SENSORIMOTOR INTEGRATION AND BODY REPRESENTATION IN ADOLESCENT IDIOPATHIC SCOLIOSIS: REHABILITATIVE AND EDUCATIONAL PERSPECTIVES

INTEGRAZIONE SENSORI-MOTORIA E RAPPRESENTAZIONE CORPOREA NELLA SCOLIOSI IDIOPATICA DELL'ADOLESCENTE: PROSPETTIVE RIABILITATIVE ED EDUCATIVE

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ABSTRACT
Adolescent Idiopathic scoliosis is a multifactorial three-dimensional spinal deformity involving structural and neurofunctional alterations. Recent evidence highlights impaired sensorimotor integration and distorted body representation in this patients. Understanding these mechanisms is essential to develop rehabilitative and educational strategies that enhance postural control, proprioception, and treatment outcomes.

La scoliosi idiopatica adolescenziale è una patologia caratterizzata da deformità tridimensionale della colonna vertebrale a origine multifattoriale che coinvolge alterazioni strutturali e neurofunzionali. Evidenze recenti mostrano un'alterata integrazione sensori-motoria e rappresentazione corporea in questi pazienti. Comprendere tali meccanismi è essenziale per sviluppare strategie riabilitative ed educative che migliorino controllo posturale, propriocezione ed esiti terapeutici.

KEYWORDS
Rehabilitation; spine; scoliosis.
Riabilitazione; colonna vertebrale; scoliosis.

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Introduction

Scoliosis, from the Greek *σκολίωσις* ("curvature"), is a disease defined as a three-dimensional deformity of the spine involving all anatomical planes. On the frontal plane, it is characterized by a lateral deviation of the vertebrae; on the axial plane, by vertebral rotation toward the convexity of the curve; on the sagittal plane, by frequent alterations of spinal alignment, including hypokyphosis and/or hyperlordosis (Marya et al., 2022; Negrini et al., 2018).

The Cobb angle remains the gold standard for diagnosing and quantifying the severity of scoliosis (Negrini et al., 2018). It is measured on a standing posteroanterior radiograph by drawing lines along the upper endplate of the most tilted vertebra at the top of the curve and the lower endplate of the most tilted vertebra at the bottom. The angle formed by the intersection of these two lines, or by the perpendiculars to them, represents the Cobb angle. According to the Scoliosis Research Society (SRS), scoliosis is defined as a spinal deviation in the frontal plane of 10 degrees or more, as measured by this method (Marya et al., 2022; Negrini et al., 2018). In addition to curve magnitude, radiographic assessment is fundamental for evaluating skeletal maturity, an important factor in estimating the risk of curve progression. The Risser sign, based on the degree of ossification of the iliac apophysis, provides an indirect measure of remaining spinal growth: lower Risser grades (0-2) indicate high growth potential and greater progression risk, grade 3 corresponds to partial ossification and moderate risk, while grades 4-5 denote near or complete skeletal maturity with minimal likelihood of progression (Hacquebord & Leopold, 2012).

Adolescent Idiopathic Scoliosis (AIS) is the most common form of scoliosis, with a prevalence ranging from 0.47% to 5.2% depending on population, ethnicity, genetic predisposition, and screening methodologies (Aulia et al., 2023). AIS predominantly affects females, with the female-to-male disparity increasing substantially alongside curve severity, from approximately 2:1 for curves ≥10° to 10:1 for curves >30°, underlining the higher female susceptibility to curve progression (Daruwalla et al., 1985; Kamtsiuris et al., 2007; Konieczny et al., 2013; Weinstein et al., 2008). Despite decades of research, the etiology of AIS remains unknown and is therefore termed "idiopathic". Current evidence supports a multifactorial condition, resulting from the interplay of genetic, hormonal, environmental, and mechanical factors (Kikanloo et al., 2019; Pérez-Machado et al., 2020).

