4% with sublaminar wiring[15]. In parallel, anterior approaches targeted thoracolumbar and lumbar curves: Dwyer's et al.[16] system used vertebral body screws linked by a cable to compress the convexity and shorten fusion spans. Zielke's 1976 ventral derotation spondylodesis stiffened the construct and deliberately addressed apical rotation, providing improved axial control and selective fusion options[17]. Comparative series and reviews indicate that these anterior systems often achieved stronger rotational correction and shorter fusion segments than distraction-based posterior instrumentation, with trade-offs including kyphogenic effects and approach-related cardiopulmonary and vascular risks[18].

The Third-generation: 3D Correction: Cotrel-Dubousset (CD) Achieving 3D Mastery

The decisive shift came with the field's embrace of scoliosis as a 3D deformity-coronal deviation, axial rotation, and sagittal malalignment-embodied by the mid-1980s introduction of CD instrumentation[5,19]. The CD system used multiple hooks, transverse connectors, and deliberate rod rotation/derotation to build a rigid frame; critically, construct stability meant external bracing could often be abandoned[20]. Subsequent "third-generation" systems built on this platform: the Texas Scottish Rite Hospital system paralleled CD concepts with double-rod constructs and cross-links that enhanced frame rigidity and facilitated 3D correction[4,5], while the ISOLA system leveraged translation via a cantilever technique (with optional sublaminar augmentation) to improve coronal and rotational correction in clinical series[4-7,21,22]. In this context, Alici and Pinar[23] described the Alici spinal system, a modular anterior-posterior instrumentation allowing three-plane correction and stable fixation in scoliosis, reporting a 92-patient series (58 idiopathic, 20 congenital, 12 paralytic, 2 neurofibromatosis) in which 24 patients underwent staged combined anterior-posterior fusion and 68 posterior-only fusion[24].

In parallel, thoracic pedicle-screw fixation gained broad adoption in the mid-1990s, enabling powerful segmental three-column control and reliable multiplanar correction in AIS[2,25]. The addition of direct vertebral rotation (DVR) further improved apical derotation and coronal outcomes compared with simple rod derotation, and bilateral transpedicular screw constructs are now widely accepted as a reliable foundation for 3D correction in AIS (Figure 1)[26].

Thoracic Pedicle-Screw Era→DVR and Selective Fusion

With the transition to segmental three-column control, thoracic pedicle-screw constructs have become the cornerstone of AIS surgery, offering stronger multiplanar correction than hook-based systems and often enabling shorter fusions[2,27]. The introduction of DVR leveraged this screw purchase to address apical rotation more effectively than simple rod derotation, improving coronal and rotational correction in thoracic AIS[28,29]. Classification-guided planning matured in parallel: the Lenke system standardized curve typing and modifiers and underpins selective thoracic fusion (STF), in which only the structural thoracic curve is fused and the compensatory lumbar curve is left mobile[1]. Contemporary series report favorable spontaneous lumbar curve correction with STF when selection criteria are met, but also highlight risks-adding-on and coronal/lumbar decompensation-underscoring the need for careful indication and intraoperative alignment targets[30,31]. Although hybrid constructs remain in use, modern evidence and practice trends support all-screw constructs as a reliable foundation for 3D correction in AIS, with ongoing debate about rod characteristics and density tailored to pattern and goals (Figure 2)[32].

Advanced Techniques for Complex Deformity

For rigid or severe deformities, highly technical osteotomies are employed to achieve correction where flexibility is lost. The earliest such technique was the Smith-Petersen osteotomy (1945), a posterior column-shortening procedure that provides roughly 10° of correction per level in extension-based deformities[33]. More recently, the radical posterior-only vertebral column resection, popularized by Suk et al.[34], became the procedure of choice for fixed, severe deformities, although it is associated with a high risk of neurological and mechanical complications.

Growth Modulation

The drive to avoid the complications of definitive fusion, especially in very young patients, has spurred the development of fusionless techniques based on the Hueter-Volkmann principle, whereby increased compression inhibits physeal growth. Growth-modulation strategies include:

Anterior vertebral stapling: Shape-memory or metallic staples are placed on the convex side of the curve to temporarily modulate growth, with early and mid-term series showing feasibility in selected juvenile and adolescent patients with moderate curves[35].

Anterior vertebral tethering: A minimally invasive anterior approach using screws and a flexible tether to restrict growth on the convex side, indicated for skeletally immature patients with moderate, flexible curves. Early and mid-term results demonstrate progressive correction with preservation of motion but also report risks of over- or under-correction and need for revision or conversion to fusion (Figure 3)[36-38].

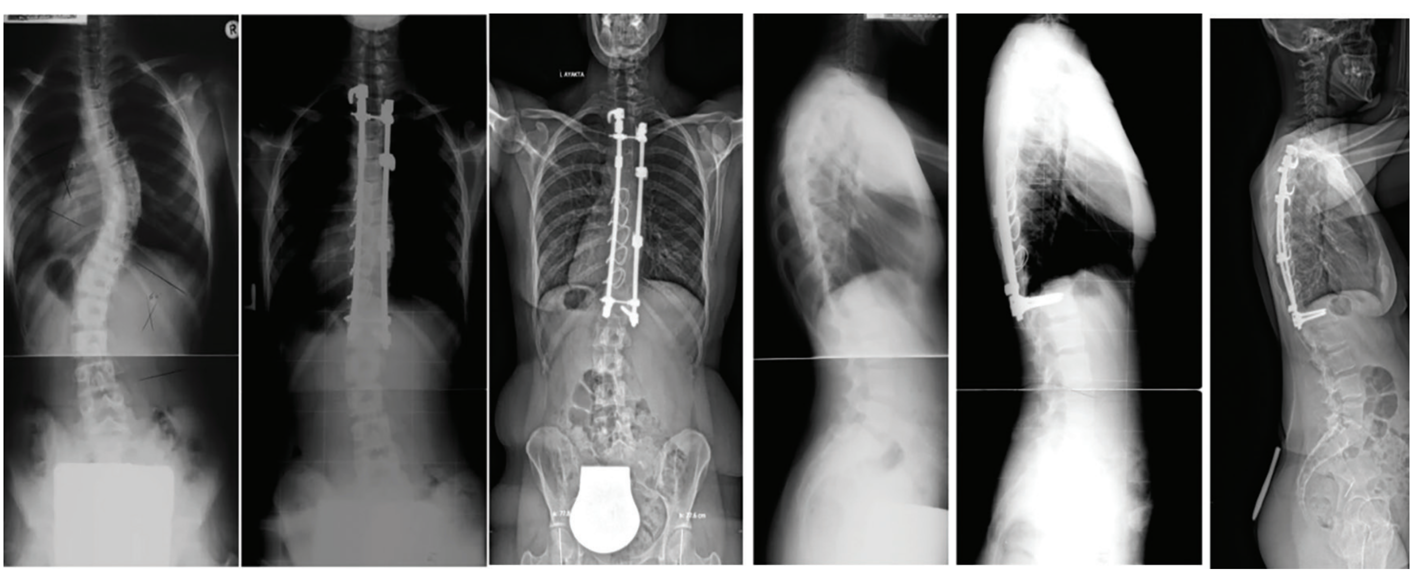

Figure 1. Standing whole-spine anteroposterior and lateral radiographs of a 12-year-old girl treated with posterior hook-screw instrumentation for adolescent idiopathic scoliosis. At 29-year follow-up, coronal and sagittal alignment remain well balanced with maintained deformity correction

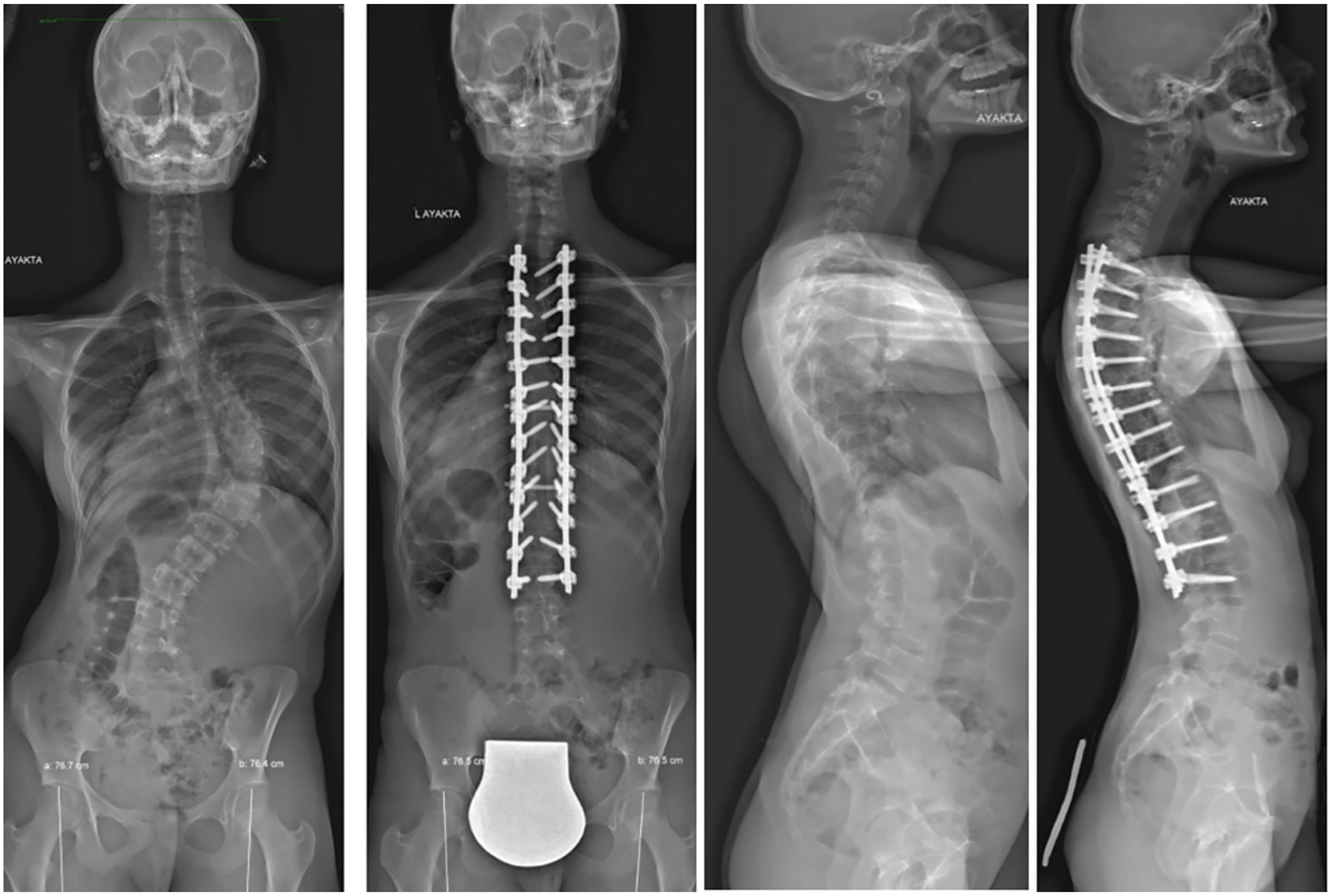

Figure 2. Pre- and postoperative standing whole-spine anteroposterior and lateral radiographs of a 15-year-old girl with adolescent idiopathic scoliosis treated with posterior pedicle-screw instrumentation

The Cutting Edge: Minimally Invasive and Digital Surgery

The latest evolution in AIS surgery focuses on minimizing the surgical footprint while maximizing precision. Minimally invasive surgery (MIS) for AIS, introduced around 2010-2011, aims to reduce muscle stripping, scarring, blood loss, and recovery time. Comparative studies and a recent meta-analysis suggest that MIS is associated with reduced estimated blood loss, lower transfusion rates, and less postoperative opioid use, although operative time is often longer and radiographic correction and functional scores may slightly favor conventional open posterior fusion[39].

Surgical precision is being enhanced by new technologies. Computed tomography (CT)-based navigation and O-arm-assisted systems improve pedicle-screw placement accuracy compared with traditional freehand techniques in deformity surgery, including AIS, albeit sometimes at the cost of increased operative time and higher radiation exposure to the patient and operating room staff. Robot-assisted systems have similarly demonstrated higher accuracy rates than freehand placement in complex spinal constructs, though their routine use in AIS remains center-dependent and cost-sensitive[39,40].

ERAS pathways have become an important adjunct to surgical technique in AIS. Protocols that integrate optimized analgesia, early mobilization, multimodal antiemesis, and standardized perioperative care consistently shorten hospital stay without increasing complications or readmissions[40].

Implant Strategy: Screw Density and Rod Characteristics

Current evidence does not support a single universally "optimal" pedicle-screw density in AIS correction. Lower-density constructs can achieve comparable radiographic correction and complication rates in appropriately selected patients, while offering potential advantages in cost, blood loss, and operative time compared with high-density patterns[41]. However, some series still associate higher screw density with slightly greater immediate Cobb angle correction, suggesting that implant strategy should be individualized rather than protocol-driven[42]. In parallel, rod material and diameter have emerged as key determinants of construct behavior. Stiffer, larger-diameter cobalt-chromium rods (e.g., 6.0-6.35 mm) may improve coronal and sagittal correction, especially kyphosis restoration, but at the expense of higher mechanical stress at the bone-implant interface and possibly increased reoperation risk, whereas titanium rods (often 5.5 mm) provide a more forgiving, biologically "friendlier" construct[42].

Image Guidance, Robotics, and Augmented Reality (AR)

Image-guided navigation, robotic assistance, and AR are increasingly used to refine implant placement and workflow.

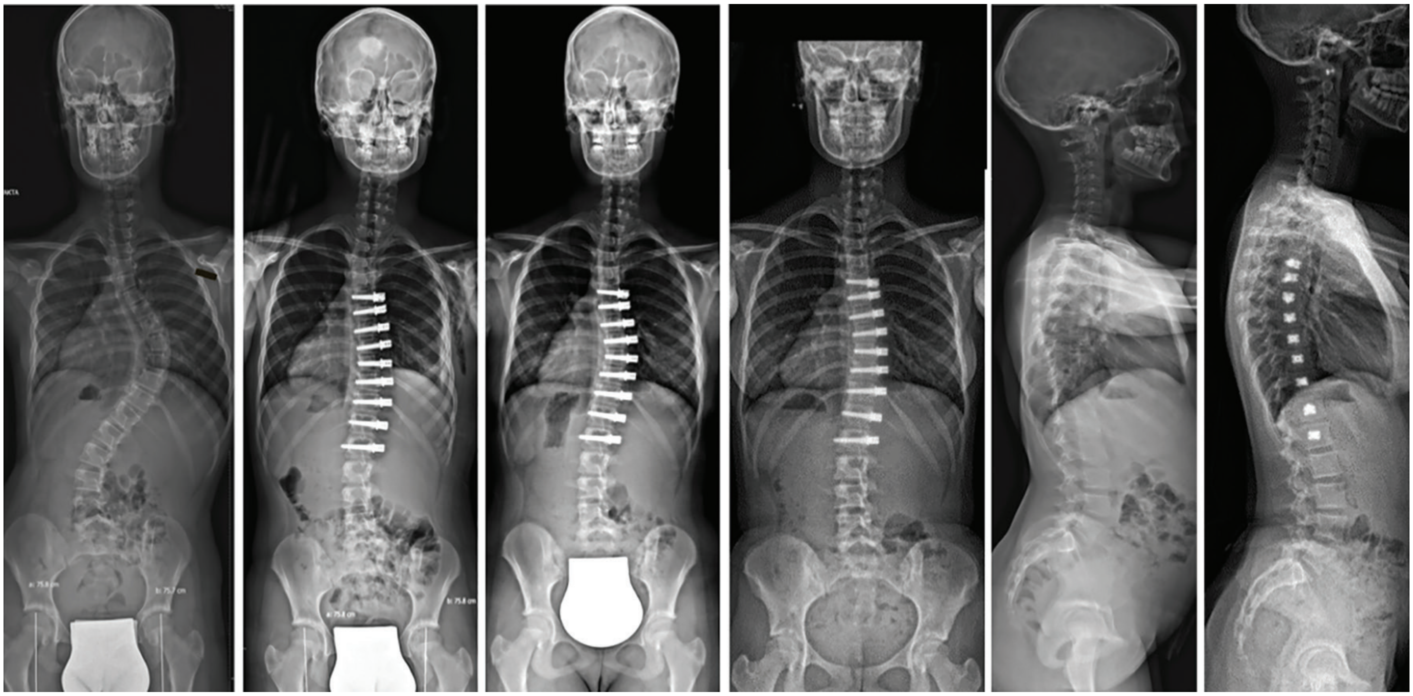

Figure 3. Standing whole-spine radiographs of a skeletally immature patient treated with VBT for a 70° main thoracic curve. Early postoperative AP radiograph shows residual deformity, which gradually remodels to 8° at 3-year follow-up. Lateral radiographs demonstrate improvement of thoracic kyphosis from 15° to 33° with preserved global sagittal alignment. VBT: Vertebral body tethering, AP: Anteroposterior

Systematic reviews and large database studies indicate that CT-based navigation and robotic systems can improve pedicle-screw accuracy compared with traditional freehand techniques; however, this often comes at the cost of longer operative times and increased radiation exposure[43]. In AIS, the cumulative ionizing dose is particularly relevant, with some models estimating a measurable increase in projected lifetime cancer risk when heavy intraoperative CT use is combined with preoperative imaging[44]. Experienced deformity surgeons may achieve comparable accuracy using freehand or fluoroscopy-assisted techniques with substantially less radiation, underscoring the importance of surgeon expertise and case selection[43-45]. AR-assisted navigation and next-generation robotics show promise for enhancing visualization, accuracy, and workflow, but high-quality, pediatric deformity-specific outcome data remain limited, and their role in routine AIS practice is still evolving[46].

