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Understanding Adult Spinal Deformity: Clinical Perspectives and Therapeutic Approaches

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ABSTRACT

Adult spinal deformity (ASD) stands as a multifaceted and demanding condition, characterized by a wide array of anomalies that result in spinal misalignment and curvature loss. This review article aims to deliver an all-encompassing overview of adult spinal deformity, covering its clinical implications and treatment strategies. The review sheds light on clinical perspectives, discussing the classification systems for various types of adult spinal deformities, their etiology and pathophysiology, diagnostic measures for precise evaluation, and the significance of prompt and accurate diagnosis. The review pivots to therapeutic approaches for ASD management, exploring both non-surgical conservative methods and surgical interventions for treatment. Non-surgical options include physical therapy, bracing, medications, injections, and aquatic therapy; while surgical procedures embrace osteotomies, decompression, and instrumented spinal fusion. Additionally, the article underlines the interdisciplinary nature of ASD management and outlines its impact on the quality of life of those affected, demonstrating how ASD can lead to both physical and psychological impairments. It delves into the multitude of challenges and considerations in ASD treatment to offer deeper insight into treatment planning and patient satisfaction. In summary, this review amalgamates the current knowledge in the field of ASD, providing clinicians with a wide-ranging resource to deepen understanding and enhance the management of this challenging condition.

Keywords: *Adult spinal deformity; Etiology and pathophysiology; Non-surgical treatment; Surgical interventions; Quality of life*

1. INTRODUCTION

Adult spinal deformity (ASD) is defined as an abnormal curvature or malalignment of the spine resulting from three-dimensional changes during adulthood, as identified in studies by Kim et al. [1, 2] and Ames et al. [3]. This condition includes various spinal disorders, notably scoliosis, kyphosis, and lordosis, which are distinguished by the direction and location of the spinal curvature. Scoliosis refers to a sideways curvature of the spine, found in the thoracic, lumbar, or thoracolumbar regions as highlighted by Hawes et al. [4]. Kyphosis is characterized by a forward curvature of the spine, leading to a hunched back or rounded back posture, as noted by Ailon et al. [5] and Yaman et al. [6]. On the other hand, Lordosis is identified by an excessive inward curvature of the lower back, giving a swayback appearance, as explored by Sparrey et al. [7] and Been et al. [8]. ASD often originates from degenerative changes that affect spinal alignment and stability, leading to issues such as disc degeneration, osteoporosis, vertebral fractures, and deformity [3, 5]. This condition significantly impacts patients, causing pain and functional impairment that can affect their overall physical and mental well-being. Managing ASD requires a comprehensive and multidisciplinary approach involving physical therapists, orthopedic surgeons, neurosurgeons, and psychologists [9]. Both non-surgical and surgical interventions are employed to alleviate the symptoms of ASD.

ASD is increasingly recognized as a significant health issue, particularly as the population ages, leading to a greater prevalence of spinal deformities. Global statistics show that the general adult population has a 2-32% prevalence of ASD, while this rate increases to 30-68% in the elderly population (aged 65 years or older) [10, 11]. There are approximately 703 million people aged 65 years or older globally, and it is projected that this number will exceed 1.5 billion by 2050. This will lead to a substantial increase in the number of patients with spinal deformities and place immense pressure on the healthcare system. While ASD affects both males and females, some studies have shown a higher incidence rate of spinal deformities in females [12, 13]. Other factors such as genetic predisposition, lifestyle, and access to healthcare also contribute to varying prevalence rates of ASD in different geographical regions [14, 15].

Given the health risks and progressive nature of the condition, it is crucial to comprehend ASD in clinical practice. Early and precise diagnosis, combined with a comprehensive assessment approach that identifies degenerative changes, the type of deformities, and their impact on spinal misalignment, plays a pivotal role in disease management. Moreover, understanding the clinical aspects of the disease helps in developing personalized treatment plans, including well-planned surgical interventions. This ultimately leads to favorable treatment outcomes and also helps in anticipating and managing future complications. The current review explores clinical perspectives, therapeutic approaches, etiology, pathophysiology, diagnostic methods, and treatment measures for ASD. It also discusses the adverse impact of ASD on quality of life and emphasizes the need for further research in this field.

2. DIFFERENT TYPES OF ASD, ALONG WITH THEIR CAUSES AND THE UNDERLYING PATHOLOGICAL PROCESSES

ASD can be classified into several types, depending on their causes. These types have been discussed in the sections below.

