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Review Article

Evaluation of gait analysis as a Prognostic Tool in traumatic brain injury

Larsen A^{1*}, Hansen I² and Pedersen K³

¹Department of Clinical Rehabilitation Research, Narmada Institute of Physical Medicine, Finland

²Department of Rehabilitation Research, Euphrates Research Center for Rehabilitation Research, Norway

³Department of Rehabilitation Research, Congo Academy of Rehabilitation Research, Norway

***Address for Correspondence:** Anders Larsen, Department of Clinical Rehabilitation Research, Narmada Institute of Physical Medicine, Finland; E-mail: anders.larsen@narmada.edu

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Abstract

Background: Traumatic brain injury (TBI) frequently produces persistent gait abnormalities, yet global severity scores and imaging findings do not reliably capture the motor consequences that shape long-term functional recovery [5,6].

Objective: This review evaluates the evidence for instrumented gait analysis as a prognostic tool in TBI, covering measurement approaches, prognostically relevant gait parameters, and the link between early gait findings and long-term outcome.

Methods: We synthesized cohort studies, systematic reviews, and validation studies addressing gait instrumentation, spatiotemporal and kinematic parameters, and functional outcome in TBI populations across acute rehabilitation and long-term follow-up.

Findings: Reduced gait velocity, spatiotemporal asymmetry, and specific kinematic patterns such as stiff-knee gait and equinovarus posture are consistently associated with functional independence, discharge disposition, and assistive device dependence; wearable sensing has expanded feasible assessment settings but reliability is reduced by cognitive impairment and injury severity, and methodological heterogeneity across studies limits pooled synthesis.

Conclusions: Instrumented gait analysis provides prognostic information after TBI beyond global severity indices and should be used as a structured complement to, rather than a replacement for, established prognostic frameworks, pending larger severity-stratified studies with standardized assessment timing.

Keywords: gait analysis; traumatic brain injury; prognosis; rehabilitation; functional outcome

1. Introduction

Traumatic brain injury (TBI) remains one of the leading causes of long-term disability worldwide, and the heterogeneity of its presentation makes early prognostication one of the most persistent challenges in rehabilitation medicine [1]. Global outcome scales such as the Glasgow Outcome Scale were developed to capture broad categories of recovery, but they were never designed to detect the fine-grained motor changes that determine whether a survivor can walk safely in the community [2]. Cognitive recovery trajectories after TBI have been mapped in considerable detail [3], yet the motor domain, and gait in particular, has historically received less systematic prognostic attention despite walking ability being one of the strongest predictors that clinicians and families use informally to judge recovery [4].

Disordered walking after TBI is common rather than exceptional: population studies estimate that a substantial proportion of survivors display measurable gait abnormalities well into the chronic phase, ranging from subtle asymmetries to severe spasticity-dominated patterns that preclude independent ambulation [5]. These abnormalities arise from a combination of diffuse axonal injury, focal contusion, cerebellar and brainstem involvement, and secondary musculoskeletal changes such as contracture and disuse atrophy, and the same global injury severity score can be associated with markedly different gait phenotypes [6]. This heterogeneity is precisely why instrumented gait analysis, which quantifies spatiotemporal, kinematic, kinetic, and increasingly neuromuscular parameters of walking, has been proposed as a more sensitive and specific prognostic tool than global severity indices alone [7].

This review evaluates the evidence for gait analysis as a prognostic tool in TBI, covering the instrumentation used to capture gait, the specific parameters shown to track outcome, the evidence linking early gait findings to

functional and neurological trajectories, and the practical and methodological barriers that have limited its adoption into routine prognostic practice.

2. Instrumentation and measurement approaches

Clinical gait analysis spans a spectrum of technical complexity, from simple observational scales to full three-dimensional motion capture with synchronized force plates and electromyography [8]. Three-dimensional optoelectronic systems, following the reduction techniques first standardized by Davis and colleagues, remain the reference standard for research-grade kinematic and kinetic data, providing joint angle, moment, and power curves across the gait cycle that are far more granular than what can be judged by eye [9]. These laboratory systems, however, require dedicated space, calibration expertise, and patient cooperation over multiple gait cycles, constraints that are often incompatible with the fatigue, cognitive impairment, and behavioral disturbance common in the early post-TBI period [10].