Traditional approaches to AIS management have primarily targeted the structural and biomechanical aspects of the deformity. According to the International Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT) guidelines, treatment is tailored to curve magnitude, skeletal maturity, and progression risk, ranging from observation and physiotherapeutic scoliosis-specific exercises (PSSE) to bracing or surgical correction. Mild curves (<25° Cobb) are typically managed with PSSE, moderate curves (25°-40°) with full-time bracing, and severe or progressive curves (>40-45°) with surgical intervention (Negrini et al., 2018). However, increasing evidence suggests that AIS should not be interpreted solely as a structural deformity but also as a disorder involving the central nervous system (CNS) (Burwell et al., 2008). In particular, preliminary findings indicate that patients with AIS may exhibit alterations in central sensorimotor functions (Paramento et al., 2024). Moreover, recent studies suggest that AIS management interventions may influence central body representation, an internal map that integrates sensory, proprioceptive, and motor inputs, and which can therefore serve as an indirect index of sensorimotor brain activity (Pialasse et al., 2017). Conservative treatments, particularly PSSE and bracing, can act not only on spinal alignment but also on sensorimotor functioning by enhancing proprioceptive input and improving congruence between body morphology and the neural body schema. Conversely, surgical correction produces a rapid structural change that necessitates subsequent adaptation of the internal body map. Alterations in body representation may, in turn, compromise treatment efficacy and adherence to corrective strategies by impacting postural stability, motor planning, and self-perception (Bertuccelli et al., 2023). Therefore, understanding how alterations in the CNS and in sensorimotor integration may contribute to AIS development and progression is of fundamental importance. The aim of this paper is to summarize current evidence on sensorimotor and body representation alterations in AIS patients and to describe rehabilitation and educational approaches that specifically target these aspects.

1. Sensorimotor integration in AIS

Sensorimotor integration refers to the continuous process during which the CNS combines proprioceptive, visual, vestibular, and tactile inputs with motor commands to generate coherent, adaptive movement and postural control (Pialasse et al., 2017). This integration primarily involves the posterior parietal cortex, primary and supplementary motor areas, cerebellum, basal ganglia, and brainstem vestibular nuclei, which together form distributed neural networks that enable the brain to construct and update an internal representation of the body in space (Fortin et al., 2019). Efficient sensorimotor integration allows for accurate coordination, balance, and movement planning; conversely, disruptions within these networks can lead to postural instability, movement asymmetries, and distorted body representation (Pialasse et al., 2017). AIS has increasingly been recognized as a disorder that, beyond spinal deformity, may also involve atypical central processing of sensory and motor information. Neurophysiological and neuroimaging studies suggest that AIS could be associated with altered cortical excitability and impaired multisensory integration (Paramento et al., 2024). For instance, electroencephalographic investigations have revealed atypical oscillatory activity during postural control tasks, characterized by enhanced low-frequency theta power and altered alpha distribution, particularly under sensory deprivation conditions (Formaggio et al., 2022; Panara et al., 2024; Paramento et al., 2025). Theta and alpha oscillations are important neural markers of balance control, reflecting how the brain integrates sensory input and allocates attentional resources. Increased theta power, particularly in frontal and central regions, has been associated with heightened sensory processing, error monitoring, and attentional engagement during demanding postural tasks (Formaggio et al., 2022; Gebel et al., 2020; O'Keeffe et al., 2020). Alpha oscillations index somatosensory cortical excitability, with decreases in alpha power reflecting greater cortical activation to support balance (Formaggio et al., 2022; Fortin et al., 2019; Kahya et al., 2022; Lanthier et al., 2020).

Somatosensory evoked potentials further have demonstrated delayed conduction latencies correlating with gait asymmetries and abnormal ground reaction forces, suggesting slowed central transmission and impaired proprioceptive processing (Chang et al., 2017). Complementary imaging studies have provided structural and functional evidence of these abnormalities: voxel-based morphometry and diffusion tensor imaging have shown alterations in white matter integrity within interhemispheric and sensorimotor tracts (Hitier et al., 2015; Shi et al., 2009; Shi et al., 2011), while functional magnetic resonance imaging (MRI) demonstrated compensatory hyperactivation of motor planning areas such as the supplementary motor area during simple motor tasks (Domenech et al., 2011).