CONCLUSION

Across seven decades, AIS correction has evolved from coronal distraction to subtle 3D strategies. Segmental pedicle-screws with DVR remain the gold-standard treatment; fusion levels are increasingly tailored using Lenke principles, implant strategy (density, rods) is individualized, and ERAS optimizes recovery. Guidance/robotics/AR assistance should be deployed cautiously-balancing accuracy gains against time, cost, and radiation-while VBT remains a specialized option for carefully selected, skeletally immature patients.

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Footnotes

Authorship Contributions

Surgical and Medical Practises: M.E., A.H., Concept: İ.D., M.E., Design: B.A., Data Collection or Processing: H.M., Analysis or Interpretation: İ.D., S.K., M.E., Literature Search: B.A., H.M., Writing: B.A., M.E.

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EVOLUTION OF ORTHOTIC MANAGEMENT IN SPINAL DEFORMITIES: THE EGE UNIVERSITY EXPERIENCE

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ABSTRACT

Spinal orthoses are a cornerstone of conservative management for spinal deformities, and their primary objectives are to halt curve progression, to reduce pain, and to preserve function. This study summarizes the historical development, current classifications, indications, fabrication principles, and institutional experience. Orthoses are classified by stiffness (flexible, semirigid, or rigid) and by mode of action (dynamic or passive). Historically, rigid devices were used first. Although effective, they had a propensity for complications such as fixed deformity, muscle atrophy, and pressure-related skin necrosis, which led to the development of semirigid alternatives. Custom cast-based design and accurate pad placement are critical for biomechanical effectiveness; material selection is also important, since overly rigid thermoplastics may diminish the intended dynamic effects. The most common indication is adolescent idiopathic scoliosis. Bracing is initiated for curves of approximately 20 to 40 degrees or when progression is documented; average daily wear of 21 hours and close radiographic follow-up are recommended. Night-time wear can exert greater corrective forces in the supine position, and treatment success improves when combined with physiotherapeutic scoliosis exercises. In addition to use in scoliosis, thoracolumbosacral orthoses are useful in the conservative management of fractures to reduce pain and kyphosis; device selection should consider age, comorbidities, and respiratory tolerance, particularly in young children. For more than three decades, thousands of patients have been treated at our center, and we believe that the outcomes, techniques, and practical insights we have gained will be instructive.

Keywords: Spinal deformity, scoliosis, orthosis, conservative treatment, bracing

INTRODUCTION

Spinal orthoses stabilize the spine and, by preventing the progression of developing spinal deformities[1-3], aim, when feasible, to correct the deformity, reduce pain associated with spinal pathologies, and restore lost function[4].

The use of orthoses in the treatment of spinal pathologies dates back to antiquity. Hippocrates (460 to 370 BCE) applied traction for the treatment of scoliosis. Galen of Pergamon (129 to 216 CE) proposed applying lateral pressure for deformity manipulation[5,6]. The emblem of orthopedics, the bent tree trunk braced to a straight stake, is among the most illustrative examples of orthosis use and of correction achieved by lateral pressure[7]. Before spinal fusion (Hibbs, 1915), now among contemporary treatment options, came into use, the only treatment for spinal pathologies was bracing. The "Milwaukee brace", which is currently used as a conservative treatment, was first used by Blount and Schmidt in 1946 following surgical treatment of spinal deformities. From 1958 onward, this method was also adopted as a nonoperative conservative treatment option[6,8].

Orthoses used in current practice are diverse and are generally classified as flexible, semirigid, or rigid. Historically, rigid orthoses were used first. Although effective, their tendency to cause complications such as fixed deformities, muscle atrophy, and pressure induced skin necrosis prompted the development of semirigid designs, which remain in use today as alternatives. Orthoses may also be classified by their mechanism as dynamic (active) or passive.

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While orthoses were initially used widely in the treatment of all spinal deformities, their indications have progressively narrowed with advances in surgical techniques. Although many different orthosis types have been described for spinal deformities, it is not feasible in practice for a physician to know and apply every type in detail. Moreover, most spinal orthoses are custom-fabricated from patient-specific casts[6]. This, in turn, means that owing to the technical capacity of workshops involved in orthosis production and the knowledge level of technicians, the manufacture of every type of orthosis may not be feasible in all centers. Similarly, procuring the required materials is not always possible. In Ege University Orthotics-Prosthetics Workshop, we initially used leather and metal in orthosis fabrication; subsequently, we began employing polyethylene commonly used in the footwear industry. The materials we used had a hardness of approximately 45-50 shore (Sh), suitable for fabricating orthoses with a thickness of 4-5 mm. With orthoses fabricated from materials with these properties, we achieved highly successful outcomes. Today, however, thermoplastic sheets with a hardness of approximately 65 Sh are used more commonly. This, unfortunately, tends to make an orthosis that is intended to be semi-rigid or flexible become more rigid. Consequently, the expected biomechanical benefit of the orthosis is reduced.

The most common use of spinal orthoses is the conservative treatment of scoliosis. In scoliosis management, the primary goal is to prevent curve progression. Winter et al.[9] stated that "the purpose of bracing is to keep small curves from getting bigger, not to make big curves smaller". Typically, curves of 20-40° constitute an indication to initiate orthotic treatment[1,10-12]. Another indication relates to the rate of progression; an increase of 5° over 3-6 months is also an indication to start bracing[13]. Severe thoracic lordosis is a contraindication to brace treatment. Before puberty, treatment should be reviewed every six months. During puberty, because spontaneous resolution is expected in infantile idiopathic curves, application of an orthosis may be deferred. In this period, follow-up every three months is appropriate. Although bracing is not directly effective in the childhood management of congenital spinal curves, it aims to gain time for surgery by helping the trunk remain upright and stable.

Spinal orthoses may also be used postoperatively in patients who have undergone surgery. They are employed to control compensatory curves, maintain stability, and reduce pain. In older or osteoporotic patients, particularly in kyphotic spinal pathologies, they are used to prevent pullout and failure of surgically placed screws.

Optimal brace wear is approximately 21 hours per day (range, 16-23 h/day, adjusted for age and tolerance); wearing the brace for fewer than 12 hours per day is ineffective[10]. Weaning should be gradual: after skeletal maturity, reduce daily wear time by about 2 hours every 3 months. A standing radiograph should be obtained with the brace in place. Thereafter, obtain radiographs every six months, both in-brace and out-of-brace. The difference in Cobb angle between the two should not exceed 3-4°; if it does, revert to the previous wear schedule.

Corrective forces are greater in the supine than in the upright position[5]. Therefore, nighttime wear of the brace is more commonly recommended. Patients who use a brace should always be prescribed an individualized exercise program. A well-designed home program will increase the success of bracing[14]. In particular, physiotherapeutic scoliosis-specific exercises such as the Schroth method, scientific exercise approach to scoliosis, Barcelona Scoliosis Physical Therapy School, the fixation, elongation, derotation method, functional ındividual therapy of scoliosis, and side-shift exercises should be recommended[15].

At the initiation of orthotic treatment, the patient's height and weight should be measured; these data are important for monitoring the course of treatment and for decisions regarding brace adjustment or replacement. Failure to gain more than 1 cm in height within six months is a criterion for discontinuing bracing[10]. Conversely, an increase of more than 5 cm is an important criterion for replacing the brace. Orthoses are also used in patients with diverse etiologies such as cerebral palsy, myelomeningocele, spinal muscular atrophy, and trauma. Neuromuscular deformities may be spastic or flaccid, and sensory deficits may be present. To prevent pressure necrosis, initial wear periods should be short, and the skin should be inspected very frequently.

When orthoses are used in conditions such as kyphosis and scoliosis, dynamic corrective orthoses should be selected. However, the use of corrective braces invariably entails various challenges. These challenges are borne first and foremost by the patient, and also by the family, the physician, the physical therapist, and the orthotist/prosthetist. The fabrication and fitting of a brace is an art. Weakness in any of these components reduces success and may even negate it. Accordingly, with the growing popularity of the three-dimensional (3D) concept in designs[16], 3D computer-aided design/computer-aided manufacturing (CAD/CAM) braces have recently been developed. The concept is not new. The Milwaukee brace already provides 3D control in the coronal, sagittal, and axial planes[2].

In our country, commercial concerns have led to a separation between those who fabricate braces and those who fit them. This has resulted in manufacturing based on digital measurements and probabilistic assumptions. In practice, fabricators produce the brace without seeing the patient, and fitters apply it to the patient without having observed its fabrication. However, the curve's response to treatment and its progression vary for each patient. Despite many years of clinical experience and approximately 10.000 orthotic applications, we cannot predict the outcome in advance. Although a correction of at least 50% is anticipated at the first fitting, a correction of 30% to 50% is considered adequate[17].

In cases with large curves, laterally applied forces have limited effect, whereas distraction forces are more effective. Conversely, in small curves, lateral forces are more effective. The site of application of lateral forces is crucial in practice. For correction of thoracic deformities, the force-transmitting pad should be positioned just below the apex, with placement adjusted according to curve magnitude. If, in pronounced curves, the pads are placed above the apex, the corrective effect of lateral forces diminishes and may even worsen the deformity.

While achieving correction, the orthosis should impose minimal restriction on pulmonary expansion. Orthoses are most often used in growing children. In these cases, particularly in younger age groups who cannot adequately communicate discomfort, circumferential application should be avoided (Figure 1). Excess pressure over the chest must be prevented, as it may lead to complications such as the development of new deformities and respiratory difficulties.

Another area of use for orthoses is in older and osteoporotic patients. In this group, varying results have been reported. In patients with osteoporotic vertebral fractures, the effects of rigid, flexible, and dynamic orthoses have been investigated, with no significant differences observed[18]. In patients with age-related postural hyperkyphosis, spinal orthoses used to address impaired balance and the increased risks of falls, new fractures, and pain have been reported to be effective[19]. In our clinic, we employ lumbosacral orthoses fabricated from polyethylene in a total contact design.

When an orthosis completely encircles the trunk, it forms a semi-rigid cylinder around the spine and torso. The abdominal contents are compressed. In the literature, the view that increased intra-abdominal pressure reduces spinal pressure is not strongly supported. It was reported (1964) that the use of an abdominal orthosis reduced lumbar intervertebral disc pressure by approximately 30%, although intra-abdominal pressure generally remained low, at most 6 kPa[20]. Orthoses affect all structures in the region to which they are applied, and they may therefore cause unintended adverse effects. Potential issues that warrant attention include muscle weakening, loss of body water (dehydration), skin injury under pads due to increased pressure, and declines in renal function[21,22].

Over more than thirty years of clinical practice, we have followed over 10.000 patients with scoliosis managed conservatively with bracing, for whom long-term outcomes have not been reported. In the study we conducted between 1989 and 1995, we evaluated a total of 206 patients: 48 treated with the Milwaukee brace and 158 with the Boston brace. In our series, braces were worn a mean of 21 hours per day, and the mean follow-up duration was 38 months. At the end of follow-up, curve progression was absent at completion of treatment in 88 patients; progression was <5° in 50 patients and >5° in 11 patients. Fifty-seven patients were excluded due to loss to follow-up. At baseline, the Cobb angle was 30.12° (14°-57°), the Risser stage was 1.73 (0-5), and rotation was 1.85° (0°-4°). Of the patients, 126 were female and 80 were male, and the mean age was 12.2 years (3-20 years). At the last follow-up after treatment, the mean improvement in Cobb angle was 33%.

In this review, we aimed to introduce the orthoses that we frequently fabricate and apply in our clinic for spinal pathologies and to share our long-standing experience, practical insights into their application, and, perhaps most importantly, the conclusions we have drawn.

Boston Brace Thoracolumbosacral Orthosis (TLSO)

Boston brace TLSO is among the most important orthoses reported to be successful in the treatment of scoliosis[3,4,14,21]. Developed in 1972 by Bill Miller, certified prosthetist-orthotist, and John Hall, MD, at Boston Children's Hospital. The original brace was produced by adapting six prefabricated molds to the patient[10]. It is applied by repositioning the pads according to patient-specific needs. Based on my experience, in 1992 I had the opportunity to discuss with John Hall, MD, the method of application of the brace. In our clinical experience, I consider braces fabricated after taking a patient-specific cast, which is

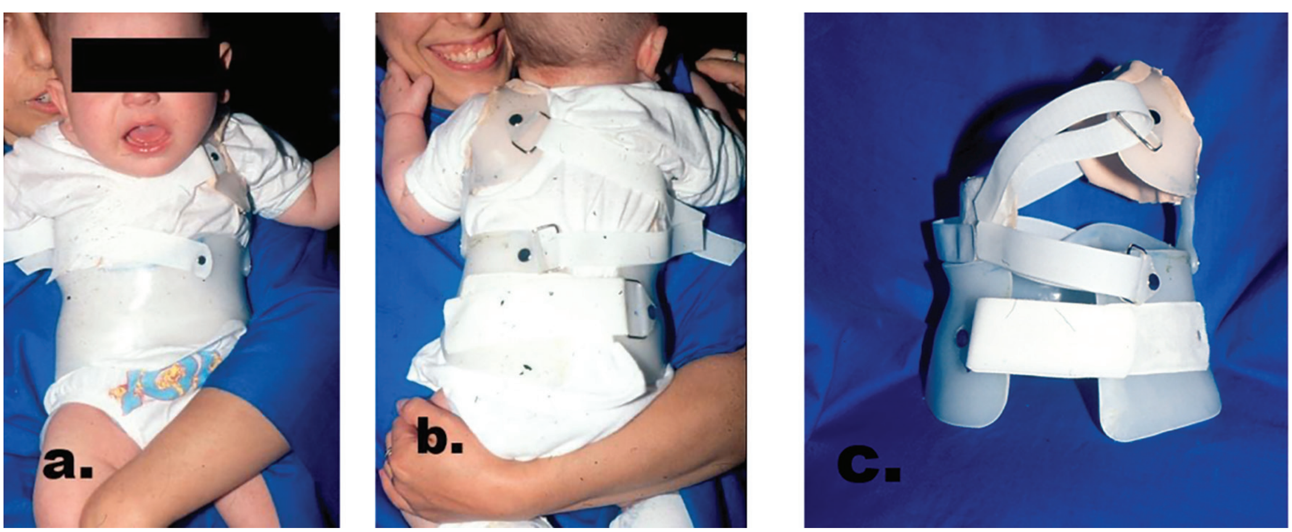

Figure 1. TLSO used in children. Because of the risk of complications, circumferential designs should be avoided in younger children. **a)** anterior view; **b)** posterior view; **c)** lateral view. TLSO: Thoracolumbosacral orthosis

the general rule[20], to be more successful. After discussing this view with John Hall (International Society for Prosthetics and Orthotics, 1992), we began producing in the Ege University Faculty of Medicine workshop a design similar to a modified Boston brace that is fabricated on a cast. In line with this approach, the 2003 manual of Boston Brace International also modified the brace by increasing the number of prefabricated molds, consistent with our view (Figure 2)[14]. Likewise, Jones and Uustal[20] in their 2024 guideline on the use, fabrication, and principles of spinal orthoses, made statements aligned with our approach.

The same orthosis design has been used for 32 years. The orthosis is indicated for deformities with an apex at or below the eighth thoracic vertebra (T8)[22]. It is lightweight, compact, and cosmetically acceptable, and its low cost is a major reason for preference. The orthosis is classified as semiflexible and dynamic. Casting technique plays a key role in fabrication. Plain radiographs should be reviewed carefully beforehand, with attention to torsion, thoracic kyphosis, and lumbar lordosis. During casting, the patient should be kept supine under traction, and the plaster should be allowed to harden after the necessary reductions have been achieved. The design should permit hip flexion up to 95°.

The presence of 15°-20° of lumbar lordosis is important for treatment. Although this degree of lordosis may negatively affect pelvic stability, the overall effect is more favorable. In this context, it has been suggested that lumbar flexibility is more effective in lateral (coronal) curves (Figure 3).

The Boston brace is particularly more effective in the treatment of lumbar spinal curves. If appropriate traction can be achieved during casting, there is no need for additional pads. This is a major advantage of the cast-fabricated modified Boston brace over the original prefabricated Boston brace system.

After the cast is removed, the patient's body should be checked for pressure points. In this method, a space is created from the outset on the concave side of the curve. Subsequently, new windows (fenestrations) should be carefully opened to avoid obstruction and to provide better rotational control. Orthoses should deliver maximum performance with minimum weight and surface area.

The Boston brace orthosis can stabilize the shoulder from one side to control rotation in the thoracic region. To achieve this, when necessary, the thoracic side that rotates anteriorly is reinforced by adding an aluminum rod to the plastic[23]. The opposite side is left free to allow passive correction[14]. Our primary reason for the widespread use of this orthosis is that the Boston brace is the most suitable device to meet all of these requirements. After the orthosis is fabricated, a standing plain radiograph must be obtained within 3 to 15 days for evaluation.

