The Pathophysiology of Scoliosis Across the Spectrum of Human Physiological Systems

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Abstract
Scoliosis is a medical condition characterized by an abnormal lateral curvature of the spine. It can lead to various health issues, affecting mobility, respiratory function, and overall quality of life. There are several types of scoliosis, including idiopathic, congenital, neuromuscular, degenerative, and functional. The severity of scoliosis is measured by the degree of spinal curvature, typically expressed in degrees through a system known as the Cobb angle. Early detection and intervention are fundamental in managing scoliosis, as more severe forms may necessitate bracing or surgical intervention. Healthcare professionals must understand the different types of scoliosis and their unique characteristics to tailor appropriate treatment plans.

Scoliosis can significantly impact various physiological systems, including the circulatory, digestive, endocrine, integumentary, lymphatic, muscular, nervous, and respiratory systems. In the circulatory system, scoliosis can cause hemodynamic changes, impaired venous return, cardiac strain, and pulmonary complications. In the digestive system, scoliosis can lead to gastric displacement, impaired intra-abdominal pressure, gastroesophageal reflux, and nutritional implications. The endocrine system can be affected by scoliosis, leading to neuroendocrine dysregulation, growth hormone...
abnormalities, cortisol dysregulation, and impact on thyroid function. Scoliosis can also affect the integumentary system, leading to pressure ulcers, altered skin sensation, and hygiene challenges. In the lymphatic system, scoliosis can cause lymphatic obstruction, impaired immune response, altered inflammatory responses, fibrosis, and secondary lymphedema. Scoliosis can affect the muscular system, leading to muscle imbalance, myofascial pain, respiratory muscle weakness, and mobility issues. The nervous system can also be impacted by scoliosis, leading to neural compression, central nervous system impact, neurological dysfunction, and coordination challenges. In the respiratory system, scoliosis can cause thoracic deformities, reduced lung compliance, ventilation-perfusion mismatch, respiratory muscle weakness, increased work of breathing (WOB), and an increased risk of respiratory infections. Recognizing and addressing the interplay between scoliosis and these physiological systems is integral for healthcare professionals to provide comprehensive care to individuals with scoliosis.

Current research on scoliosis has made progress in diagnostic tools and techniques, including the use of imaging methods like MRI and X-ray, wearable sensors, and 3D reconstruction techniques for better evaluation of spinal motion and function, along with treatment strategies like Schroth exercises and braces, and management measures for respiratory and circulatory problems. However, there are limitations to current studies, such as the heterogeneity of scoliosis, compartmentalized approaches, limited longitudinal studies, reliance on retrospective data, and the need for standardized measures and diagnostic criteria. Future research prospects include advancements in genetic research, biomechanics, artificial intelligence and machine learning, longitudinal studies, non-invasive treatments, and multidisciplinary collaborations among researchers, clinicians, and technologists.

**Abbreviations:** CNS: Central Nervous System; DVT: Deep Vein Thrombosis; MRI: Magnetic Resonance Imaging; GERD: Gastroesophageal Reflux Disease; HPA: Hypothalamic-Pituitary-Adrenal; WOB: Work of Breathing

### Introduction

Scoliosis, or curvature of the spine, has been a recognized medical condition since ancient times. Aristotle, Hippocrates, and Galen all mentioned spinal curvature in their writings. The first known treatment for scoliosis was described by Ambroise Paré in the 16th century, who recommended stretching the patient on a rack [1]. Later, in the 18th and 19th centuries, various physicians developed different types of braces to correct spinal curvature, and surgeries were eventually developed in the 20th century [2]. Notable researchers and physicians in scoliosis history include Drs. D.S. Bradford, Lawrence G. Lenke, and Clyde Lester (Les) Nash, Jr.; universities such as Johns Hopkins and Washington University have also contributed to scoliosis research [1–3].

Public health and medical organizations such as the American Academy of Orthopaedic Surgeons, American Academy of Pediatrics, and Scoliosis Research Society recognize scoliosis as a medical condition and provide resources for education, diagnosis, and management [4,5].

