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Review Article

Emerging Role of gait analysis in the Diagnosis of traumatic brain injury

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Abstract

Background: Gait disturbance is among the most common and functionally consequential sequelae of traumatic brain injury (TBI), yet it is frequently underrecognized by routine bedside neurological examination alone [5,6].

Objective: This review synthesizes the evidence on gait disturbance after TBI and evaluates the diagnostic and monitoring value of clinical and instrumented gait analysis across the injury severity spectrum.

Methods: We synthesized observational cohort studies, instrumented gait analysis validation studies, dual-task paradigm research, and wearable sensor literature addressing gait assessment in TBI and closely related neurological populations.

Findings: Gait velocity and stride variability show a severity-graded decline relative to uninjured controls and remain measurably abnormal even in patients judged to have recovered on simple ambulation status; dual-task paradigms reveal cognitive-motor interference that single-task testing misses, and wearable inertial sensors are extending quantitative assessment beyond the gait laboratory, though TBI-specific validation of these devices remains comparatively limited.

Conclusions: Instrumented and dual-task gait analysis add meaningful diagnostic and monitoring sensitivity beyond bedside functional tests in TBI, and wearable sensor technology is well positioned to bring this sensitivity into routine, longitudinal clinical use as validation evidence accumulates.

Keywords: traumatic brain injury; gait analysis; dual-task gait; wearable sensors; balance

1. Introduction

Traumatic brain injury (TBI) remains one of the leading causes of acquired disability worldwide, and gait disturbance is among its most common and functionally consequential sequelae. Population surveillance data estimate that TBI accounts for millions of emergency department visits, hospitalizations, and deaths annually, with survivors frequently left with impairments that limit community mobility long after discharge [1]. A widely cited consensus statement defined TBI as an alteration in brain function, or other evidence of brain pathology, caused by an external force, broad enough to capture the heterogeneous mechanisms, from focal contusion to diffuse axonal injury, that converge on disordered locomotor control [2]. Because gait requires coordinated cortical planning, basal ganglia and cerebellar regulation, and spinal pattern generation, a hierarchy described extensively in the motor control literature, even mild diffuse injury can produce measurable gait abnormalities before deficits are apparent on routine examination or structural imaging [3]. Kinematic and kinetic gait analysis techniques developed originally for orthopedic and pediatric neurology populations, and formalized in reference texts on normal and pathological gait, provide the measurement framework subsequently applied to acquired brain injury [4].

Clinicians have long relied on observation and simple bedside tests to judge whether a patient with TBI is safe to mobilize, but these methods are subjective and insensitive to the small deviations that predict falls, fatigue-related decline, or later cognitive-motor interference. Over the past two decades, instrumented gait analysis, spanning laboratory motion capture, pressure-sensitive walkways, and wearable inertial sensors, has moved from a research curiosity toward a plausible adjunct diagnostic and prognostic tool in TBI care. This review synthesizes what is known about gait disturbance after TBI, the clinical and instrumented methods used to characterize it, its diagnostic value across injury severities, and the

technology extending gait analysis toward point-of-care and community settings.

2. Pathophysiology of gait disturbance after traumatic brain injury

Gait abnormalities after TBI arise from a combination of direct motor pathway injury, diffuse axonal shearing, and disrupted higher-order control of balance and attention. Basford and colleagues, assessing gait and balance in a cohort with predominantly mild to moderate TBI several years post-injury, found that even patients without overt hemiparesis walked more slowly, with reduced stride length and increased double-support time relative to matched controls, and performed worse on standardized balance measures [5]. These findings established that gait deficits after TBI are not confined to patients with obvious focal motor deficits and that subtle timing abnormalities can persist for years.