Milwaukee Brace [Cervicothoracolumbosacral Orthosis (CTLSO)]

Developed by Blount et al.[2] in 1946, the Milwaukee brace has been shown to be statistically successful in the treatment of spinal deformities. It includes a pelvic component, which was originally made of leather and was later replaced by thermoplastics. In our practice, we use polyethylene, which provides good moldability. During shaping, pressure-sensitive areas require relief; therefore, space should be left over the anterior superior iliac spines and beneath the costal margins. The anterior shell should extend to the xiphoid process. The brace has two posterior uprights and one anterior upright. These were initially made of iron; we now fabricate them from aluminum bars. We also employ high-density polyethylene uprights, which can be easily formed with a heat gun; their elasticity enhances the dynamic effects of the brace. All three

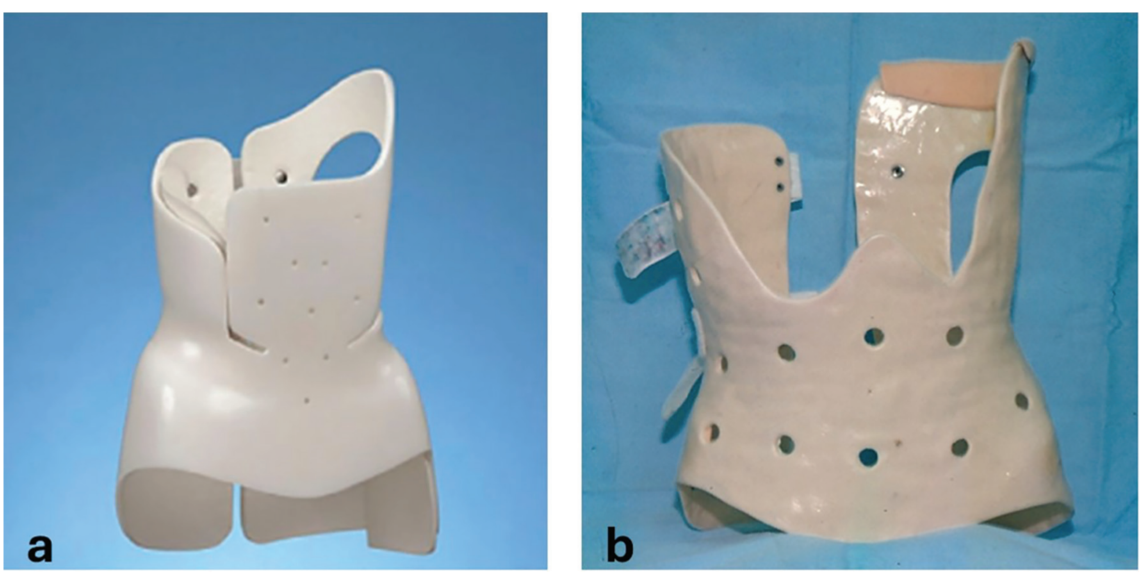

Figure 2. a) Original Boston Brace manufactured using prefabricated molds[23], **b)** Modified Boston Brace fabricated on a patient-specific cast

vertical bars attach to the neck ring and continue to form two occipital pads and one anterior mandibular pad. The vertical bars must be aligned precisely with the pelvic component and the neck ring. Occipital supports permit the application of axial forces through muscle contractions.

Milwaukee brace can be used for all types of spinal deformity (Figure 4). However, it is less preferred in children under three years of age and in curves whose apex lies below the seventh thoracic vertebra (T7), because application is more difficult in these settings. Although it can be effective for more proximal curves such as T2-T3, practical difficulties may arise. For braces fabricated for curves at these levels, the axillary pad is critical. This pad determines the position of the neck ring and applies a superiorly directed force, which may cause discomfort. It can also lead to arm swelling or neurologic symptoms. Because its use is technically demanding, both the prescribing physician and the orthotist/prosthetist who fabricates the brace should be experienced in this technique[24].

The Milwaukee brace can be used in kyphotic deformities with a high apex. It is employed to arrest progression and reduce pain, particularly in kyphoses of about 50° and in Scheuermann kyphosis. For this purpose, a dorsal pad is placed at the same level as the apex. If the pectoral muscles are tight, pads may also be applied to these areas. The pelvic band should be positioned according to the degree of lumbar lordosis.

Although the Milwaukee brace used in the treatment of kyphosis is effective, its use is challenging with respect to comfort and cosmetic acceptability. The brace can place families and children

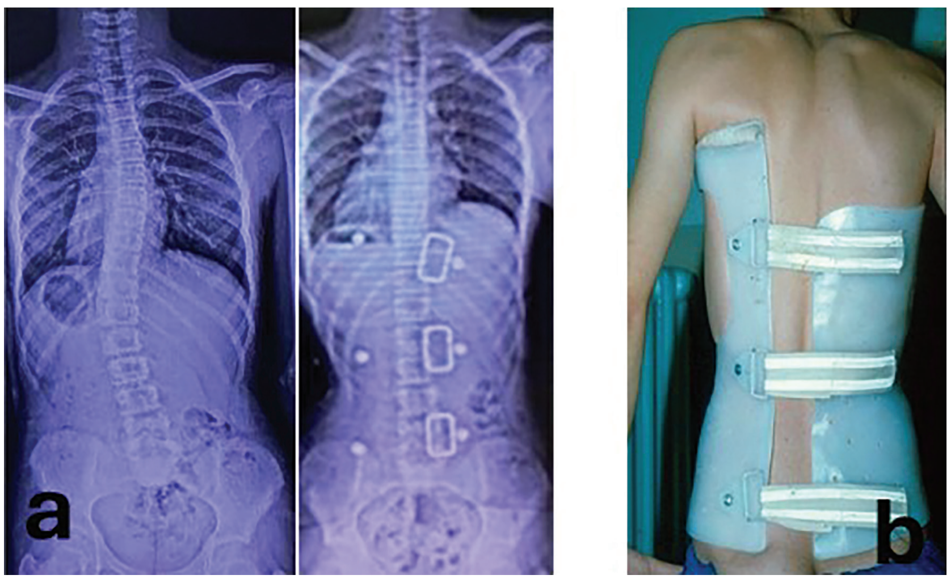

Figure 3. a) Correction achieved with the Boston Brace in a lateral spinal curve; standing radiographs in-brace and out-of-brace, **b)** Lateral deviation of the trunk (thorax) in a patient wearing a Boston Brace

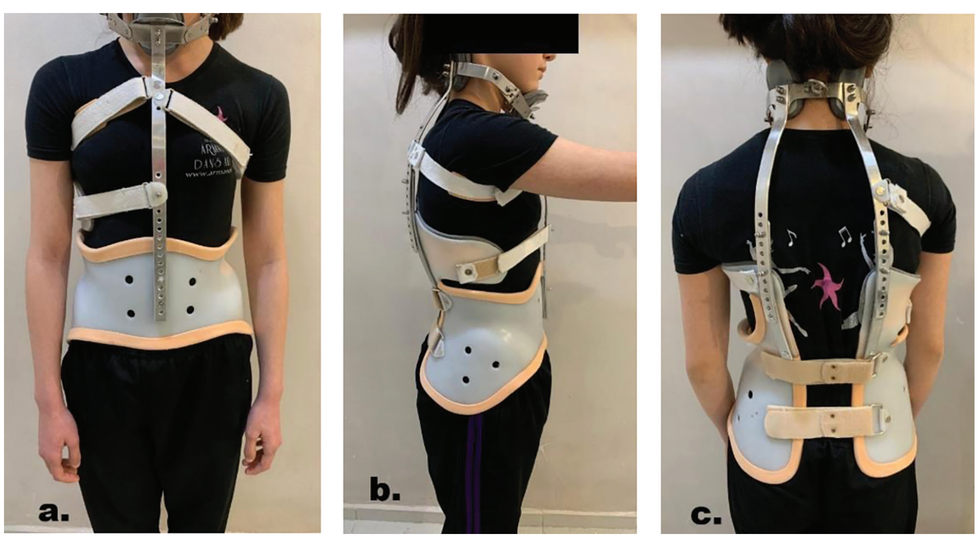

Figure 4. Milwaukee brace (CTLSO) with bilateral straps centering the neck ring; **a)** anterior view; **b)** lateral view; **c)** posterior view. CTLSO: Cervicothoracolumbosacral orthosis

in a difficult process. For this reason, it may be modified to extend only to the axillary level. The modified Milwaukee brace includes one sternal pad and two dorsal supports. The pelvic band is adjusted according to the degree of lumbar lordosis. The sternal pad is secured bilaterally to the posterior supports with hook-and-loop straps (Figure 5).

Jewett TLSO

Used solely to control spinal flexion. It has no controlling effect on lateral bending or rotational motion. Although not directly recommended for vertebral fractures, it may be used in mild to moderate compression fractures with minimal pain, particularly T6-L1. In such cases, it helps prevent kyphosis and maintain reduction. However, using it as a primary corrective orthosis may increase or prolong pain. It should not be used in unstable fractures. Likewise, it is not effective in the treatment of kyphosis or scoliosis[25].

Charleston Bending Brace (TLSO)

A nighttime-only TLSO used for the treatment of scoliosis. It employs overbending to the contralateral side of the curve. The biomechanical rationale follows the Hueter-Volkmann law, which states that increased mechanical pressure suppresses growth, whereas decreased pressure accelerates bone growth[26]. Although theoretically useful, treatment is challenging. Fabrication requires an experienced technician who can accurately interpret plain radiographs, and the workshop must have a special casting table to obtain optimal molds. Because the brace exerts high localized pressures, meticulous skin care is necessary to prevent pressure ulcers. Weaning is relatively short. In our clinic, we applied the Charleston brace to three patients. Two discontinued the brace due to complaints and were switched to a Boston brace; the third patient was lost to follow-up.

TLSO

Used in the conservative or postoperative management of spinal fractures (Figure 6)[27]. In the treatment of vertebral fractures, TLSOs have been shown to be effective, particularly for reducing pain and correcting kyphotic deformity[28]. When postoperative stabilization is desired, and especially when conservative treatment is planned, the TLSO should be custom-fabricated on a patient-specific cast. If conservative treatment is planned, fracture reduction during casting is critical; appropriate compression and traction should be applied during the procedure.

To avoid complications, physician supervision is required during casting, and orthotist-prosthetist technicians must be knowledgeable and experienced. The orthosis should be adjusted according to the fracture level. The distal portion must control the pelvis. The proximal portion should be higher for high-level and multiple fractures to provide rotational control. If necessary, it can be extended to the cervical region and used as a CTLSO.

Complications related to orthosis use can be serious. Frequent follow-up reduces risk. One should be vigilant for mesenteric syndrome, bowel perforation, and neurologic deficits, and reduction should be verified on plain radiographs. If needed, pads should be placed to maintain reduction. The orthosis should be open on both sides and secured with hook-and-loop

Figure 5. Modified Milwaukee brace (CTLSO). **a)** anterior view; **b)** lateral view; **c)** posterior view.
CTLSO: Cervicothoracolumbosacral orthosis

straps. While the patient is supine, the anterior shell may be removed in a controlled manner.

Full-time wear for approximately three months is recommended, followed by part-time wear during high-risk activities. In postoperative cases, wear for 1.5 to 2 months is advised. In neuromuscular patients, because active muscle contraction is lacking, this type of orthosis should be preferred over dynamic orthoses.

Lyon (Stagnara) Brace (TLSO)

This orthosis, which we have used only in a limited number of cases in our clinic, was employed successfully in Germany and across Europe in the 1940s. However, because of its metal components, hinges, and locks, complexities arise in both fabrication and use. The procurement and quality of these parts may also pose problems.

The Lyon (Stagnara) brace is a dynamic yet rigid orthosis. It opens anteriorly. To achieve rotational control, it stabilizes both pectoral regions . For this reason, its impact on pulmonary function is greater than that of the Boston brace[23].

Lumbosacral Orthosis (LSO)

Used for lumbar-level pathologies such as scoliosis, spondylosis, and spondylolisthesis. The orthosis should conform closely to the pelvis. It is a semi-rigid orthosis fabricated from thermoplastic materials.

Lumbosacral Corset with Steel Stays (LSO)

Made of fabric and classified as flexible. It minimally restricts lumbar spinal motion. Its prefabricated design makes it cost-effective. Used in conditions such as osteoarthritis. It increases intra-abdominal pressure, thereby enhancing stability.

Cervical Orthosis (CO)

Soft type: Made of foam or Plastazote. It is easy to use, provides warmth, and mildly restricts cervical motion. By maintaining warmth, it is used to relieve muscle spasm and reduce pain[29].

Rigid type: Made of 1 mm polyethylene. When occipital and mandibular extensions are present, it restricts cervical motion, providing partial control particularly of flexion and extension. It has no effect on rotation, lateral bending, or axial movements.

Philadelphia Collar (CO)

It consists of two pieces and is made of Plastazote. It is effective for pathologies from C6 to T2. It restricts flexion and extension by approximately 60-65%. Control of lateral bending is limited, and rotation can be controlled only to about 50%. Because it retains warmth around the neck, it may cause sweating and skin ulceration. It is lightweight.

Four-post Collar (CTO)

A rigid, conventional orthosis. It controls flexion, extension, and rotation at various levels of the cervical spine. The four uprights that stabilize the head via the cervical spine are height-adjustable (Figure 7). Consequently, it is generally well tolerated. It reduces lateral bending by approximately 50%[30].

Dynamic Torticollis Orthosis (CTO)

It is custom-molded. The device consists of a head-controlling component and a trunk component, which are connected by a plastic rod (Figure 8). Because torticollis is a 3D deformity, correction must occur simultaneously in all three planes. Simple collars cannot accomplish this. The dynamic torticollis orthosis is distinctive in that it can act on all three planes at once.

Figure 6. TLSO used in the conservative treatment of vertebral fractures. **a)** anterior view; **b)** lateral view.
TLSO: Thoracolumbosacral orthosis

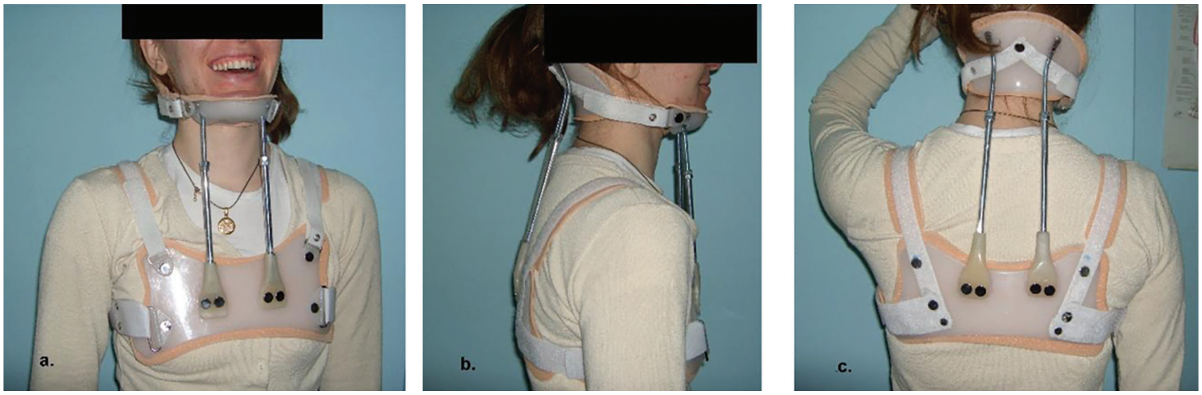

Figure 7. Four-post collar. **a)** anterior view; **b)** lateral view; **c)** posterior view

Figure 8. Dynamic torticollis orthosis. The amount of correction at the cervical level can be adjusted. **a)** anterior view without the orthosis; **b)** anterior view with the orthosis; **c)** lateral view with the orthosis

It can be used conservatively and postoperatively. To enhance the effectiveness of the cranial component, the hair should be kept short. Although it can be applied at any age, control of the head piece is difficult in very young children; in such cases, application should be deferred.

Halo-thoracic Orthosis (CTO)

A metal or carbon-epoxy ring that encircles the head circumferentially and is secured with pins, connected by rods to a thoracic orthosis. It is used postoperatively after surgery for cervical spine fractures. Application requires a surgeon, an orthotics team, and appropriate equipment. The halo is fixed to the skull with four pins. After the thoracic brace is fitted, the head ring is connected to the thoracic section with four rods. Vigilance is required for infection at the halo and thoracic interfaces and for pressure necrosis. Most systems are prefabricated today; however, if a thoracic pathology coexists, the thoracic component should be custom-molded.

CONCLUSION

Bracing remains a cornerstone of conservative care for spinal deformities, with the primary goal of preventing curve progression and preserving function. Effectiveness depends on correct indications, individualized cast-based design and precise pad placement, close radiographic follow-up, and high adherence supported by physiotherapeutic scoliosis-specific exercises. In our practice, the Boston brace is preferred particularly for lumbar curves; the Milwaukee brace is reserved for high apex kyphosis, scoliosis and selected proximal thoracic curves; the Jewett orthosis is used for flexion control rather than correction; nighttime devices such as the Charleston brace are options for carefully selected single curves but have practical limitations; and custom TLSOs are valuable in fracture care. Material choice and fabrication technique matter, since overly rigid builds may diminish the intended biomechanical benefit, and circumferential designs in small children can compromise ventilation and comfort. Complications, including skin injury and deconditioning, must be anticipated and mitigated through multidisciplinary supervision. Drawing on more than three decades of institutional experience, including a cohort treated between 1989 and 1995, we find that outcomes vary with patient factors and craftsmanship, and that success relies on coordinated work among physicians, orthotists, therapists, patients, and families. Future studies should include prospective designs with standardized indications, objective wear monitoring, and direct comparisons of cast-based custom orthoses versus CAD/CAM approaches to refine best practice.

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Footnotes

Authorship Contributions

Surgical and Medical Practises: A.Ö., D.B., M.H.Ö., Concept: A.Ö., D.B., M.H.Ö., Design: A.Ö., D.B., M.H.Ö., Data Collection or Processing: A.Ö., D.B., M.H.Ö., Analysis or Interpretation: A.Ö., D.B., M.H.Ö., Literature Search: A.Ö., D.B., M.H.Ö., Writing: A.Ö., D.B., M.H.Ö.