At the behavioral level, these central alterations can manifest as impairments in postural and locomotor control. Force-platform studies have revealed increased center-of-pressure (COP) displacement, greater sway area and velocity, and asymmetrical COP distribution in AIS patients compared to healthy peers (Beaulieu et al., 2009; Cațan et al., 2020; Dalleau et al., 2011; Leteneur et al., 2017; Struber et al., 2022; Stylianides et al., 2013). When sensory information is perturbed, for example through eyes-closed conditions, foam surfaces, or proprioceptive vibration, AIS patients show greater instability, reflecting an overreliance on vestibular and somatosensory cues to maintain balance (Khanal et al., 2016; Kuo et al., 2010; Piątek-Krzywicka et al., 2022; Piątek et al. 2020). These compensatory strategies may arise from an impaired ability to integrate multisensory feedback efficiently. Gait analyses similarly demonstrated asymmetric step cycles, reduced joint mobility, and increased energy expenditure in AIS subjects, suggesting that altered central integration could be linked to biomechanical inefficiency (Liu et al., 2022; Mahaudens et al., 2009; Zhu et al., 2021).

Therapeutic interventions appeared capable of modulating these sensorimotor patterns. Bracing could transiently disrupt proprioceptive feedback and increase postural sway (Kavyani et al., 2020; Pavone et al., 2022), whereas some long-term studies reported improvements in mediolateral stability after bracing (Khanal et al., 2016). PSSE and self-correction techniques have shown promise in enhancing proprioceptive awareness, reducing sway amplitude, and improving gait symmetry (Marin et al., 2021, 2022).

2. Body schema and body image in AIS

Body schema and body image are related but distinct aspects of how the human brain represents the body. The body schema is a dynamic and largely unconscious representation of the body’s position, configuration, and orientation in space. It is continuously updated through proprioceptive, vestibular, and visual inputs, and underlies balance, spatial orientation, automatic motor control, and postural adjustments (Assaiante et al., 2014; Vallar, 2025) Functionally, it serves as an implicit, action-oriented map that enables fluid interaction with the environment and adaptation to morphological changes. In contrast, body image refers to the conscious and affective appraisal of one's physical appearance, integrating cognitive and emotional dimensions (Assaiante et al., 2014; Vallar, 2025). Body image shapes self-perception, identity, and psychological well-being (Assaiante et al., 2014; Vallar, 2025).

Although conceptually distinct, body schema and body image are not entirely independent, influencing each other (Bertuccelli et al., 2023). The continuous sensorimotor feedback shaping body schema may influence conscious body image, while body image attitudes may, in turn, affect sensorimotor processing (Bertuccelli et al., 2023).

In AIS, spinal curvature could create a discrepancy between the physical deformity and the brain's internal sensorimotor representation of the trunk. Several authors have hypothesized that the neural map of the spine in AIS may fail to adequately update in response to progressive deformity, potentially contributing to the persistence and progression of scoliosis (Burwell & Dangerfield, 2002). This notion aligns with the "neuro-osseous escalator theory", which suggests a developmental mismatch between rapid skeletal growth during adolescence and the slower maturation of sensorimotor integration processes in the cortex (Burwell et al., 2008).