Williams and colleagues, studying a broader cohort spanning mild to severe TBI, reported gait abnormalities in a substantial proportion of ambulatory patients on standardized observational protocols, with abnormality rates rising with injury severity and with associated orthopedic or vestibular injury [6]. Diffuse axonal injury disrupts the long white-matter tracts connecting frontal executive regions to brainstem and cerebellar locomotor centers, which likely explains why gait deficits so often co-occur with, and are worsened by, concurrent cognitive demand, a theme returned to below [7]. Vestibular and oculomotor injury, common after blunt head trauma, further compounds postural instability by degrading the vestibulo-ocular and vestibulo-spinal reflexes that stabilize gaze and trunk orientation during locomotion [8]. Konrad and colleagues noted that vestibular contributions to balance are particularly vulnerable to the rotational and shear forces typical of closed head trauma, which helps explain why gait deficits after TBI so often present alongside dizziness rather than as isolated motor weakness [9]. Katz-Leurer and colleagues, comparing gait

and balance across pediatric TBI, cerebral palsy, and typically developing children, found the TBI impairment pattern more closely resembled a diffuse coordination deficit than the focal spasticity of cerebral palsy, reinforcing that TBI-related gait disturbance is best understood as network-level rather than purely peripheral [10].

3. Clinical and instrumented gait assessment methods

Bedside functional tests remain first-line in TBI rehabilitation because they are quick, inexpensive, and require no specialized equipment. The Timed Up and Go test, originally validated in frail older adults, has been widely adopted in brain injury as a global mobility marker incorporating transfers, turning, and gait initiation in one timed maneuver [11]. The Berg Balance Scale and the Performance-Oriented Mobility Assessment provide complementary information on static and dynamic postural control that correlates with, but is not identical to, gait quality [12,13]. The Activities-specific Balance Confidence Scale adds a self-reported dimension that frequently diverges from performance-based scores and independently predicts activity restriction after TBI [14], while the Four Square Step Test probes multidirectional stepping demands that forward-walking tests miss, adapted from vestibular and geriatric balance practice [15]. These tools suit triage and gross tracking, but their coarse resolution limits detection of subtle deviations that instrumented analysis can quantify. Simple lower-limb strength testing remains a useful adjunct, since weakness distal to the hip commonly and modifiably contributes to slowed, asymmetric gait after TBI [16].

Instrumented gait analysis, via optoelectronic motion capture, pressure-sensitive walkways, or force-plate treadmills, provides continuous spatiotemporal measures (velocity, cadence, stride length, step width, double-support time) and, where captured, joint-level kinematics and kinetics. Wren and colleagues, reviewing

clinical gait analysis across neurological populations, concluded that instrumented assessment changes treatment decisions and improves outcomes relative to observation alone in a meaningful proportion of cases, informing its gradual extension from cerebral palsy clinics into adult brain injury services [17]. Baker's methodological review emphasized that the clinical value of instrumented data depends on standardized protocols, appropriate normative comparison, and integration with the broader clinical picture rather than isolated thresholds [18]. Cimolin and Galli argued that summary indices, condensing many raw kinematic variables into a single deviation score, make instrumented data more interpretable for non-specialist clinicians [19]. McFadyen and colleagues extended assessment beyond level-ground walking, showing that patients with good apparent recovery still had measurable deficits in obstacle negotiation, stair climbing, and dual-task locomotion that overground timed tests alone missed [20], supporting a layered strategy of bedside screening supplemented by instrumented analysis of demanding tasks when covert deficits are suspected.

Table 1: Commonly used bedside and instrumented gait and balance assessment tools in traumatic brain injury rehabilitation [11,12,13,15,18].			
Tool	Primary domain	Typical setting	Key reference
Timed Up and Go	Global functional mobility	Bedside / clinic	[11]
Performance-Oriented Mobility Assessment	Static and dynamic balance	Bedside / clinic	[12]
Berg Balance Scale	Static and dynamic balance	Bedside / clinic	[13]
Four Square Step Test	Multidirectional stepping	Clinic	[15]
Instrumented gait analysis (motion capture / walkway)	Spatiotemporal and kinematic parameters	Gait laboratory	[18]

4. Diagnostic and discriminative value of gait parameters

A central question is whether gait parameters discriminate TBI patients from controls and scale with severity. Gait

velocity is the most consistently affected parameter, with patients across the mild-to-severe spectrum walking measurably slower than matched controls, tracking broadly with severity classification and residual balance impairment [5,6]. Stride length reduction and increased step time and step width variability follow a similar gradient and have been proposed as more sensitive markers of subtle central nervous system involvement than velocity alone, since variability reflects consistency of motor output rather than its average magnitude [21].