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IN MEMORIAM: PROF. DR. EMİN ALICI - A PERSPECTIVE ON OSTEOTOMIES IN SPINAL DEFORMITY SURGERY

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ABSTRACT

Spinal deformity is a condition that can arise at any age, from early childhood to advanced age, and may result from a wide range of causes (congenital, neuromuscular, etc.). Spinal deformities can affect the entire spine, causing dysfunction at a young age; however, when they occur later in life, they can lead to progressive asymmetric degeneration, resulting in clinical problems ranging from axial back pain to neurological deficits. Advances in implant technology and surgical techniques have enabled more effective treatment of spinal deformities. While spinal alignment can be achieved with standard methods in flexible deformities, vertebral osteotomies are required to obtain the correction necessary for clinical improvement in rigid cases. Generally, osteotomies can be categorized into three main types: posterior column osteotomies (PCO), including Smith-Petersen osteotomy (SPO) and Ponte osteotomy; pedicle subtraction osteotomies (PSO); and vertebral column resections (VCR)/posterior VCR (PVCR). A single-level PCO achieves 10-20 degrees of correction for kyphotic deformities. When surgical experience is insufficient to permit more extensive osteotomies, PCOs (SPO and Ponte) are considered the least complex procedures available. PSO is a three-column osteotomy in which the pedicles and portions of the vertebral body are resected to form a wedge. With maximal bone resection, PSO typically provides approximately 30 degrees of correction at the lumbar level. Bone-disc-bone osteotomy can be considered an extended osteotomy within this group, in which bone sections are removed from both the upper and lower regions at the disc level. Generally, this technique corrects deformities between 35° and 60°. Domanic osteotomy, a type of total wedge osteotomy, involves the resection of the posterior and middle columns, terminating at the anterior cortex while preserving the anterior longitudinal ligament. With Domanic osteotomy, a maximum correction of 65 degrees can be achieved in a single procedure.

VCR/PVCR involves the aggressive removal of one or more vertebral bodies. These osteotomies are the most powerful posterior osteotomy methods, enabling successful correction of severe and complex deformities. Because these surgeries are technically demanding and carry a high risk of complications, it is recommended that they be performed only by experienced teams.

Keywords: Osteotomies, spine deformity, deformity correction

In Memory

Spine surgery in our country, as in the rest of the world, was initiated and advanced by outstanding mentors whose contributions are irreplaceable. Among these esteemed teachers, our beloved mentor Prof. Dr. Emin Alıcı, whom we lost recently and remember with gratitude, holds a foremost place.

Two key moments involving our great mentor, Prof. Dr. Emin Alıcı, played an important role in my own entry into spine surgery. The first occurred during my residency when I watched him narrate a cervical procedure on TRT 1. The patient improved so remarkably that, when instructed to move the neck slowly, the patient replied, "I am fine; I can even do it firmly", and moved the neck with confidence.

The second moment came when Prof. Dr. Emin Alıcı, at the invitation of Prof. Dr. Ünal Kuzgun, visited University of Health Sciences Türkiye, Şişli Hamidiye Etfal Training and Research Hospital, where I was a resident. Without hesitation and tirelessly, he spoke to us about the establishment and foundations of spine surgery in our country, its evolution up to

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that time, and the outcomes achieved with the Alıcı implants he had developed and used in various operations.

In the following years, we continued to follow our mentor closely, sustaining our excitement by watching his spirited yet affectionate exchanges with another of our great teachers, Prof. Dr. Ünsal Domaniç. I was fortunate to take my associate professorship examination at the Orthopedics and Traumatology Department of Dokuz Eylul University, where Prof. Dr. Emin Alıcı served as rector and head of the clinic, and to have the honor of receiving my associate professor's gown from his hands.

His guidance was also my compass on the illuminated path that ultimately led me to the presidency of the Turkish Spine Society, which he founded.

Dear mentor, your determination, your working methods, and your boundless contributions to spine surgery in our country will continue to illuminate us. We will persist in being steadfast advocates and practitioners of spine surgery on this path. I am certain that your spirit continues to watch over us and that your light continues to guide our way. As your students, we pledge to follow this bright path and continue serving our patients, our country, and humanity.

INTRODUCTION

Spinal deformity is a condition that can arise from a wide range of causes (congenital, neuromuscular, etc.) from early childhood to advanced age. Spinal deformities may involve the entire spine in the coronal, sagittal, and axial planes and can lead to substantial functional impairment. Deformities that present later in life (adult scoliosis) may cause progressive asymmetric degeneration of spinal elements, creating clinical problems ranging from axial back pain to neurologic deficits[1,2].

With the emergence of pedicle screw-rod constructs and an improved understanding of spinal anatomy, complex posterior-only vertebral osteotomy techniques have become increasingly popular in recent years for the correction of coronal and sagittal spinal deformities[3].

Alongside advances in medicine and technology, global life expectancy has increased, leading to a growing elderly population and, compared with the past, shifting expectations regarding what constitutes a satisfactory quality of life[4].

Although advances in surgical instrumentation and deformity correction techniques are frequently used during spine surgery to restore alignment, patients with fixed deformities often require vertebral osteotomies to achieve the degree of correction necessary for meaningful clinical improvement. Long-term outcomes for newer technologies and developments are still limited; therefore, this remains a continual learning process. Each vertebral osteotomy has advantages and disadvantages that must be carefully considered during preoperative planning. This review aims to discuss the surgical techniques and clinical outcomes of the major osteotomy methods used in spinal deformity[4].

Osteotomies in Spinal Deformity

Spinal deformities are complex structural changes arising from disruption of normal alignment in the sagittal and coronal planes. Although these deformities can be encountered at any age from childhood to advanced years, their clinical manifestations vary depending on age, deformity type, and rate of progression. In pediatric patients, cosmetic concerns and postural disturbance often predominate, whereas in adults, pain, loss of mobility, impaired balance, fatigue, and reduced functional capacity are more prominent. The primary goal of surgical treatment is to restore balanced alignment and improve quality of life while preventing progression and recurrence.

Severe spinal deformities may occur in conditions such as Scheuermann kyphosis, neuromuscular disorders, congenital and degenerative diseases, and severe rheumatologic disorders such as ankylosing spondylitis. Osteotomies occupy a critical place in the surgical treatment of spinal deformity. A spinal osteotomy is a surgical procedure in which a portion of bone is resected to correct spinal alignment. Conceptually, osteotomy refers to restoring mechanical harmony by the controlled removal of a defined spinal segment.

Spinal osteotomy can markedly improve symptoms caused by deformity. By reducing pain and restoring balance, it allows the patient to stand upright without the need to flex the hips or knees. It improves cosmetic appearance, restores horizontal gaze, and may also lead to improvement in visceral organ function.

In rigid and advanced deformities, instrumentation and ligamentous releases alone are insufficient. Severe deformities can be corrected only with osteotomies; therefore, bony structures must be removed in a controlled manner, and the spine must be brought into a new alignment. Selection of osteotomy depends on many factors, including deformity rigidity, location, the amount of correction required, and the surgeon's experience. Spinal deformities are often multiplanar, involving components of flexion-extension, rotation, and translation; therefore, the corrective maneuver must also be multidirectional[5].

SRS-Schwab Classification Based on Resected Anatomical Structures[6]

I. Grade 1: Partial facet joint resection (inferior facet and joint capsule).
II. Grade 2: Complete facet joint resection (resection of ligamentum flavum and facet joints).
III. Grade 3: Pedicle and partial vertebral body (partial wedge resection of the posterior vertebral body and posterior elements).
IV. Grade 4: Pedicle, partial vertebral body, and disc (wider wedge resection of the posterior vertebral body, posterior elements, and a portion of more than one endplate and the intervertebral disc).
V. Grade 5: Complete vertebra and both adjacent discs.
VI. Grade 6: Multiple vertebrae and discs.

Main Types Of Osteotomy

Goals of Deformity Correction:

a. To re-establish global sagittal balance.
b. To align the position of the head and trunk.
c. To reduce biomechanical loading that causes pain.
d. To increase functional capacity and walking endurance.

In general, osteotomies can be considered under three main headings:

a. Posterior column osteotomies (PCO) [Smith-Petersen osteotomy (SPO) and Ponte osteotomy]
b. Pedicle subtraction osteotomy (PSO)
c. Vertebral column resection (VCR)

During surgical planning, the expected correction achievable with the chosen osteotomy is compared with the target ideal alignment. While PCOs may be sufficient for lower-grade flexible deformities, more aggressive techniques such as PSO or VCR are required for high-grade rigid kyphotic deformities.

PCO (SPO and Ponte)

PCO (Figure 1A-B) are based on resection of posterior elements to allow opening through the disc space(7). Mobility of the disc is required for these osteotomies. Because correction is achieved through the disc space, this osteotomy is considered an anterior column lengthening procedure. The resected structures include the facet joints, laminae, and posterior ligaments (supraspinous, interspinous ligaments, and ligamentum flavum).

SPO was first described in 1945 by Smith-Petersen et al.(8). In general, SPO corresponds to grade 1 in the SRS-Schwab classification, whereas the Ponte osteotomy is classified as grade 2. Historically, SPOs were performed in the lumbar spine for ankylosing spondylitis. In 1984, Ponte described a very similar PCO(9). The Ponte osteotomy is used for aggressive posterior resection of the thoracic spine, most commonly in kyphotic deformities. When performed asymmetrically, both SPO and Ponte osteotomies can also contribute to coronal correction. When surgical experience does not permit more extensive osteotomies, PCOs (SPO and Ponte) are the least complex procedures that can be performed.

PCO can be performed at multiple levels, enabling harmonious restoration of sagittal balance. Typically, a single-level PCO provides 10-20 degrees of kyphosis correction. It has been suggested that approximately 1 mm of resection may yield about 1 degree of correction (Figure 2).

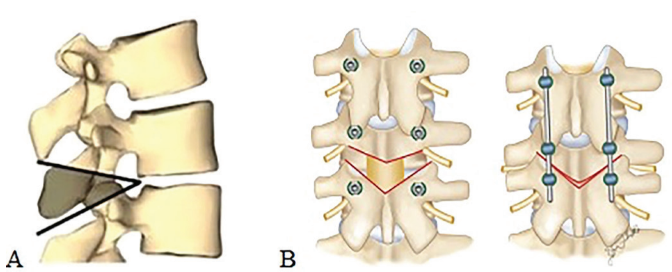

Figure 1. A) Schematic sagittal diagram of PCO. **B)** Smith Petersen osteotomy. PCO: Posterior column osteotomies

This is ideal for conditions such as Scheuermann kyphosis, where gradual and staged correction is required. If necessary, they can be performed sequentially or at alternating levels. PCOs may also be used as adjunctive procedures at additional levels during more comprehensive correction(10-13).

PSO

PSO is a three-column osteotomy in which the pedicles and portions of the vertebral body are resected in a wedge shape (Figure 3). Similar to SPO, it involves resection of posterior elements and facet joints, and additionally includes removal of part of the vertebral body together with the pedicles. It was first described in 1985 by Thomasen(14) and by Heining(15), with minor technical differences. Thomasen removed bone using an osteotome, whereas Heining preferred decancellation of the vertebral body using the 'eggshell' technique(14,15).

PSO involves all three spinal columns (posterior, middle, and anterior). When the osteotomy is closed and compressed, the posterior spine is shortened, and neural tissues are relatively decompressed/relaxed. It is also philosophically similar to closed wedge osteotomies used for the correction of deformities in the extremities. This corresponds to a grade 3 resection in the SRS-Schwab classification. An extended PSO corresponds to grade 4.

PSO is highly suitable for patients with marked, rigid sagittal imbalance(7). Etiologies of fixed sagittal plane deformity include ankylosing spondylitis, flatback syndrome, and iatrogenic causes. Lumbar kyphosis can be caused by congenital anomalies, trauma and pathological fractures, infections, metabolic or neoplastic diseases. Patients with type 2 sagittal deformities with sagittal vertical axis >12 cm, those with sharp kyphosis, and those with 360-degree fusion in multiple segments who cannot undergo SPO can be considered ideal candidates for PSO. When PSO is performed asymmetrically, it can be a

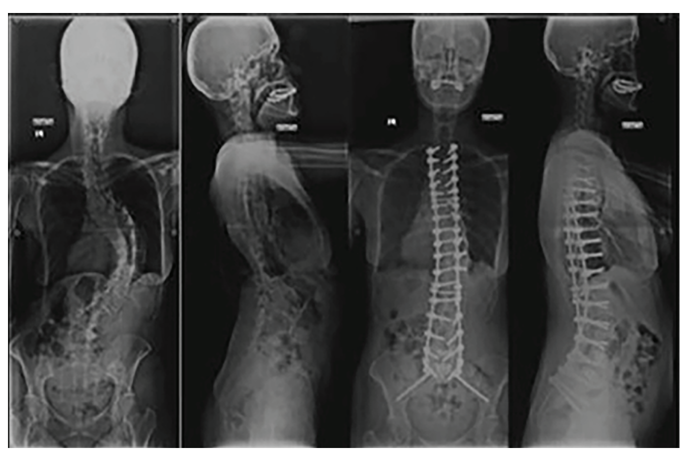

Figure 2. Adult scoliosis deformity, 58-year-old female patient. Correction in sagittal and coronal planes with multiple asymmetric SPO (From Prof. Dr. Azmi Hamzaoğlu archive). SPO: Smith-Petersen osteotomy

solution for type 1 coronal and type 2 sagittal imbalances. In these cases, osteotomy can be evaluated between a standard PSO and VCR[16]. With maximal bone resection, PSO typically provides approximately 30 degrees of correction at lumbar levels and is most beneficial when performed at the apex of the deformity.

Although primarily defined in the lumbar spine, it can be used in all regions of the spine, including the cranial or caudal aspects of the conus medullaris, as well as the cervical and thoracic regions. It is best performed at the apex of a sharp deformity. It provides greater correction of lordosis compared to SPO. In some cases, it can also be applied sequentially or alternately (skipped levels) (Figure 4). However, these cases are more significant in terms of stabilization and complications[10-12].

Bone-disc-bone Osteotomy (BDBO)

This osteotomy involves removal of the disc level together with bony portions immediately adjacent to both the superior and inferior endplates. In general, this technique provides 35-60 degrees of deformity correction. It is used when the apex of the deformity is typically at a disc level and when greater correction than PSO is required. It can be performed in three configurations (Figure 5)[17].

Technically, the disc is removed along with its proximity to the lower endplate, and an oblique osteotomy is performed on the bone above it. Conversely, an oblique osteotomy can be performed on both the disc and the bone below it. Alternatively, a convergent oblique osteotomy can be performed on both the upper and lower bones, and the disc is removed along with it. In this latter type, the maximum sagittal angle correction can be achieved. Fixation should be achieved by applying pedicle screws to at least two (often three) upper and two lower segments of the osteotomy line. The osteotomy line is closed by compression, ensuring complete bone-to-bone contact. If an open area remains in the osteotomy region, or if the anterior column needs to be lengthened to prevent dural buckling, the anterior section should be supported with a metal cage, strut allograft, or autogenous bone graft. Because the disc is completely removed and bony surfaces are brought into contact, a major advantage of this osteotomy is a lower risk of pseudarthrosis[18,19]. Compared with posterior VCR (PVCR), it can be used more safely, particularly in the lumbar region and in cases where the apex is at the disc level, because nerve root

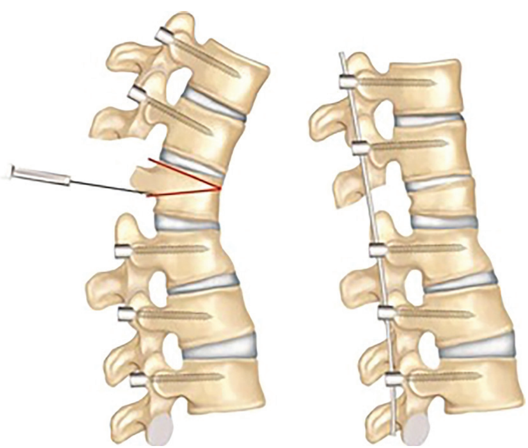

Figure 3. Pedicle subtraction osteotomy

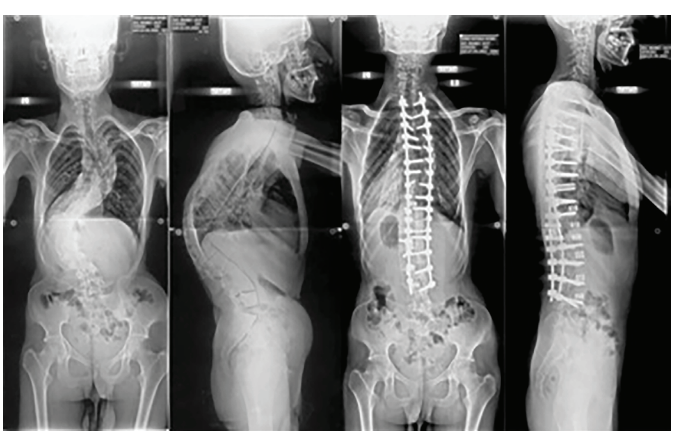

Figure 4. Nineteen-year-old male patient with kyphoscoliosis deformity. PSO at T12 level. Second stage: interbody fusions [via anterior thoracolumbar approach (from Prof. Dr. Azmi Hamzaoğlu archive)]. PSO: Pedicle subtraction osteotomies

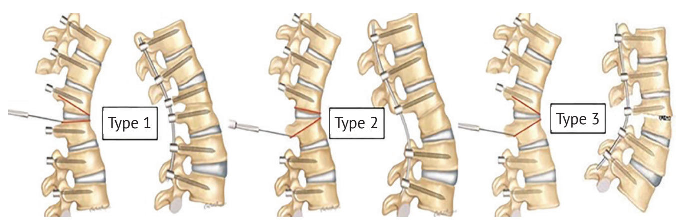

Figure 5. Three types of bone-disc-bone osteotomies

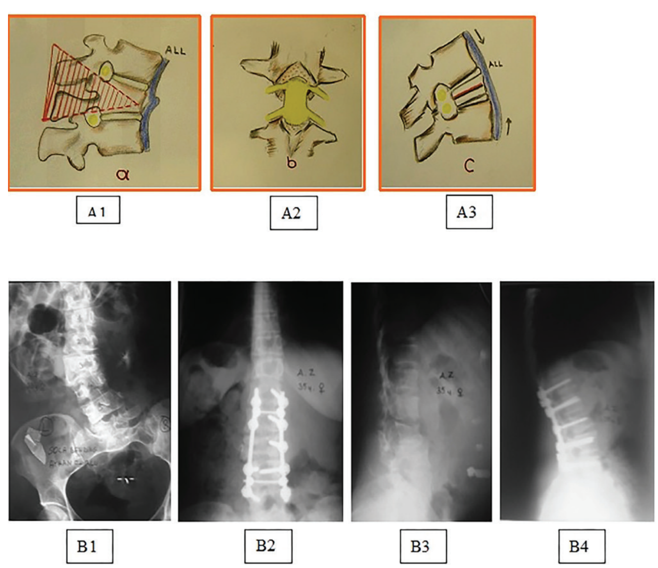

Figure 6. **A1-A2-A3)** An osteotomy drawing by Prof. Dr. Ünsal Domaniç, named after him (with the permission of Prof. Dr. Ünsal Domaniç). **B1-B2-B3-B4)** A case example of coronal and sagittal plane correction achieved with Domaniç osteotomy (from Prof. Dr. Ünsal Domaniç archive)

sacrifice is not required. Domanic osteotomy is similar to type 3 BDBO but includes nuanced differences[7,17,19].