Scoliosis is a spinal condition characterized by an abnormal lateral curvature of the spine, affecting its optimal alignment. Typically, the spine should appear straight when viewed anteriorly or posteriorly, but in scoliosis, it deviates laterally, forming a curve or multiple curves. This condition is not only a matter of aesthetics but can also lead to various health issues, affecting mobility, respiratory function, and overall quality of life [6].

Scoliosis emerges as a disruptive force across various physiological systems. The intricate relationships between spinal curvature and the circulatory, digestive, endocrine, integumentary, lymphatic, muscular, nervous, and respiratory systems underscore the need for a broad awareness of the implicit multi-systemic impact of this condition.

### Discussion

The primary aim of this paper is to examine the negative impacts of scoliosis on different physiological systems. However, it is relevant to provide a concise overview of the various types and causes of scoliosis as a foundation (Table 1) [7–12].

#### Table 1: Types and Causes of Scoliosis

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
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<tbody>
<tr>
<td>Idiopathic Scoliosis[7, 8]</td>
<td>- Most common type, often occurs during adolescence</td>
</tr>
<tr>
<td></td>
<td>- Accounts for approximately 80% of all scoliosis cases</td>
</tr>
<tr>
<td></td>
<td>- Categorized into infantile, juvenile, and adolescent based on age of onset[7].</td>
</tr>
</tbody>
</table>
|                     | - The International Statistical Classification of Diseases and Related Health Problems (ICD-11) includes a code for infantile idiopathic scoliosis under the category of "Scoliosis"
<p>| Congenital Scoliosis[9] | - Occurs at birth due to abnormalities in spine development                |
|                     | - Results from improper formation of vertebrae                              |</p>
<table>
<thead>
<tr>
<th>Scoliosis Type</th>
<th>Characteristics</th>
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</table>
| Neuromuscular Scoliosis[10]   | - Associated with neuromuscular conditions like cerebral palsy, muscular dystrophy, or spinal cord abnormalities  
|                               | - Weakness or paralysis of spine-supporting muscles contributes to lateral curve development |
| Degenerative Scoliosis[11]    | - Develops in older adults as a result of natural aging process                  
|                               | - Associated with wear and tear on the spine leading to curvature                |
| Functional Scoliosis[12]      | - Temporary curve not caused by spinal abnormalities                             
|                               | - Arises from issues in surrounding structures such as muscle imbalances or leg length differences  
|                               | - Correcting underlying cause can often resolve the scoliosis                     |

The severity of scoliosis is often measured by the degree of the spinal curvature, typically expressed in degrees through a system known as the Cobb angle. Mild scoliosis ranges from 10 to 20 degrees, moderate from 20 to 40 degrees, and severe scoliosis is characterized by a curvature exceeding 40 degrees [13].

Recognizing the types of scoliosis and their unique characteristics is essential for healthcare professionals to customize appropriate treatment plans. Periodic screenings—particularly during adolescence when scoliosis often develops—contribute to early identification and intervention, ultimately optimizing outcomes for individuals with this spinal deformity.

**Scoliosis Effects Across a Spectrum of Human Physiological Systems**

**Circulatory System**

1. Hemodynamic Changes:
   - Scoliosis induces hemodynamic alterations, disrupting the normal blood flow within the circulatory system. The abnormal curvature of the spine can lead to compression and deformation of the thoracic cavity, causing changes in intrathoracic pressure, which affects the filling and ejection of blood from the heart, compromising cardiac output and leading to potential circulatory insufficiencies [15,16].

2. Impaired Venous Return:
   - One notable consequence of scoliosis is the compromise of venous return, an integral component of circulatory dynamics. The spinal curvature can exert pressure on the veins coursing along the spine, impeding the efficient return of deoxygenated blood to the heart. This venous stasis may contribute to conditions such as deep vein thrombosis (DVT) and chronic venous insufficiency, further exacerbating the circulatory burden on affected individuals [17].

3. Cardiac Strain and Dysfunction:
   - The heart, a central player in the circulatory system, faces increased challenges in the presence of scoliosis. The altered geometry of the chest can impose mechanical stress on the heart, leading to hypertrophy and changes in myocardial function. Over time, this cardiac strain may contribute to conditions such as cardiomyopathy, jeopardizing the overall efficiency of the cardiovascular system [18,19].

