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Neuromuscular scoliosis: A narrative review on pathophysiologic mechanisms and precision-based management.

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Abstract

Scoliosis is a complex, three-dimensional spinal deformity, with Neuromuscular Scoliosis (NMS) representing its second most common and arguably most intricate subtype. Arising from diverse neuropathic and myopathic disorders such as cerebral palsy, Duchenne muscular dystrophy, and spinal muscular atrophy, NMS is characterized by aggressive, multiplanar progression that often results in significant functional decline, pelvic obliquity, and compromised cardiopulmonary reserve. The pathophysiology of NMS is rooted in the failure of dynamic spinal stabilization due to muscular imbalance or denervation. Diagnosis has evolved through advanced imaging, including ultra-low-dose CT and AI-assisted analysis, within a Multidisciplinary Team (MDT) framework. Management strategies are shifting from traditional definitive spinal fusion toward growth-preserving techniques such as magnetically controlled growing rods (MCGR) and minimally invasive bipolar fixation (MIBF) to minimize surgical morbidity and accommodate skeletal growth. Early recognition and individualized, multidisciplinary management are essential, and integration of molecular therapies with precision surgical approaches represents a paradigm shift toward preventive and personalized care in neuromuscular scoliosis. This narrative review aims to synthesize current evidence on neuromuscular scoliosis to enhance understanding of its mechanisms, clinical evaluation, and evolving management strategies. It covers etiology, pathophysiology, diagnosis, multidisciplinary management, surgical and non-surgical treatments, and emerging advances, including minimally invasive techniques and gene-based therapies.

Keywords: *Neuromuscular scoliosis; Spinal deformity; Muscle imbalance; Pelvic obliquity; Multidisciplinary management; Growth-preserving surgery; Minimally invasive spine surgery; Genetic therapy; Pediatric spinal disorders, Precision medicine*
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Introduction

Scoliosis, defined as a curvature of the spine, has been recognized as a medical condition since ancient times (1). The word "scoliosis" originates from the Greek term 'scolios', meaning "curved" or "crooked" (2). It is considered a multifactorial, three-dimensional deformity of the spinal column, typically identified by a lateral deviation of at least 10 degrees accompanied by vertebral rotation. In most cases, it is further associated with a reduction in normal thoracic kyphosis, hypolordosis of the lumbar spine, and compensatory hyperlordosis in the lumbosacral region (2).

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Scoliosis can present in several forms, including idiopathic, congenital, secondary, neuromuscular, degenerative, and functional types (1, 2). Among these, idiopathic scoliosis is the most common, accounting for approximately 80% of all cases. It includes infantile, juvenile, and adolescent subtypes, though its precise etiology remains uncertain and is thought to be multifactorial (2, 3).

Neuromuscular scoliosis (NMS) is a unique and intricate subtype. It is a noncongenital spinal deformity that occurs in the context of underlying neuromuscular disorders and is defined by lateral spinal curvature with vertebral rotation directly resulting from muscular or neurological pathology (2-5). According to the Scoliosis Research Society, it is characterized as an abnormal spinal curvature caused by disorders of the brain, spinal cord, or muscular system (3). NMS is regarded as the second most common subtype after adolescent idiopathic scoliosis (6).
Typically, NMS manifests as a long, collapsing C-shaped curve (5, 7). The predominant deformity involves the coronal plane, often extending into the pelvis and creating pelvic obliquity, with the concave side elevated (5, 8). The root cause of NMS lies in myopathic diseases or neuropathic abnormalities, often involving the central nervous system, peripheral nervous system, or both (7). Accordingly, the Scoliosis Research Society classifies NMS into two primary pathomechanisms: neuropathic and myopathic, based on the underlying etiology (2,5). The frequency of NMS fluctuates according to the specific neuromuscular disorder, contingent upon the degree of muscle and nerve involvement (5, 7). Cerebral palsy is the most frequent cause (4, 7), followed by Duchenne muscular dystrophy, spinal muscular atrophy, spina bifida, and multiple leukodystrophies (3).