Domanic Osteotomy (Posterior Total Wedge Resection Osteotomy)[19]

Although the first case was operated on in 1989, the technique was first presented internationally as an oral presentation at the complex deformity spine meeting held in Arcachon in 1991 as a series of eight cases. The expanded series was published as an international manuscript in Acta Orthopaedica Scandinavica in 2004 (Figure 6).

Total wedge osteotomy, in essence, involves resection of the posterior and middle columns that terminates at the anterior cortex of the spine, while preserving the anterior longitudinal ligament. The osteotomy is typically performed at the apex of a kyphotic deformity spanning two vertebrae. The upper and lower boundaries of the osteotomy are just below the transverse processes of the upper and lower vertebrae, respectively. The apex of the posterior-based triangular osteotomy is planned to be in the anterior vertebral body or the anterior longitudinal ligament. The osteotomy is performed carefully to avoid excessive penetration of the anterior cortex or the anterior longitudinal ligament, to prevent translation, to provide a hinge point, and to avoid injury to major or radicular vessels.

With the domanic osteotomy, up to 65 degrees of correction can be obtained in a single stage. After osteotomy and wedge resection are completed, the remaining portions of the upper and lower vertebrae usually form an intervertebral foramen containing two spinal nerves on either side of the resection site. The operation is completed by placing the rods[15]. Although this osteotomy was primarily designed for rigid kyphotic deformity, with increasing experience it has also been applied successfully to selected rigid frontal and sagittal deformities (Figure 7).

Figure 7. Two great masters, two great friends and companions, two great teachers. Prof. Dr. Emin Alıcı (left), Prof. Dr. Ünsal Domaniç (right)

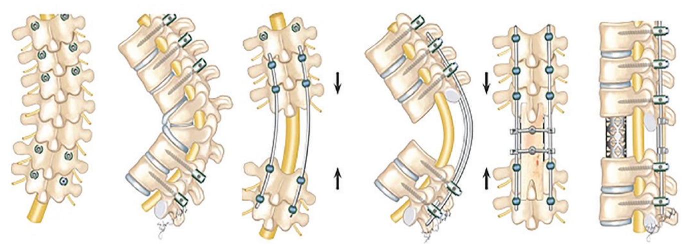

Figure 8. Vertebral column osteotomies

VCR

VCR represents aggressive removal of one or more vertebral bodies (Figure 8). To protect the great vessels, a thin bony rim may be left anteriorly. In the SRS-Schwab classification, this corresponds to a grade 5 osteotomy. An extended version that includes the adjacent disc space should be considered grade 6. PVCR is the most powerful posterior osteotomy technique, allowing correction of rigid and complex deformities. However, it requires longer operative time and greater blood loss compared with less invasive osteotomies, is technically demanding, and carries a high complication risk. Therefore, it should be performed only by a highly experienced surgical team. Spinal cord neuromonitoring is essential to prevent potentially catastrophic neurological injuries. VCR is the most suitable form of osteotomy for the most complex and intricate spinal deformities[7]. VCR was first described by MacLennan[20] in 1922 as a combined anterior and posterior procedure. PVCR was first introduced by Suk et al.[21] and popularized by Lenke et al.[22] for severe spinal deformities. It provides the maximum correction achievable with any spinal osteotomy. These deformities include rigid multiplanar deformities, fixed coronal imbalances, hemivertebra excisions, and sharp angular deformities. It is a challenging procedure reserved for severe spinal deformities with very limited or no flexibility. It allows for translational and rotational correction of the spine and provides controlled manipulation of both anterior and posterior columns simultaneously in a single approach. With these osteotomies, correction of 35-60 degrees in deformities can be achieved. It involves complete resection of one or more vertebral segments, along with the posterior elements, and the entire vertebral body, including adjacent discs. Since VCR creates a large defect in the spine, spinal fusion is also performed at these levels for reconstruction. Spinal fusion can be achieved using a structural autograft, a structural allograft, or a metal mesh. Initially, VCR was performed with a combined anterior and posterior approach, but it can now also be performed with only a posterior approach[10-12].

PSO and VCR are three-column osteotomies in which bone is removed; the less bone is resected, the easier it is to achieve spinal alignment. In type 2 and type 3 osteotomies, more bone is resected, making it more difficult to achieve spinal alignment, and these osteotomies are more prone to complicated results[5]. Hamzaoglu et al.[23] reported an average correction rate of 62% in the coronal plane and 72% in the sagittal plane in their series of 102 adult patients with severe deformities. Lenke et al.[22] reported significant improvements in curvature in 51% of scoliosis cases, 55% of general kyphosis cases, 58% of angular kyphosis cases, 54% of kyphoscoliosis cases, and 60% of congenital scoliosis cases after PVCR. In other PVCR studies involving adults and children with severe deformities, correction rates were reported as 69% for scoliosis, 54% for general kyphosis, 63% for angular kyphosis, and 56% for kyphoscoliosis[21-23].

Neurological complications can occur as a result of neurological injuries and also spinal subluxation, dural buckling, and compression of the spinal cord by remaining bone or soft tissues in the canal after correction. These complications are alarming for this surgical technique. Suk et al.[21] reported an overall complication rate of 34.3% and a neurological complication rate of 17.1%. Lenke et al.[22] reported a similar overall complication rate of 40% and a neurological complication rate of 11.4%[19]. Hamzaoglu et al.[23] also reported an overall complication rate of 7.84%, including transient nerve palsy in 1.96% of patients.

When these risky surgeries are performed in the operating room with neuromonitoring, under good imaging and/or navigation, by experienced teams, and when postoperative intensive care and clinical monitoring are adequately carried out, excellent results can be achieved in resolving difficult cases.

It has also been reported that the use of PSO and VCR has decreased recently due to technical difficulties, susceptibility to complications, and high probability of morbidity[3,24-26]. However, three-dimensional preoperative planning using CT-based methods and O-arm has increased confidence in its application. Advances in intraoperative navigation have increased the safety of these three-column osteotomies, especially in complicated cases where advanced correction is required[26-29]. It is clear that the use of navigation in osteotomy procedures is an important step towards increasing safety.

Halo-gravity Traction

Preoperative halo-gravity traction may be used to reduce surgical risks[30,31]. Adult indications are theoretically similar to pediatric indications, for example, in the presence of osteoporosis, comorbidities, and respiratory insufficiency[32]. Among other medical benefits, halo-gravity traction has been shown to significantly reduce VCR rates. A recent study in a cohort of adolescents and young adults demonstrated that preoperative halo-gravity traction resulted in a lower rate of surgical complications[31]. Complications such as neck pain, screw infections, screw penetration, and cranial nerve injuries can occur[33].

Restoration of Anterior Column Alignment

Theoretically, PSO alone may not fully restore lordosis. Anterior and anterolateral approaches can compensate for lordosis loss. In addition, anterior lumbar interbody fusion (ALIF) allows more extensive disc removal and better visualization of the endplates; however, ALIF is associated with risks of injury to peritoneal visceral contents, ureter, and the hypogastric plexus[33]. More recently, the minimally invasive anterior column realignment (ACR) approach has become popular. In this approach, anterior annulus fibrosus and anterior longitudinal ligament release should be performed to allow for the placement of "hyperlordotic" cages. The exact definition of the method is the lateral lumbar interbody fusion approach, also known as transpsoas interbody fusion[30-34].

In a recent literature review, Cheung et al.[11] suggested that ACR could be effectively used in patients who had previously undergone posterior instrumentation fusion in addition to primary cases but acknowledged that the limited number of studies in the literature have not yet clearly defined the role and indications of ACR in adult deformity surgery. Godzik et al.[35] worked to optimize the structural design during the same period. Adapting and utilizing such efforts could form the basis of a literature similar to that written on more traditional techniques[35].

One of the debated issues regarding spinal osteotomy surgeries is whether it is appropriate for one or two specialist spinal surgeons to perform these operations. The generally accepted view is that two spinal surgeons should participate in the surgery. However, it is necessary for the senior surgeon to be more experienced, better trained, and experienced in the management of complex spinal deformities. Another important issue is the need for the anesthesia team to be sufficiently experienced. Neuromonitoring is a technique that must be used in these cases, and it is recommended that a technician be present in the operating room, as well as a neurologist who monitors the surgery online. After a successful operation, another important issue is having an intensive care team ready to monitor and follow up with the patient in the intensive care unit. In complex pediatric cases, a multidisciplinary approach is also very important. Therefore, it is extremely important that many specialists, including dieticians, pediatricians, cardiologists, pulmonologists, gastroenterologists, and other child-related social workers, participate in these surgeries along with experienced spinal surgeons[12].

Complications

Complication rates in adult spinal deformity surgery range from 10.5% to 96%. The prospective, multicenter scoli-risk-1 study showed an acute decrease in lower-extremity motor strength in 22.18% of patients undergoing complex deformity surgery for adult scoliosis. At 6 months, this largely improved; 20.52% of patients demonstrated improvement in motor strength compared with preoperative status, while 10.82% did not improve. Revision spine surgery increases these risks[36-39].

Three-column osteotomies have increased complication rates due to the nature of spinal deformity and the invasiveness of the procedure. In a series by the International Spine Study Group, complications were observed in 78.0% of patients following three-column osteotomy for adult deformities. Significant complications were observed in 61% of patients. Another study showed that 11.1% of 108 adults treated with PSO for kyphotic deformity experienced neurological deficits. In children, Lenke et al.[22] found a 40% overall complication rate and an 11.4% neurological complication rate.

Complications may include iatrogenic injury to the spinal cord and nerves, dural injury, infection, or pseudomeningocele. Additionally, injury to adjacent structures such as pneumothorax, pleural effusion, large vessel injury, abdominal injury, or medical sequelae such as deep vein thrombosis, myocardial infarction, or pneumonia may occur.

After surgery, the patient should be monitored for instrumentation failure and the development of proximal junction kyphosis or proximal junctional insufficiency.

CONCLUSION

Balance is the ultimate goal of deformity correction[16]. Osteotomies offer powerful and effective correction options for advanced spinal deformities. Selection should be based on deformity type, rigidity, and patient needs. While PCO provides a safer and more reproducible approach, PSO and VCR have greater correction capacity. Navigation, three-dimensional planning, and modern instrumentation techniques continue to improve the safety and effectiveness of these operations. The patient's overall medical condition and the surgeon's level of experience are other factors in determining the ideal treatment. The high complication rate associated with osteotomies has also created a recent trend towards less invasive methods[10,29-34]. It should be emphasized that using osteotomies for deformity requires skill not only in the operating room but also in preparing a detailed, patient-specific preoperative plan. Looking ahead, multicenter studies and inter-team collaboration, together with effective technologies and digitized segmental, regional, and global preoperative planning, will provide more evidence-based guidance for complex clinical scenarios.

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Footnotes

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ADJACENT SEGMENT DISC DEGENERATION AFTER FUSION IN ADOLESCENT IDIOPATHIC SCOLIOSIS: THE IMPORTANCE OF A BALANCE-CENTERED APPROACH: A REVIEW

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ABSTRACT

The aim of this narrative review is to summarize current evidence regarding the epidemiology, pathophysiological mechanisms, and risk determinants of adjacent segment disc degeneration (ASDD) following adolescent idiopathic scoliosis (AIS) surgery and to emphasize the importance of a balance-centered, rather than level-centered, surgical planning strategy for long-term spinal health. Published data were synthesized within a descriptive framework focusing on selection of fusion levels [upper and lower instrumented vertebra (LIV)], coronal and sagittal alignment parameters, TK restoration, pelvic incidence-lumbar lordosis (PI-LL) harmony, and distal disc geometry. The reported incidence of ASDD following AIS surgery increases with follow-up duration, reaching approximately 25% at 10 years and exceeding 30% after 14 years. The development of ASDD is not solely dependent on the level of the LIV. Local and global alignment characteristics-such as LIV translation, adjacent disc wedging, sagittal vertical axis, insufficient LL, and PI-LL mismatch-have been consistently identified as major risk factors. Fusion extending to L4 or more distal levels has been associated with an increased risk of degeneration, particularly in the presence of sagittal imbalance. Nevertheless, with the widespread adoption of modern segmental pedicle screw-rod systems and three-dimensional correction techniques, the isolated impact of fusion level selection appears to be attenuated. ASSD following AIS surgery represents a multifactorial process rather than a purely mechanical consequence of fusion length. Global spinal balance, sagittal alignment, and the quality of surgical correction play pivotal roles in long-term outcomes. Strategies aimed at minimizing the risk of degeneration should prioritize achieving near-neutral sagittal balance, adequate TK, and optimal distal segment geometry, while preserving the shortest feasible fusion. In this context, balance-centered surgical planning emerges as a fundamental principle for achieving durable radiological and clinical outcomes following AIS surgery.

Keywords: Adolescent idiopathic scoliosis, adjacent segment disease, junctional failure

INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity with multifactorial etiology that affects approximately 2-3% of adolescents[1,2]. The primary goals of treatment are to halt curve progression, restore trunk and shoulder balance, and preserve motion segments by achieving the shortest feasible fusion[1,3-5]. Flat-back deformity and distal overload, common in the Harrington era, have markedly declined with the advent of segmental pedicle screw-rod systems and three-dimensional correction techniques[3,6]. Nevertheless, over time, adjacent segment disc degeneration (ASDD) may develop in the mobile segments caudal to the fusion mass[2,6-11].

ASDD is characterized by increased biomechanical stress, impaired diffusion, and structural dysfunction occurring in the mobile discs distal to the fusion[12-14]. Clinically, it may manifest as low back pain, stiffness, or functional loss; radiologically, it is typically defined by the Pfirrmann grading on magnetic resonance imaging (MRI)[14-16] and, when present, Modic end-plate changes[7,8,17]. Contemporary meta-analyses report ASDD rates rising to 25% within 10 years and to 32% by 14 years after AIS surgery[7]. However, the correlation between radiological findings and clinical symptoms is generally weak to moderate[6,8,11,16,18]. This indicates that ASDD is not merely a mechanical outcome, but a multifactorial process closely linked to the quality of surgical alignment and the patient's biomechanics[7,9].

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The aim of this review is to examine, in light of current literature, the epidemiology, pathophysiology, risk determinants, and clinical implications of ASDD following AIS surgery, thereby highlighting the importance of a balance-centered rather than a level-centered surgical approach. To this end, the literature on ASDD following AIS surgery was systematically searched in international biomedical databases, primarily PubMed, using a systematic search strategy; the findings of the included studies were narratively synthesized in terms of their epidemiological, biomechanical, and clinical dimensions.

Selecting Fusion Levels: From Traditional to Balance-centered Concepts

In AIS surgery, the selection of fusion levels influences not only deformity correction but also long-term spinal health. Historically, the Lenke et al.[1] and King et al.[5] classifications have provided the fundamental framework for defining structural curves and determining fusion limits. In modern concepts, Trobisch et al.[3] emphasize that fusion planning should consider not only structural vertebrae but also global balance and sagittal alignment-a strategy termed balance-centered fusion.

Selection of the Upper Instrumented Vertebra (UIV)

UIV selection plays a pivotal role in preventing proximal junctional kyphosis and shoulder imbalance. Because the thoracic spine is naturally stabilized by the rib cage, motion preservation is of secondary importance; the principal goals are maintaining shoulder symmetry and sagittal balance.

Trobisch et al.[3] recommend jointly evaluating T1 tilt, shoulder level, and the rigidity of the proximal thoracic (PT) curve during planning. When T1 tilt and shoulder imbalance are concordant, inclusion of the PT curve in the fusion is warranted; when discordant, stopping at T2-T3 may suffice[3,19]. Ilharreborde et al.[19] identified the T1 tilt-shoulder balance relationship as an independent determinant, whereas Kuklo et al.[20] found the clavicle angle to be the best predictor of postoperative shoulder balance.