4. Pulmonary Complications:
   - Scoliosis often goes hand in hand with pulmonary complications, which can significantly impact circulatory health. The curvature of the spine can impede the normal expansion of the lungs, reducing vital lung capacity and compromising oxygen exchange. The resulting hypoxemia stresses the circulatory system, potentially leading to adverse effects on various organs and tissues [20–23].

5. Orthostatic Challenges:
   - Individuals with scoliosis may experience orthostatic challenges due to the altered biomechanics of the spine. Orthostatic hypotension, a drop in blood pressure upon standing, can be more prevalent in patients with scoliosis. This phenomenon further underscores the intricate relationship between spinal curvature and the regulation of circulatory dynamics [24].

6. Impact on Peripheral Vascular Resistance:
   - Scoliosis can contribute to changes in peripheral vascular resistance, affecting blood flow to various tissues and organs. The altered biomechanics and structural abnormalities associated with scoliosis may lead to localized vascular constriction or dilation, disrupting the finely-tuned balance of circulatory homeostasis [25–27].

**Digestive System**

1. Thoracic Deformities and Gastric Displacement:
   - One notable consequence of scoliosis is the alteration of thoracic anatomy, potentially leading to the displacement of abdominal organs. As the spine undergoes lateral curvature, the gastrointestinal structures, including the stomach, may be repositioned. This displacement can contribute to gastric compression, impacting the normal digestion processes and potentially leading to functional gastrointestinal disorders [28,29].

2. Impact on Intra-abdominal Pressure:
   - Scoliosis induces changes in intra-abdominal pressure, a core factor in optimal digestive function. The abnormal curvature of the spine can result in an uneven
distribution of pressure within the abdominal cavity, potentially affecting food movement along the digestive tract. This disturbance in intra-abdominal dynamics may contribute to symptoms such as bloating, discomfort, and altered bowel habits [30].

3. Gastroesophageal Reflux (GERD):
The altered biomechanics associated with scoliosis can predispose individuals to gastroesophageal reflux, where stomach contents flow back into the esophagus. The curvature of the spine may contribute to a dysfunctional lower esophageal sphincter, leading to increased susceptibility to acid reflux. Chronic GERD not only impairs the quality of life but can also give rise to more severe complications such as esophagitis and Barrett's esophagus [31,32].

4. Nutritional Implications:
Scoliosis may have implications for nutritional status, with potential consequences for overall digestive health. Individuals with severe spinal curvature may experience challenges in maintaining a healthy and balanced diet due to physical discomfort during meals or altered eating postures. Nutritional deficiencies can arise, impacting the absorption of essential nutrients and contributing to various digestive complications [20,33].

5. Constipation and Bowel Function:
The influence of scoliosis on the autonomic nervous system can affect bowel function. The altered neural signaling may contribute to constipation, as the regular rhythmic contractions of the intestines are disrupted. This gastrointestinal motility impairment can lead to discomfort, bloating, and a compromised ability to eliminate waste, further highlighting the multifaceted impact of scoliosis on digestive health [34,35].

6. Surgical Considerations and Gastrointestinal Complications:
For individuals undergoing spinal surgery to address scoliosis, the procedure can introduce additional gastrointestinal concerns. Surgical interventions may involve manipulation of adjacent structures, potentially leading to postoperative gastrointestinal complications. Awareness of these potential issues is primary for healthcare providers to implement comprehensive care strategies [36,37].

**Endocrine System**

1. Neuroendocrine Dysregulation:
Scoliosis has been associated with neuroendocrine dysregulation, highlighting the intricate interplay between the spine and hormonal signaling. The altered biomechanics and neural input associated with spinal curvature may disrupt the delicate balance of endocrine function. This dysregulation can manifest as hormonal imbalances, potentially impacting growth, metabolism, and other core physiological processes [38].

2. Growth Hormone Abnormalities:
Scoliosis may influence the secretion and action of growth hormones. Spinal curvature can affect the growth plates and alter the mechanical forces acting on bones, potentially leading to abnormalities in longitudinal bone growth. This effect can result in stature discrepancies and may affect overall skeletal health [32,39].