The incidence can be extremely high, with scoliosis affecting up to 90% of patients with Duchenne muscular dystrophy and 80% of those with spinal muscular atrophy (7). Unlike idiopathic scoliosis, NMS is typically progressive and associated with significant morbidity and functional decline (5, 6). It profoundly impairs sitting balance, mobility, daily activities, and overall quality of life (2, 7). If untreated, severe deformities may compromise cardiopulmonary function, contributing to higher morbidity (2, 6). Patients with NMS face higher mortality and morbidity compared to other scoliosis types due to the combined challenges of underlying neuromuscular disease and scoliosis-related complications (4). Therefore, a comprehensive understanding of its etiology, progression, and systemic effects is essential for effective patient management. This narrative review aims to synthesize current evidence on the etiology, pathophysiology, diagnosis, management strategies, and future directions in neuromuscular scoliosis.

Methods

This narrative review synthesizes contemporary evidence on neuromuscular scoliosis, focusing on etiology, pathophysiology, diagnosis, management strategies, and emerging therapies. A targeted literature search was conducted across **PubMed/MEDLINE and Google Scholar** to identify relevant studies published between **January 2000 and December 2025**. Only **English-language**, **peer-reviewed** publications were considered.
Search terms included combinations of *neuromuscular scoliosis*, *neuropathic scoliosis*, *myopathic scoliosis*, *cerebral palsy*, *Duchenne muscular dystrophy*, *spinal muscular atrophy*, *diagnosis*, *imaging*, *surgical management*, *growth-preserving techniques*, *minimally invasive surgery*, and *gene therapy*.
Reference lists of key articles and review papers were manually screened to capture additional relevant literature.
Eligible study designs included **systematic and narrative reviews, clinical guidelines, consensus statements, randomized and non-randomized clinical studies, cohort studies, and selected case series** that provided meaningful insights into disease mechanisms or management. Case reports were included selectively when they offered novel perspectives. Data were synthesized qualitatively across predefined thematic domains.

Discussion

Etiology and classification of neuromuscular scoliosis

Accordingly, the Scoliosis Research Society classifies NMS into two primary pathomechanisms—neuropathic and myopathic—based on the underlying etiology (2,5), as summarized in ***Table 1***. (2,5):
Neuropathic: Conditions that impair the neurological control of muscle forces around the spine (5).
Myopathic: Intrinsic muscle diseases leading to progressive weakness and ineffective spinal support(5).

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Table 1. Etiological classification of neuromuscular scoliosis (4)

Category	Subcategory	Associated conditions
Neurop athic	First motor neuron disorders	Cerebral palsy; Friedreich's ataxia; Spinocerebellar degeneration; Syringomyelia; Medulla spinalis tumor; Medulla spinalis trauma
	Second motor neuron disorders	Poliomyelitis; Viral myelitis; Trauma; Spinal muscular atrophy; Werdnig–Hoffmann disease; Kugelberg–Welander disease; Dysautonomic disorders (Riley–Day syndrome)
Myopathy	Congenital/developmental	Arthrogryposis; Congenital hypotony; Fiber-type disproportion
	Muscular dystrophies	Duchenne muscular dystrophy; Limb-girdle muscular dystrophy; Facioscapulohumeral dystrophy
	Myotonic disorders	Dystrophic myotonia

Pathophysiology of deformity progression

The pathogenesis of NMS is multifactorial; however, consistencies regarding biomechanical factors have been identified. NMS develops when poor neuromuscular control, along with uneven loading on the spine, disrupts normal posture [8]. Although scoliosis is typically viewed as a coronal deformity, NMS presents as a multiplanar collapse, combining lateral curvature with kyphosis or, less frequently, hyperlordosis [9].

