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Review Article

Emerging Role of gait analysis in the Diagnosis of post-stroke hemiparesis

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Abstract

Background: Hemiparesis after stroke disrupts nearly every measurable feature of walking, and visual bedside description of "hemiplegic gait" is too coarse to reliably guide targeted rehabilitation or to track recovery over time.

Objective: This review synthesizes the published evidence on gait analysis as a diagnostic and classification tool in post-stroke hemiparesis, spanning kinematic, kinetic, electromyographic, spatiotemporal, and wearable sensor-based methods.

Methods: We reviewed laboratory-based motion capture and force-plate studies, electromyographic investigations, wearable and accelerometer-based monitoring studies, and cluster-analysis classification work addressing hemiparetic gait after stroke.

Findings: Kinematic analysis consistently identifies reduced ankle dorsiflexion, diminished knee and hip motion, and compensatory circumduction on the paretic side; spatiotemporal asymmetry and reduced paretic propulsion measured by ground reaction force each carry independent diagnostic information beyond gait speed alone; cluster-based classification of kinematic and kinetic data separates patients into clinically distinct subgroups; and wearable inertial sensors extend assessment from brief laboratory sessions into everyday community walking.

Conclusions: Quantitative gait analysis has matured from a descriptive research tool into a genuinely diagnostic one, capable of identifying specific, targetable impairments underlying post-stroke hemiparesis, and continued integration of wearable sensing with laboratory-derived classification schemes is likely to bring this capability into routine clinical use.

Keywords: gait analysis; post-stroke hemiparesis; hemiplegic gait; gait asymmetry; wearable sensors

1. Introduction

Walking is one of the first functions clinicians use to judge recovery after stroke, and one of the most reliably disrupted. Hemiparesis, the partial weakness that follows damage to the contralateral corticospinal pathways, changes nearly every measurable feature of gait: step timing, stride distance, joint rotation at the hip, knee, and ankle, and the muscle activation bursts that drive each phase of stance and swing. Perry and colleagues, working from one of the earliest clinical gait laboratories dedicated to stroke, showed that walking handicap in this population is a graded spectrum, from patients who cannot bear weight on the paretic limb at all to those who walk at near-normal community speeds with only subtle residual deviations [1]. That heterogeneity is why gait analysis has moved from a research curiosity into a practical diagnostic tool: a bedside description of "hemiplegic gait" is too coarse to guide targeted rehabilitation, while a quantified account of which specific deviation drives a given patient's disability can point at a treatable impairment.

This review synthesizes the literature on gait analysis applied to post-stroke hemiparesis, covering classical kinematic and kinetic description, spatiotemporal and asymmetry measures, electromyographic and ground-reaction-force methods, wearable instrumented systems, and classification schemes that translate measurement into actionable categories, closing with the limitations that still separate research-grade analysis from routine diagnosis.

2. Epidemiological and Clinical Rationale for Gait Analysis

Impaired walking is nearly universal early after stroke, and even survivors who regain independent ambulation often never return to their prior level of community mobility. Cohorts following patients from the acute phase through six months after severe middle cerebral artery stroke show that the trajectory toward independent walking can be

predicted from early impairment measures, though the accuracy depends heavily on which variables are captured [2]. Kwakkel and colleagues, reviewing recovery patterns broadly, argued that gait recovery follows a proportional pattern in most patients, with the achievable ceiling set largely by initial deficit severity, making early accurate characterization clinically important rather than merely descriptive [3].

Community ambulation requires substantially higher gait speed and endurance than many rehabilitation programs test, and Lord and colleagues found it both highly valued by patients and predictable from a small set of quantifiable gait and balance measures obtained before discharge [4]. Because misjudging walking capacity carries real consequences, either unnecessary restriction or a preventable fall, the case for instrumented over purely visual assessment has become central in stroke rehabilitation. Wren and colleagues, reviewing the efficacy of clinical gait analysis broadly, concluded that instrumented analysis meaningfully changes treatment decisions in a substantial share of cases, a finding directly relevant to a population in which visual gait assessment is notoriously variable between observers [5].

