

Spine–foot axis in scoliosis: a narrative review

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Medical Studies

DOI: <https://doi.org/10.5114/ms/221463>

Key words: plantar pressure, scoliosis, pedobarography, spine curve, spine–foot axis.

Abstract

Idiopathic scoliosis, a three-dimensional spinal deformity, is a common musculoskeletal condition that may affect body biomechanics, particularly the alignment of the pelvis and lower limbs. Here, we review the effects of scoliosis on the spine–foot musculoskeletal axis, assessed by pedobarography, in relation to body balance, pelvic and trunk stability, and gait patterns. We searched for papers indexed in the PubMed and Google Scholar databases published during the last decade. The primary finding reported in patients with scoliosis is asymmetric distribution of plantar pressure, which may reflect compensatory musculoskeletal mechanisms. Scoliosis-related pelvic rotation and functional leg-length discrepancy may alter foot loading. Chronic, unequal foot loading may be associated with structural defects, such as flatfoot or pes cavus, and gait pattern abnormalities. Pedobarography is a valuable tool for assessing the structure and function of the spine–foot axis and for evaluating the adverse biomechanical consequences of scoliosis.

Introduction

Idiopathic scoliosis, defined as a three-dimensional spine deformity of unknown cause, is a common condition that affects individuals of all ages, but is especially prevalent during the period of pediatric intensive growth [1]. It affects global body biomechanics, leading to compensatory changes in the alignment of the pelvis and lower limbs [2]. Pedobarographic examination, measuring plantar pressure and contact area, is a non-invasive diagnostic tool that allows assessment of the feet during both static (standing) and dynamic (gait) conditions. The test provides information on foot loading, postural stability, gait patterns, and bone alignment, for which the spine curvature is a key element [3]. Understanding how scoliosis affects the foot, as reflected in pedobarographic examination, is important for a comprehensive assessment of the mutual structural and functional interplay in disorders of the spine–foot axis and, consequently, for effective therapy implementation. Therefore, this narrative aims to present contemporary knowledge on the effects of scoliosis on plantar pressure distribution, which is crucial for maintaining body balance, pelvic and trunk stability, and gait patterns.

Material and methods

We used the following combined code phrases for the literature search in databases: “Gait Analy-

sis” OR “Pedobarography” OR “Baropodometry” OR “Plantar Pressure” OR “Foot Pressure” OR “Underfoot Pressure” AND “Scoliosis” OR “spinal deformity” OR “spinal curvature” for PubMed and “Scoliosis” AND “Pedobarography” OR “Plantar Pressure” OR Baropodometry” for Google Scholar. The search results were limited to human studies published in the English language between 2015 and 2025. The search included the following reports:

- Controlled randomized clinical trials, reviews, and case series.
- Effects of scoliosis on body posture, balance, gait kinetics, and combinations thereof.
- Pedobarographic examination and symmetry of foot loading in scoliosis.
- Technical, diagnostic, and therapeutic aspects combining plantar pressure distribution and scoliosis.
- Functional biokinetic changes and physiotherapeutic rehabilitation.
- Treatment outcomes and complications.

The abstracts of identified papers were screened for relevance. We then selected publications that provided evidence-based results for discussion in this narrative. A total of 206 papers were initially identified, including 39 in PubMed and 167 in Scholar Google. After removing incomplete and duplicate records, we assigned 172 papers for abstract screening. The number of papers further decreased during the sequential steps of PRISMA analysis for subject