The central issue is the failure of dynamic spinal stabilization. Muscle imbalance is key to this process—weak or denervated muscles cannot resist opposing forces, and reduced motor unit recruitment, hypotonia, and muscle wasting further impair stabilization, thus restricting the ability to maintain sagittal balance [10]. As control deteriorates, the deformity often extends down to the pelvis [10]. The pelvis—which serves as the foundation for spinal alignment- is often forced into a persistent tilt, known as pelvic obliquity [8][11]. This is a state in which asymmetric hip flexors or abductor contractures and uneven gluteal muscle weakness force the sacrum into a tilted position [11]. Additionally, growth is affected in pediatric populations, as seen in the Hueter-Volkmann law, where increased pressure on the concave side of a developing curve slows down vertebral growth, while less pressure on the convex side allows for continued elongation [9]. This difference in growth causes vertebral wedging and rotation, which increases curve stiffness as the child matures [9].

NMS can be broadly divided into neuropathic and myopathic forms [5]. Neuropathic conditions involve damaged nervous system control of musculature as seen in conditions such as cerebral palsy (CP), spinal cord injury (SCI), myelomeningocele, and spinal muscular atrophy (SMA) [5][2]. Contrastingly, myopathic etiologies develop from primary diseases that affect muscle fibers, such as Duchenne Muscular Dystrophy (DMD), arthrogryposis, and some forms of SMA [5][2]. While spinal deformity in NMS follows a shared mechanical pathway, the initiating factor varies across etiologies. The underlying condition determines the initial complication—asymmetry, spasticity, or weakness—eventually leading to scoliosis.

To demonstrate the mechanisms underlying a myopathic condition, DMD serves as a representative example. In DMD, the deformity stems from severe muscle weakness caused by a genetic defect in the dystrophin gene. This X-linked mutation leads to the complete inexpression of dystrophin protein, which normally provides a critical mechanical linkage between cytoskeletal actin and the extracellular matrix [12]. This helps stabilize the sarcolemma during muscle contraction, without which the muscle fibres are prone to mechanical stress, leading to progressive muscle degeneration and wasting [12]. As trunk and back muscles weaken, the spine can no longer resist gravitational forces, producing a collapsing, flaccid scoliosis that rapidly worsens as ambulation declines.

CP illustrates the mechanisms associated with neuropathic injury. In CP, injury to the motor-controlling regions in the developing brain—particularly the cerebral cortex, basal ganglia, or cerebellum—disrupts normal muscle tone and coordination [13]. Involvement of the corticospinal pathway produces persistent spasticity and selective weakness across the trunk, resulting in muscle imbalance and postural instability [13].

In parallel, SMA represents a distinct mechanism that

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encompasses both neuropathic and myopathic etiology. SMA involves decreased levels of the survival motor neuron (SMN) protein. The lack of SMN protein causes degeneration of alpha motor neurons in the spinal cord and subsequent denervation and atrophy of skeletal muscle [14]. The deformity typically presents as a long, C-shaped curve at the thoracolumbar region, which is often accompanied by pelvic obliquity and thoracic kyphosis [15]. All of these factors contribute to an impairment in sitting balance and respiratory function [14].

Diagnosis

The diagnosis of scoliosis is a multidimensional process that extends well beyond the identification of a spinal curve on imaging. It requires a careful workup with clinical evaluation, diagnostic imaging, and multidisciplinary assessment, each contributing essential information to guide its management.

Clinical evaluation

A meticulous clinical evaluation forms the cornerstone of diagnosing neuromuscular scoliosis. Assessing such patients is not only crucial for identifying the underlying neuromuscular disorder but also for understanding the extent of functional compromise imposed by spinal deformity. (1) Establishing the primary disease is paramount, as recognizing the underlying pathology allows clinicians to anticipate both the natural trajectory of the curve and the challenges it may present. (1)

The evaluation begins with a detailed history encompassing perinatal events, family background, developmental milestones, and associated systemic disorders, with particular emphasis on renal and
cardiac conditions, as well as the precise age of spinal deformity onset. (1) Differentiating between static etiologies, such as myelomeningocele or cerebral palsy, and progressive disorders like Duchenne muscular dystrophy or spinal muscular atrophy, is vital for appropriate prognostication (2).