3. Kinematic Characteristics of Post-Stroke Hemiparetic Gait

The kinematic signature of hemiparetic gait was described well before instrumented systems became widely available, and the classical account by Olney and Richards remains the reference point for newer technologies. Their joint-angle analysis identified a consistent constellation on the paretic side: reduced peak knee flexion during swing, diminished ankle dorsiflexion at initial contact and stance, and compensatory circumduction or hip hiking used to clear a limb that cannot adequately advance through normal knee and ankle motion [6]. Chen and colleagues extended this by comparing hemiparetic patients with controls walking at matched speeds, showing that many kinematic differences persist even

when speed is controlled for, indicating hemiparetic gait is qualitatively distinct rather than simply a slowed version of normal gait [7].

Table 1: Principal joint-level kinematic deviations of the paretic limb across the gait cycle, with the associated compensatory strategy commonly observed [6,7,8].

Gait phase	Joint-level deviation	Common compensatory strategy
Initial contact / loading	Reduced ankle dorsiflexion	Foot-flat or forefoot contact
Mid-stance	Reduced knee flexion, knee hyperextension	Prolonged single-limb support on non-paretic side
Pre-swing / toe-off	Diminished ankle plantarflexor push-off	Increased hip flexor pull-off
Swing	Reduced peak knee flexion, foot drop	Hip circumduction or hip hiking
Throughout cycle	Increased trunk lateral flexion to paretic side	Widened base of support

Trunk and proximal kinematics have received growing attention as an extension of the classical distal-joint description. Van Criekinge and colleagues, reviewing trunk biomechanics systematically, found consistent increased trunk lateral flexion toward the paretic side and altered rotation timing, reflecting both the underlying weakness and a compensatory balance strategy [8]. Boudarham and colleagues, examining kinematic variability across repeated sessions, showed these deviations are reasonably reproducible within an individual, supporting a single instrumented session as a meaningful diagnostic snapshot [9]. Regression work by Olney and colleagues tied specific kinematic and kinetic variables directly to gait speed, establishing which deviations carry the most clinical weight [10].

4. Spatiotemporal Parameters and Gait Asymmetry

Spatiotemporal parameters, cadence, step length, stance and swing duration, and double support time, are the most widely reported outputs of clinical gait analysis because they are captured simply and map intuitively onto functional ability. Hsu and colleagues showed that strength, spasticity, and balance impairments each independently reduce gait velocity and increase

asymmetry after mild to moderate stroke, establishing that these measures integrate information from multiple impairments rather than reflecting any single deficit [11]. This integrative property is part of why gait speed has become one of the most frequently used single numbers in stroke rehabilitation, serving as outcome measure, prognostic indicator, and proxy for community ambulation potential [4].

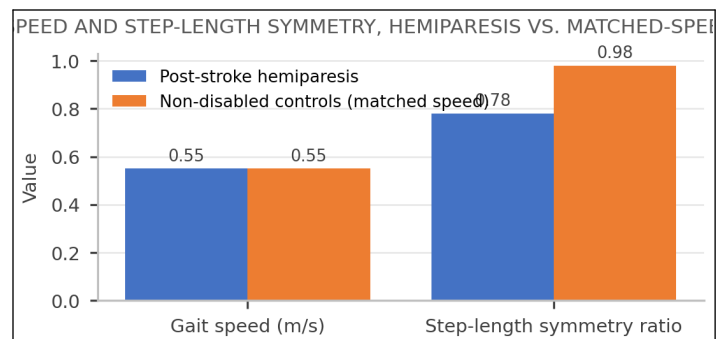


Figure 1: Comparative walking speed and paretic step length symmetry ratio in post-stroke hemiparesis versus non-disabled controls walking at matched speeds, illustrating that gait deviations persist even when overall speed is controlled for [7,12].

Asymmetry between the paretic and non-paretic limbs behaves less predictably than overall speed. Balasubramanian and colleagues found step-length asymmetry correlates with walking performance in chronic hemiparesis, but not linearly: some patients favor a longer paretic step, others the opposite, and the direction carries independent clinical meaning beyond magnitude [12]. Patterson and colleagues, studying community-ambulating survivors, confirmed asymmetry persists even after substantial functional recovery, indicating asymmetry and overall function are only partially overlapping constructs [13]. Roerdink and Beek showed the mechanism driving step-length asymmetry differs by whether the paretic or non-paretic leg controls the asymmetric swing, a distinction that changes how a given finding should be treated [14]. Wall and Turnbull's early description of asymmetry in residual hemiplegia, and Titianova and Tarkka's linkage of walking asymmetry to postural sway, together established that asymmetry extends into weight-bearing and balance control, not just

swing-phase timing [15,16]. Wonsetler and Bowden's systematic review concluded that asymmetry ratios tracked longitudinally add diagnostic information beyond speed alone about a patient's compensatory strategy [17].