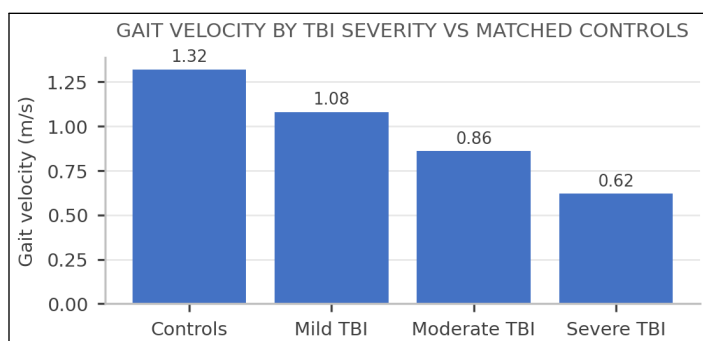


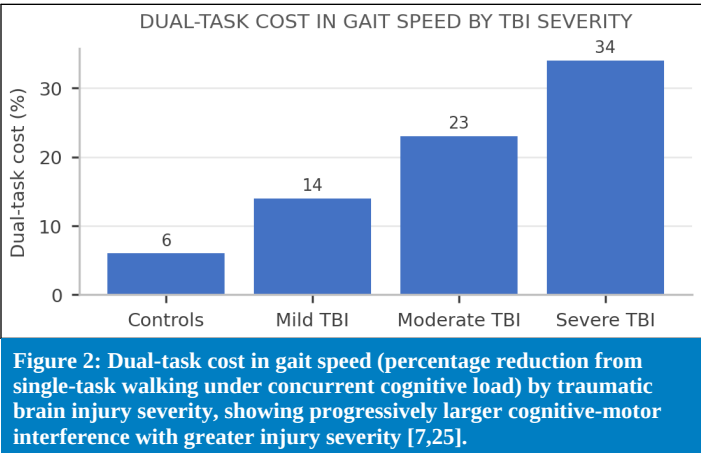
Figure 1: Mean self-selected gait velocity by traumatic brain injury severity relative to matched uninjured controls, illustrating the severity-graded slowing reported across observational and instrumented cohorts [5,6].

Repeatability is an important prerequisite for diagnostic use: Williams and colleagues found acceptable test-retest reliability for gait speed and timed walking in TBI, supporting their use as monitoring and trial outcomes, though reliability was lower for tasks requiring more complex motor planning such as obstacle crossing [22]. Kuys and colleagues, tracking gait speed longitudinally during inpatient rehabilitation, found speed improved steadily but remained below community-ambulation benchmarks at discharge for many patients, underscoring that instrumented speed is as useful for discharge planning as for initial characterization [23]. Taken together, gait velocity and variability are practical, moderately sensitive markers for flagging covert impairment and tracking recovery, while single-parameter, single-time-point interpretation should be avoided, particularly early after injury when spontaneous recovery is still occurring [24].

5. Dual-task and cognitive-motor interactions in gait after traumatic brain injury

Because walking safely in daily life requires simultaneous cognitive processing, attention, conversation, decision-making at intersections, dual-task paradigms have become an important extension of gait analysis in TBI. Yogev-Seligmann and colleagues argued that gait is far more cognitively demanding than traditionally assumed and that dual-task interference reveals functional reserve single-task assessment cannot [7]. In TBI, adding a concurrent cognitive load such as serial subtraction or verbal fluency during walking produces disproportionately larger reductions in speed and increases in variability than the same manipulation in healthy controls, a dual-task cost that scales with injury severity and persists beyond apparent single-task recovery [25].

Muir-Hunter and Wittwer's review of dual-task gait testing as a fall-risk predictor in older adults found consistent associations between elevated dual-task cost and prospective falls, motivating similar predictive work in TBI given the fall risk this group shares with frail older adults [26]. Because dual-task paradigms probe the integration of cognition and locomotion rather than either domain alone, they may be particularly suited to detecting the diffuse, network-level disruption characteristic of TBI, complementing single-task measures more sensitive to focal motor pathway involvement.