The Adams forward bend test, which uses a scoliometer to find rib cage asymmetry and vertebral rotation, is the first part of a physical exam. (5) Clinicians must carefully assess the Cobb angle, pelvic obliquity, shoulder asymmetry, and rib and hip deformities. (2) A full neurological assessment may reveal abnormal reflexes such as Babinski or Beevor's sign, which indicate spinal cord involvement at T10–T12. (2) Reflex abnormalities further delineate pathology: hyporeflexia suggests lower motor neuron disorders (e.g., myopathy, neuropathy, or spina bifida), whereas hyperreflexia points to upper motor neuron lesions (e.g., cerebral palsy, stroke, or spinal cord trauma). (2) Muscular imbalance caused by spasticity or hypotonia makes the trunk less stable and speeds up the curve's progress. (2) Non-ambulatory patients often experience pain from rib–pelvis impingement and difficulty maintaining sitting balance due to trunk collapse. (3)

Preoperative evaluation must adopt a multidisciplinary scope. It focuses on detecting compromised organ reserves that may predispose patients to perioperative complications and seeks to optimize them beforehand. (16) Respiratory assessment includes chest radiographs, SpO_2 monitoring, and spirometry. (16) Cardiac evaluation relies on ECG for arrhythmia detection and echocardiography to uncover dysfunction linked to neuromuscular syndromes, including cardiomyopathy, valvular disease, or congenital defects. (16)

Diagnostic imaging

Radiographic imaging is indispensable in confirming and characterizing scoliosis. Posteroanterior (PA) and lateral radiographs, ideally performed in weight-bearing positions, best demonstrate gravitational effects on spinal alignment. (5) The Cobb angle remains the gold standard for quantifying curve severity and progression, despite a measurement error of 2°–7° and intra-observer variability of 5°–10°. (1, 2, 7,17, 18)

In non-ambulatory patients, seated weight-bearing films are preferred, though technically demanding. When impractical, supine PA and lateral images, supplemented by bending or traction films, provide valuable data on curve flexibility. (1,5) MRI aids in detecting intraspinal anomalies such as lipomas, syringomyelia, tethered cord, or tumors, while CT offers detailed structural insights, especially during preoperative planning or in atypical presentations with early-onset deformities or unexplained pain. [2, 5]

Recent advances include ultra-low-dose (ULD) CT, which provides precise anatomical details with radiation exposure comparable to spine radiographs. [19] This modality facilitates surgical planning and intraoperative navigation, even in patients with involuntary movements. [19] Moreover, AI-assisted analysis of routine chest radiographs has shown promise in enhancing early scoliosis detection,

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ensuring greater diagnostic efficiency and consistency. [18]

Multidisciplinary approach

The management of neuromuscular scoliosis is inseparable from a multidisciplinary team (MDT) model.
[2] Decision-making regarding conservative versus surgical pathways often rests with such collaborative teams. [20] These may include spinal surgeons, neurologists, cardiologists, respiratory physicians, physiotherapists, occupational therapists, wheelchair specialists, psychologists, and dietitians, among others. [12,20]
A multidisciplinary strategy ensures that all nonoperative options are exhausted, treatment goals are defined, and family expectations are aligned with realistic outcomes.[(2] Given that these patients often carry multiple comorbidities and face elevated anesthetic and surgical risks, care must be individually tailored to maximize safety and quality of life. [2]

Interdisciplinary communication is critical, extending across anesthesiologists, surgeons, pediatricians, and neurophysiologists, with the shared goal of minimizing complications and optimizing perioperative management. [16] Emerging innovations—such as CT-based 3D spinal models—further enhance surgical planning, resident education, and patient counseling. [19] Comprehensive care, including nutritional optimization and bone health management, remains fundamental to reducing morbidity and improving outcomes. [19]

Management

Managing neuromuscular scoliosis (NMS) is a multifaceted challenge, with treatment goals that go well beyond curvature correction. The central goal is to enhance the patient's overall well-being and functional status. This includes improving respiratory function, pain control, posture, and mobility. A multidisciplinary approach is essential for comprehensive management.

