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Review Article

Emerging Role of gait analysis in the Diagnosis of spinal cord injury

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Abstract

Background: Spinal cord injury (SCI) disrupts the descending and ascending pathways that coordinate walking, and gait disturbance is often the earliest and most visible functional signature of the lesion, yet bedside neurological examination alone captures this locomotor consequence only coarsely.

Objective: This review examines the emerging role of clinical and instrumented gait analysis, ranging from timed walking tests to wearable sensors and three-dimensional motion capture, as a diagnostic and prognostic adjunct in the assessment of spinal cord injury.

Methods: We synthesized the peer-reviewed literature on the pathophysiology of post-SCI gait disturbance, the principal gait assessment modalities in current use, and their evidence base for diagnosis, localization, and prognosis of ambulatory outcome.

Findings: Quantitative gait metrics localize dysfunction to specific spinal segments and tracts with greater granularity than manual motor testing, predict eventual ambulatory outcome from measurements taken early in rehabilitation, and are sensitive to change during locomotor training and neuromodulation interventions; wearable sensors and markerless motion capture are narrowing the practical gap between laboratory-grade precision and routine clinical feasibility.

Conclusions: Gait analysis is maturing from a specialized research tool into a clinically meaningful adjunct to the neurological examination in spinal cord injury, and continued development of standardized, portable, and multimodal gait assessment protocols is likely to accelerate its integration into routine diagnostic and rehabilitation pathways.

Keywords: spinal cord injury; gait analysis; gait kinematics; wearable sensors; locomotor rehabilitation

1. Introduction

Spinal cord injury (SCI) disrupts the descending motor and ascending sensory pathways that coordinate walking, and the resulting gait disturbance is often the first and most visible functional signature of the lesion. Traditional bedside diagnosis relies on the American Spinal Injury Association (ASIA) Impairment Scale, manual muscle testing, and sensory mapping, all reproducible but coarse, and none directly quantifies the locomotor consequence of incomplete injury [1]. Because incomplete cervical and thoracic SCI often spares some corticospinal and propriospinal input to the lower limbs, patients can retain the capacity to walk while still carrying clinically important deficits in speed, symmetry, and coordination that manual examination cannot resolve precisely [2]. Gait analysis, from simple timed walking tests to three-dimensional motion capture, offers a quantitative window onto this residual locomotor function, and interest in incorporating it into the diagnostic and prognostic pathway for SCI has grown steadily [3].

The rationale for using gait analysis diagnostically rests on several converging observations. Spatiotemporal parameters such as walking speed, cadence, and step length asymmetry correlate with injury severity and level more tightly than global ordinal scales in many cohorts [4]. Kinematic and electromyographic signatures of specific pathways, such as reduced ankle push-off or abnormal hip-knee coupling, can localize dysfunction in ways a manual motor score cannot [5]. Gait metrics are also sensitive to change over short intervals, making them useful both for diagnosis and for tracking recovery during rehabilitation [6]. This review synthesizes the evidence on gait analysis as a diagnostic and prognostic adjunct in SCI, covering pathophysiology, the principal analytic modalities, the evidence for diagnosis and prognosis, and barriers to clinical adoption.

2. Pathophysiology of Gait Disturbance After Spinal Cord Injury

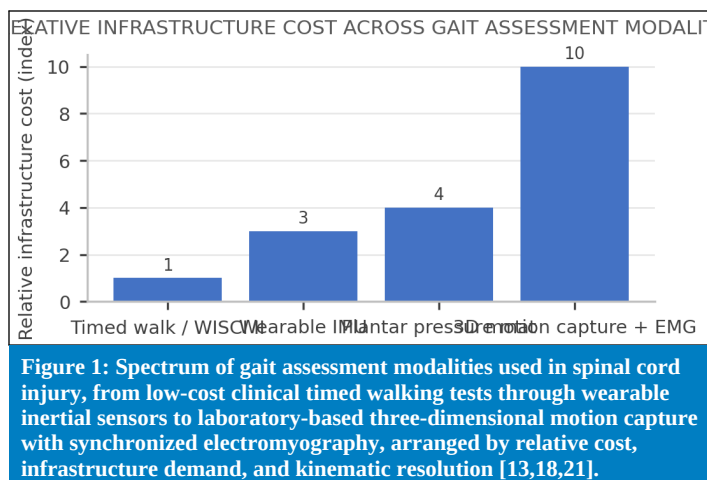
Locomotion depends on a distributed network spanning supraspinal centers, spinal interneuronal circuits capable of generating rhythmic stepping even without descending drive, and peripheral sensory feedback from muscle spindles, tendon organs, and cutaneous receptors that continuously updates the pattern generator [7]. SCI interrupts this system at multiple levels: corticospinal fibers are damaged in proportion to lesion severity, propriospinal relays coordinating inter-segmental timing are disrupted, and proprioceptive feedback needed for online correction of foot placement is degraded [8]. The resulting clinical gait pattern, whether spastic, ataxic, or mixed, reflects the relative sparing of these subsystems rather than any single deficit, which is part of why gait phenotype in incomplete SCI is so heterogeneous across patients with similar neurological levels [9].