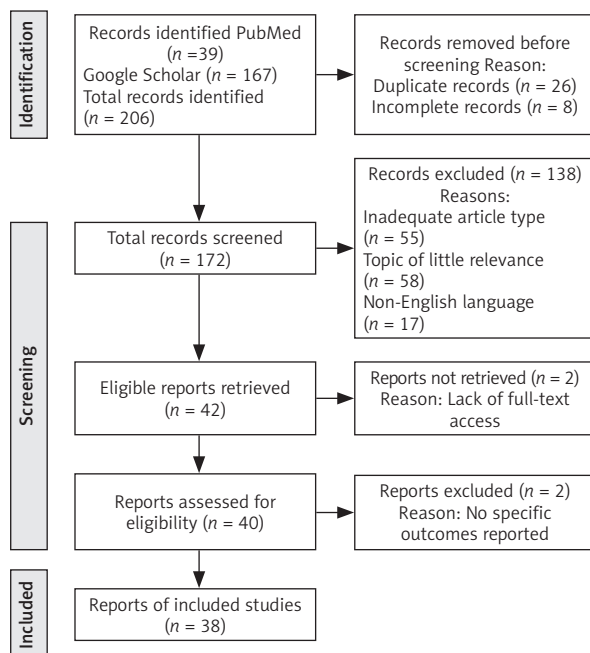


Figure 1. PRISMA flowchart of the literature search and study selection process in this review

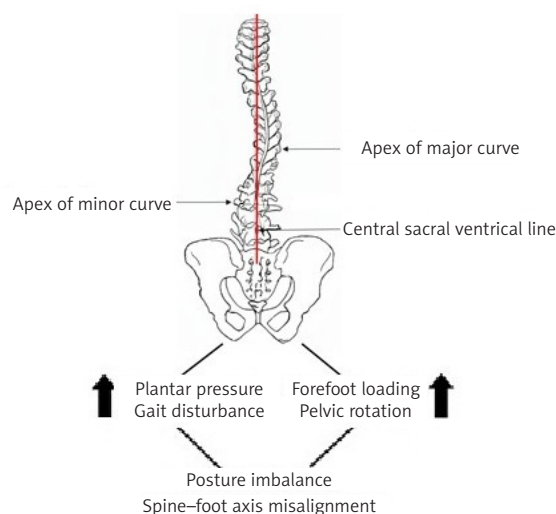


Figure 2. Schematic representation of spinal scoliosis and its associations with the foot from anatomical, mechanical, and clinical perspectives

relevance. Papers with methodological or substantive limitations, inadequate content, incongruous topics, or unsupported outcomes, as well as those published in languages other than English, were excluded, as depicted in the flow diagram (Figure 1). Thirty-eight papers were finally included in the analysis. The eligibility criteria included the originality of the paper, clearly formulated research questions and outcomes, evidence-based findings, adequate data presentation,

and appropriate support of the arguments with references. Published conference proceedings, commentaries, and short communications were a priori excluded from the analysis. Two independent assessors conducted the screening process.

Results and discussion

Asymmetry of foot loading – key finding in scoliosis

The most consistently reported finding in scoliosis is an asymmetric distribution of plantar pressures. Uneven foot loading may reflect compensatory musculoskeletal mechanisms in response to spinal deformity. Studies have shown that asymmetry in plantar pressure distribution may be greater on the side of the spinal curvature, and has been associated with changes in gait kinetics, uneven leg pressure distribution, and increased gait energy costs [4, 5]. Furthermore, increased forefoot loading on the side opposite the curvature has been observed, potentially reflecting compensatory pelvic rotation during gait [6]. Gait asymmetry in children with idiopathic scoliosis has also been reported. It manifests, among other features, as a difference between pelvic rotation and ground reaction force [7]. In individuals with scoliosis, differences in the pedobarographic pattern have been reported according to the side of the spinal curvature: a left-sided curve was associated with higher pressure in the right forefoot, whereas a right-sided curve was associated with higher pressure in the left forefoot [8, 9].

Factors influencing pressure distribution

The degree and nature of foot loading asymmetry in scoliosis may depend on several factors. Primarily, an association has been reported between the magnitude of the Cobb angle, a radiographic measure of spinal curve severity, and the severity of plantar pressure asymmetry (Figure 2). It has been observed that a 10° increase in the Cobb angle was associated with an 18% increase in foot loading asymmetry, especially under the head of the first metatarsal [10]. Another study reported that moderate and severe scoliosis were associated with increased plantar pressure in the medial and lateral heel regions by as much as 35% compared with mild scoliosis and reduced midfoot loading [11]. People with severe scoliosis and trunk balance disorders have been reported to exhibit greater loading foot asymmetry; greater curve severity has also been associated with greater postural instability [12].