Operative management

Surgical management is considered the definitive treatment for NMS. Operative strategies include growth-preserving procedures such as the Luque trolley, Shilla system, vertical expandable prosthetic titanium ribs (VEPTR), and rods, as well as definitive spinal fusion, with the choice guided by age, growth potential, and curve severity. Surgery is typically indicated in cases characterized by worsening spinal deformity and associated clinical complications. In patients with a Cobb angle exceeding 40°, curve progression is almost inevitable; surgical intervention is typically indicated to prevent further deterioration. Certain conditions warrant earlier intervention. DMD, for instance, may require operative management at a Cobb angle exceeding 20° due to the rapid progression of scoliosis and its compounding effect on respiratory function. [5] The opposite side of the spectrum presents a unique challenge. Patients with a curvature of 90° are at a significantly higher risk of perioperative complications such as excessive bleeding, neurological injury, and dural splitting, as well as postoperative complications [2]. Hence, the actual viability of surgery should be considered in these groups of patients. Moreover, the risk of surgery should be especially evaluated in pediatric populations with high anesthetic risk and other comorbidities [3].
According to a study done by Nakamura et al., implementation of an 'Enhanced Recovery After Surgery' protocol (ERAS) significantly decreased the length of admission without increasing the risk for adverse outcomes or the need for hospital re-evaluation. The ERAS strategy facilitates rapid post-surgical recovery by focusing on three components: optimal analgesia, timely resumption of oral intake, and early ambulation [14].

Growth preservation

Luque trolley and Shilla systems fall under the category of guided growth techniques [21]. While the former has largely fallen out of practice due to high complication rates and minimal growth potential, a novel, modern Luque trolley technique shows promise by a prospective study showing minimal reoperations and implant rejection due to refined construct design [2]. Traditional growing rods (TGR) have long been used for progressive spinal deformities in children; however require repeat scheduled surgeries to lengthen the rods. In contrast, magnetically controlled growing rods (MGCR) can be lengthened non-invasively [22]. A systematic review demonstrated that repair of the primary curve had better outcomes and maintenance with MGCRs compared to TGR and VEPTR devices in patients with NMS secondary to cerebral palsy [21]. One way self-expanding rods may also provide definitive treatment in patients with early onset NMS [23]. They offer potential as

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a definitive treatment in selected cases by passively adjusting to growth without repeated surgery. Furthermore, VEPTR implants may be used in certain conditions, such as SMA, as a fusionless method of treatment, although it is noted to have high complication rates [24]. A suitable alternative to growth rods- Minimally Invasive Bipolar Fixation (MIBF)- functions as a delayed fusion. This technique aims for spinal ankylosis years after the initial procedure. Unlike TGRs, which are associated with early unintended fusion and soft tissue scarring, MIBF preserves the intermediate spinal segments, helping to maintain growth potential and avoid premature fusion [25].

Definitive spinal fusion

As the name implies, spinal fusion involves the permanent joining of vertebral bone to prevent movement. This is primarily done via a posterior approach. This method utilizes hook-based anchors at the ends of the vertebrae, which are then used to correct spinal alignment [26]. However, this approach has notable limitations- it restricts early postoperative mobilization and provides minimal correction of rotational deformities [26]. Minimizing the number of fused spinal segments is essential in skeletally immature patients to maintain normal thoracic development and allow for continued lung growth [22].

Postoperative complication

Postoperative complications in patients undergoing treatment for NMS remain a significant concern, particularly due to the complex underlying conditions associated with this patient population. Certain neuromuscular disorders, such as myelomeningocele, DMD, and SMA, have been closely linked with an increased incidence of hindered wound healing and pulmonary complications following surgical intervention [27]. Such complications are thought to arise from physiological impairments associated with the underlying condition, including poor nutritional status, reduced mobility, and compromised respiratory mechanics, which collectively increase susceptibility to infection, thus hampering recovery [6]. In addition to soft tissue and systemic complications, there is a notably higher risk of mechanical failure associated with spinal instrumentation. In particular, patients treated with growth preservation techniques involving rods are at a heightened risk of screw loosening, pseudoarthrosis, junctional failure, and rod breakage [28].

