Gait as a Multidimensional Neurological and Psychological Biomarker: Mechanisms, Clinical Significance, and Emerging Technologies

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Abstract

Human gait is increasingly recognized as a complex biomarker reflecting the integrated functioning of neurological, sensory, cognitive, and psychological systems. Beyond a simple mechanical process of locomotion, gait represents a dynamic expression of brain function involving coordinated activity across cortical networks, basal ganglia circuits, cerebellar pathways, brainstem locomotors centres, and multisensory feedback systems. Consequently, disturbances in gait can provide important insights into underlying neurological and psychological conditions.

This chapter examines the neurophysiological foundations of human gait and its clinical relevance as a biomarker in neurological disorders. Key components of gait—including spatiotemporal parameters, kinematic and kinetic variables, and gait variability—are discussed in relation to neural mechanisms responsible for posture, balance, and locomotors coordination. Disease-specific gait patterns observed in conditions such as Parkinson’s disease, cerebella ataxia, stroke, multiple sclerosis, and diabetic peripheral neuropathy are highlighted, emphasizing distinctive features such as bradykinesia, increased gait variability, asymmetry, impaired coordination, and altered sensory integration.

The chapter also explores the relationship between gait and psychological states, suggesting that locomotors behaviour may reflect cognitive and emotional processes. Advances in motion capture, wearable sensors, and digital gait analysis enable objective detection of subtle abnormalities, supporting early diagnosis, disease monitoring, and personalized rehabilitation. Overall, gait is presented as a multidimensional biomarker with significant diagnostic and therapeutic potential.

Keywords: Gait analysis, neurological biomarker, gait variability, neurodegenerative disorders, locomotors control, Digital Biomarkers, Wearable Sensors

1. Introduction

Human gait is increasingly recognized as more than a mechanical process of ambulation; it is a sensitive biomarker reflecting neurological, cognitive, and psychological health. Traditionally, gait analysis focused on identifying physical impairments caused by trauma, orthopaedic injuries, or neurological and metabolic disorders. However, contemporary research suggests that locomotors patterns also reflect emotional states, cognitive load, and overall mental health. Subtle variations in gait symmetry, variability, and velocity can reveal underlying neurophysiological or psychological disturbances before overt clinical symptoms emerge.

Evidence suggests that emotional and psychological conditions can influence locomotors patterns. For example, Nagano et al. demonstrated that general mental health status is associated with gait asymmetry, highlighting the potential of wearable sensors and digital gait analytics in identifying psychological correlates of locomotion.[1] These findings support the growing concept of gait as a behavioral and physiological marker that integrates brain function, emotional regulation, and sensorimotor coordination.

Gait and postural impairments are among the most common manifestations of neurological diseases (ND), including stroke, traumatic brain injury (TBI), Parkinson’s disease (PD), cerebellar ataxia (CA), and multiple sclerosis (MS). These disturbances significantly reduce independence and quality of life by limiting activities of daily living and increasing fall risk. Bonanno et al. defined gait analysis as a systematic procedure used to observe, record, analyze, and interpret locomotion, emphasizing its translational role in bridging research findings with clinical neuro-rehabilitation practices.[2]

Neurodegenerative disorders progressively damage neural circuits responsible for motor control, resulting in deterioration of postural stability, coordination, and locomotors efficiency. Distinct gait signatures often emerge across different pathologies, reflecting the underlying neural mechanisms affected in each condition. These disease-specific patterns provide valuable insights into diagnosis, disease progression, and rehabilitation strategies.[2] Consequently, gait assessment is increasingly viewed not only as a rehabilitation metric but also as a multidimensional biomarker reflecting systemic neurological and psychological function.

2. Fundamentals of Human Gait

Human locomotion is a complex motor behavior requiring precise coordination between musculoskeletal mechanics and neural control systems. Although significant technological advancements have been made in motion capture and gait analysis, a comprehensive understanding of coordinated gait development and control remains incomplete.[3] Gait represents a learned motor skill that integrates sensory feedback, central neural processing, and motor output to produce stable and efficient locomotion.

The gait cycle consists of two primary phases: the stance phase, which accounts for approximately 60% of the cycle and begins with heel strike and ends with toe-off, and the swing phase, which constitutes the remaining 40% and extends from toe-off to the subsequent heel strike. Within the stance phase, several subphases occur, including initial contact, loading response, mid-stance, and the propulsive phase. Each of these stages requires precise timing and coordination to maintain forward progression and balance.

Gait analysis commonly evaluates spatiotemporal parameters, including step length, stride length, step width, and foot progression angle. These spatial characteristics provide information about symmetry and locomotor efficiency. Temporal parameters such as stride velocity, cadence, and step time reflect the dynamic aspects of walking. Deviations in these variables can indicate impairments in neuromuscular coordination, balance control, or central motor planning.