Spasticity, a near-universal accompaniment of incomplete SCI above the lumbar cord, complicates the relationship between structural injury and observed gait, since it can impede stepping through co-contraction and clonus or, at moderate levels, provide extensor tone that assists weight-bearing [10]. Central pattern generator circuitry in the lumbosacral cord retains substantial capacity to produce alternating flexor-extensor activity even when largely disconnected from supraspinal input, most dramatically demonstrated by epidural and pharmacological stimulation studies evoking stepping-like electromyographic bursts in clinically complete injury [11]. This residual circuitry means gait analysis captures the net output of a distributed sensorimotor system rather than a single descending command, which is why quantitative gait metrics reveal function invisible to manual motor examination [12].

3. Clinical and Instrumented Gait Assessment Modalities

The simplest quantitative gait tools are timed performance tests, principally the 10-meter and 6-minute walk tests, both validated for reliability and

responsiveness in ambulatory SCI populations and adopted widely because they need no specialized equipment [13]. The Walking Index for Spinal Cord Injury (WISCI II) extends this by grading the assistive devices and personnel required for ambulation, an ordinal but clinically intuitive scale that correlates with neurological impairment [14]. These clinical tools are the entry point of gait assessment but are limited by ceiling effects in higher-functioning patients and cannot characterize the underlying kinematic or muscular abnormality driving impaired performance [15].



Three-dimensional optical motion capture, using reflective markers tracked by multi-camera arrays, remains the reference standard for kinematic analysis, yielding joint angle trajectories and derived indices such as the gait deviation index that summarize overall pattern abnormality, building on biomechanical conventions established well before SCI-specific applications emerged [16,17,18]. Synchronized surface electromyography adds a diagnostic layer by revealing the timing of muscle activation relative to the gait cycle, exposing co-contraction of antagonist muscle pairs characteristic of spastic gait [5]. Instrumented treadmills with embedded force plates, originally developed for locomotor training, have themselves become monitoring tools, since ground reaction force asymmetry recorded during supported treadmill walking tracks neurological recovery over the

subacute period [19].

More recently, wearable inertial measurement units (IMUs) have emerged as a lower-cost, portable alternative capable of capturing spatiotemporal and some kinematic parameters during community ambulation, which optical systems cannot do [20]. Studies comparing IMU-derived metrics against laboratory motion capture in SCI cohorts report good to excellent agreement for spatiotemporal parameters and moderate agreement for joint angles, supporting their use for longitudinal monitoring [21]. Plantar pressure and force plate systems characterize loading asymmetry and abnormal center-of-pressure trajectories accompanying impaired distal motor control, relevant to fall-risk assessment in ambulatory SCI [22].

4. Diagnostic Value: Localizing and Characterizing Injury

A central diagnostic promise of gait analysis is its capacity to reveal impairment patterns that map onto specific neurological levels and tracts with more granularity than the ASIA examination alone. Kinematic studies of incomplete cervical SCI have shown that reduced peak ankle power during push-off correlates specifically with corticospinal tract integrity measured by motor evoked potentials, a functional counterpart to electrophysiological localization [5]. Asymmetric hip and knee flexion during swing has been linked to lateralized corticospinal involvement in Brown-Séquard-type presentations, a correlation not reliably captured by manual muscle testing, which samples strength but not intralimb coordination [3].