Clinical studies support the presence of body representation alterations in AIS. For instance, Cheung et al. (2002) employed a laser line projection task to assess trunk posture perception indirectly, finding significant correlations between task performance and scoliosis severity: greater deformity was associated with less accurate body schema representation (Cheung et al., 2002). Similarly, Le Berre et al. (2017) assessed dynamic proprioception in 114 adolescents with right thoracic AIS and 81 controls. While static balance measures did not differ significantly, AIS patients exhibited impairments in dynamic proprioception, particularly in displacement and rotational angles during the Fukuda-Utenberger stepping test (Le Berre et al., 2017). Later, Le Berre et al. (2019) evaluated subjective postural vertical

(SPV) and subjective visual vertical (SVV) under static and optokinetic conditions. SPV was significantly shifted to the right and correlated with frontal tilt, indicating an altered internal reference frame for verticality, whereas SVV remained unchanged (Le Berre et al., 2019).

Further evidence highlighted distortions in trunk awareness and global body perception. Picelli et al. (2016), using a silhouette judgment task, showed that AIS patients systematically underestimated thoracolumbar curvature and overestimated thoracic and lumbar curvature, indicating inconsistencies between perceived and actual spinal morphology (Picelli et al., 2016). Yagci et al. (2020), with the Awareness-Body-Chart test, reported significantly lower awareness scores across multiple body regions in AIS patients compared to controls, reinforcing the notion of impaired sensorimotor integration and reduced global body awareness (Yagci et al., 2020).

These perceptual and sensorimotor disturbances may have clinically relevant consequences. At the motor level, they can cause postural instability and difficulties in movement planning; at the perceptual level, they may create mismatches between the actual body and its internal representation, affecting self-awareness and the lived experience of the body. They may also reduce the effectiveness of conservative treatments, as patients lacking an accurate central representation of spinal alignment may struggle to execute postural exercises correctly or perceive corrective forces applied by braces (Paramento et al., 2025; Paramento et al., 2024). Moreover, distortions in body schema may explain why some adolescents continue to report imbalance or discomfort despite objective improvements in curve correction (Paramento et al., 2025; Paramento et al., 2024). Finally, as previously highlighted, the continuous altered sensorimotor feedback shaping body schema may influence conscious body image and vice versa (Bertuccelli et al., 2023). During adolescence, a critical period for identity formation, this reciprocal relationship may exacerbate psychological vulnerability, potentially undermining motivation and adherence to treatment (Assaiante et al., 2014; Bertuccelli et al., 2023).

3. From biomechanics to body representation: therapeutic and educational perspectives in AIS

In recent years, increasing attention has been dedicated to highlighting the limitations of interventions focused solely on the mechanical correction of spinal curvature. While bracing and PSSE remain essential for preventing curve progression, a purely biomechanical approach may fail to address the alterations in sensorimotor representation and body awareness that recent evidence suggests can accompany the condition. In AIS, the mismatch between the internal body schema and the actual spinal morphology can lead to motor inefficiency, reduced adaptability, and difficulties in perceiving or reproducing corrective postures, which may in turn compromise the effectiveness of both exercise programs and brace treatment (Bertuccelli et al., 2023; Burwell et al., 2008). For this reason, rehabilitation should not be limited to mechanical alignment but should also aim to restore and refine sensorimotor integration processes. Even the most traditional conservative management, including bracing and PSSE, may influence body schema promoting alignment between perceived and actual body configuration (Table 1).

Curve severity (Cobb angle)	**Skeletal maturity (Risser)**	**Primary goal**	**Recommended treatment**	**Sensorimotor implications**
Mild (<25°)	0-3	Prevent progression	PSSE	PSSE may improve postural control and proprioception
Moderate (25°-40°)	0-3	Prevent progression	Bracing + PSSE	Brace wear can modify somatosensory feedback and trunk awareness

Severe (>40°)	Any	Correct deformity	Surgical correction	Structural realignment requires sensorimotor recalibration during postoperative rehabilitation
Any	≥4 (stable curves)	Maintain and improve function	Physical activity + long-term follow-up	Focus on postural maintenance and proprioception

Table 1. Treatment recommendations for AIS according to SOSORT guidelines and their sensorimotor implications.