2.1 Degenerative scoliosis:

Degenerative scoliosis, also known as de novo degenerative lumbar scoliosis (DNDLS), commonly affects older individuals, with a prevalence ranging from 6% to 68% in adults over 60 years of age [16]. This condition is characterized by the asymmetric, age-related degeneration of facet joints and intervertebral discs in the lumbar spine, leading to the collapse of the spine's lateral curvature. Symptoms of DNDLS include back pain due to facet and disc degeneration, sagittal deformity, muscle fatigue, neurogenic claudication, leg pain, and radiculopathy. While mild cases may be treated with physical therapy, severe cases may require surgical interventions such as osteotomies, decompression, and spinal fusion [16-18]. A meta-analysis by Ledonio et al.[19] demonstrated the efficacy of surgical treatments in improving degenerative scoliosis, as evidenced by significant improvements in Cobb’s angle, coronal balance, Visual Analog Scale (VAS) scores, and Oswestry Disability Index. Another systematic review by Liang et al [20] combined results from 16 retrospective studies that involved a total of 533 patients and showed that surgical interventions effectively mitigated degenerative scoliosis. In a retrospective case-control study, Li et al [21] compared the outcomes of operative and non-operative treatments for degenerative scoliosis over a two-year period, revealing the higher efficacy of surgical intervention in alleviating the disease, as evidenced by a reduction in pain, improved quality of life, and better mental health.

2.2 Adult idiopathic scoliosis:

Adult idiopathic scoliosis, distinct from degenerative scoliosis which is common in older individuals, typically starts in childhood or early adolescence and continues into adulthood. This condition is exceedingly rare, affecting just 2-3% of the adult population. It can lay dormant for extended periods, with some patients experiencing sudden symptom flare-ups. These symptoms can include back pain, leg pain due to nerve root irritation, and, in severe cases, significant spinal narrowing and neurological deficiencies. Initially, non-surgical options are pursued for adult idiopathic scoliosis; however, in more severe instances, surgical intervention may be necessary. Surgery carries its own set of risks, and therefore, it requires thorough preoperative evaluation and a multidisciplinary approach to mitigate potential negative outcomes [22, 23]. Research by Negrini et al. [24] has proven the effectiveness of specific SEAS exercises for scoliosis in controlling the progression of this condition in adults. Moreover, a study by Shapiro et al.[25] highlighted the benefits of elective anterior and posterior surgical reconstruction in treating adult idiopathic thoracolumbar and/or lumbar scoliosis, showcasing improvements in structural balance, pain relief, and functional recovery. Similarly, a study by Takahashi et al. [26] reported enhanced outcomes following surgical correction, including pain reduction, decreased Cobb’s angle, and adjustments to the sagittal alignment.

2.3 Post-traumatic adult spinal deformity:

The term "post-traumatic adult spinal deformity" refers to a type of deformity that typically occurs following a traumatic injury, such as spinal fractures, spine dislocations, or ligamentous injuries in adulthood. The symptoms of this condition include radicular pain, back pain, and neurologic defects that can progress to neural compression, instability, and deformities such as kyphosis and scoliosis. Addressing post-traumatic adult spinal deformity requires an integrated approach involving both traditional non-surgical and surgical interventions. A recent study by Borzykh et al. [27] evaluated the effectiveness of surgical treatments for correcting post-traumatic adult spinal deformities. The study noted several intraoperative and postoperative complications associated with surgical correction, including site-specific infections and intraoperative blood loss. Minimally invasive transpedicular fixation during surgical intervention was found to result in the lowest amount of blood loss and the lowest infection rate. Another study by Rerikh et al. [28] demonstrated the beneficial effects of staged combined surgical treatment in correcting posttraumatic deformities in the thoracic and lumbar spine. This study showed postoperative correction of segmental kyphotic deformity, improvements in the Oswestry Disability Index and Visual Analog Scale, and lower preoperative blood loss in patients undergoing staged surgical treatment for the alleviation of post-traumatic deformities.

2.4 Post-surgical adult spinal deformity:

ASD can be linked to various factors, such as surgical complications, improper healing after surgical procedures, and implant-related issues. Martini et al. [29] identified that ASD may result from improperly executed surgeries or failure to heal properly after surgical procedures. Lee et al. [30] associated the development of proximal junctional kyphosis with post-surgical ASD, where kyphotic deformity occurs at the junction of fused and unfused spinal segments above the instrumented fusion. Barone et al. [31] demonstrated that implant-related complications, such as screw breakage, loosening, and proximal/distal junctional failure, can lead to post-surgical ASD. Lindsay et al. [32] linked post-surgical ASD to pseudoarthrosis, where inadequate fixation and poor bone quality result from improper healing of the spinal fusion. Iorio et al. [33] and Kim et al. [34] found that neurological complications such as spinal cord compression and nerve root injuries contribute to the progression of post-surgical ASD. Bioshardy et al. [35] associated post-surgical ASD with improper execution of surgical interventions designed to address ASD, which can lead to surgical site infections in 3-5% of cases. Factors like obesity, age, diabetes, and surgical complexity can exacerbate these infections.