Wearable inertial measurement units and pressure-sensitive walkways have emerged as pragmatic alternatives that preserve much of the clinical value of instrumented analysis while reducing the burden on patients and staff [11]. Accelerometer- and gyroscope-based systems can capture temporal-spatial parameters such as step length, cadence, and gait velocity directly at the bedside or on a ward corridor, and have been validated against optoelectronic systems across several neurological populations [12]. Reliability studies specific to the TBI population, however, show that measurement consistency depends heavily on gait velocity and cognitive engagement, and that test-retest reliability for step length and step width can be markedly lower in patients with more severe injury or reduced attention [13,14]. Wearable inertial sensors have also demonstrated acceptable reproducibility for temporal and spatial parameters in broader rehabilitation cohorts,

supporting their extension to bedside TBI assessment where full laboratory analysis is impractical [15]. Continuous physiological monitoring devices developed in other chronic disease populations illustrate the broader trend toward wearable sensing replacing intermittent clinic-based assessment, a trend gait analysis in TBI is now following [16]. A scoping review of sensor-based gait and balance measurement in TBI concluded that, despite growing device availability, standardized protocols for when and how to apply these tools prognostically remain underdeveloped [17]. Clinical gait analysis texts summarizing the underlying biomechanics remain the essential reference for interpreting these outputs correctly at the bedside [18].

Table 1: Comparison of gait analysis instrumentation used in traumatic brain injury research and clinical practice [8,9,11,17].			
Method	Parameters captured	Setting	Key limitation in TBI
3D optoelectronic motion capture	Kinematics, kinetics, joint moments/powers	Dedicated laboratory	Requires cooperation over multiple gait cycles
Pressure-sensitive walkway	Spatiotemporal parameters, footfall pattern	Clinic corridor	Limited capture length, no kinematic detail
Wearable inertial sensors	Step length, cadence, velocity, trunk sway	Bedside, ward, community	Reliability drops with cognitive impairment/fatigue
Observational gait scales	Qualitative pattern classification	Any clinical setting	Low sensitivity to subtle asymmetries

3. Gait parameters associated with functional outcome

Several specific gait parameters have accumulated evidence linking them to functional trajectory after TBI. Reduced self-selected walking speed is consistently the single most robust correlate of poorer community mobility and lower functional independence scores, mirroring findings from stroke and other acquired brain injury populations [19]. Spatiotemporal asymmetries, including step length and stance time asymmetry between limbs, have been associated with slower recovery of independent ambulation and a higher likelihood of

requiring an assistive device at discharge [20]. Kinematic classification systems developed specifically for TBI populations have identified recurrent patterns, including stiff-knee gait, equinovarus foot posture, and circumduction, each of which carries different implications for orthotic and surgical management as well as different natural recovery trajectories [21,22].

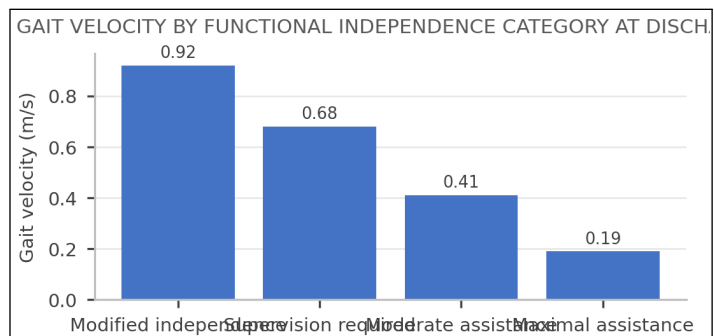


Figure 1: Self-selected walking speed by functional independence category at discharge from inpatient rehabilitation after traumatic brain injury, illustrating the consistent gradient between gait velocity and functional status reported across cohort studies [19,20].