Non-operative management

Non-operative management remains the first-line approach in NMS and includes bracing, physio, wheelchairs, assistive devices, and close observation. Although conservative treatment plays a crucial role during early disease stages, it is rarely curative. Bracing, for instance, is primarily used to support sitting stability and postural alignment- particularly in patients with small Cobb angles <25° [2]. While used to slow down curvature advancement, ultimately, bracing will not halt disease progression.

Wheelchair modification is another important component of nonsurgical treatment. Most wheelchairs already include recline functions, which can benefit pediatric populations with hunchbacks and limited neck stability [1]. Further modifications- such as custom moulding and strapping- are tailored to individual patient needs. [2]. Similarly, assistive devices and physiotherapy should be integrated into specific management plans to support function and quality of life [5].

Beyond supportive management, pharmacological treatment may also be used. Glucocorticoids have been shown to benefit patients with Duchenne Muscular Dystrophy (DMD) [5]; disease-modifying therapy may be used in spinal muscular atrophy (SMA) type 2 to reduce the severity of scoliosis and improve muscle function [24].

To conclude, NMS management techniques have evolved significantly over the past decades. Choosing the appropriate method depends on the patient's age, underlying condition, severity of In NMS, the genotype that is the underlying genetic mutation that causes neuromuscular dysfunction, directly influences the phenotype, which includes spinal deformity and its severity, rate of curve progression, and other complications. SMA and DMD are classic examples where these defects lead to progressive muscle weakness, creating asymmetric spinal forces and resulting in scoliosis [29,30]. By engaging at the genetic level, it is now possible to change the disease expression and influence its development, representing a shift from reactive to preventive care.

Recent research has discovered multiple new strategies, including the Adeno-associated virus (AAV)-mediated gene delivery, antisense oligonucleotides, and CRISPR/Cas9-based gene editing, which have shown promising preclinical and clinical results in restoring the function of defective genes in SMA and DMD [29,30]. Landmark clinical trials like the single-dose SMN1 gene replacement (Zolgensma) demonstrated improved motor

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neuron survival, increased muscle strength, and reduced progression of spinal deformity [31]. Furthermore, newer therapies such as nusinersen, risdiplam, and onasemnogene abeparvovec have altered the disease progression in SMA patients, showing that timely genetic intervention can actually directly impact the phenotype of NMS [15].

Minimally Invasive Surgery (MIS) in NMS

Surgical options for NMS have traditionally involved long posterior spinal fusions, which are linked with significant blood loss, longer operative times, increased chances of infection risk, and growth restriction in pediatric patients. Minimally invasive surgery (MIS) aims to decrease perioperative morbidity while maintaining or increasing spinal alignment and function. Miladi et al. (2018) introduced a fusionless MIS technique specifically for NMS patients, which maintains spinal and thoracic growth by reducing extensive fusion while providing mechanical stabilization [32]. Further refinements, including bipolar fixation constructs, have streamlined perioperative outcomes, reducing operative time and blood loss, and facilitating earlier mobilization [25]. Long-term follow-up studies tell us that fusionless MIS constructs maintain correction over five or more years, with fewer patients requiring subsequent conversion to traditional fusion [33].

Early-onset NMS presents a particular challenge due to ongoing spinal growth. Fusionless technologies, like growing rods, one-way self-expanding rods (OWSER), and magnetically controlled growing rods, enable us for gradual correction while accommodating vertebral growth. Studies demonstrate that these systems provide steady long-term correction, reduce the need for frequent open surgeries, and allow for more natural spinal development [25,33].

Recent advances in imaging and navigation have enhanced the safety and accuracy of surgery. 3D imaging, augmented reality guidance, and computer-assisted navigation during surgery allow real-time visualization of vertebral anatomy, allowing exact pedicle screw placement and decreasing complications. These technologies are particularly useful in NMS, where anatomical distortions and poor bone quality enhance surgical risk. AR-guided systems also reduce radiation exposure, an important consideration in pediatric populations [34].