3. Impact on Pubertal Development:
Scoliosis can influence the timing and progression of pubertal development, a period marked by significant hormonal changes. The altered spinal mechanics may contribute to hormonal imbalances that affect the onset of puberty and the development of secondary sexual characteristics. Acknowledging these endocrine disruptions is imperative for clinicians managing the care of adolescents with scoliosis [20,40].

4. Cortisol and Stress Response:
The stress associated with living with scoliosis can contribute to alterations in cortisol, a key stress hormone. Chronic stress and the psychological impact of spinal curvature may lead to dysregulation of the hypothalamic-pituitary-adrenal (HPA) axis, affecting cortisol secretion. This hormonal imbalance can have broad implications, influencing metabolism, immune function, and the body's stress response [36].

5. Thyroid Function and Metabolic Consequences:
The endocrine influence of scoliosis extends to thyroid function, with potential consequences for metabolism. Altered spinal mechanics may impact the neural input to the thyroid gland, disrupting thyroid hormone production and secretion. Such disturbances can result in metabolic changes, potentially contributing to weight fluctuations and energy regulation challenges [41].

6. Insulin Sensitivity and Metabolic Syndrome:
Scoliosis may also influence insulin sensitivity, linking spinal curvature to metabolic health. The altered mechanical forces on the spine can impact neural signaling to tissues involved in glucose metabolism. This disruption may contribute to insulin resistance, potentially predisposing individuals with scoliosis to metabolic syndrome and its associated cardiovascular risks [42–46].

**Integumentary (Cutaneous) System**

1. Pressure Ulcers and Skin Shear:
Scoliosis can predispose individuals to develop pressure ulcers, particularly in areas where the body's bony prominences are subjected to increased pressure. The curvature of the spine may create uneven weight distribution, leading to localized pressure points. These pressure points and potential skin shear forces contribute to skin breakdown, exposing individuals to the risk of pressure ulcers, especially in the regions overlying the scoliotic curves [47].
2. Altered Skin Sensation:
The altered biomechanics associated with scoliosis may impact sensory nerve function, leading to changes in skin sensation. Individuals with scoliosis may experience altered sensitivity, numbness, or tingling in the areas affected by spinal curvature. Appreciating these sensory changes is important for healthcare providers to address potential skin care and injury prevention challenges [48,49].

3. Skin Folds and Hygiene Challenges:
The asymmetry resulting from scoliosis may lead to the formation of skin folds, particularly in the trunk and back regions. These skin folds create environments conducive to moisture retention and friction, increasing the susceptibility to dermatological issues. Maintaining proper hygiene becomes challenging, and individuals with scoliosis may be more prone to fungal infections, intertrigo, and other skin conditions in these fold areas [50,51].

4. Cosmetic Considerations and Self-esteem:
Beyond the physical implications, scoliosis can have cosmetic effects on the skin's appearance. Asymmetric alignment of the spine may lead to noticeable changes in the contour of the back, impacting body image and self-esteem, especially in adolescents. Addressing the psychosocial aspects of scoliosis is constructive, recognizing the potential impact on mental well-being and overall quality of life [49,52].

5. Surgical Scars and Wound Healing:
For those undergoing spinal surgery to correct scoliosis, the surgical process directly impacts the integumentary system. The placement of incisions, closure techniques, and postoperative wound care are crucial considerations. Surgical scars may have aesthetic implications. Proper wound healing helps prevent complications such as infection or hypertrophic scarring [53].

6. Vascular Changes and Skin Perfusion:
Scoliosis may affect the vascular supply to the skin, influencing perfusion and overall skin health. The altered biomechanics can impact blood flow to the skin, potentially leading to changes in skin color, temperature, and healing capacity. Awareness of these vascular changes is important for healthcare providers to monitor skin health and intervene promptly in case of compromised perfusion [54–60].