Electromyographic co-activation patterns provide complementary diagnostic information. Excessive, prolonged co-contraction between the tibialis anterior and triceps surae during stance, a hallmark of spastic paraparesis after incomplete cervical or thoracic SCI, correlates with clinical spasticity scores, and its resolution during rehabilitation tracks with functional gains that spasticity scales alone underrepresent [7]. In ataxic gait

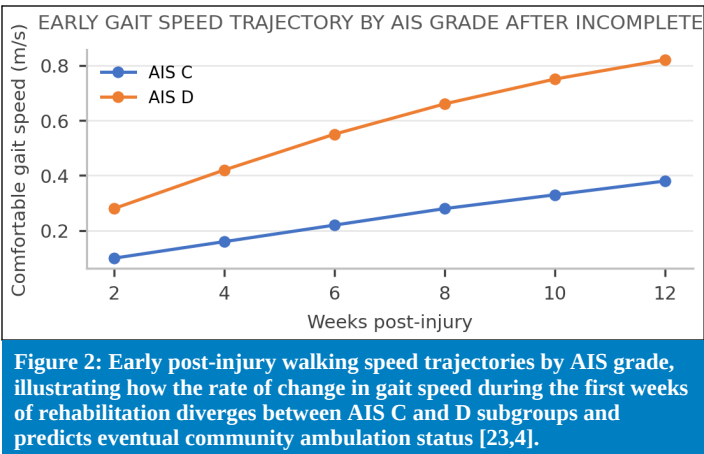
following dorsal-column-predominant injury, gait analysis reveals increased step-to-step variability of foot placement and trunk sway, a far more sensitive index of proprioceptive loss than bedside joint-position-sense testing [15]. Together these findings support gait analysis not as a replacement for the neurological examination but as a functional extension of it.

Table 1: Representative gait analysis findings and their proposed neurological correlates in incomplete spinal cord injury [5,3,7,15].		
Gait finding	Measurement modality	Proposed neurological correlate
Reduced peak ankle push-off power	3D kinematics / kinetics	Corticospinal tract integrity
Asymmetric hip/knee flexion in swing	3D kinematics	Lateralized corticospinal involvement
Prolonged tibialis anterior-triceps surae co-contraction	Surface electromyography	Spasticity / impaired reciprocal inhibition
Increased step-to-step foot placement variability	3D kinematics / IMU	Dorsal column proprioceptive loss

5. Prognostic and Monitoring Applications

Beyond diagnosis at a single time point, gait analysis has an established role in predicting and tracking recovery of ambulatory function. Early spatiotemporal gait parameters, particularly walking speed and step length symmetry obtained during the first weeks of rehabilitation, predict long-term ambulatory outcome with accuracy comparable to or exceeding models built solely on ASIA motor scores, particularly in AIS C and D subgroups where recovery is most heterogeneous [4]. Serial gait metrics, including the WSCI II and 10-meter walk test, show that early rate of change in walking speed is itself prognostic of eventual community ambulation status, independent of baseline severity [23]. Electrophysiological correlates recorded alongside gait add further predictive power when combined with gait-derived measures, supporting a combined neurophysiological-functional prognostic model [24]. Gait speed measured within the first three months after incomplete SCI predicts eventual ambulation status better

than admission strength scores alone, reinforcing early, standardized gait assessment [25].



Gait analysis is also central to evaluating rehabilitation interventions, including body-weight-supported treadmill training, robotic-assisted gait orthoses, and functional electrical stimulation, where kinematic and electromyographic outcomes provide mechanistic insight into how an intervention changes locomotor pattern rather than only whether overall function improved [26]. Robotic-assisted locomotor training studies have used gait kinematics to show that improvements in overground walking speed are accompanied by specific changes in hip extension at terminal stance and reduced compensatory circumduction, invisible to a global measure such as the WSCI II alone [27]. Epidural and transcutaneous spinal stimulation trials rely heavily on quantitative gait and electromyographic analysis to characterize evoked stepping patterns and demonstrate task-specific improvements [28]. Systematic reviews of locomotor training outcomes conclude that measurable gains in speed and endurance occur across several training approaches, though responder characteristics remain incompletely defined [29].

6. Barriers to Clinical Adoption

Despite this accumulating evidence, instrumented gait analysis remains far from routine in SCI clinical pathways, for reasons that are largely practical rather than scientific.

Full laboratory-based three-dimensional motion capture requires dedicated space, expensive equipment, and technical expertise in marker placement and data processing that most SCI rehabilitation centers, outside large academic hospitals, do not possess [18]. Data processing time, the need for standardized inter-session protocols, and the lack of a single, widely agreed diagnostic threshold analogous to the gait deviation index used in cerebral palsy have slowed development of SCI-specific normative databases [15].