5. Kinetic and Electromyographic Analysis

Kinetic analysis, using force plates to measure the ground reaction force exchanged with the floor, exposes deficits kinematic measures alone cannot. Kim and Eng showed that symmetry in vertical ground reaction force during stance does not necessarily accompany symmetry in temporal and distance variables, so a patient can appear symmetric by stopwatch while bearing weight very unevenly [18]. Bowden and colleagues extended this to anterior-posterior force, showing that the paretic limb's contribution to forward propulsion, distinct from its weight-bearing capacity, correlates with overall performance independently [19]. Nadeau and colleagues identified plantarflexor weakness as a specific limiting factor for gait speed and described compensatory hip flexor activity, linking a measurable kinetic deficit to a targetable muscle group [20].

Electromyography complements kinetics by showing which muscles activate, when, and with what timing relative to normal gait. Den Otter and colleagues, studying how activation shifts as speed decreases toward very slow walking, provided an essential reference for interpreting hemiparetic electromyography, since much altered activity reflects a normal response to slow walking superimposed on genuinely pathological patterns [21]. Chen and colleagues showed the specific combination of kinetic and kinematic compensations changes systematically across recovery stages, so a single session is best interpreted against the patient's recovery stage rather than one universal template [22]. Buurke and colleagues, following patients longitudinally, documented which parameters change most over recovery and which remain persistently abnormal even after functional walking returns, information relevant to distinguishing a resolving

deficit from a fixed one [23].

6. Instrumented and Wearable Sensor-Based Gait Analysis

Three-dimensional motion capture and force-plate walkways remain the reference standard, but cost, space, and staffing needs have limited routine clinical use outside dedicated laboratories. Wearable sensors have substantially closed this gap. Tao and colleagues described how inertial units combining accelerometers and gyroscopes reconstruct much of the spatiotemporal, and some kinematic, gait signal outside the laboratory at a fraction of the cost of optical capture [24]. Mizuike and colleagues applied a tri-axial accelerometer to stroke patients, showing accelerometry-derived symmetry and smoothness indices correlate with clinical severity and distinguish patients from controls without a dedicated laboratory [25]. Muro-de-la-Herran and colleagues' broader overview highlighted that applications like stroke follow-up, where repeated, low-burden, real-world measurement matters more than laboratory-grade spatial precision, are best suited to wearable systems [26].

This shift matters because laboratory gait analysis captures only a brief, self-conscious walking sample that may not represent typical community mobility. Prajapati and colleagues used ambulatory accelerometry to quantify everyday walking in subacute stroke patients, finding that many who perform adequately during a short laboratory walk accumulate very little real-world activity, a discrepancy invisible to single-session analysis but directly relevant to functional diagnosis [27]. Reliability work by Kesar and colleagues, establishing the minimal detectable change for treadmill-based variables, provides the statistical grounding to distinguish genuine longitudinal change from measurement noise [28].

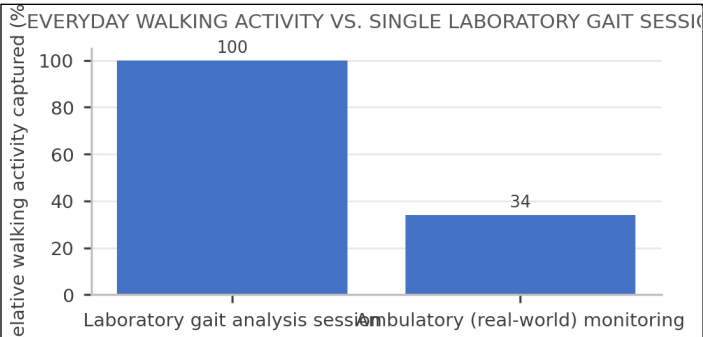


Figure 2: Relative proportion of everyday walking activity captured by ambulatory accelerometry versus a single instrumented laboratory gait analysis session in subacute stroke patients, showing the gap between brief clinic-based assessment and real-world community mobility [27,25].