In summary, UIV selection should not rely solely on curve morphology; rather, it should follow balance-centered planning principles based on PT rigidity, shoulder balance, and sagittal alignment[3].

Selection of the Lower Instrumented Vertebra (LIV)

The choice of the LIV is a key determinant of ASDD risk after fusion[20]. Beyond the selected vertebral level, the geometric characteristics of the LIV-particularly tilt, translation, and the angle of the subjacent disc-directly affect long-term load distribution and mechanical balance[9]. Lonner et al.[9] demonstrated that an LIV translation ≥2 cm and a subjacent disc wedge ≥5° increase the 10-year risk of ASDD by approximately sixfold.

Traditional approaches, based on the Lenke et al.[1] and King et al.[5] classifications, advocate ending the fusion at the neutral vertebra closest to the central sacral vertical line[1,5]. However, Knapp et al.[21] reported that in King type IV (long thoracic) curves, stopping one level proximal to the stable vertebra (often at L3) may be safe and preserve an additional motion segment. Burton et al.[22] suggested that, for optimal LIV selection, the disc below should be neutral or opening opposite on bending, and the rotation of the vertebra below should be ≤15°. Similarly, Suk et al.[23] emphasized that lumbar vertebral rotation is more important than curve magnitude or flexibility; planning based on the neutral rotated vertebra-end vertebra relationship is decisive for surgical success. Finally, Trobisch et al.[24] noted that inadequate preservation of sagittal parameters- pelvic incidence-lumbar lordosis (PI-LL) harmony, sufficient thoracic kyphosis (TK), and near-neutral sagittal vertical axis (SVA)- leads to increased distal loading and early disc degeneration.

Consequently, the modern approach focuses not only on “where” the fusion ends but also on “how” it is aligned. Optimal LIV selection should aim to balance coronal alignment, sagittal harmony, and distal segment biomechanics[9,23,24].

Epidemiology and Clinical Implications

Burgos et al.[7] reported ASDD incidences of 24.8% at 10 years and 32.3% at a mean of 13.8 years following AIS surgery. MRI-based studies tend to show higher rates than series defined solely by radiography[7]. Chiu et al.[16] and Nohara et al.[25] observed that degenerative changes cluster predominantly at L4-5 and L5-S1, attributed to increased mechanical load transfer distal to the fusion.

ASDD is often asymptomatic. Green et al.[6] reported minimal radiologic changes at juxta-fusion levels and low pain scores during long-term follow-up with modern segmental systems. In contrast, Jakkepally et al.[11] and Bartie et al.[18] found lower scoliosis research society-22 questionnaire (SRS-22) scores and a higher prevalence of low back pain when the fusion extended further distally. Collectively, these data indicate that ASDD is not merely a morphologic phenomenon; sagittal balance, pelvic parameters, and age-related biologic factors substantially influence clinical expression[7,16].

Pathophysiology: From Mechanics to Molecules

Fusion rigidifies the instrumented segment, shifting motion and loads to adjacent levels[11,24]. This redistribution results in excessive stress on posterior elements, increased intradiscal pressure (IDP), and enlargement of facet contact areas[10,11]. Auerbach et al.[12] demonstrated a significant increase in intradiscal pressure in caudal segments after fusion, potentially initiating degeneration. In combined *in vivo*+finite-element models by Zhou et al.[13], L4-S1 fusion produced a 0.8 mm decrease in posterior disc height, increased strain/stress in the posterolateral annulus at L3-4, and an ~0.29 MPa rise in IDP, quantitatively implicating biomechanical stress as a primary trigger of degeneration.

Such mechanical loading disrupts end-plate permeability and hampers nutrient diffusion into the disc[26]. Consequently, nucleus pulposus water content declines, annular fissures develop, and Pfirrmann et al.[15] grades progress. Histologically, proteoglycan loss and collagen remodeling trigger an inflammatory response consistent with Modic-type changes[14,26].

Factors Influencing ASDD

ASDD after AIS surgery is a multifactorial process that becomes more apparent with time. The most consistent observation is a time-dependent rise in incidence: a global rate of ~25% at 10 years increases to 32% by a mean of 13.8 years[7]. In series initiated in the Harrington era with 27-51 years of follow-up, the prevalence of disc degeneration reached 66-77%, accompanied by deterioration in sagittal parameters (SVA, PI-LL, PT)[17,27]. Increasing mean Pfirrmann grades with age further support this temporal effect[16].

The LIV is particularly decisive for long-term outcomes. Meta-analytic data suggest that stopping at L3 or above reduces the risk of degeneration compared with fusions extending below L3[7]. In very long-term cohorts, an LIV at L4 or below has been associated with reduced LL, increased SVA, and higher disc degeneration scores[26,27]. A 10-year prospective registry analysis identified L4 as carrying the highest risk for clinically significant degeneration[9]. Nevertheless, a meta-analysis restricted to modern pedicle screw-rod constructs found no significant MRI-based difference between L3 and L4, implying a potential effect of era and technique[2]. Clinically, fusions extending to L4 or below have been associated with worse pain-related scores[16].

The local geometry of the distal transition zone is a trigger for ASDD. Specifically, a subjacent disc wedge ≥5° and an LIV translation ≥2 cm increase the likelihood of degeneration by roughly sixfold[9]. Elevated L4 tilt/obliquity at baseline and at 10-year follow-up correlates with degeneration[25]. Thus, the critical question is not only "how far" but also "with what distal geometry"?

The number of remaining mobile segments also modulates load transfer. Fewer unfused discs are associated with higher distal Pfirrmann et al.[15] grades; similarly, Nohara et al.[25] 10-year follow-up found more frequent degeneration in patients with fewer mobile segments. Conversely, in a 9.1-year series, progression occurred in only one-quarter of patients and was typically limited to a single Pfirrmann grade, without a strong association with the number of mobile segments[11]. These discrepancies imply sensitivity to patient selection and correction quality.

Sagittal balance and restoration of thoracic contour have marked effects on long-term biomechanics. Smaller LL, higher SVA, greater PI-LL mismatch, and increased PT have been associated with degeneration during long-term follow-up[27]; notably, the L4-or-lower LIV group exhibits lower LL and higher SVA[17]. In the mid-term, thoracic hypokyphosis shows a significant inverse relationship with degeneration; inadequate kyphosis restoration creates an unfavorable milieu for distal discs[28].

Level-specific analyses suggest that L5-S1 (and to a lesser extent L4-5) is the most vulnerable link. Long-term MRI studies have identified most new pathologies at L5-S1, with the greatest jump in mean Pfirrmann grade at this level[6]; contemporary series employing direct vertebral rotation/rod derotation techniques similarly show marked increases at L4-5 and L5-S1 below the LIV[28]. Selective thoracic fusion preserves motion segments yet is associated, on follow-up, with modest increases in degeneration at unfused levels and greater facet degeneration at the first two levels below the LIV, while clinical scores often remain comparable[10]. Very long-term Harrington-era series underscore era-related differences, with higher rates of Modic changes and worse Oswestry disability index (ODI)/function scores[8].

Clinical impact is heterogeneous; nonetheless, meta-analysis demonstrates worsening of SRS-22 domains (function, self-image, satisfaction) in the presence of degeneration[7]. Pain outcomes tend to be worse when fusions extend to L4 or below[16], although some series report weak or inconsistent associations between imaging and SRS-22/ODI[6,9,18]. In aggregate, shared principles to mitigate ASDD risk include-when feasible-ending at L3 or above, minimizing distal disc wedging and LIV translation, adequately restoring TK, and optimizing global sagittal balance with appropriate LL-PI harmony[7,9,17,27,28].

The long-term effects of thoracic hypokyphosis extend beyond the lumbar spine to the cervical region. Young et al.[29] at a mean 30-year follow-up, reported substantially increased rates of cervical disc disease and surgery in AIS patients. The rate of anterior cervical discectomy and fusion was nearly tenfold higher than in the general population, and 58% of radiographically assessed patients exhibited moderate-to-severe cervical osteoarthritis and disc degeneration. Crucially, thoracic hypokyphosis was significantly associated with cervical disc degeneration $p<0.01$. Suggesting that inadequate TK restoration increases cervical loading and accelerates degenerative changes[29]. Taken together, these findings highlight the multifactorial nature of ASDD, as summarized in Table 1.

Table 1. Overview of risk factors, pathophysiological mechanisms, and outcomes of ASDD after AIS spinal fusion

Category	Summary of findings
Epidemiology	• ~25% at 10 years • ~32% at ≥14 years • Higher rates in very long-term Harrington-era cohorts (up to 66-77%) • MRI-based studies report higher prevalence than radiography
Biomechanical consequences	• Motion restriction • Altered load transfer • Reduced segmental mobility
Surgical and radiological risk factors	• Distal fusion to L4 or below • LIV translation ≥2 cm • Subjacent disc wedging ≥5° • Thoracic hypokyphosis • PI-LL mismatch • Increased sagittal vertical axis • Reduced number of mobile segments
Pathophysiological mechanisms	• Increased intradiscal pressure • Facet joint overload • Impaired disc nutrition and diffusion • Annular strain • Endplate microdamage
Radiological manifestations	• Pfirrmann grade progression • Disc height reduction • Decreased T2 signal intensity on MRI • Modic endplate changes
Clinical implications	• Frequently asymptomatic • Possible low back pain • Reduced SRS-22 and functional scores • Potential long-term impact on global spinal balance

ASDD: Adjacent segment disc degeneration, AIS: Adolescent idiopathic scoliosis, MRI: Magnetic resonance imaging, LIV: Lower instrumented vertebra, PI-LL: Pelvic incidence-lumbar lordosis, SRS-22: Scoliosis research society-22 questionnaire

CONCLUSION

In AIS, ASDD is a multifactorial process that should be managed with balance-centered planning. The L3 versus L4 decision is not singularly determinative; regardless of the terminal level, a horizontal/centralized LIV, near-neutral SVA, and LL targets appropriate for age and PI appear pivotal for long-term risk reduction. Avoiding thoracic hypokyphosis is essential not only to limit distal ASDD but also to reduce the risk of cervical degeneration.

Footnotes

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THE INTEGRATION OF ARTIFICIAL INTELLIGENCE IN SPINAL CARE ASSESSMENT AND SURGERY: A COMPREHENSIVE NARRATIVE REVIEW

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ABSTRACT

Artificial intelligence (AI) and machine learning (ML) are driving a paradigm shift in spine surgery, augmenting surgical decision-making with data-driven insights. This review synthesizes the current landscape of AI applications across the surgical care continuum and evaluates its potential to enhance precision, personalization, and value. A narrative review was conducted through a critical analysis of contemporary literature, including original research, systematic reviews, and editorials from high-impact orthopaedic and spine surgery journals. Key themes were identified and organized to provide a coherent overview of AI's role in preoperative planning, intraoperative execution, and postoperative economics. AI demonstrates significant utility in automating spinal imaging analysis, with convolutional neural networks enabling rapid vertebral segmentation and accurate measurement of alignment parameters. Predictive ML models excel in forecasting individualized patient risks, with specific algorithms outperforming surgeons in predicting complications and long-term outcomes. Intraoperatively, AI-driven navigation and robotic systems achieve a pedicle screw placement accuracy exceeding 94% while reducing radiation exposure. Furthermore, AI applications are emerging in health economics, effectively predicting costs and automating administrative tasks. Despite this, various challenges continue to hinder progress, notably the black-box nature of algorithms, data bias, ethical dilemmas, and barriers to clinical adoption.

The available evidence positions AI not as a proven superior alternative, but as a promising adjunct with proof-of-concept applications across the spine care continuum. AI serves as a powerful adjunctive tool in spine surgery, promising to enhance procedural precision, personalize patient care, and improve economic efficiency. While limitations regarding transparency, data diversity, and ethical frameworks must be addressed, the ongoing development of explainable AI and robust datasets indicates a transformative future for spinal surgical practice. To ensure safe and equitable adoption, the next steps require prospective multicenter validation, active surgeon participation in governance and education, and global collaborations to develop diverse datasets.

Keywords: Artificial intelligence, machine learning, spine surgery, predictive analytics, surgical navigation, value-based care, explainable AI

INTRODUCTION

From its conceptual origins in Alan Turing's theoretical work of the 1950s, artificial intelligence (AI), characterized by its capacity to emulate human intelligent behavior, has matured into a transformative force within modern healthcare. The foundational event was the 1956 Dartmouth College conference, which formally established AI as a field of study. Machine learning (ML), a core element of AI, allows systems to learn from experience and enhance their performance by discerning complex relationships in data, thereby producing inferences and predictions without being explicitly programmed for every individual scenario. The rapid expansion of literature, technology, and clinical use makes understanding AI/ML applications increasingly imperative in spine surgery, where their capacity for sophisticated pattern recognition and prediction is uniquely suited to the field's intricate and multifactorial nature (Figure 1)[1].

The management of complex spinal pathologies, such as adult spinal deformity (ASD), tumors, and infections, demands the synthesis of a vast array of factors, from intricate radiographic parameters and biomechanical considerations to patient-specific comorbidities and goals, making surgical decision-making a highly nuanced process, particularly for conditions like ASD which require a holistic assessment of

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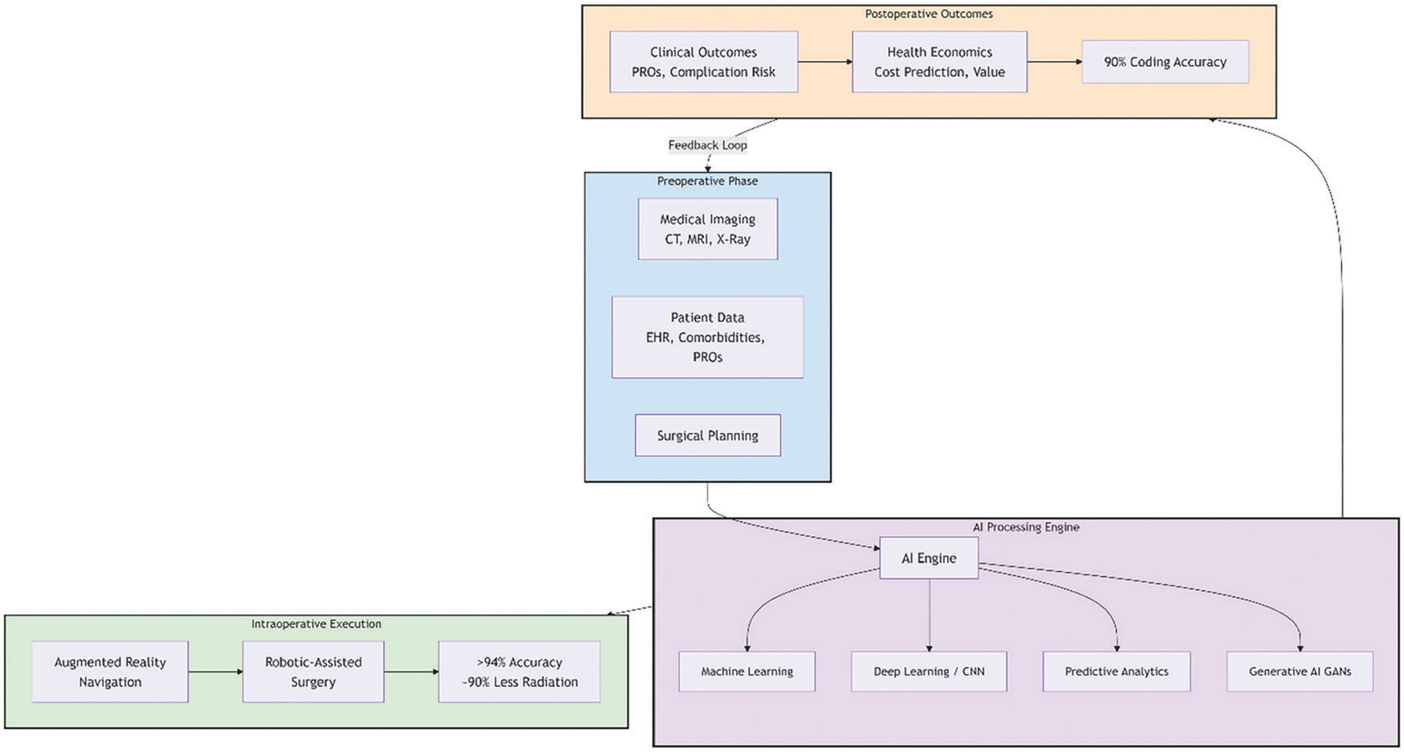

Figure 1. Workflow of AI integration in spine surgery
This schematic illustrates the continuous, cyclical framework of AI integration across the core phases of spine surgical care. The model is built upon a continuous learning feedback loop (grey arrow), where postoperative outcomes are used to refine and improve the AI algorithms, creating a system that evolves with each case. Preoperative phase (blue): the process initiates with the synthesis of multifaceted preoperative data, including medical imaging (X-Ray, CT, MRI, EOS), patient-specific variables from EHRs (comorbidities, demographics), and PROs. This data informs the initial surgical planning. AI processing engine (central purple hub): the raw data is processed by a central AI engine utilizing a suite of ML methodologies. These include supervised learning for predictive analytics, deep learning (e.g., CNNs) for image segmentation and analysis, and generative AI (e.g., GANs) for data augmentation and synthetic image generation. Intraoperative phase (green): the AI-generated surgical plan is executed with enhanced precision in the operating room. AI-driven technologies such as AR navigation systems and robotic-assisted surgery platforms translate the preoperative plan into action, significantly improving the accuracy of instrument placement (e.g., >94% for pedicle screws) and drastically reducing radiation exposure (e.g., by up to 90%) for the patient and surgical team. Postoperative phase (orange): the outcomes of surgery are quantitatively measured, capturing both clinical endpoints (e.g., complication rates, achievement of MCID in PROs) and health economic metrics (e.g., resource utilization, cost prediction, automated medical coding). This data is the crucial output that feeds back into the system. Feedback loop (grey): postoperative outcome data is aggregated and used to retrain the AI models in the central engine. This closed-loop system ensures continuous refinement, validation, and improvement of the predictive algorithms and surgical planning tools, ultimately leading to progressively superior, personalized, and value-based patient care. AI: Artificial intelligence, CT: Computed tomography, MRI: Magnetic resonance imaging, EHRs: Electronic health records, PROs: Patient-reported outcomes, ML: Machine learning, CNNs: Convolutional neural networks, GANs: Generative adversarial networks, AR: Augmented reality, MCID: Minimal clinically important difference,

the entire skeletal structure for comprehensive radiographic evaluation[2]. While traditional statistical methods are powerful for hypothesis testing and establishing associations in well-understood domains with structured datasets, such as public health, ML is better suited for generating individualized predictions from high-dimensional data in innovative fields like omics, radiodiagnostics, and personalized medicine. AI and ML algorithms excel in this predictive capacity, offering the potential to personalize care, enhance surgical precision, improve risk stratification, and optimize resource allocation. As emphasized by Ali et al.[3] technologies are driving significant transformations in spinal surgery. Neural networks enhance the accuracy of preoperative planning, while the use of augmented reality refines intraoperative navigation and reduces radiation exposure. Furthermore, postoperative predictive analytics enable risk stratification, thereby enabling improved precision in surgery, optimization of clinical workflows, and personalization of patient care.