**Lymphatic System**

1. Lymphatic Obstruction and Fluid Accumulation:
Scoliosis may induce mechanical compression on the lymphatic vessels alongside the spine, leading to obstruction. The altered biomechanics and pressure exerted by the deformed spine can impede the normal flow of lymph, causing fluid accumulation in the interstitial spaces. This lymphatic stasis contributes to edema, particularly in regions affected by the spinal curvature, and may exacerbate inflammation and compromise tissue nutrition [61].

2. Impaired Immune Response:
Scoliosis-induced lymphatic obstruction may compromise the immune response. Impaired lymphatic drainage can hinder the efficient transport of immune cells, potentially leading to localized immunosuppression and increasing susceptibility to infections in affected regions [61,62].

3. Altered Inflammatory Responses:
Scoliosis can influence the inflammatory milieu within the interstitial spaces surrounding the spine. The compromised lymphatic drainage may contribute to the persistence of inflammatory mediators, perpetuating a chronic inflammatory state. This altered inflammatory response can have systemic implications, affecting the local tissues and contributing to a pro-inflammatory environment that extends throughout the body [61].

4. Fibrosis and Tissue Remodeling:
Chronic lymphatic obstruction in scoliosis may lead to fibrotic changes in the affected tissues. The accumulation of lymph and inflammatory mediators can stimulate fibroblast activity, contributing to tissue fibrosis and remodeling. These structural changes may further impede lymphatic flow, creating a cycle of dysfunction that can impact the elasticity and resilience of the affected tissues [61].

5. Secondary Lymphedema:
In severe cases of scoliosis, persistent lymphatic obstruction can give rise to secondary lymphedema. This condition involves the accumulation of protein-rich fluid in the interstitial spaces, leading to chronic swelling. Secondary lymphedema can affect the regions adjacent to the spine and may extend to the extremities, posing challenges for affected individuals regarding mobility and overall quality of life [63].

6. Surgical Interventions and Lymphatic Complications:
For individuals undergoing spinal surgery to address scoliosis, the procedures may introduce additional considerations for the lymphatic system. Surgical interventions may disrupt lymphatic vessels and nodes, potentially leading to postoperative lymphatic complications. Awareness of these potential issues is necessary for healthcare providers to implement strategies for monitoring and managing lymphatic function during the postoperative period [54–60].

**Muscular System**

1. Muscle Imbalance and Asymmetry:
One of the primary consequences of scoliosis is the development of muscle imbalances and asymmetries. The lateral curvature of the spine prompts the muscles on one side to undergo adaptive changes to counterbalance the deformity. This imbalance can lead to hypertrophy and increased tone in certain muscle groups, while the muscles on the opposite side may...
experience atrophy and reduced functional capacity. The resulting asymmetry can compromise overall musculoskeletal function and contribute to postural abnormalities [64,65].

2. Myofascial Pain and Trigger Points: Scoliosis often induces myofascial pain and the formation of trigger points in affected muscles. The altered biomechanics associated with spinal curvature create increased tension and stress on specific muscle groups. This chronic muscle strain can result in the development of trigger points and localized areas of muscle hyperirritability. Myofascial pain syndrome in patients with scoliosis can contribute to discomfort, reduced range of motion, and a heightened susceptibility to muscle spasms [66].

3. Reduced Muscle Strength and Endurance: The adaptive changes in muscle structure and function associated with scoliosis can reduce muscle strength and endurance. Muscles that maintain spinal alignment may weaken over time, compromising the ability to sustain optimal posture. This reduction in muscle endurance can contribute to fatigue, particularly during activities that require prolonged periods of sitting or standing, impacting the overall functional capacity of affected individuals [67].

4. Respiratory Muscle Impairment: Scoliosis, especially when severe, can influence the function of respiratory muscles. The altered thoracic shape may limit the expansion of the chest during inhalation, affecting the respiratory muscles’ efficiency. Respiratory muscle impairment can result in decreased lung capacity and respiratory function, leading to challenges in oxygenation and ventilation. This respiratory compromise is particularly significant in individuals with scoliosis, necessitating attention to respiratory health in managing the condition [68].

5. Gait Abnormalities and Mobility Issues: Scoliosis-induced muscle imbalances can contribute to gait abnormalities and mobility issues. Asymmetric muscle development and altered biomechanics may affect the coordination and stability required for smooth, efficient gait. Individuals with scoliosis may experience challenges in walking, running, or engaging in physical activities, influencing their overall mobility and participation in daily life [69].