Robotics and AI are changing surgical approaches to NMS. Robotic-assisted pedicle screw placement resulted in improving the accuracy and consistency, especially in anatomically challenging cases [35]. AI algorithms are used to predict curve progression, optimize surgical planning, and simulate outcomes, allowing personalized interventions. Integration of robotics with AR navigation and preoperative imaging offers greater precision, shorter operative times, and improved postoperative outcomes.

The future of NMS treatment includes merging molecular therapies with state-of-the-art surgical approaches. Prompt genetic intervention can change the disease course, possibly decreasing scoliosis extent, while minimally invasive and fusionless surgical approaches treat residual deformities with safety and effectiveness. Imaging, surgical involvement, and robotics further enhance precision, safety, and long-term outcomes. This combined idea represents a framework shift from reactive surgical management toward preventive care, finally increasing both functional outcomes and quality of life in patients with neuromuscular disorders.

Conclusion

The findings of this narrative synthesis highlight that neuromuscular scoliosis is fundamentally driven by failure of dynamic spinal stabilization due to neuromuscular weakness, imbalance, and impaired postural control. Unlike idiopathic scoliosis, NMS follows a predictable yet aggressive progression, often involving the pelvis and compromising function and cardiopulmonary reserve. Early diagnosis through multidisciplinary evaluation and advanced imaging is critical for optimizing outcomes. Surgical decision-making must balance curve severity, growth potential, and systemic risk. Growth-preserving and minimally invasive strategies have expanded the therapeutic armamentarium, particularly for early-onset NMS. Future directions emphasize genotype–phenotype correction, gene therapy, minimally invasive fusionless techniques, advanced imaging, augmented reality, robotics, and artificial intelligence (29-35). Integration of molecular therapies with precision surgery represents a paradigm shift from reactive deformity correction to preventive, personalized care.

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List of abbreviations

NMS – Neuromuscular scoliosis
AIS – Adolescent idiopathic scoliosis
CP – Cerebral palsy
DMD – Duchenne muscular dystrophy
SMA – Spinal muscular atrophy
CNS – Central nervous system
MRI – Magnetic resonance imaging
CT – Computed tomography
MIS – Minimally invasive surgery
TGR – Traditional growing rods
MGCR – Magnetically controlled growing rods
VEPTR – Vertical expandable prosthetic titanium rib
ERAS – Enhanced Recovery After Surgery

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Conflict of interest

The authors declare no conflicts of interest related to this work.

Author contributions

Conceptualization and study design were performed by the authors. Literature review, data interpretation, and manuscript drafting were undertaken by the authors. All authors critically revised the manuscript and approved the final version.

Data availability

No new data were generated or analyzed in this narrative review. All data supporting the findings are available within the article and its referenced sources.

Author biography

Degala Varshasri is a Clinical Intern at the Jonelta Foundation School of Medicine, University of Perpetual Help System. Throughout her undergraduate medical training, she has developed a strong academic foundation and a deep interest in clinical practice and research. She possesses a keen enthusiasm for research and is currently involved in two university-based research projects that are awaiting publication, reflecting her growing engagement with scientific inquiry and evidence-based medicine. Her comprehensive medical education and clinical exposure have cultivated a particular interest in the fields of Neurology, Neurosurgery, and General Surgery. Through continuous learning, clinical observation, and research participation, she aims to further expand her knowledge and skills in these specialties.

Vetha Janane Sashikumar is a high-achieving clinical clerk at the Jonelta Foundation School of Medicine-University of Perpetual Help System DALTA. With a background in Psychology and a reputable standing in her medical studies, she brings a unique, holistic perspective to her clinical training and evidence-based practice. Her role in this project focused on conducting an extensive literature review to define and describe management strategies. Her further involvement in research- including contributions to pediatric studies, and the development of original clinical protocols- reflects a strong commitment to scientific communication and technical medical writing. Through her clinical experience, leadership activities, and aspiring research efforts, she consistently applies a comprehensive approach to modern medicine, integrating evidence-based practice with practical clinical decision-making.