The drive for innovation is further underscored by the alarmingly high complication rates in complex procedures. Effective presurgical planning must address critical patient-specific risk factors, such as age, body mass index (BMI), smoking, and osteoporosis, to mitigate complications, as evidenced by Akıntürk et al.[4] whose analysis of 26,207 patients revealed a

34.5% complication rate predominantly from implant failure (e.g., screw loosening, junctional kyphosis), neurologic deficits (10.8%), infection (3.6%), and cardiopulmonary events (4.8%), all of which adversely impact patient outcomes, length of stay, and readmission rates. This stark reality necessitates moving beyond traditional risk assessment and underscores the critical need for tools that can optimize every phase of care, from patient selection to postoperative management.

The proliferation of large, multi-institutional datasets, enhanced computational resources, and advanced algorithms are accelerating the adoption of AI in spine surgery, where it is enhancing diagnostics, increasing surgical precision, and enabling personalized rehabilitation through early risk assessment and adaptive therapies, despite persistent challenges such as data limitations and ethical considerations[5].

The aim of this review is to synthesize recent literature findings and provide a comprehensive overview of the current state of AI in spinal surgery. It will explore the fundamental types of ML, detail its applications in imaging, surgical planning, outcome prediction, and health economics, and discuss the significant ethical and practical challenges that must be addressed for its successful integration into routine clinical practice.

MATERIALS AND METHODS

This narrative review was conducted through a synthesis of contemporary literature identified from the provided articles, which represent a cross-section of recent editorials, reviews, and original research in high-impact orthopaedic and spine surgery journals. The provided documents were systematically analyzed to extract information on the principles of AI/ML, specific applications in spine surgery (e.g., imaging, prediction models, surgical techniques, health economics), and discussed limitations.

Key themes and sub-themes were identified and organized into logical sections to construct a coherent overview of the field. The focus was placed on applications with direct clinical relevance, including:

a. The use of AI for automated measurement of spinal parameters and image segmentation.

b. The development of predictive models for surgical outcomes, complications, and cost.

c. The integration of AI into surgical navigation, robotics, and augmented reality systems.

d. The role of AI in health economics and value-based care.

e. The ethical and practical challenges facing implementation.

This approach offers a comprehensive, detailed analysis of AI's current role in spinal surgery, incorporating the latest consensus and innovations from recent literature.

RESULTS

Fundamentals of ML in Spine Surgery

ML is broadly categorized into four main paradigms: supervised learning, which uses labeled data to map inputs to outputs for tasks such as classification and regression; unsupervised learning, which identifies hidden patterns and structures in unlabeled data through clustering and dimensionality reduction; semi-supervised learning, which leverages both labeled and unlabeled data to improve prediction accuracy when labeled data is scarce; and reinforcement learning, which enables an agent to learn optimal behaviors through environmental feedback based on rewards and penalties, a method particularly suited for complex domains such as robotics and autonomous systems[6]. Understanding these paradigms is crucial for interpreting the literature. Recent reviews have highlighted an increasing emphasis on transparency and interpretability in clinical settings. In this context, explainable AI (XAI) not only provides the underlying algorithmic prediction but also supplies explanations that offer insights into the prediction's reliability[7]. Furthermore, generative adversarial networks (GANs), which employ two competing AI models (a generator and a discriminator) to produce high-quality synthetic data, are emerging as a powerful tool for medical imaging and data augmentation (Table 1)[8].

Supervised Learning: Algorithms are trained on a labeled dataset in which the target output (e.g., "fracture" or "no fracture") is predefined. The model acquires the ability to map input data to their correct labels and is later evaluated on unlabeled datasets to assess its performance. Common supervised models include:

Decision Trees (DT) and Random Forests (RF): These models use a tree-like structure of decisions (e.g., "Is the posterior ligamentous complex intact?") to reach an outcome (e.g., "stable" or "unstable"). RF is an ensemble learning technique that operates by constructing a multitude of DT. This approach improves overall accuracy and mitigates the danger of overfitting, which is common in single DT. They are highly interpretable and have been used for risk stratification and classification, such as the AOSpine fracture classification, need of blood transfusion, preoperative planning/selection, patient type clustering, adverse events and serious complications[5,9].

Support Vector Machines (SVM): SVMs are a supervised learning model used for classification, regression, and outlier detection. Their mechanism involves finding the mathematically optimal decision boundary (hyperplane) that maximizes the margin between different classes in a high-dimensional feature space. These models demonstrate particular efficacy in image-based diagnostic and prognostic tasks, including the classification of disc degeneration and scoliosis types, the automated detection and localization of lumbar spine and vertebral compression fractures, and the prediction of postoperative outcomes[5,10].

Unsupervised Learning: Algorithms process unlabeled datasets autonomously without human guidance, discovering hidden patterns or intrinsic structures. A common application is clustering patients into novel subgroups based on a combination of clinical and radiographic features, which may predict distinct outcomes or complication profiles[11].

Artificial Neural Networks (ANN) and Deep Learning (DL): ANNs are composed of layered, interconnected nodes

Table 1. ML paradigms and algorithms in spine surgery research

Paradigm/concept	Key idea	Common algorithms	Clinical relevance and examples
Supervised learning	Learns a function that maps inputs to outputs using a labeled dataset for tasks like classification and regression.	DT, RF, SVM, linear/logistic regression, neural networks	Classification and risk stratification: RF/DT for AOSpine fracture classification (stable/unstable), predicting need for blood transfusion, adverse events, and serious complications. SVMs for image-based tasks like classifying disc degeneration, scoliosis types, and detecting lumbar spine or vertebral compression fractures.
Unsupervised learning	Identifies hidden patterns and intrinsic structures within unlabeled data through clustering and dimensionality reduction.	K-means clustering, hierarchical clustering, principal component analysis, autoencoders	Patient phenotyping: clustering patients into novel subgroups based on clinical/radiographic features to predict distinct outcomes or complication profiles.
Semi-supervised learning	Leverages both labeled and unlabeled data to improve predictive accuracy where labeled data is scarce.	Label propagation, self-training, generative models	Data augmentation: overcoming annotation scarcity; e.g., a 2.5D U-Net framework with a cascade design and level set function for precise vertebral segmentation, including fractures.
Reinforcement learning	An agent learns optimal behaviors through environmental feedback based on rewards and penalties, suitable for complex domains.	Q-learning, deep Q-networks, policy gradient methods	Robotic surgery: autonomous surgical planning; e.g., SafeRPlan, a DRL approach for pedicle screw placement that achieves >5% higher safety rates under noise.
Deep learning (specialized architectures)	A subset of ML using multi-layered networks to learn complex, hierarchical data representations, often applied in a supervised manner.	CNN, recurrent neural networks, transformers	Medical image analysis and prognostics: CNNs are used for vertebral segmentation, automated Cobb angle measurement, fracture detection, and prognostic modeling (e.g., forecasting postoperative outcomes, relapse after discectomy, mortality rates, and readmissions/reoperations) to aid preoperative planning.
XAI	A suite of techniques designed to make the predictions of complex "black box" models transparent and interpretable to humans.	SHAP, LIME, attention mechanisms	Clinical adoption: providing surgeons with a rationale for a model's prediction of surgical risk or diagnosis to foster trust and facilitate integration into care.
GANs	A framework using two competing networks (generator and discriminator) to produce high-quality synthetic data instances.	Deep convolutional GANs, StyleGAN, CycleGAN	Addressing data scarcity: generating synthetic medical images (e.g., spine CTs/MRIs) to augment training datasets and protect patient privacy.

This table outlines key ML paradigms and AI concepts in spine surgery research, categorizing them by principle, common algorithms, and clinical applications. It demonstrates how these technologies advance diagnostic precision, data-driven planning, and personalized care. ML: Machine learning, AI: Artificial intelligence, DT: Decision trees, RF: Random forests, SVM: Support vector machines, DRL: Deep reinforcement learning, CNN: Convolutional neural networks, XAI: Explainable artificial intelligence, SHAP: SHapley additive exPlanations, LIME: Local interpretable model-agnostic explanations, GAN: Generative adversarial networks, CT: Computed tomography, MRI: Magnetic resonance imaging

(neurons) designed to process input data, mirroring the structure and function of the human brain. DL refers to ANNs with many hidden layers, capable of learning complex, hierarchical representations of data. A specialized type of ANN, the convolutional neural network (CNN), is particularly powerful for image processing. Inspired by the visual cortex, CNNs are adept at processing pixel data and are the backbone of most modern medical imaging AI applications, from vertebral segmentation to automated Cobb angle measurement[12]. Beyond image analysis, CNNs are increasingly employed for advanced prognostic modeling, demonstrating strong predictive utility in forecasting favorable postoperative outcomes, estimating the risk of relapse following discectomy, the diagnosis of cervical myelopathy, calculating mortality rates after surgery for spinal epidural abscess, and predicting probabilities of readmission or reoperation after posterior lumbar interlaminar fusion, thereby directly informing preoperative planning and surgical candidate selection, particularly in complex cases[6].

Semi-supervised Learning: To overcome the scarcity of annotated fracture data in spinal computed tomography (CT) segmentation, Pan et al.[13] developed a semi-supervised 2.5D U-Net framework that leverages both labeled and unlabeled datasets. Their approach incorporates a cascade design aligned with clinical workflows to enhance segmentation precision across vertebrae. In addressing computational constraints, Huang et al.[14] strategically employed 2D network training supplemented with 2.5D inputs to optimize performance. The model utilizes a dual-branch encoder with multi-scale Swin

Transformer modules for improved feature extraction and introduces a level set function to ensure consistency between pixel classification and geometric regularization. This method demonstrates strong performance across evaluation metrics, highlighting the efficacy of semi-supervised learning and advanced architectural designs in medical image segmentation. In a separate clinical prediction task, Park et al.[15] evaluated several supervised ML algorithms to forecast whether patients with cervical spondylotic myelopathy would achieve a minimum clinically important difference (MCID) in neck pain following surgery. They emphasized that model selection should be guided by dataset characteristics and the specific clinical question. For their balanced dataset, precision was identified as the most relevant metric to optimize the identification of true MCID achievers. Logistic regression achieved the highest precision across both short- and long-term follow-up intervals, demonstrating consistent superiority among the tested models and reaffirming its utility for clinical classification problems.

Reinforcement Learning: In their study, Ao et al.[16] introduce SafeRPlan, a safety-aware deep reinforcement learning approach for autonomous pedicle screw placement in robotic spine surgery. This method incorporates an uncertainty-aware safety filter to ensure safe actions, uses pre-trained neural networks to compensate for incomplete intraoperative anatomical information, and employs domain randomization to improve generalization under noise. Experimental results demonstrated that SafeRPlan achieved over 5% higher safety rates compared to baseline methods, even under realistic surgical conditions.

XAI: As AI models, particularly complex DL systems, become more integral to clinical decision-making, the demand for transparency and interpretability has surged. XAI refers to a suite of techniques designed to make the predictions of these "black box" models understandable to human experts. This is achieved by providing insights into the model's confidence, highlighting the features most influential to a decision (e.g., specific image regions in a CT scan), and generating a rationale for its output. In spine surgery, XAI is critical for fostering clinical trust and facilitating adoption, as it allows surgeons to validate an AI's recommendation for fracture classification, surgical planning, or risk prediction before integrating it into patient care[7].

GANs: GANs represent a category of DL frameworks wherein two neural networks operate in opposition, a generator that produces synthetic data instances, and a discriminator that distinguishes between authentic and generated data. Through this iterative competition, the system progressively improves its ability to generate convincingly realistic synthetic outputs. In medical imaging, GANs address the critical challenge of data scarcity and privacy by creating high-quality synthetic spine CT or magnetic resonance imaging (MRI) images[8]. These generated datasets can be used to augment limited training data, improving model robustness and generalizability, or to create anonymized data for research without compromising patient confidentiality. Applications include data augmentation for segmentation models and simulating anatomical variations for training purposes[17].

Applications in Spinal Imaging and Diagnostics

AI has made significant strides in automating and enhancing the interpretation of spinal images, reducing inter-observer variability and surgeon workload.

Automated Vertebral Segmentation and Identification: CNNs form a fundamental framework for diagnostic and therapeutic planning by allowing highly accurate, automated detection and localization of vertebrae in various imaging modalities such as X-Ray, CT, MRI, and ultrasound. These systems significantly outperform manual methods in consistency and precision, reducing the mean absolute error in Cobb angle measurements to less than 3° compared to manual variability of 2.8°-8°. AI-based approaches also demonstrate robustness in analyzing spinal curvature from suboptimal images, such as off-center, angulated, or smartphone-captured images, and support radiation-free scoliosis screening via ultrasound through automatic extraction of anatomical landmarks for 3D spinal reconstruction. Additional applications include quantitative assessment of thoracolumbar compression fractures to inform clinical management[18]. This is crucial for surgical navigation systems, as it allows for automatic registration of the patient's anatomy to preoperative images, facilitating the planning of pedicle screw trajectories. Burström et al.[19] created an automated spine segmentation algorithm for this purpose, based on 3D reconstructions obtained from cone-beam CT.

Classification of Pathology: ML algorithms excel at classifying spinal pathologies through medical imaging analysis, demonstrating particular strength in automatically grading intervertebral disc degeneration according to standardized systems such as Pfirrmann classification, with CNNs achieving remarkable agreement (up to 95.6%) with expert radiologists[20]. These techniques have been successfully extended to identify various spinal conditions including stenosis, fractures, sacroileitis, and tumors. For neural compression pathologies, AI systems analyze morphological features to diagnose disc herniation and nerve root compression with high accuracy and exceptional reliability[21-23]. Additionally, AI models demonstrate sophisticated diagnostic capabilities in distinguishing benign from malignant vertebral fractures on CT scans, matching or surpassing radiology residents' performance, and in grading metastatic spinal cord compression by precisely delineating margins of involvement[24].

Automated Measurement of Radiographic Parameters: AI enables automated measurement of key spinopelvic parameters, including coronal and sagittal vertical axes, as well as key sagittal alignments such as thoracic kyphosis, lumbar lordosis, and the pelvic parameters of incidence, tilt, and sacral slope, from standing whole-spine radiographs. These AI-derived measurements demonstrate excellent agreement with expert surgical assessments, achieving intraclass correlation coefficients exceeding 0.90 and mean absolute errors below 3° or 3 mm, thereby providing a rapid and reliable alternative to manual methods[25].

Generative AI for Enhanced Imaging: Recent advances have introduced the use of GANs for anatomical image reconstruction. Santilli et. al.[26] developed a publicly available GAN model that generates synthetic STIR sequences of the lumbar spine from standard T1- and T2-weighted MRI scans. Expert radiologists assessed these synthetic datasets and judged them to be of comparable or superior quality in approximately 77% of cases, underscoring their potential to streamline and improve imaging workflows for preoperative evaluation. Importantly, the generated images were shown to be diagnostically equivalent to conventional acquisitions while demonstrating superior overall image quality, supporting their possible integration into routine clinical practice.

Predictive Modeling for Surgical Outcomes and Complications

AI enables personalized risk stratification and outcome prediction in spine surgery, advancing the field toward truly individualized patient care (Table 2)[5].

The potential of AI is not merely theoretical but now demonstrates tangible superiority in specific domains. A compelling example lies in outcome prediction, where an algorithm developed by the International Spine Study Group demonstrated 89% accuracy in forecasting risks. This stands in stark contrast to a study of 39 experienced deformity surgeons, whose predictions for the same set of cases were highly discordant and inconsistent, with estimates for complication rates ranging from 0% to 100%. This highlights the inherent limitations of human cognition when processing multivariate data and the confounding role of emotional bias, where a recent negative outcome can unconsciously skew a surgeon's prediction for a subsequent, similar patient. This concept is further explored by Martin and Bono[27], who note that while traditional regression techniques are well-suited for assessing causation, they are poorly optimized for prediction, a gap that ML specifically aims to fill.