6. Surgical Considerations and Muscular Recovery: For those undergoing surgical interventions to correct scoliosis, the procedure impacts the muscular system. Surgical correction involves manipulating muscles and soft tissues, potentially leading to postoperative muscle weakness and stiffness. Rehabilitation and targeted exercises are valuable components of postoperative care to optimize muscular recovery and restore functional capacity [54–60].

Nervous System
1. Neural Compression and Radiculopathy: Scoliosis can induce neural compression, affecting the spinal nerves as they exit the spinal column. The abnormal curvature may lead to foraminal stenosis, narrowing the passageways through which spinal nerves travel. This compression can result in radiculopathy, characterized by pain, numbness, or weakness radiating along the path of affected nerves. Grasping these neurological implications is crucial for healthcare professionals in diagnosing and managing the symptoms associated with nerve compression in patients with scoliosis [70].

2. Impact on Central Nervous System: The altered biomechanics associated with scoliosis influence the central nervous system (CNS). The spinal cord may undergo adaptive changes in response to the lateral curvature. These changes can affect the transmission of neural signals, potentially leading to altered sensory perception and motor function. The impact on the CNS underscores the need for a complete neurological assessment in individuals with scoliosis [48].

3. Neurological Dysfunction and Coordination Challenges: Scoliosis-induced changes in neural signaling can result in neurological dysfunction, affecting coordination and motor control. The altered proprioceptive input due to spinal curvature may lead to challenges in maintaining balance and executing precise movements. Individuals with scoliosis may experience difficulties in tasks requiring fine motor skills and coordination, emphasizing the intricate relationship between spinal alignment and neurological function [48,71].

4. Sympathetic Nervous System Dysregulation: The sympathetic nervous system, responsible for the “fight or flight” response, may undergo dysregulation in the presence of scoliosis. The altered biomechanics and potential neural compression can influence sympathetic nerve activity. This dysregulation may contribute to autonomic dysfunction, impacting cardiovascular function, blood pressure regulation, and other physiological responses. Acknowledgment of sympathetic nervous system involvement is advantageous for healthcare providers to address potential autonomic complications in individuals with scoliosis [72].

5. Cognitive and Psychosocial Impact: Scoliosis can have cognitive and psychosocial implications related to the nervous system. The altered body image and potential neurological dysfunction may influence the psychological well-being of individuals with scoliosis. Addressing these psychosocial aspects is supportive, recognizing the potential impact on mental health and overall quality of life [49,73].
6. Surgical Considerations and Neurological Monitoring:
The procedures directly impact the nervous system of those undergoing spinal surgery to correct scoliosis. Surgical interventions involve manipulation of the spine and adjacent neural structures, necessitating meticulous care to avoid neurological complications. Continuous neurological monitoring during surgery is standard practice to preserve neural function and promptly detect potential issues [54–60].

**Respiratory System**

1. Thoracic Deformities and Respiratory Restriction:
   One of the primary consequences of scoliosis is the alteration of thoracic anatomy, leading to thoracic deformities that impact respiratory mechanics. The abnormal curvature of the spine can restrict the normal expansion of the chest during inhalation. This restriction compromises vital capacity, the maximum amount of air a person can exhale after maximum inhalation, leading to decreased lung volumes and impaired respiratory function [68,74].

2. Reduced Lung Compliance:
   Scoliosis can influence lung compliance, the measure of lung expandability. The altered biomechanics associated with spinal curvature may affect the elastic properties of the lung tissue, leading to reduced lung compliance. Decreased lung compliance makes it more challenging for the lungs to expand and contract efficiently during the breathing cycle, contributing to respiratory limitations [68,75].

3. Ventilation-Perfusion Mismatch:
   The impact of scoliosis on respiratory mechanics can contribute to ventilation-perfusion mismatch, a condition where air and blood flow are not optimally matched in the lungs. The altered ventilation and perfusion patterns may result in regions of the lungs receiving inadequate airflow or blood supply, impairing oxygen exchange. This mismatch can lead to hypoxemia, a condition characterized by low oxygen levels in the blood, and hypercapnia, a condition characterized by having high levels of carbon dioxide in the blood [76].