2.5 Congenital adult spinal deformity:

Congenital adult spinal deformity is a condition present from birth, characterized by improperly formed vertebrae during early fetal development. This leads to structural malformations in the spine and spinal cord. Congenital ASD can result from missing, fused, or partially formed vertebrae, and may be caused by genetic factors like defects in the Notch signaling pathway and chromosomal translocations in chromosomes 13 and 17. Additionally, environmental factors such as exposure to carbon monoxide, maternal diabetes, and the use of antiepileptic medications can contribute to congenital ASD. Clinical manifestations of congenital ASD typically include sagittal plane abnormalities like lordosis or kyphosis, and sometimes affect the coronal plane, leading to scoliosis. Physical symptoms may include a tilted pelvis, difficulty walking, strained breathing, abnormal curvature, and uneven torso, hips, and waist [36, 37]. According to a study by Pizones et al. [36], back pain, impairment of function, and self-image are the primary drivers for surgery, as opposed to the radiographic deformity itself. A retrospective study by Rajavelu et al. [38] on the long-term outcome of patients diagnosed with congenital adult spinal deformity reported neurological deficits as a rare major complication. The study identified surgical intervention as the optimal treatment for congenital adult spinal deformity, as it helps prevent further neurodegeneration and stabilize the deformity.

2.6 Neuromuscular (NMS) adult spinal deformity:

Neuromuscular ASD prominently involves both the nervous and muscular systems and frequently occurs in children who no longer have control over the muscles supporting the spine. Neuromuscular Spinal Deformities (NMS) appear early in life, in stark contrast to idiopathic ASD, and they advance rapidly, leading to worsened conditions by adulthood. These deformities are linked with medical issues that influence either the body’s musculature, neurological system, or both. The prevalence of NMS spinal deformity significantly escalates in conditions such as cerebral palsy, spinal muscle atrophy, Friedreich's ataxia, Duchenne muscular dystrophy, and myelodysplasia [39]. The disease manifests through symptoms like asymmetrical shoulders, uneven waistline, rib prominence on one side, and one hip higher than the other [40, 41]. Research led by Lin et al. [42] evaluated the benefits of nonoperative versus surgical interventions, specifically posterior spinal fusion (PSF), in addressing Neuromuscular Scoliosis (NMS). The study's outcomes revealed a decrease in discounted life expectancy but an improvement in quality-adjusted life years (10.8 years and 4.8 years) compared to nonoperative care (11.2 years and 3.21 years). Moreover, findings by Rumalla et al. [43] indicate that leveraging Intraoperative neurophysiological monitoring alongside posterior-only surgical approaches can potentially mitigate complications linked with neuromuscular scoliosis. These complications entail escalating healthcare costs, numerous comorbidities, and the necessity for blood transfusions.

3. DIAGNOSIS OF ASD

The diagnosis of ASD is a multifaceted approach and requires the skillful execution of multiple steps for an accurate evaluation of the underlying deformity.

3.1 Physical examination:

In order to conduct a comprehensive assessment of ASD, it is essential to begin with a thorough physical examination of the patient to check for any visible deformities or asymmetries, such as kyphosis or scoliosis. Additionally, the spine should be palpated to detect any tenderness or abnormal prominence, followed by an evaluation of spine flexibility using a range of motion testing [3, 11, 44].

3.2 Radiographic imaging:

A comprehensive assessment of the spine for Ankylosing Spondylitis (AS) involves using X-rays to evaluate the spine in both the sagittal and coronal planes, as well as CT scans and MRI scans to assess for neural compression or spinal anatomical changes. Bess et al. [45] emphasized the importance of radiographic evaluation of the entire spine (cervical, thoracic, and lumbar) and the pelvis for an accurate diagnosis of AS. Similarly, Smith et al. [46] highlighted the significance of assessing regional alignment parameters (lumbar lordosis, thoracic kyphosis, C2–C7 lordosis), global alignment (C7 SVA, C2–C7

SVA, and T1 pelvic angle), pelvic compensation, and morphology (pelvic tilt, pelvic incidence, C2-pelvic tilt, and T1 slope) for an accurate diagnosis of AS. Other studies by researchers also recommended evaluating spinal abnormalities by assessing Cobb's angle to quantify sagittal and coronal plane deformities, pelvic tilt, pelvic incidence, and sacral slope to assess global spinal alignment, and sagittal vertical axis to evaluate the forward translation of the spine [47, 48].