7. Classification and Diagnostic Correlation

A central goal of gait analysis is classification: grouping patients into clinically meaningful subtypes pointing toward different impairments and treatment targets. Mulroy and colleagues applied cluster analysis to kinematic and kinetic data from patients in early and late recovery, identifying distinct subgroups defined by different combinations of knee and ankle deviations, and showing their relative frequency shifted between recovery phases, information a single averaged description would have obscured [29]. This directly informs treatment: a patient whose subgroup reflects inadequate ankle push-off benefits from a different intervention than one defined by excessive knee hyperextension, even at similar overall gait speed.

Correlating instrumented findings with standardized clinical tools has been essential to establishing diagnostic credibility. Flansbjerg and colleagues established the reliability of a gait performance test battery in hemiparetic patients, a foundation needed before any parameter can be used confidently in individual patients [30]. Jonsdottir and Cattaneo validated the dynamic gait index in chronic stroke, showing functional scales correlate with but do not substitute for instrumented findings, supporting a complementary relationship between bedside and laboratory-grade assessment [31]. Peters and colleagues' comparison of shorter walk tests against the standard

ten-meter walk test showed abbreviated protocols preserve much diagnostic value while reducing patient burden [32]. Tyson and colleagues, examining balance disability after stroke, reinforced that gait findings must be interpreted alongside balance assessment, since impaired postural control often underlies deviations otherwise attributed purely to weakness [33], and Cheng and colleagues showed that weight-distribution training informed by such combined assessment measurably reduces fall risk [34].

Table 2: Principal modalities used in gait analysis for post-stroke hemiparesis, the parameters each captures, and its typical clinical role [5,24,29,31].

Modality	Primary parameters captured	Typical clinical role
3D optical motion capture	Joint kinematics, segment trunk motion	Reference-standard research and subtype classification
Force-plate instrumented walkway	Ground reaction force, propulsion, weight-bearing symmetry	Kinetic deficit identification
Surface electromyography	Muscle activation timing and amplitude	Motor control and compensation assessment
Wearable IMU / accelerometry	Spatiotemporal parameters, symmetry, real-world activity	Community-based longitudinal monitoring
Standardized functional scales	Gait speed, dynamic balance, endurance	Bedside screening and outcome tracking

8. Limitations and Future Directions

Several limitations separate research-grade gait analysis from routine diagnostic use. Laboratory motion capture remains resource-intensive, and the classical literature establishing normative hemiparetic patterns, while valuable, was generated predominantly in specialized academic laboratories whose populations and equipment may not generalize to typical community settings [35]. Titianova and Tarkka's early work linking asymmetry to postural sway illustrates a broader point that persists: gait deviations are entangled with balance and proprioceptive deficits that pure gait-focused analysis cannot fully disentangle, arguing for multimodal rather than isolated

assessment [16].

The clearest path forward combines the ecological validity of wearable monitoring with the classification power of laboratory-derived taxonomies. As inertial units and machine-learning classification mature, screening for the hemiparetic gait subtypes first described through laboratory cluster analysis using inexpensive wearable sensors during ordinary daily walking becomes increasingly realistic [29,24]. This will require larger validation cohorts than the foundational studies provided, attention to how recovery trajectories interact with sensor-derived classification over time, and continued reliability work to ensure apparent longitudinal change reflects genuine recovery rather than measurement variability [2,3,28].

9. Conclusion

Gait analysis has moved from a descriptive research tool into a genuinely diagnostic one for post-stroke hemiparesis, identifying the kinematic, kinetic, spatiotemporal, and electromyographic deviations that distinguish clinically meaningful subtypes and point toward targeted rather than generic rehabilitation [6,29]. Spatiotemporal parameters and asymmetry indices remain the most accessible measures, but ground reaction force and electromyographic analysis expose deficits in paretic propulsion and muscle timing that simpler measures can miss [18,19,21]. Wearable sensors have extended this power beyond the laboratory into everyday walking, closing the gap between brief instrumented assessment and actual community mobility [24,27]. As classification, reliability standards, and sensor technology continue to converge, quantitative gait analysis is well positioned to become a routine component of diagnostic assessment after stroke.

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