4. Respiratory Muscle Weakness:
   The muscular imbalances associated with scoliosis can extend to the respiratory muscles, including the diaphragm and intercostal muscles. As these muscles work against the altered biomechanics, they may experience increased fatigue and weakness. Respiratory muscle weakness further contributes to the overall respiratory compromise in individuals with scoliosis.

5. Increased Work of Breathing (WOB):
   Scoliosis induces changes in breathing mechanics, increasing the WOB for affected individuals. The altered chest wall dynamics and reduced lung compliance necessitate greater effort to maintain adequate ventilation. This increased WOB can lead to respiratory fatigue, particularly during exertion, and may reduce tolerance for physical activities [75].

6. Risk of Respiratory Infections:
   The compromised respiratory function in individuals with scoliosis may elevate the risk of respiratory infections. Reduced lung volumes, ventilation-perfusion mismatch, and respiratory muscle weakness create an environment conducive to retaining respiratory secretions. This susceptibility to retained secretions may predispose individuals to respiratory infections, emphasizing the importance of respiratory hygiene and preventive measures [74].

7. Surgical Considerations and Respiratory Monitoring:
   For those undergoing surgical interventions to correct scoliosis, the procedures directly impact the respiratory system. The manipulation of thoracic structures and potential effects on lung function necessitates careful monitoring of respiratory parameters during surgery. Postoperative respiratory care is basic to prevent complications such as atelectasis and pneumonia [77].

   Scoliosis can negatively influence the circulatory, digestive, endocrine, integumentary, lymphatic, muscular, nervous, and respiratory systems. It is advantageous to appreciate its diverse impacts. This multifaceted condition calls for a unified and inclusive approach to optimize outcomes across physiological systems [21,78].

**Diagnostic Techniques, Treatment Strategies, and Management Measures**

One focus in scoliosis research has been the development of diagnostic tools and techniques. Imaging methods like magnetic resonance imaging (MRI) and X-ray have been widely adopted to evaluate spine structure in patients with scoliosis [49,79]. While conventional imaging methods can provide accurate visualizations of the spinal curves, these methods may not be sufficient to quantify the function or motion of the spine [80,81]. Recent advances in wearable sensors and 3D reconstruction techniques may offer new possibilities to efficiently evaluate spinal motion and function, particularly in pediatric and adolescent patients [82,83].

Another relevant area of scoliosis research is evaluating and optimizing different treatment strategies. Schroth exercises are a form of physiotherapy that involves postural training, breathing exercises, and stretching to reduce spinal deformity and elevate quality of life [84]. Studies have shown that this method can effectively reduce spinal curves and improve respiratory function in adolescent and adult patients [85–87]. Similarly, bracing is another widely-used treatment technique for scoliosis that involves applying external pressure to the spine to correct spinal curves. Moreover, researchers have developed new braces, such as the 3D Rigo Chêneau-type brace, providing enhanced results for
restoring spinal alignment and reducing disability [88–90].
Management and prevention of scoliosis complications are also a principal area of research. One of the most common complications of scoliosis is the development of respiratory problems. Studies have shown that physiotherapy techniques, such as controlled breathing exercises and respiratory muscle training, can upgrade respiratory function [91–93]. Furthermore, wearable respiratory sensors and biofeedback techniques can effectively monitor and manage respiratory function in patients with scoliosis [94–96]. Another complication of scoliosis is the development of circulatory problems, such as cardiac arrhythmia and systemic hypertension. Prevailing studies have shown that daily aerobic exercise and lifestyle modifications can support cardiovascular health in patients with scoliosis, particularly those with severe spinal deformities [97–100].
The current state of scoliosis research has made significant strides in developing diagnostic techniques, treatment strategies, and management measures. However, further progress in treating scoliosis will require fortified knowledge of the underlying mechanisms and greater cooperation between researchers, clinicians, and technologists.