3.3 Neurological evaluation:

The neurological assessment involves evaluating neural motor functions such as muscle strength, coordination, and muscle tone, followed by assessment of touch sensation, vibration, temperature, gait, and balance, and then evaluation of deep tendon reflexes. In a study conducted by Frost et al. [49], researchers explored the connection between standing balance control and foot skin sensitivity in patients with chronic back pain and radiculopathy. The study revealed reduced sensitivity to 250 Hz frequency vibration in the affected feet of the patients, indicating a direct link between foot sensitivity deficits and changes in balance control. In addition to the fundamental neurological assessment, advanced neurophysiological testing includes electromyography (EMG) and nerve conduction studies to rule out potential neurological issues. EMG and nerve conduction studies are helpful in distinguishing between radiculopathy caused by nerve root compression and myelopathy caused by spinal cord dysfunction. A study by Drake et al. [50] showcased the usefulness of Intraoperative neurophysiological monitoring (IONM) in resolving complex pediatric spinal deformities, where the loss of transcranial electrical motor evoked potentials (MEPs) was identified as a significant prognostic indicator for diagnosing spinal deformities. Another study by Chen et al. [51] highlighted the importance of multimodality monitoring, combining EMG with somatosensory evoked potential (SSEP) and MEP for detecting lumbar nerve root injuries. Additionally, the results of a neurological assessment lead to better outcomes when correlated with radiographic analysis, enabling clinicians to determine if the observed neurological findings are associated with spinal deformities or other pathological conditions [5]. The process begins with a comprehensive evaluation of the patient's physical, radiographic, and neurological status, followed by assessing their disability level and functionality. Clinicians take a multidimensional approach, comparing observations at each level and conducting a comprehensive analysis to reach an accurate diagnosis. This assessment provides a baseline for determining the treatment approach.

4. TREATMENT FOR ASD

Several strategies have been proposed for the clinical treatment of ASD, which include both non-surgical as well as surgical procedures for amelioration of the condition. However, a number of factors are considered when deciding between surgical and non-surgical interventions to alleviate the existing condition [1, 52]. Predominantly, the deformity's severity emerges as a critical determinant in shaping the management trajectory. Mild instances of ASD may be efficaciously managed through non-invasive strategies, including bracing and analgesic injections, which proactively thwart the progression thereof, thereby obviating the immediate recourse to surgical interventions [53]. Conversely, moderate deformities often necessitate an integrative approach that marries physical therapy with surgical interventions [54]. In these scenarios, strategies such as compression techniques coupled with selective instrumented fusion might serve to not only rectify the deformity but also ameliorate concomitant symptomatic radiculopathy. The advent of severe deformities, however, unequivocally mandates the deployment of surgical interventions, including but not limited to anterior or posterior instrumented fusion accompanied by decompressive techniques, to reinstate spinal alignment and rectify curvature malalignments [55].

Moreover, the manifestation of neurological sequelae within the patient, such as radiculopathy or myelopathy, undeniably necessitates surgical recourse. The degree of disability represents another pivotal criterion, with patients enduring severe pain, disability, or functional impairment potentially benefiting more significantly from surgical modalities. In addition, certain clinical manifestations of ASD may exhibit refractoriness towards non-invasive treatments like bracing and pharmacological pain management, thus predicating the need for surgical intervention [56, 57]. In addition to these determinants, the patient's consent to surgery, premised upon a well-informed risk assessment, alongside the surgeon's acumen, profoundly influences the choice between surgical and non-surgical remedies for ASD amelioration. Lastly, the patient's comorbidities and the heightened risk entailed by surgical interventions may precipitate a predilection for non-surgical measures to palliate ASD symptoms.

4.1 Non-surgical methods

ASD can be treated using both surgical and non-surgical means, depending on the severity of the deformity, the patient's age, symptoms of the disease, and several other factors.

4.1.1. Physical therapy program:

It is crucial to prioritize core strengthening, modify activities, and adhere to an exercise regimen to reduce pain, enhance muscle tone and function, and maintain proper surgical alignment without resorting to surgery. Successful implementation of physical therapy and exercise routines can help fortify abdominal and back muscles, leading to improved core strength, enhanced spinal stability, and reduced pain resulting from progressive degenerative changes associated with ASD. Furthermore, the physical therapy program offers neuromuscular re-education to support rehabilitation, improved postural control, and spinal stability [58, 59]. Physiotherapeutic scoliosis-specific exercises (PSSE) have been shown to be more effective in addressing ASD, except when Cobb's angle exceeds specific parameters, in which case bracing is recommended [24].

4.1.2. Bracing:

There is some evidence suggesting that the use of bracing techniques can help minimize pain, improve comfort, and slow down the progression of Adolescent Idiopathic Scoliosis (AIS) in patients with a mild degree of scoliosis [22, 60-62]. However, a questionnaire-based study by Kotwicki et al. [63] suggested that bracing at the onset of scoliosis in adolescent girls reduced stress arising due to deformity. Similar findings were reported in another study by Schreiber et al.[64], which also associated bracing with the prevalence of adverse events, including discomfort, pain, fear of injury, and stress, contributing to an overall reduction in physical activity in affected patients.

4.1.3. Medications and injections:

A variety of medications and injections can be used to manage the discomfort associated with painful ASD. These include non-steroidal anti-inflammatory drugs such as naproxen, aspirin, and ibuprofen, as well as analgesics like acetaminophen, which can relieve pain but do not have an anti-inflammatory effect. The use of steroids may also help reduce inflammation and swelling of the affected nerves. In addition to medications, epidural steroid injections (ESIs), consisting of a combination of corticosteroids and analgesics, can be directly injected into the space surrounding the spinal nerves to reduce swelling and alleviate pain in the affected area [65].