The location of the main scoliotic curvature has also been associated with the loading pattern (Figure 3). Thoracic scoliosis has been associated with increased pressure on the lateral heel, while lumbar scoliosis has been associated with increased pressure in the medial forefoot, with the asymmetry be-

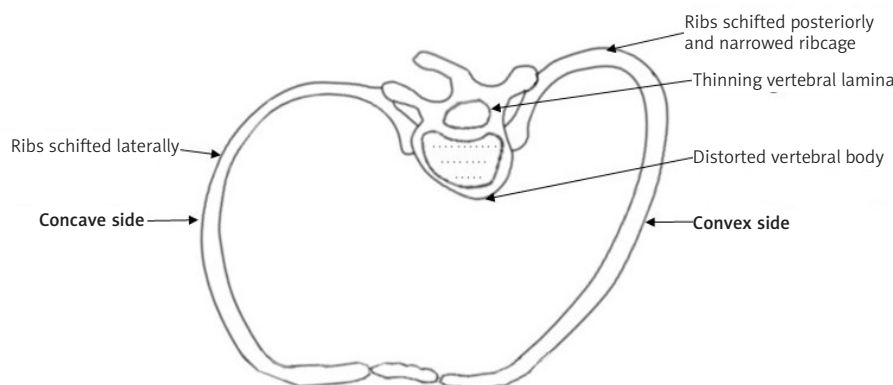


Figure 3. Schematic representation of vertebral and ribcage torsional derangement in left-sided thoracic scoliosis

ing more pronounced in thoracic scoliosis [9]. Pelvic asymmetry and the associated functional leg length discrepancy (LLD) are other significant factors. Scoliosis is often accompanied by pelvic obliquity [13, 14], leading to LLD even when the limbs are structurally equal [15, 16]. Functional shortening of one limb significantly disrupts the load distribution, typically leading to greater loading on the shorter limb. Even a small LLD (1–3 cm) may affect lateral pelvic tilt and gait compensation, potentially contributing to foot pressure asymmetry [17]. Additionally, pelvic rotation during gait, also associated with scoliosis, may alter forefoot loading [2].

Scoliotic consequences for foot and gait

Chronic, asymmetric foot loading, reported in patients with scoliosis, may contribute to the development or exacerbation of foot structural disorders, such as flatfoot (*pes planus*) or high-arched foot (*pes cavus*), and may affect gait pattern. Flatfoot may develop as a consequence of scoliosis-evoked muscle asymmetry and foot overload [18, 19]. The high prevalence of high-arched feet in patients with scoliosis suggests the possibility of shared neurological mechanisms underlying spinal and foot distortions, rather than a cause-and-effect relationship [20–22]. Interestingly, a converse correlation has been observed between increased lumbar lordosis, which often accompanies certain types of scoliosis, and a lower longitudinal foot arch [23]. Regardless of scoliosis's impact on foot structure, loading asymmetry may be associated with alterations in gait pattern, leading to differences in stride length, stance time, or pelvic rotation [7, 24].

The spine-foot axis may involve bidirectional interactions. Foot deformities, such as an asymmetric high arch, may in turn be associated with alterations in body posture, including pelvic and spinal alignment [23]. In the context of child and adolescent idiopathic scoliosis, where uneven growth may contribute to shape changes, the dominant direction

of influence appears to proceed from spinal dealignment downward to the pelvis and lower limbs, as reflected in asymmetric foot loading [7]. A direct relationship between scoliosis and specific structural foot defects has not been unequivocally established. However, the consensus is that chronic loading asymmetry impacts foot biomechanics and contributes to pain and fatigue symptoms [6, 25].

Therapeutic interventions

Pedobarographic examination is useful in monitoring changes associated with scoliosis treatment. For instance, the use of orthopedic braces may alter global posture and may be associated with reductions in step length and foot acceleration on the side opposite the curvature. Such postural compensation signs may be reflected in pedobarographic plantar pressure recordings [9, 26, 27]. Targeted, non-surgical exercise programs, such as proprioceptive neuromuscular facilitation (PNF), may improve foot loading symmetry. The Schroth method is a patient-tailored physical therapy approach for patients with idiopathic scoliosis that incorporates rotational breathing to address trunk asymmetry and promote expansion of restricted thoracic regions [28, 29]. The method may reduce pain associated with postural asymmetry and uses breathing techniques intended to de-rotate the trunk, in addition to potentially improving respiratory function [30].