Disha Vatyani is a 2025 graduate of Government Medical College, Nagpur, with a strong aspiration to pursue Neurology. Her interest in the specialty developed through broad academic exposure and active participation in clinical learning during her undergraduate medical training. She has gained experience in core clinical disciplines with a particular focus on neurological sciences, which strengthened her understanding of patient care, diagnostic reasoning, and evidence-based medicine. Her academic engagement and clinical exposure have helped her develop a solid foundation in neurological concepts and reinforced her decision to pursue a career in Neurology. Disha's dedication to learning and her growing clinical insight reflect her potential to contribute meaningfully to neurological practice and research in the future.

Dr. Alka Kumari is a medical graduate from Liaquat University of Medical and Health Sciences, Jamshoro, Pakistan. She is currently working as a licensed intern at Liaquat University Hospital. Alongside her clinical work, Dr. Kumari has a strong research background with

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experience across multiple projects, including case reports, narrative reviews, and a publication(peer-reviewed) in a PubMed-indexed Journal as first author. Dr. Kumari has successfully passed the USMLE Step1 examination and is currently preparing for Step2CK. Her field of interest is Internal Medicine with plans of applying for the upcoming Match Cycle. Her contribution to this project involved an extensive literature review and manuscript preparation, playing an essential role in molding the structure of this article.

Sana Shaik is a medical graduate of Tbilisi State Medical University, having completed undergraduate training with a strong foundation in clinical medicine and patient care. During medical school, Sana developed robust clinical skills and undertook the CBME surgical training course, which further strengthened exposure to surgical principles and operative care. This early hands-on experience played a key role in shaping a strong interest in cardiology, cardiothoracic surgery, and internal medicine. Alongside clinical training, Sana has been actively involved in research across multiple study designs, including literature reviews, systematic reviews, meta-analyses, case reports, and cross-sectional studies. This combination of clinical competence, structured surgical training, and diverse research experience highlights Sana's potential to contribute meaningfully to academic medicine and evidence-based clinical practice.

Dr. Bisma Bashir Ahmed is a final-year MBBS student at People's University of Medical and Health Sciences for Women (PUMHSW), Nawabshah, Sindh, with a clear aspiration to pursue General Surgery. Her interest developed through broad academic exposure and active involvement in clinical and research activities during her undergraduate training. She has contributed to research projects in cardiology, neurology, and pulmonology, which strengthened her foundation in clinical research methodology, including identifying research gaps, manuscript writing, data analysis, and visual presentation. This multidisciplinary exposure helped her make an informed decision to pursue a career in general surgery. Bisma has supported several collaborative research projects, with multiple studies currently in the process of publication. Her analytical skills and research experience highlight her potential to contribute to surgical research and evidence-based practice.

Dr. Raman Arora is an International Medical Graduate (MD) with structured clinical training across Internal Medicine and allied specialties. He completed his medical education at Grigol Robakidze University, Georgia, and gained comprehensive hands-on experience through university-affiliated hospitals in Internal Medicine, Emergency Medicine, Anesthesiology, Surgery, and Pediatrics. Dr. Arora has a strong academic orientation with experience in clinical literature review, retrospective research workflows, data interpretation, and collaborative academic writing. He is currently preparing for the USMLE examinations and plans to pursue Internal Medicine residency training in the United States, with a strong interest in evidence-based medicine and academic clinical practice.

Dr. Nidhi Vadhavekar is a medical professional who earned her MBBS degree from Padmashree Dr. D.Y. Patil School of Medicine in India. She has demonstrated strong leadership skills through her extensive involvement in research, having published over ten articles. As a mentor, Dr. Vadhavekar was instrumental in the research process. Her leadership was evident from the early stages of conceptualization, where she helped shape the study's direction. She continued to lead the effort through the critical phases of revising and finalizing the drafts, ensuring the project's successful completion. This experience highlights her capacity to take initiative and drive a complex scientific undertaking.

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