4.1.4. Aquatic therapy:

For individuals who are unable to participate in traditional physical training programs, the buoyancy of water helps alleviate pressure on the spine, leading to improved muscle tone and enabling more comfortable exercise. This, in turn, may reduce significant back pain and alleviate weight-bearing nerve symptoms [66].

Unfortunately, there is not enough evidence to support the use of non-operative strategies in managing ASD. In a systematic review of non-surgical treatments for ASD, Everett et al. [67] found level III/IV evidence for steroid injection (level IV) and level III evidence for physical therapy and bracing. Another study by Glassman et al. [68] reported that non-operative treatment did not lead to a significant improvement in the quality of life for ASD patients despite the high cost of $10,815 per patient. However, despite the lack of evidence, conventional treatments have benefited some ASD cases by improving the quality of life, slowing disease progression, and avoiding the need for surgical treatments.

4.2 Surgical Methods

ASD often necessitates surgical intervention due to the challenges associated with non-surgical management. Before proceeding with surgical management, it is crucial to consider several important criteria. Moal et al. [48] and Lafage et al. [69] recommend evaluating the patient's specific radiological alignment using the SRS–Schwab classification. Additionally, factors such as identifying the drivers of deformity, setting clear alignment goals, and assessing flexibility should be taken into account [70, 71]. Over the past two decades, advancements in surgical techniques have led to the development of various methods for managing ASD. These methods typically involve decompression, osteotomy, and fusion. While there are no strict guidelines specifying which method is best suited for a particular condition, Silva et al.[72] have outlined a general guideline involving six different surgical techniques for managing ASD. These techniques include decompression alone, instrumental posterior spinal fusion coupled with decompression, instrumental lumbar curve fusion coupled with decompression, anterior and posterior instrumented fusion coupled with decompression, extended fusion, and thoracic instrumentation, and osteotomies for specific deformities.

4.2.1. Osteotomies:

The primary purpose of osteotomies is to surgically cut, realign, and reconstruct bones to improve spinal alignment and correct sagittal imbalance in cases of ASD [73]. Surgeons must consider several factors before performing osteotomies, including curve type, muscle and bone quality, patient symptoms, etiology, pathophysiology, and long-term operative goals [74]. Schwab et al. [75] proposed different types of osteotomies based on the anatomical classification of the spine and the severity of spinal injury. These types include Grades I to VI, each involving various degrees of resection of spinal structures, such as facets, pedicles, and vertebral bodies. Three main osteotomy techniques have been proposed:

Smith-Peterson osteotomy (SPO):

The pedicle subtraction osteotomy (PSO) is utilized to correct mild to moderate sagittal imbalances, requiring a correction of no more than 10 degrees. PSO typically involves an opening wedge osteotomy, which includes the removal of the posterior elements such as the lamina, bilateral facet joints, spinous processes, and ligamentum flavum. A recent study by Luo et al. [76] compared three different approaches to periacetabular osteotomy: the improved ilioinguinal (I-I) approach, the two-incision Smith-Peterson (TSP) approach, and the modified Smith-Peterson (MSP) approach, in terms of their operation time, blood loss, intraoperative and postoperative blood transfusion, and postoperative complications. The MSP approach was found to be superior in performing periacetabular osteotomy due to lower blood loss and a reduced number of post-operative complications. Nevertheless, during PSO, it's crucial to safeguard the compression of neural elements at all costs, which can be achieved through meticulous foraminal and central decompression [77, 78].

Pedicle subtraction osteotomy (PSO):

PSO is a surgical procedure that involves removing a portion of the vertebral body as well as the posterior elements. It is used to correct cases of ASD requiring significant sagittal plane correction, typically around 20-25 degrees in the thoracic area and 30-35 degrees in the lumbar area [79-81]. A study conducted by Alzakri et al. [82] evaluated the radiographic and functional outcomes, complications, and surgical specificities of L5 pedicle subtraction osteotomy in patients undergoing surgeries to correct fixed sagittal and coronal malalignments. The study reported the safety and clinical efficacy of PSO in treating and correcting the fixed sagittal imbalance, as evidenced by improvements in mean lumbar lordosis and the alignment of the sagittal vertical alignment axis post-operatively. Similarly, a retrospective study by Eskilsson et al. [83] also demonstrated the safety and efficacy of PSO in correcting sagittal plane imbalance in a study involving 104 patients. Another retrospective study by Bekmez et al. [84] identified PSO as a better technique for correcting severe and rigid neuromuscular scoliosis due to its ability to correct pelvic obliquity without increasing operative time, transfusion needs or hospitalization stay duration when compared to other posterior column osteotomy (PCO) techniques.