Limitations of Studies
While contributing valuable insights, studies on scoliosis face several limitations that warrant consideration in pursuing a broad understanding of this complex condition. One primary constraint is the heterogeneity of scoliosis itself. Scoliosis manifests in various forms, including idiopathic, congenital, neuromuscular, degenerative, and functional, presenting unique challenges. The diverse etiologies and patient populations contribute to variability in study outcomes, making it challenging to generalize findings across scoliotic conditions [101,102]. Moreover, most scoliosis studies often focus on specific aspects of the condition, such as its impact on musculoskeletal structures or associated systemic effects. While valuable for in-depth exploration, this compartmentalized approach can lead to an incomplete comprehension of the holistic repercussions of scoliosis on the body [49,103]. A more integrative and interdisciplinary perspective is paramount to capture the multifaceted nature of scoliosis and its implications across various physiological systems.
The limited longitudinal studies tracking scoliotic progression over extended periods pose another challenge. Scoliosis is a dynamic condition, and its course can evolve, especially during periods of growth and development. Many studies are cross-sectional, providing snapshots of the condition at specific points [104–108]. Longitudinal studies tracking patients from adolescence into adulthood are utile to decipher the origin and progression of scoliosis. Furthermore, the reliance on retrospective data in some studies introduces potential biases and limitations in data accuracy [109]. Prospective, well-controlled studies with larger sample sizes can enhance scoliosis research [110]. Additionally, there is a need for standardized outcome measures and diagnostic criteria across studies to facilitate meaningful comparisons and meta-analyses [111].
Incorporating advanced imaging modalities and computational modeling techniques can enhance the precision of scoliosis studies [112,113]. However, accessibility to these technologies, especially in resource-constrained settings, remains limited. Addressing these constraints is consequential to advancing scoliosis research and translating findings into more effective clinical interventions and patient care strategies.

Future Research Prospects
In pursuing an encyclopedic understanding of scoliosis, future research holds promising avenues. Advancements in genetic research may unravel the interplay between genetics and scoliosis, focusing on specific markers for personalized interventions [114]. Biomechanics represents another frontier, exploring how altered spinal mechanics contribute to progression and offering innovative interventions. Integrating artificial intelligence and machine learning could uncover nuanced patterns in vast datasets, enhancing diagnostic precision [113]. Longitudinal studies tracking patients from childhood through adulthood are necessitous for grasping scoliosis’ natural history, emphasizing factors like genetics and biomechanics. Future investigations may explore non-invasive treatments like targeted physical therapies, minimizing daily impact while effectively managing scoliosis. Collaboration among researchers, clinicians, and technologists will be pivotal in these endeavors, ushering in a multidisciplinary approach and technological advancements that promise more precise diagnostics, personalized treatments, and improved outcomes for individuals afflicted by this spinal condition.

Conclusion
Scoliosis is a spinal condition characterized by an abnormal lateral curvature of the spine that can profoundly affect various physiological systems. This condition has several classifications, most notably idiopathic, congenital, neuromuscular, degenerative, and functional. Healthcare professionals must understand the unique characteristics of these classifications to tailor appropriate treatment plans and address the interplay between scoliosis and physiological systems.
Multiple physiological systems can be affected by scoliosis, including the circulatory, digestive, endocrine, integumentary, lymphatic, muscular, nervous, and respiratory systems. Recognizing how scoliosis can impact these systems is indispensable for providing comprehensive care to individuals with this condition. Current studies on scoliosis have limitations, including the heterogeneity of scoliosis, compartmentalized approaches, limited longitudinal studies, reliance on retrospective data, and the need for standardized measures and diagnostic criteria. Future research prospects for scoliosis include advancements in genetic research, biomechanics, artificial intelligence and machine learning, longitudinal studies, non-invasive treatments, and multidisciplinary collaborations among researchers, clinicians, and technologists. Early detection and intervention are decisive in managing scoliosis, as more severe forms may necessitate bracing or surgical intervention. With appropriate care and appreciation of the interplay between scoliosis and various physiological systems, healthcare professionals can help individuals with scoliosis maintain their overall quality of life.

**Conflict of Interest Statement**

The authors declare that this paper was written without any commercial or financial relationship that could be construed as a potential conflict of interest.

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