6. Wearable sensor and technology-based approaches

Translation of gait analysis from the motion-capture laboratory to clinical and community settings has been driven largely by wearable inertial sensors. Muro-de-la-Herran and colleagues described how accelerometer- and gyroscope-based devices can approximate laboratory-grade spatiotemporal, and increasingly kinematic, measures at a fraction of the cost and footprint [27]. Tao and colleagues catalogued the growing use of body-worn sensors across neurological populations, noting that sensor placement, sampling rate, and processing algorithm all materially affect derived-parameter accuracy, and that validation against gold-standard motion capture remains uneven [28]. Iosa and colleagues reviewed inertial sensors for movement analysis in rehabilitation, highlighting suitability for longitudinal, in-clinic and take-home monitoring impractical with laboratory-bound systems [29]. Howcroft, Kofman, and Lemaire's review of inertial fall-risk assessment in geriatric populations offers a template TBI researchers have begun to adapt, given the mechanistic overlap between fall risk in frail aging and acquired brain injury [30].

Early feasibility work applying wearable sensors within TBI cohorts suggests that metrics from a single lumbar- or ankle-worn sensor can distinguish patients from controls

with reasonable accuracy and track change over rehabilitation, though large-scale validation against clinical outcome and laboratory motion capture in TBI-specific samples remains limited [31]. Virtual reality and treadmill-based training platforms incorporating real-time gait feedback are a related, rapidly growing application of the same sensor technology, extending its role from assessment into therapy [32]. Split-belt treadmill paradigms, driving the two limbs at different speeds, have probed locomotor adaptation and interlimb coordination after central nervous system injury; the resulting adaptation curves offer a further quantitative window on gait plasticity that overground walkway analysis cannot capture, though TBI-specific application remains early and exploratory [33]. Williams and Schache proposed a conceptual framework for retraining high-level mobility skills, including running, cutting, and obstacle negotiation, arguing that treatment targets should be selected using the same instrumented analysis used for diagnosis so progression is guided by measured deficit rather than generic protocol [34].

Table 2: Wearable and portable technologies extending gait analysis beyond the laboratory, with their principal reported application [27,28,29,30].			
Technology	Principal measure	Reported application	Key reference
Body-worn accelerometers / gyroscopes	Spatiotemporal parameters, limb kinematics	Community and clinic monitoring	[27]
Multi-sensor body networks	Segment-level kinematics	Neurological gait characterization	[28]
Single inertial measurement unit	Movement quality, symmetry	Longitudinal rehabilitation tracking	[29]
Inertial sensor fall-risk algorithms	Balance and stability indices	Fall-risk screening	[30]

7. Clinical implications and rehabilitation

The evidence supports several practical implications. First, gait assessment should extend beyond binary ambulation status to capture quantitative parameters, even with only inexpensive tools such as timed walking

tests and portable pressure walkways, because these carry prognostic and monitoring value ambulation status alone does not [17]. Second, dual-task gait assessment should be considered routinely in patients who appear recovered on single-task testing but report functional difficulty in complex real-world environments, since single-task recovery can mask cognitive-motor integration deficits relevant to return-to-driving, return-to-work, and fall-risk decisions [20,25]. Third, longitudinal outcome data from large TBI rehabilitation cohorts indicate that functional recovery, including mobility, continues well beyond the first year post-injury for a meaningful subset of patients, arguing against relying on early single-time-point gait assessment for long-term prognosis [35].

Wearable sensor technology is likely the mechanism by which quantitative gait analysis becomes routinely available outside specialist gait laboratories, provided validation studies establish TBI-specific accuracy and reliability benchmarks and clinicians receive adequate training interpreting sensor output alongside conventional assessment [27,29]. Until that validation base matures, instrumented gait analysis is best regarded as a complement to, not a replacement for, comprehensive clinical evaluation incorporating vestibular, cognitive, and musculoskeletal assessment [8].

8. Conclusion

Gait disturbance is a common, functionally important, and often underrecognized consequence of TBI across the full severity spectrum. Bedside functional tests remain appropriately central to routine triage, but instrumented gait analysis, from laboratory motion capture to portable wearable sensors, adds diagnostic sensitivity particularly valuable for detecting covert deficits in patients whose gross mobility appears recovered [5,17]. Gait velocity and variability are the most consistently useful discriminative parameters identified to date, and dual-task paradigms extend that sensitivity further by revealing cognitive-motor integration deficits invisible to

single-task testing [6,7]. As wearable sensor technology matures and TBI-specific validation accumulates, quantitative gait analysis is well positioned to move from a specialist research tool toward a routine, low-burden component of both the diagnostic work-up and the longitudinal monitoring of recovery after traumatic brain injury [27,30].

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