Vertebral column resection (VCR):

Vertebral column resection (VCR) is utilized to correct severe sagittal imbalance, often requiring up to a 45-degree correction angle. This procedure is used to address spine kyphosis associated with conditions such as tumors, infections, fractures, congenital kyphosis, and severe rigid scoliosis. VCR entails the complete removal of more than one vertebral body, including pedicles, adjacent disks, and posterior segments. It is suitable for Grade V and Grade VI osteotomies according to Schwab's anatomical classification [85-87]. A retrospective study by Hamzaoglu et al.[85] analyzed the safety and efficacy of VCR in managing severe spinal deformities in 102 patients. The results of the study demonstrated VCR to be an effective technique in ameliorating severe spinal deformities. Lee et al. [30] investigated the clinical and radiological outcomes of patients undergoing posterior VCR (PVCR) and found significant improvement in VCR angle, lumbar lordosis, sagittal vertical axis (SVA), and thoracic kyphosis in patients undergoing this technique for alleviating ASD. Furthermore, Wang et al. [88] performed a retrospective study evaluating the efficacy and safety of VCR for correcting angular and isolated congenital kyphosis. The study identified PVCR as the preferred technique for managing congenital kyphosis due to its shorter operative time, reduced blood loss, and significant post-surgical improvement of segmental kyphosis and sagittal vertical axis.

Despite the technological advancements, osteotomies are associated with extremely high risk and complications involving prolonged surgical time, profuse blood loss, as well as the possibility of neurological deficits, pseudarthrosis, dural tears, and proximal junctional kyphosis.

4.2.2. Decompression:

Decompression surgery is utilized in managing cases of ASD accompanied by neurological manifestations and involves the strategic removal of disc or bone material. This procedure aims to alleviate pressure on the spinal nerves, thereby reducing symptoms associated with neurogenic claudication or radiculopathy [89]. The presence of clinical signs such as numbness, radiating pain, and weakness in the extremities necessitates the application of decompression techniques. Among the variety of decompression methodologies, laminectomy is noteworthy; this procedure entails the extirpation of the lamina or vertebral roof, thereby engendering space for the adjacent nerves [90]. Discectomy, on the other hand, focuses on the removal of the herniated segment of the bulging disk, facilitating nerve decompression [91]. Furthermore, foraminectomy constitutes an enlargement of the foramina, which assists in the unimpeded exit of nerves from the spinal column [92]. Notably, decompression can be synergistically combined with spinal deformity correction through osteotomy. This integrative approach has been documented to provide a significant reduction in neurogenic pain. A comparative study conducted by Nerland et al. [93] evaluated the clinical efficacy of microdecompression versus laminectomy in patients presenting with central lumbar spinal stenosis. The findings revealed equivalently favorable outcomes for both interventions after a follow-up period of one year, demonstrating their comparative efficacy. Further investigation by Dietz et al. [94] has illustrated enhanced outcomes when decompression is concomitantly performed with fusion, as evidenced by lower rates of infection, reoperation, and complications. Conversely, a study by Yang et al. [95] indicated that decompression coupled with lumbar interbody fusion resulted in prolonged hospital stays and increased blood loss. Moreover, a comparative analysis of microscopic decompression versus endoscopic decompression highlighted a significant increase in the hospitalization duration and operative time for the former.

In contrast, research conducted by Chang et al. [96] evaluated the effectiveness of decompression with and without fusion for lumbar spinal stenosis (LSS). The findings evidenced no clinical improvements in patients who underwent the combined procedure over a period of two years when compared to decompression alone. This study underscored the drawbacks of spinal fusion- extended hospitalization and augmented blood loss, thereby challenging the perceived benefits of combining decompression with spinal fusion.

Despite the innumerable benefits of the procedure, decompression needs to be performed with utmost care. It is often associated with a risk of infection, bleeding, spinal instability, as well as exacerbation of ASD if the deformity is improperly corrected [97].

4.2.3 Instrumented spinal fusion:

The methodology under examination employs mechanical adjuncts, including rods, screws, and plates, to facilitate the fusion of bones, thereby reinstating the structural integrity of the spine weakened due to tumorigenesis, trauma, or surgical interventions. Traditional spinal fusion methodologies pivot around the construction of a "bone bridge", utilizing either autografts—grafts procured from the patient's own body—or allografts sourced from a bone repository, across the targeted site for bone fusion. In addition, bone morphogenetic proteins may be deployed to augment bone growth during the fusion process [98]. Instrumented spinal fusion, diverging from the conventional pathway, enlists mechanical instruments to maintain bone alignment, thereby facilitating the fusion process. Herein, screws and hooks serve as anchoring points to the vertebral column, linking it to a metallic scaffold constituted by rods transcending the compromised segments. This metallic framework bestows immediate stability to the spinal structure; however, its therapeutic efficacy is transient, subsisting solely until the completion of the bone fusion process, post which, the instruments tender into a state of fragility [99, 100]. In an empirical analysis conducted by Hesih et al. [101], the efficacy of an amalgamated approach involving anterior lumbar interbody fusion and instrumented posterolateral fusion was juxtaposed with a solely posterior approach, revealing a significant enhancement in both sagittal and coronal plane alignment in the former methodology. Concomitantly, a study by Zhu et al. [102] examined the effectiveness of selective segmental transforaminal interbody fusion (SSTIF) in conjunction with a posterior-instrumented spinal fusion technique in mitigating degenerative scoliosis, deducing a reduction in long-term sequelae and thus, proclaiming a superior efficacy in the amelioration of degenerative scoliosis. A parallel inquiry by Castro et al. [103] elucidated the ameliorative impact on mild scoliotic deformations, evidenced by enhancements in both coronal and sagittal plane alignments coupled with a reduction in pain, through the application of a minimally disruptive lateral transpsoas retroperitoneal technique aimed at achieving interbody fusion in patients with degenerative scoliosis. Moreover, Ha et al. [104] delineated a higher recuperation rate via a long fusion approach as opposed to a short fusion approach in the treatment of adult scoliosis. In a prospective purview, Philips et al. [105] documented improvements in clinical and radiological indices among patients with adult degenerative scoliosis undergoing extreme lateral interbody fusion (XLIF).