Spine stabilization exercises have been associated with reductions in excessive pressure in specific foot regions, e.g., under the lateral heel or the head of the 5th metatarsal [31, 32]. Furthermore, individually prescribed orthopedic insoles may alter plantar pressure distribution, reduce loading asymmetry, and improve gait parameters [33–35]. The pathophysiology of scoliosis, involving alterations in body posture, balance, and gait kinetics, appears multifactorial, and may include plausible compensatory modifications of the central control of motion as indicated by changes in electroencephalographic activity in scoliosis [36].

Yet, neurophysiological markers of scoliosis remain to be established. Innovative attempts to combine pedobarographic examinations with artificial intelligence (AI) algorithms raise new possibilities for standardized classification and assessment of scoliosis in the context of plantar pressure redistribution [37].

Limitations

This review has limitations inherent in the literature search. Biases stem from the assessor's interpretation of the relevance of screened publications, which, to a degree, may be influenced by clinical engagement and experience with the topic. Thus, the assessment of the merit and quality of publications may vary, particularly in a review like this one, where the subjects of analysis and interpretation encompass a range of different pathophysiological and clinical entities, whose clinical meaning and management are contentious or not fully settled. The selection of papers may vary depending on the combination of keywords used in the search strategy. Further, the selection may not comprehensively cover the entire scope of the literature. To mitigate these biases, we relied on the sequential steps of the PRISMA flowchart, predefined search criteria, and relevance criteria for paper selection. We also focused the review on the spine-foot axis in scoliotic disorders, which helped to contextualize the significance of the available evidence.

Beyond the issues outlined above, several limitations within the current body of literature on the spine-foot axis must be acknowledged. First, there is significant heterogeneity in pedobarographic assessments across the cited studies. Differences in equipment (e.g., spatial resolution and sampling frequency of pressure platforms) and varying testing protocols (static standing vs. dynamic gait, barefoot vs. shod, self-selected vs. controlled gait speed) make cross-study comparisons challenging. Second, the clinical populations studied varied with respect to the exact curve topology (thoracic vs. lumbar), Cobb angle severity, and the presence of concomitant compensatory mechanisms, such as functional leg length discrepancy or pelvic obliquity. This heterogeneity often precludes identification of a single, universal pedobarographic pattern for scoliosis.

Further, most current literature relies on cross-sectional study designs. While these studies report the presence of asymmetrical plantar loading and altered gait mechanics in scoliotic patients, they limit the ability to establish causality or track the temporal evolution of biomechanical adaptations. Future longitudinal studies utilizing standardized pedobarographic protocols are necessary to better characterize temporal relationships and potential causal pathways within the spine-foot axis.

Despite the limitations, we believe we have highlighted the growing body of knowledge on the spine-

foot axis, the role of pedobarography in the assessment of scoliosis, and the plausible involvement of central mechanisms involved in the control of body balance and motion in scoliotic functional and structural disorders. Scoliosis, a common disorder, is subject to rapid technological and methodological advances.

Conclusions

Idiopathic scoliosis is associated with an asymmetric plantar pressure distribution, as detected by pedobarographic examination. The degree and nature of this asymmetry may be associated with the magnitude and location of the spinal curvature and the accompanying pelvic alignment. Chronic asymmetrical plantar loading may be associated with structural and functional disturbances in the foot, as well as alterations in body balance and gait. These adaptations may involve compensatory changes in the central control of body posture and movement, an area of ongoing research.

Pedobarography provides measurements of plantar pressure distribution and may provide information relevant to foot loading during gait. It is a valuable tool for characterizing the biomechanical features of scoliosis and for monitoring changes associated with therapeutic interventions, such as bracing, specific exercises, or the use of orthopedic insoles. Early assessment and appropriate management may help minimize the biomechanical consequences of spinal deformity in the foot and lower limbs. The integration of pedobarography with AI algorithms opens up new avenues for the assessment and monitoring of scoliotic sequelae.

Funding

The study received no external funding.

Ethics and consents

Not applicable.

Competing interests

None.

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Received: 26.02.2026

Accepted: 05.05.2026

Online publication: 28.09.2026