Higher-level mobility deficits, distinct from basic walking ability, have prognostic significance of their own: patients who walk independently on level ground but struggle with stair negotiation, running, or dual-task walking often have persistent participation restrictions that basic gait speed alone fails to predict, motivating development of the High-Level Mobility Assessment Tool specifically for this population [23]. Balance and postural control parameters captured during gait, including trunk sway and centre-of-pressure excursion, have similarly been linked to fall risk and to broader measures of perceived quality of life during community reintegration [24,25]. Neuroimaging correlation studies add mechanistic weight to these behavioral findings: regional grey matter volume loss and diffusion tensor imaging metrics of white matter integrity correlate strongly with gait and postural control impairment in young TBI survivors, suggesting that gait parameters may serve as an accessible behavioral proxy for underlying structural damage that would otherwise require advanced imaging to detect [26,27].

4. Early gait findings and long-term prognosis

The prognostic value of gait analysis depends substantially on when in the recovery course it is applied. Studies obtaining gait data during acute inpatient rehabilitation have found that early spatiotemporal parameters, particularly gait velocity and cadence measured within the first weeks after injury, predict functional independence measure scores and discharge disposition with meaningful accuracy, adding predictive value beyond admission Glasgow Coma Scale and imaging severity scores alone [28]. This finding is consistent with broader prognostic work showing that physiological and functional measures often outperform purely radiological severity indices in predicting meaningful outcome after TBI [29].

Longitudinal cohorts extending gait assessment into the chronic phase, two, five, and even ten years post-injury, have shown that gait abnormalities identified early do not uniformly resolve, and a substantial subset of patients with abnormal early gait patterns remain symptomatic and functionally limited at long-term follow-up, reinforcing gait analysis as a durable rather than transient prognostic signal [30]. Age at injury interacts with this trajectory: older adults with TBI show slower and less complete recovery of ambulatory independence than younger cohorts with comparable injury severity, a pattern documented in multicenter functional outcome studies and relevant to interpreting gait-based prognosis across the age spectrum [31]. Systematic review evidence assessing gait and balance deficits broadly across the TBI population confirms that abnormalities are frequent, heterogeneous in pattern, and only partially explained by conventional severity classification, which is the central rationale for using instrumented gait findings as an independent prognostic input rather than a mere corollary of injury severity [5,20].

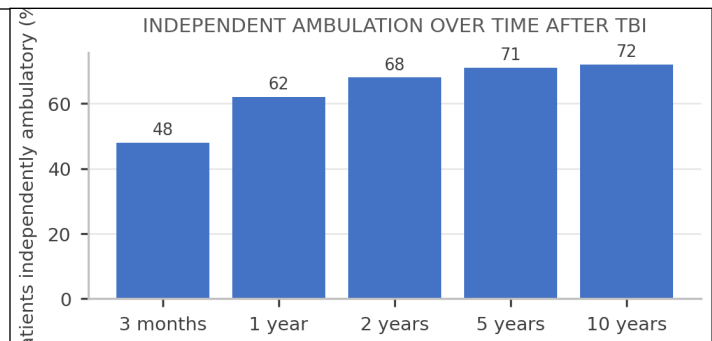


Figure 2: Proportion of patients ambulating independently at successive follow-up intervals after traumatic brain injury, showing that a substantial subset of patients with abnormal early gait remain functionally limited at long-term follow-up [30,28].

5. Rehabilitation implications and outcome measurement

Beyond pure prognostication, gait analysis findings directly shape rehabilitation planning, and the two functions are difficult to separate in practice. Systematic reviews of rehabilitation for moderate-to-severe acquired brain injury consistently identify task-specific gait and balance training as core components of effective programs, with gait analysis findings used to target specific impairments such as equinovarus deformity or asymmetric loading for orthotic or physiotherapeutic intervention [32,22]. Broader rehabilitation medicine reviews of TBI management situate gait retraining within a multidisciplinary framework that also addresses cognitive, behavioral, and vocational recovery, underscoring that motor prognosis cannot be considered in isolation from these other domains [33].