In summation, spinal fusion presents itself as a favorable therapeutic intervention by virtue of its capacity to confer immediate spinal stability, elevate rates of bone fusion success, and avert further spinal deformity. Nonetheless, it is not devoid of potential detriments, encompassing an elevated risk of infection, mechanical complications stemming from rigidity, and an increased propensity for tissue disruption followed by post-operative pain [106, 107].

4.3 Emerging treatments and technologies:

The integration of minimally invasive techniques, which necessitate smaller incisions, thereby minimizing muscle damage and expediting recovery, is being effectively utilized alongside traditional surgical methods, including compression and fusion. The employment of robotics and navigational tools during Minimally Invasive Surgeries (MIS) is enhancing the efficiency of spinal reconstructions, leading to improved outcomes [108]. The use of biologics, such as stem cells and growth factors, is augmenting the recovery process while mitigating the potential complications associated with traditional surgeries. Furthermore, the adoption of bone substitutes, autografts, and allografts plays a pivotal role in providing structural support, addressing the limitations related to donor site morbidity, and preventing site-specific infections [109, 110]. Innovations such as custom-made, 3-D printed implants fashioned from patient-specific anatomical data, and motion-preserving devices, have proven beneficial in enhancing bone fusion rates and reducing the incidence of adjacent segment degeneration typically observed in conventional surgical procedures [111, 112]. Additionally, robot-assisted surgeries present an advantage by eliminating radiation exposure to both staff and surgeons, and by reducing the dependence on intraoperative fluoroscopy. However, it is important to note that these surgeries carry a higher cost and may increase patient radiation exposure, presenting some disadvantages.

Table 1. A comprehensive list of studies regarding ASD

Author	Type of Study	Sample size	Study Aim/Treatment	Conclusion
Scheer et al, 2015	Retrospective study	421 samples	Comparison of open surgery versus non-operative cases	1. Significant improvement in back and leg pain in patients who were surgically treated for ASD in comparison to non-surgical cases. 2. A higher degree of pain improvement was observed in patients subjected to compression treatment in comparison to

				osteotomies.
Hesih et al, (2015)	Retrospective study	110 samples	Comparison of combined anterior lumbar interbody fusion and instrumented posterolateral fusion with posterior alone approach	1. A higher rate of sagittal and coronal plane alignment was achieved in case of combined anterior lumbar interbody fusion and instrumented posterolateral fusion in comparison to the posterior alone approach.
Zhu et al, (2014)	Retrospective study	95 patients	Investigation of long-term clinical outcomes of selective segmental transforaminal interbody fusion combined with posterior-instrumented spinal fusion technique for degenerative scoliosis	Selective segmental transforaminal interbody fusion combined with posterior-instrumented spinal fusion appears to have reasonable long-term clinical and radiographic outcomes for the treatment of DS
Anand et al, (2014)	Retrospective study	50 patients	circumferential minimally invasive surgery (cMIS) for moderate to severe scoliosis	cMIS provides good clinical and radiographic outcomes for moderate cases of adult idiopathic scoliosis
Castro et al, (2014)	Retrospective study	35 patients	Usage of minimally disruptive lateral transpsoas retroperitoneal technique to accomplish interbody fusion in adult degenerative scoliosis.	Mild scoliotic deformities showed reasonable coronal and sagittal correction, as well as improvements in pain and function using a lateral approach
Ha et al, (2014)	Retrospective study	59 patients	Comparison between short-fusion (n = 29) and long-fusion (n = 30) to treat adult scoliosis	A higher rate of recovery was achieved using long fusion including the proximal neutral vertebrae.
Kim et al, (2014)	Retrospective study	198 patients	Comparison between upper thoracic versus lower fusion for adult scoliosis treatment	Both upper thoracic as well as lower thoracic fusion have similar outcomes for adult scoliosis treatment
Philips et al, (2014)	Prospective study	67 patients	Treatment of adult degenerative scoliosis by extreme lateral interbody fusion (XLIF)	Treatment of adult degenerative scoliosis by XLIF showed good clinical and radiographical outcomes, with a substantially lower complication rate
Daubs et al, (2013)	Retrospective study	85 patients	Open surgery, mix procedures	Improvement in coronal and sagittal imbalance of patients operated for adult spinal deformity
Hassanzadeh et al, (2013)	Retrospective study	59 patients	Comparison of clinical and functional outcomes of primary and revision spinal deformity surgery	Almost similar rate of clinical and functional outcomes of primary as well as revision spinal deformity surgery
Smith et al, (2011)	Retrospective study	206 patients	Comparison of the clinical and functional outcome of scoliosis surgery in young and elderly patients	Higher rate of improvement in disability and pain with surgery in elderly patients
Tsai et al,	Retrospective	58 patients	Evaluation of clinical and	Higher rate of patient satisfaction as