Predicting Complications: ML models have been developed to predict a wide range of complications with high accuracy. These include:

Reoperation and Major Complications: ML algorithms synthesize high-dimensional data from clinical, imaging, and patient sources to produce personalized risk assessments and predictions for surgical results. For instance, Scheer et al.[9] developed a model predicting major complications after ASD surgery with 87.6% accuracy, while Pellisé et al.[28] employed random forest models trained on more than 100 variables to forecast major complications, reoperations, and hospital readmissions, with model performance yielding area under the curve (AUC) scores between 0.67 and 0.92. Building upon this, sophisticated ML techniques, including LightGBM and RF, have been leveraged to generate probabilistic forecasts for ideal surgical outcomes. These are defined as a clinically significant enhancement in quality of life without major complications, achieved by incorporating modifiable risk factors into their analytical architecture.

Proximal Junctional Kyphosis/Failure (PJK/PJF): AI and ML models hold considerable promise for predicting PJK and PJF after ASD surgery, with some studies reporting prediction

Table 2. AI for predictive modeling of surgical outcomes and complications in spine surgery

Prediction category	Specific target	Reported performance/key finding
General complications	Major complications, reoperation, readmission	87.6% accuracy; AUC: 0.67-0.92 for various outcomes; forecasts "ideal outcome" (QoL improvement without complications)
Mechanical complications	PJK/PJF pseudarthrosis	Up to 86% accuracy; AUC: 0.89 91% accuracy; AUC: 0.94; identifies adipose tissue biomarkers
Surgical site infection	Postoperative infection	93% positive predictive value; identifies key predictors (modic changes, glucose, etc.)
Other clinical outcomes	Transfusion, length of stay, opioid use	Predictive capability demonstrated
Patient-reported outcomes	MCID on SRS-22, QALYs	Models probability of achieving MCID; predicts QALYs gained; external validation performed
Risk stratification	Novel ASD classifications	Creates patient clusters with distinct risk/PROMs profiles for better selection and counseling
Surgical planning	Upper instrumented vertebra selection, PJK prevention	87.5% accuracy in UIV selection; optimizes surgical angles
Economic outcomes	Catastrophic costs, financial outliers	Identifies high-cost patients (>$100k); AUC: 0.845-0.883 for cost outliers; $469k saved from scheduling AI

This table demonstrates how AI shifts spine surgery from subjective assessment to quantitative, data-driven prediction, achieving high accuracy in forecasting both clinical outcomes and economic value. These models enhance surgical precision and advance value-based care through personalized risk stratification. AI: Artificial intelligence, AUC: Area under the curve, QoL: Quality-of-life, PJK: Proximal junctional kyphosis, PJF: Proximal junctional failure, MCID: Minimum clinically important difference, SRS-22: Scoliosis research society-22 questionnaire, QALYs: Quality-adjusted life year, ASD: Adult spinal deformity, PROMs: Patient-reported outcomes measures, UIV: Upper instrumented vertebra accuracies as high as 86%[29]. For instance, research by Lee et al.[30] and Ryu et al.[31] has shown that random forest models deliver notably high accuracy and AUC values in forecasting PJK/PJF occurrence and pinpointing major reoperation risk factors. Nevertheless, Tretiakov et al.[32] note a critical limitation: although powerful, RF models may overestimate target outcomes in binary classification tasks due to elevated out-of-bag error, underscoring the importance of transparency and rigorous methodology in predictive modeling.

Pseudarthrosis: Recent advances in ML demonstrate strong predictive capabilities for postoperative complications in spine surgery. Johnson et al.[33] identified adipose tissue features on MRI as potential biomarkers for pseudarthrosis risk, independent of BMI. Further advancing this domain, Scheer et al.[34] devised ensemble decision tree-based models capable of predicting PJK/PJF with 86% accuracy (AUC: 0.89) and pseudarthrosis with 91% accuracy (AUC: 0.94) in a multicenter ASD patient population. Similarly, a separate model for predicting pseudarthrosis at 2-year follow-up after ASD surgery demonstrated 91% accuracy[35]. Complementary to these approaches, Wang et al.[36] developed a nomogram model showing clinical utility for predicting pseudarthrosis probability, highlighting the growing sophistication of AI-driven prognostic tools in spinal surgery outcomes.

Surgical Site Infection (SSI): AI demonstrates promising capabilities in predicting SSI risk following spinal procedures. While a systematic review by Ndjonko et al.[37] noted that AI models show potential for excellent classification accuracy in predicting spinal SSI, the authors caution that most studies remain in early developmental stages, and reported performance metrics should be interpreted with appropriate scrutiny.

Other Outcomes: Models also predict transfusion requirements, length of hospital stay, and prolonged opioid use[5].

Predicting Patient-reported Outcomes Measures (PROMs): AI is increasingly used to predict PROMs following spine surgery, with common targets including the modified Japanese Orthopaedic Association score for cervical, Oswestry disability index for lumbar, and scoliosis research society-22 questionnaire (SRS-22) for deformity pathologies, alongside pain assessments like visual analog scale and numeric rating scale. Predictive models incorporate diverse features ranging from demographics and surgical characteristics to preoperative PROMs, imaging findings, and psychosocial factors. Research by Ames et al.[38] and Oh et al.[39] demonstrates ML's capability to forecast quality-of-life improvements, such as achieving MCID on SRS-22 or predicting quality-adjusted life years (QALYs). A significant challenge remains the lack of PROM standardization, which complicates comparison across studies and limits consensus on optimal implementation.

Risk Stratification and Surgical Planning: AI significantly enhances risk stratification and surgical planning in spine care. Unsupervised learning models analyze hundreds of variables to create novel ASD classification systems, predicting distinct risk profiles and patient-reported outcomes to improve preoperative counseling and patient selection. For surgical planning, algorithms automate critical decisions, such as selecting the upper instrumented vertebra with 87.5% accuracy or optimizing the proximal junctional angle to prevent mechanical complications[40].

AI-enhanced Surgical Techniques: Navigation, Robotics, and Augmented Reality

AI is the engine behind several advanced intraoperative technologies that are increasing surgical precision and safety.

Augmented Reality Surgical Navigation (ARSN): ARSN systems, use CNN-based segmentation of intraoperative 3D cone-beam CT images. The system then projects the preoperatively planned screw trajectories directly onto the patient's anatomy via a headset or display, creating an "X-ray vision" effect. This approach has been demonstrated to increase the accuracy of percutaneous pedicle screw placement to over 94%, while significantly reducing radiation exposure compared to conventional fluoroscopy[41]. Recent innovations include marker-less registration that uses deep neural networks to autonomously identify spinal structures and determine their positional configuration in real-time, yielding a median angulation error of 1.6° with a translational error of 2.3 mm at the screw entry site, all without the time and radiation exposure of traditional methods[42].

Robotics: Robotic-assisted spine surgery systems rely on AI algorithms for planning and executing screw placement. The robotic arm guides the surgeon to the pre-planned trajectory based on intraoperative imaging. Studies report optimal placement rates exceeding 97-98%, comparable to the best results achieved with navigation. The robot adds a layer of precision and eliminates human tremor, standardizing a key step of the procedure. A significant learning curve exists; success rates improve and conversions to manual placement decrease with increased surgeon experience[43].

The integration of AI into preoperative planning is becoming increasingly seamless and accessible. Emerging platforms now allow surgeons to upload radiographic images via mobile applications, where algorithms automatically perform all necessary measurements and synthesize relevant risk variables to generate a patient-specific surgical plan. The efficacy of such tools is significant; they have been shown to reduce the risk of critical complications like implant failure and rod breakage following osteotomy from historical rates of up to 22% down to 4.7%, representing a monumental improvement in procedural safety and reliability[44].

AI in Health Economics and Value-based Care

AI advances value-based spine surgery through three core mechanisms: enhancing patient agency via improved health literacy and remote monitoring, automating administrative and operational tasks to reduce costs, and augmenting clinical decision-making through precise diagnostics, surgical planning, and outcome prediction. Despite its potential, AI implementation faces significant challenges including professional resistance, data quality and privacy concerns, and substantial financial investment in infrastructure[45].

Predicting Cost and Resource Utilization: ML models demonstrate significant capability in predicting financial outcomes in spine surgery. Karnuta et al.[46] implemented a Naïve Bayes algorithm that accurately predicts perioperative outcomes, including hospitalization costs, duration of admission, and discharge destination for patients undergoing lumbar fusion procedures, demonstrating good-to-excellent predictive reliability.

Cost-effectiveness Analysis: AI enables sophisticated cost-effectiveness analysis for spine surgery by integrating predictions of QALYs gained with cost projections, creating a robust framework for evaluating economic value beyond mere procedural expenses. Robotic spine surgery demonstrates cost-effectiveness through reduced revision rates, lower infections, decreased length of stay, and shorter operative times.

Operational Efficiency: AI extends its economic impact beyond the operating room into hospital administration, where algorithms can automatically extract billing codes from operative notes with approximately 90% accuracy, reducing financial losses from human coding errors and streamlining healthcare economic infrastructure. Clinically, AI enhances surgical precision through personalized interventions, particularly in scoliosis treatment where analysis of preoperative imagery helps determine the optimal level of surgical intervention tailored to individual patient needs.

DISCUSSION

The adoption of AI in spinal surgery signifies a fundamental transformation, providing new tools to improve care across all stages, including diagnosis, preoperative planning, intraoperative guidance, postoperative management, and health economic analysis. The evidence presented demonstrates that AI is moving from a research curiosity to a tangible clinical tool with validated applications in imaging, prediction, execution, and health economics.

The ability of ML models to analyze vast, complex datasets allows a more nuanced understanding of diseases like ASD. Traditional classification systems are being supplemented by data-driven clustering models that can identify patient subtypes with unique outcome profiles, enabling more personalized and effective treatment strategies. Predictive models for complications and PROMs empower surgeons to conduct detailed risk-benefit analyses with patients, setting realistic expectations and potentially avoiding high-risk surgeries in those unlikely to benefit[1,3,5,6].

In the operating room, AI-driven navigation and robotics are mitigating human error and elevating the level of precision to new heights. The high accuracy rates of percutaneous screw placement with ARSN and robotics promise to improve patient safety and reduce revision rates[41,43]. Furthermore, the reduction in fluoroscopy time benefits both the patient and the surgical team. Recent advancements, such as marker-less registration and machine-vision systems, are pushing this further, reducing radiation exposure by up to 90% and significantly cutting down procedural time[42].

Perhaps most critically for the future sustainability of spine care, AI provides tools for navigating the shift to value-based care. By predicting both outcomes and costs, AI enables a more sophisticated approach to resource allocation and reimbursement, ensuring that interventions are not only clinically effective but also economically viable[47].

However, the path to widespread adoption is fraught with challenges that the spine community must address conscientiously, many of which are underscored in the latest literature (Table 3)[1,3]:

The "Black Box" Problem and the Need for XAI: The complexity of some DL models can make it difficult to understand how a specific prediction was made, which can erode clinician trust. Efforts to improve model interpretability through XAI are therefore not just a technical necessity but a cornerstone for building trust and facilitating ethical clinical adoption.

Data Bias and Equity: If training data is not representative of the broader population (e.g., lacking diversity in race, ethnicity, or socioeconomic status), algorithms can perpetuate and even amplify existing healthcare disparities. Vigilant curation of diverse datasets is essential. Chen et al.[48] pointed to the challenge of limited dataset diversity, which adversely affects the external validity and generalizability of AI-based systems.

Data Privacy and Security: The implementation of such systems necessitates access to vast quantities of sensitive patient health information. Ensuring stringent cybersecurity protocols and strict compliance with data governance regulations, such as the general data protection regulation and health insurance portability and accountability act, is essential.

Validation and Generalizability: Most models are developed and validated on retrospective data from single or limited institutions. Broader external validation in diverse, real-world settings is essential before they can be relied upon for routine clinical decision-making. Mandate external validation in independent cohorts before clinical implementation. Emerging techniques, such as federated learning frameworks, enable continuous validation and model refinement across institutions while preserving data privacy and addressing the central challenge of data heterogeneity.

Clinical Integration and Workflow: Integrating these tools seamlessly into clinical workflows, perhaps through electronic health records systems (EHR) using standards like substitutable medical applications, reusable technologies on fast healthcare interoperability resources, is another significant hurdle that must be overcome to avoid adding to clinician burden[49]. This is particularly relevant given the spine surgery community's historical reluctance to adopt new technologies that are perceived to disrupt established workflows or offer unclear cost-benefit advantages.

Table 3. Challenges and proposed mitigations for AI in spine surgery

Challenge	Description	Potential mitigation strategies
"Black box" problem	Lack of transparency in how complex models make decisions.	Develop and use interpretable ML models; invest in XAI research.
Data bias and homogeneity	Models trained on non-representative data perpetuate disparities and lack generalizability.	Curate diverse, multi-institutional datasets; implement algorithmic fairness audits.
Privacy and security	Risk of breaching sensitive patient health information.	Implement robust encryption; adhere strictly to data protection regulations (GDPR, HIPAA).
External validation	Models may not perform well outside their original dataset.	Mandate external validation in independent cohorts before clinical implementation. Emerging techniques, such as federated learning frameworks, enable continuous validation across institutions while preserving data privacy.
Clinical integration and adoption	AI tools may disrupt workflows; spine surgeons are historically late adopters.	Co-design tools with surgeons; integrate with EHRs via standards like SMART on FHIR.
Ethical/legal liability	Unclear who is responsible when an AI system errs.	Establish clear guidelines for human oversight and accountability; update regulatory frameworks.
De-skilling	Over-reliance on AI could erode surgical skills.	Frame AI as a decision-support tool; maintain emphasis on core surgical training.
Emotional bias in humans	Human predictions are influenced by recent experiences and emotions.	Utilize AI as an objective, data-driven second opinion to mitigate cognitive bias.

This table outlines key implementation challenges for AI in spine surgery, such as the "black box" problem and data bias, alongside proposed mitigation strategies like explainable AI. It provides a balanced perspective on translating algorithmic potential into safe and equitable clinical practice. AI: Artificial intelligence, ML: Machine learning, XAI: Explainable artificial intelligence, GDPR: General data protection regulation, HIPAA: Health insurance portability and accountability act, EHRs: Electronic health records, SMART: Substitutable medical applications, reusable technologies, FHIR: Fast healthcare interoperability resources

Ethical and Legal Liability: The issue of liability arising from errors produced by AI systems, such as a diagnostic error by a CNN, remains legally and ethically unresolved. A framework for human oversight and liability must be established.

De-skilling: There is a concern that over-reliance on AI could lead to the erosion of fundamental surgical skills and clinical acumen among surgeons[50]. AI must be viewed as an augmentative tool, not a replacement for expertise.

Human Factors and Emotional Bias: Beyond processing power, AI systems offer a unique advantage: freedom from cognitive and emotional bias. AI algorithms, devoid of emotional feedback loops, provide consistent, objective predictions based solely on the empirical data of thousands of historical cases, plotting a patient's risk on a precise curve rather than a wide, subjective range.

Limitations and Challenges

The adoption of AI technologies in spine surgery continues to encounter substantial implementation barriers, including the "black box" nature of complex algorithms, which may undermine clinical trust; limited generalizability due to data bias and homogeneity; unresolved ethical and legal concerns regarding privacy, security, and liability; and practical barriers to workflow integration and potential de-skilling. The historical reluctance of spine surgeons to adopt disruptive technologies further complicates implementation. As a narrative review, this study offers a valuable qualitative synthesis but is inherently susceptible to selection bias. Greater transparency regarding the literature search strategy and inclusion criteria would enhance reproducibility. While the review is well-structured and supported by effective tables and figures, the technical descriptions of ML architectures (e.g., CNNs, GANs) may challenge clinicians without a data science background. Incorporating a glossary or expanded contextual definitions could improve accessibility without compromising technical depth. The review thoroughly identifies adoption barriers but would benefit from discussing actionable solutions. Concrete strategies, such as interoperability standards for EHR integration, structured AI training programs for surgeons, and guidance on regulatory compliance, would provide a more practical roadmap for translating AI technologies into clinical practice.

Future Directions

Looking ahead, the role of AI in spinal procedures will probably see a more advanced and seamless integration throughout the care pathway. Current investigations are increasingly directed toward refining intraoperative techniques through real-time feedback, forecasting the most effective surgical strategies, and suggesting customized implants tailored to individual anatomical requirements. The development and adoption of XAI will be paramount to building trust and understanding model decisions. Furthermore, the use of generative AI, like

GANs, for creating synthetic data to augment limited datasets is a promising frontier to combat data bias. The creation of large, diverse, multi-institutional datasets and open-access web applications that integrate ML predictions directly into the clinical workflow represent the next critical steps toward the equitable and practical point-of-care use of AI. For this future to be realized, the spine surgery community must actively engage in the development, validation, and ethical governance of these powerful tools. The journey has just begun, but the fusion of human expertise and AI marks the dawn of a new, more precise, and value-driven era in spine care.

CONCLUSION

AI is steadily transforming spine surgery, shifting practice from an experience-driven discipline toward one that is increasingly supported by objective, data-based insights. Applications in imaging, risk prediction, navigation, robotics, and economic modeling already illustrate how AI can refine precision, tailor treatment, and streamline workflows. Rather than replacing the surgeon, these tools should be understood as complementary, providing consistency and augmenting clinical judgment. For this transformation to progress responsibly, several priorities must be addressed. First, prospective multicenter trials are needed to validate algorithms in everyday clinical environments and across heterogeneous patient groups. Second, active involvement of spine surgeons in AI development and governance will ensure clinical relevance, accountability, and ethical oversight. Third, international cooperation to establish large, diverse datasets is essential to reduce bias and guarantee that innovations benefit patients globally rather than selectively. By combining rigorous validation with professional leadership and collaborative data sharing, AI can move beyond experimental promise to become a trusted partner in surgical care. This integration offers a pathway toward more precise, equitable, and value-driven spine surgery in the years ahead.

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Footnotes

Authorship Contributions

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