Conceptual frameworks distinguishing capacity, the ability to perform a task under standardized conditions such as a gait laboratory, from capability and performance, how a person actually walks in daily life, are particularly relevant to interpreting gait analysis prognostically [34,35]. A patient may demonstrate near-normal gait parameters in a controlled laboratory assessment yet remain functionally limited in the complex, distraction-laden environment of community mobility, a distinction with direct implications for how

much weight clinicians should place on laboratory-derived gait metrics when counselling patients and families about long-term prognosis [35]. The International Classification of Functioning, Disability and Health offers a structured way to situate gait parameters, which sit largely at the level of body function and activity, within the broader participation and quality-of-life outcomes that ultimately matter most to patients and their families [36,37].

Table 2: Gait analysis findings and their associated rehabilitation implications and prognostic significance in traumatic brain injury [21,22,23,32].

Gait finding	Typical mechanism	Rehabilitation implication	Prognostic significance
Reduced gait velocity	Global motor/cognitive slowing	Task-specific gait training	Predicts functional independence
Stiff-knee gait	Quadriceps overactivity, spasticity	Targeted physiotherapy, botulinum toxin	Slower recovery of stair/uneven terrain mobility
Equinovarus foot posture	Plantarflexor/invertor spasticity	Orthotic management, surgical referral	Higher assistive device dependence
High-level mobility deficit	Impaired dual-task/dynamic balance control	Community mobility and dual-task training	Predicts participation restriction

6. Methodological limitations and heterogeneity of evidence

The evidence base evaluating gait analysis as a prognostic tool in TBI is limited by considerable methodological heterogeneity. Sample sizes across the available studies are frequently small, injury severity definitions vary, and the interval between injury and gait assessment differs widely between cohorts, all of which complicate direct comparison and pooled synthesis [7]. Reliability data specific to the TBI population indicate that gait parameters, particularly those derived from a limited number of walked trials, can vary meaningfully between sessions in patients with cognitive impairment or fatigue, raising the possibility that a single assessment session

may not adequately represent a patient's underlying motor status [14,13].

Comparability between wearable-sensor-derived and laboratory-derived gait metrics also remains incompletely established for the TBI population specifically, even though validation work in other neurological and general clinical populations is more mature [11,12]. Findings from related but distinct populations, such as postural stability outcomes after mild TBI or concussion, are sometimes generalized to the broader moderate-to-severe TBI population without adequate justification, a pattern that risks overstating the precision of gait-based prognosis across injury severities that differ substantially in underlying pathophysiology [38]. Reliability work from adjacent rehabilitation populations, such as balance testing after stroke, is often cited by analogy in the TBI gait literature, which, while pragmatic, underscores how much of the field still depends on evidence borrowed from related but non-identical conditions [39]. These limitations do not undermine the overall direction of the evidence, but they do mean that gait analysis should currently be regarded as a valuable adjunct to, rather than a replacement for, established prognostic indices in TBI.

7. Conclusion

Instrumented gait analysis provides prognostic information after traumatic brain injury that global severity scores and imaging findings alone do not fully capture, particularly with respect to functional independence, discharge disposition, and long-term community mobility [28,30]. Reduced gait velocity, spatiotemporal asymmetry, and specific kinematic patterns such as stiff-knee gait or equinovarus posture each carry identifiable prognostic and rehabilitative significance [19,21], while higher-level mobility and balance parameters extend this prognostic reach into the participation domain that ultimately determines quality of life after injury [23,25]. Wearable and portable sensing technologies have made gait assessment more feasible

across the continuum of TBI care, but reliability constraints tied to cognitive impairment and injury severity, together with persistent methodological heterogeneity across the published literature, mean that gait analysis is best used as a structured complement to existing prognostic frameworks rather than a stand-alone replacement for them [17,7]. Future work incorporating larger, severity-stratified cohorts with standardized assessment timing, alongside imaging correlates of gait impairment, is needed before gait analysis can be formally incorporated into TBI prognostic algorithms [26,27].

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