(2011)	study		radiographic outcomes in patients with degenerative lumbar scoliosis after instrumented posterior lumbar interbody fusion (PLIF)	well as improvement in radiographic and clinical outcomes in patients even after 2 yrs follow-up of undergoing PLIF surgery
Zimmerman et al, (2010)	Prospective study	35 patients	Evaluation of the clinical and functional outcome of scoliosis surgery in elderly patients	Adults ≥ 40 years with symptomatic scoliosis benefit from surgical treatment, despite the high complication rate.
Transfeldt et al, (2010)	Retrospective study	85 patients	Evaluation of functional outcomes of decompression only, limited fusion, and long fusion	Improvement in Cobb scoliosis angle in long fusion group with presence of highest risk of complications
De Silvestre et al, (2010)	Retrospective study	29 patients	Evaluation of functional outcomes of Decompression and dynamic stabilization series	A significant rate of improvement in degenerative lumbar scoliosis in elderly patients undergoing Dynamic stabilization with pedicle screws in addition to decompressive laminectomy
Buell et al, (2018)	Retrospective study	71 patients	To analyze radiographic outcome and complications after single-level lumbar extended pedicle subtraction osteotomy for fixed sagittal malalignment	Extended PSO is an effective technique to correct fixed sagittal malalignment for ASD

5. IMPACT OF ASD ON QUALITY OF LIFE

ASD has been linked to a significant decline in quality of life, impacting both physical and psychological well-being. This condition is accompanied by chronic pain that particularly affects the back, neck, and legs, leading to limitations in mobility and daily activities, and increased reliance on others [113]. Individuals with ASD often experience reduced physical activity, hindering their participation in social and leisure activities. Severe cases of ASD can also lead to restricted lung capacity, breathing difficulties, and impaired cardiovascular health, further restricting physical activity [114, 115]. In addition to physical challenges, individuals with ASD may experience significant psychological stress and dissatisfaction with their self-image, leading to social withdrawal, depression, and feelings of isolation and loneliness [3]. The high cost of treatment exacerbates this already difficult situation, adding to the physical, mental, and financial burden experienced by those affected.

6. CHALLENGES AND CONSIDERATIONS FOR ASD

Dealing with ASD presents numerous challenges and potential complications that significantly impact the physical and mental well-being of affected individuals [116]. One of the initial hurdles is accurately diagnosing the disease, which is complex due to various types of common spinal disorders such as lordosis, kyphosis, scoliosis, and spinal stenosis [117]. Diagnosis requires the involvement of multiple specialists and the use of advanced techniques such as MRI and CT scans. Additionally, the progressive nature of the disease leads to rapidly worsening symptoms, including spinal misalignment and loss of curvature [97]. Chronic pain and physical disability further limit social interaction, often leading to feelings of depression, loneliness, and despair, significantly impacting quality of life. In addition to challenges in diagnosis and treatment, ASD is accompanied by a range of complications during both pre-operative and post-operative periods [118]. Neurological deficits, including spinal cord compression resulting in weakness, numbness, and, in severe cases, paralysis, are common. Thoracic spinal deformities can also cause cardiopulmonary issues, compromising breathing and increasing the risk of respiratory infections. Surgical treatment utilizing spinal fusion may lead to post-surgical complications, such as accelerated degeneration of adjacent spinal segments, necessitating further revision surgery. Moreover, revision surgery might be required to address irritation caused by surgical implants like rods, screws, and hooks used to stabilize the spine during spinal fusion [117].

7. CONCLUSION

Early detection is crucial for controlling ASD progression, enabling timely intervention and disease management to prevent exacerbation. It also alleviates neurological symptoms, chronic pain, and stiffness. Understanding genetic and biochemical factors is key to effective management. Advanced imaging and biomarker identification aid in predictive modeling. A multidisciplinary approach involving neurosurgeons, orthopedic surgeons, physical therapists, psychologists, and physiotherapists is essential for pain management and rehabilitation. Personalized treatment, including medication and physical therapy, is necessary. For severe cases requiring surgery, comprehensive pre-operative evaluation, counseling, surgical planning, and postoperative care enhance outcomes and minimize complications. Integrating research into clinical practice is essential for mitigating the burden of ASD on healthcare systems and individuals.

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