Several complementary strategies can also be proposed. Exercises that explicitly target body awareness, such as tasks requiring patients to explore trunk position and symmetry through proprioceptive feedback, tactile cues, or mirror control, can enhance perceptual accuracy and help recalibrate the internal representation of posture (Monticone et al., 2014). These exercises encourage patients to actively recognize their trunk position in space, perceive asymmetries, and seek a more functional postural alignment (Lee, 2016; Marin et al., 2021). Mirror feedback is one of the most commonly used strategies, as it allows individuals to compare their internal body representation with external visual information (Berdishevsky et al., 2016). Proprioceptive activities, including balance maintenance with closed eyes or on unstable surfaces, can increase reliance on somatosensory information and improve postural control (Berdishevsky et al., 2016; Piątek et al., 2020). Conscious breathing practices, often integrated into postural training or relaxation routines, can also play an important role in enhancing awareness of thoracic mobility and trunk orientation (Berdishevsky et al., 2016; Kato et al., 2019; Koumbourlis, 2006).

Sensorimotor training protocols that combine modern technologies represent another promising approach. Virtual reality environments, postural biofeedback systems, and balance platforms provide enriched multisensory stimulation that stimulates the CNS to integrate visual, vestibular, and proprioceptive information more effectively (Cheung et al., 2022; Fazeli Veisari et al., 2025). In particular, virtual reality systems enable the creation of immersive environments where patients can explore, adjust, and correct their posture in response to interactive stimuli (Fazeli Veisari et al., 2025). Postural biofeedback, delivered through visual, auditory, surface electromyography (sEMG)-based posture training, or haptic cues, can provide real-time information about trunk orientation, helping patients refine motor control strategies, achieve more symmetrical paraspinal muscle activity, and develop more efficient postural adjustments (Cheung et al., 2022). Recent evidence also suggests that combining virtual reality and/or biofeedback with traditional corrective exercises may accelerate learning and enhance motivation, yielding benefits at both neural and behavioral levels (Lüddecke & Felnhofer, 2022; Riva et al., 2019).

Integrative cognitive motor techniques, such as dual-task training or multimodal programs that combine strength, coordination, and awareness exercises, may further promote cortical plasticity and facilitate the transfer of therapeutic improvements to everyday activities (Berdishevsky et al., 2016; Monticone et al., 2014).

Finally, an essential aspect of these interventions lies in patient education. Persistent distortions in body schema can have an impact on self-perception and confidence. Incorporating strategies that target body representation may therefore enhance support overall psychological well-being.

Conclusions

Converging evidence from neurophysiological, neuroimaging, and biomechanical research supports the idea that sensorimotor integration and body representation may play a role in the etiology and progression of AIS. At the central level, neurophysiological and neuroimaging studies have revealed atypical cortical oscillatory patterns and morphological asymmetries, suggesting that postural and motor control in AIS can involve greater cortical engagement. Studies employing force platforms and motion analysis have also reported impaired postural stability and increased sway, particularly under conditions of altered sensory input. Nevertheless, current evidence remains fragmented due to methodological heterogeneity, small sample sizes, and the predominance of cross-sectional designs. As a result, it is still unclear whether sensorimotor alterations represent causal factors in the development and progression of AIS or secondary adaptations to spinal deformity. Longitudinal studies will therefore be important in the future to clarify temporal relationships and determine whether targeted interventions can modulate central and peripheral markers of sensorimotor integration over time.

Emerging evidence also highlights the potential for rehabilitation strategies to influence these sensorimotor processes. Traditional conservative management, when integrated with educational and innovative approaches, such as biofeedback, virtual reality, and cognitive-motor training, could promote cortical reorganization and refine motor control strategies. Therefore, research in AIS should continue to advance in this area, with the goal of translating these initial findings into clinical practice. Integrating this knowledge into patient care can lead to more personalized treatment strategies, which may be more effective and result in improved global outcomes.

Author contributions

Maria Chiara Maccarone conceived the manuscript, conducted the literature review, interpreted the data, and wrote the manuscript. She approved the final version of the paper.

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