Table 2: Comparison of gait assessment approaches used in spinal cord injury rehabilitation, weighing diagnostic resolution against practical barriers to routine clinical use [18,14,21,31].			
Approach	Resolution	Ambulatory requirement	Main barrier
Timed walk / WISCI II	Ordinal, global	Minimal stepping capacity	Ceiling effect, no kinematic detail
3D optical motion capture	High kinematic/kinetic detail	Overground or treadmill stepping	Cost, space, technical expertise
Wearable inertial sensors	Moderate kinematic detail	Community or lab stepping	Limited joint-angle accuracy vs lab systems
Surface EMG	Muscle activation timing	Any voluntary stepping attempt	Electrode placement variability, crosstalk

The broader outcome-measures literature has repeatedly flagged the absence of a consensus core gait battery as a barrier to pooling data across trials, limiting meta-analytic synthesis of gait-based diagnostic claims despite ample single-center evidence [30]. Test-retest reliability studies report generally acceptable reproducibility for spatiotemporal parameters but greater session-to-session variability for kinematic and electromyographic indices, underscoring the need for standardized protocols before threshold-based diagnostic use becomes broadly defensible [31].

Patient factors compound these technical barriers. A substantial proportion of individuals with SCI, particularly AIS A and B, are non-ambulatory and cannot generate the

gait data most instrumented protocols require, restricting the applicable population to incomplete injuries with preserved stepping capacity [14]. Fatigue, orthostatic intolerance, and bracing or assistive devices during testing introduce variability that must be controlled to allow meaningful comparison across sessions [13]. Wearable inertial sensors and simplified pressure-mat technologies are increasingly proposed as a pragmatic middle path, offering enough resolution for clinical decision-making without the infrastructure demands of full laboratory motion capture [21].

7. Future Directions

Several developments are likely to shape the next phase of gait analysis in SCI. Machine learning applied to multidimensional kinematic, kinetic, and electromyographic datasets has begun to classify injury severity and predict ambulatory outcome with accuracy exceeding simpler linear models, though external validation across independent SCI cohorts remains limited [32]. Markerless motion capture using computer vision, removing the burden of physical marker placement, has advanced rapidly in other neurological populations and is beginning to be validated in SCI gait, with early studies reporting agreement with marker-based systems sufficient for many spatiotemporal and joint-angle measures [33].

Integration of gait analysis with neurophysiological measures, including motor-evoked potentials and diffusion tensor imaging of corticospinal tract integrity, offers multimodal diagnostic panels combining structural, physiological, and functional information into a single prognostic model, an approach already showing promise in early studies correlating tract integrity with subsequent gait recovery [34]. The growing use of wearable sensors for community-based, continuous gait monitoring outside the clinic raises the possibility of detecting subtle deterioration or delayed recovery in real time, a shift from episodic laboratory assessment toward longitudinal,

ecologically valid surveillance [20]. Realizing these advances will require coordinated efforts to build large, multicenter normative and outcome databases specific to SCI, since gait signatures validated in other neurological populations do not always transfer directly to this population [3].

8. Conclusion

Gait analysis, spanning simple timed clinical tests through wearable sensors to full laboratory-based three-dimensional motion capture, has matured into a genuinely useful diagnostic and prognostic adjunct in the assessment of spinal cord injury, offering resolution of locomotor function that the ASIA examination and manual muscle testing alone cannot provide [1,4]. Its diagnostic value lies chiefly in translating structural and physiological injury patterns into quantifiable movement and muscle activation abnormalities that localize dysfunction and track its evolution during recovery, while its prognostic value lies in the demonstrated capacity of early gait metrics to forecast eventual ambulatory outcome [5,23]. The principal obstacles to routine adoption are practical rather than scientific: cost, infrastructure, technical expertise, and the restriction of most protocols to ambulatory or near-ambulatory patients [18,14]. Wearable sensors, markerless motion capture, and multimodal integration with neurophysiological and imaging biomarkers offer plausible paths past these barriers, and as normative and outcome databases specific to SCI mature, gait analysis is likely to move from a research tool used at a handful of specialized centers toward a standard component of the diagnostic and monitoring pathway for this population [33,34].

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