Locomotion is regulated by a hierarchical neural system involving cortical, subcortical, and spinal mechanisms. The motor cortex plays a critical role in initiating voluntary movement and adapting locomotion to environmental demands. The basal ganglia regulate movement scaling, automaticity, and initiation. Dysfunction in basal ganglia circuits often produces bradykinetic and hypokinetic gait patterns characteristic of disorders such as Parkinson’s disease.[4]

The cerebellum contributes to the coordination and timing of movements, ensuring smooth transitions between stance and swing phases. Damage to cerebellar structures disrupts motor synergy and adaptive control, producing ataxic gait patterns characterized by instability and irregular step timing. Different cerebellar regions contribute uniquely to locomotor coordination, balance, and motor learning.

Brainstem locomotor centers also play a critical role in gait regulation. Structures such as the pedunculopontine nucleus (PPN), dorsal raphe nucleus (DRN), and gigantocellular nucleus (GiN) integrate rhythmic locomotor signals with goal-directed behavior and postural adjustments. These brainstem circuits interact with cortical and subcortical networks to regulate gait initiation, rhythm generation, and adaptive responses to environmental changes. Disruptions in these pathways increase reliance on cognitive resources during walking and may contribute to gait instability in neurological disorders.[5]

Maintaining stability during locomotion requires continuous integration of visual, vestibular, and proprioceptive inputs. Balance control operates as a dynamic closed-loop system that adjusts motor responses based on sensory feedback. Sensory weighting mechanisms allow the nervous system to prioritize the most reliable sensory input depending on environmental conditions.[6] For example, when visual input becomes unreliable, proprioceptive and vestibular signals may dominate postural control.

Research on sensory reweighting suggests that multisensory integration operates as a reliability-weighted process rather than a simple additive mechanism.[7] Reimann et al. demonstrated that visual perturbations during walking can trigger rapid ankle muscle responses, suggesting the presence of reflexive visual-spinal pathways involved in maintaining gait stability.[8] These findings highlight the complexity of neural control systems that coordinate locomotion and maintain balance during dynamic movement.

3. Gait as a Neurological Biomarker

Gait has emerged as an important biomarker for neurological function because locomotion requires the coordinated activity of multiple neural systems. Even subtle disruptions in neural networks can manifest as measurable changes in gait parameters. Age-related studies have shown that stride variability, step width, and dual-task performance progressively change with aging, demonstrating that gait metrics are sensitive indicators of neurological integrity.[9]

Gait disorders may result from lesions at any level of the nervous system, including cortical regions, basal ganglia, cerebellum, brainstem, spinal cord, or peripheral nerves. Clinically recognizable patterns such as spastic gait, ataxic gait, parkinsonian gait, frontal gait, and functional gait disturbances provide valuable diagnostic clues. Identifying these patterns allows clinicians to localize neurological deficits and implement targeted rehabilitation strategies.[10]

Meta-analytic research has demonstrated that many neurodegenerative diseases share common gait abnormalities, including increased stride-to-stride variability and disruption of fractal gait dynamics, which normally reflect the complex temporal structure of healthy locomotion. Loss of these fractal patterns indicates reduced adaptability of the locomotor control system.[11]

Different neurological disorders exhibit distinct degrees of gait variability. Huntington’s disease, for example, demonstrates the most pronounced variability due to severe basal ganglia dysfunction. Parkinson’s disease, Alzheimer’s disease, and multiple sclerosis also show increased variability, though typically to a lesser extent.[11] These findings suggest that gait variability may serve as an early indicator of neurodegeneration.

Functional gait disorders (FGD) represent another important category of locomotor disturbances. Unlike structural neurological disorders, FGDs are characterized by inconsistent and incongruent movement patterns such as *astasia-abasia*, exaggerated sway, or knee buckling without clear neurological pathology. These patterns reflect disturbances in higher-order motor control and cognitive processes. Multidisciplinary rehabilitation approaches incorporating physical therapy, psychological support, and behavioral strategies have demonstrated both short- and long-term improvements in patients with functional gait disorders.[12]

4. Disease-Specific Gait Disturbances

4.1 Parkinson's Disease

Parkinson's disease is a neurodegenerative disorder primarily affecting dopaminergic pathways in the basal ganglia. The disease is characterized by bradykinesia, rigidity, tremor, and postural instability. Gait disturbances are among the earliest and most disabling manifestations.

Individuals with Parkinson's disease often exhibit a shuffling gait, reduced stride length, decreased arm swing, and a forward-flexed posture. Stride-to-stride variability reflects impaired postural control and diminished automaticity of locomotion. Emotional states can also influence gait patterns in Parkinson's disease, affecting walking speed and trunk posture.[13]

In advanced stages of the disease, patients may experience freezing of gait (FoG)—a sudden inability to initiate or continue walking despite the intention to move. Freezing episodes significantly increase fall risk and contribute to reduced mobility and independence.

4.2 Cerebellar Ataxia

Cerebellar ataxia results from damage to cerebellar circuits responsible for coordination and motor timing. Gait in individuals with cerebellar ataxia is typically characterized by reduced cadence, shorter step length, decreased walking velocity, and increased stride time variability.[14]

Patients often adopt a wide-based gait pattern to compensate for impaired balance. Research using the Uncontrolled Manifold (UCM) framework has shown reduced synergy indices in individuals with neurological impairments, indicating diminished coordination between movement components. These deficits are associated with delayed anticipatory postural adjustments during locomotion.[15]

4.3 Stroke

Stroke frequently leads to hemiplegic gait patterns characterized by asymmetry between the affected and unaffected limbs. Lesions in different hemispheres can produce distinct spatiotemporal and kinematic gait characteristics.[16]

Patients often demonstrate reduced step length on the affected side, prolonged stance time on the unaffected side, and decreased walking speed. Dynamic balance plays a crucial role in gait symmetry, and studies have demonstrated strong correlations between balance performance and temporal symmetry in individuals with chronic stroke.[17] Rehabilitation programs focusing on balance training, task-specific gait practice, and neuromuscular reeducation can improve locomotor symmetry and functional mobility.

4.4 Multiple Sclerosis

Multiple sclerosis (MS) is a chronic inflammatory demyelinating disease affecting the central nervous system. Gait impairment is one of the most common symptoms and often occurs even in the early stages of the disease.

Typical gait characteristics in MS include reduced walking speed, shorter stride length, increased step width, decreased hip extension, reduced knee flexion, and diminished ankle power during push-off.[18] Spasticity further exacerbates gait disturbances, particularly in individuals with pyramidal involvement.

Even individuals with mild disability may exhibit significant gait impairment, indicating that locomotor deficits may develop before severe neurological decline.[19] Factors such as fatigue, sensory deficits, and impaired dual-task performance contribute to increased fall risk in this population.[20]

4.5 Diabetic Peripheral Neuropathy

Diabetic peripheral neuropathy (DPN) affects sensory and motor nerves in the lower extremities, resulting in impaired proprioception and tactile sensation. These deficits lead to characteristic gait changes including reduced walking velocity, shorter stride length, prolonged stance time, and increased knee extension moment during walking.[21]

Postural instability in individuals with DPN arises from impaired sensory feedback, particularly involving type I proprioceptive and type II tactile afferent fibers.[22] As a result, patients often rely more heavily on visual input to maintain balance.

Sensorimotor training programs that combine balance exercises, proprioceptive training, and gait rehabilitation have been shown to improve nerve function, muscular activation, and overall stability in individuals with diabetic peripheral neuropathy.[23]

5. Psychological and Cognitive Dimensions of Gait

Emerging research suggests that gait patterns are influenced not only by neurological integrity but also by psychological and emotional states. Stress, anxiety, depression, and cognitive load can alter gait velocity, stride length, and variability. These changes reflect the integration of emotional and cognitive processes within motor control networks.

Dual-task walking paradigms, in which individuals walk while performing cognitive tasks, have demonstrated that increased cognitive demand can significantly alter gait stability. This phenomenon highlights the interaction between executive function and locomotor control.

Motor coordination deficits may also represent a transdiagnostic vulnerability across neurodevelopmental disorders. Poor motor proficiency during childhood has been associated with later cognitive and psychosocial difficulties. Early motor impairments may therefore serve as indicators of broader neurodevelopmental risk, emphasizing the importance of early screening and intervention.

6. Emerging Technologies in Gait Analysis

Recent technological advances have significantly expanded the ability to measure and analyze gait in both clinical and real-world environments. Traditional gait analysis methods relied primarily on laboratory-based motion capture systems and force platforms. While these systems provide highly precise biomechanical measurements, they are expensive and limited to controlled environments.

Wearable sensor technologies—including accelerometers, gyroscopes, inertial measurement units (IMUs), and pressure sensors—now allow continuous monitoring of gait in daily life. These devices provide objective measurements of stride length, cadence, variability, and postural transitions.

Machine learning and artificial intelligence algorithms are increasingly being used to analyze large datasets generated by wearable sensors. These computational approaches can identify subtle locomotor patterns associated with early neurological disease, potentially enabling earlier diagnosis and intervention.

Integration of gait analytics with neuroimaging, cognitive assessments, and digital health platforms may further enhance the ability to detect early neurological dysfunction and monitor rehabilitation outcomes. Such multimodal approaches have the potential to transform gait analysis into a powerful clinical biomarker for personalized medicine.

7. Conclusion

Gait represents a complex motor behavior integrating biomechanical, neurological, sensory, cognitive, and emotional processes. Distinct gait signatures observed across neurological disorders provide valuable diagnostic and prognostic information. Changes such as increased variability, asymmetry, reduced velocity, and altered spatiotemporal parameters often precede overt neurological decline, making gait a sensitive indicator of underlying brain dysfunction.

Advances in wearable sensor technology and motion analysis are enabling objective quantification of subtle locomotor changes in both clinical and everyday environments. These innovations are expanding the role of gait analysis from a rehabilitation assessment tool to a comprehensive biomarker of neurological and psychological health.

Future research should focus on integrating gait analytics with neuroimaging, cognitive profiling, and digital health monitoring to improve early diagnosis, track disease progression, and optimize personalized rehabilitation strategies. Understanding gait not merely as locomotion but as a window into brain function broadens its significance in neuroscience, clinical neurology, and mental health research.

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