Feature

Gait Analysis:
From the Clinic to the Lab

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Abstract

Gait analysis is a fundamental component of physiatric evaluation, providing objective insight into locomotor function and movement disorders. Walking is a complex biomechanical activity requiring coordinated integration of musculoskeletal, neurological, sensory, and cardiopulmonary systems to achieve efficient forward progression while maintaining stability. Understanding normal gait biomechanics is essential for recognizing pathological gait patterns and interpreting quantitative gait data. Traditionally, gait assessment relied primarily on clinical observation; however, advances in motion capture systems, force platforms, electromyography, wearable sensors, and artificial intelligence have transformed gait analysis into a sophisticated multidisciplinary science. Clinical gait analysis assists rehabilitation physicians in diagnosis, treatment planning, orthotic prescription, surgical decision-making, and outcome evaluation, while laboratory-based gait analysis objectively quantifies spatiotemporal, kinematic, kinetic, and electromyographic parameters. This review discusses normal gait biomechanics, spatiotemporal gait characteristics, clinical and instrumented gait assessment, major rehabilitation applications, and emerging advances that continue to reshape locomotor evaluation. Integration of clinical expertise with modern biomechanical technologies has significantly enhanced the precision of rehabilitation interventions across neurological, orthopaedic, paediatric, geriatric, and sports rehabilitation populations.

Keywords: Gait analysis, gait cycle, rehabilitation medicine, biomechanics, kinematics, kinetics, electromyography, motion analysis laboratory.

Introduction

Walking is one of the most important functional activities performed by humans and serves as a key indicator of independence, participation, and quality of life. Efficient gait requires coordinated interaction of the musculoskeletal, neurological, sensory, and cardiopulmonary systems. Disruption of any of these components may result in gait dysfunction, leading to impaired mobility, increased risk of falls, reduced community participation, and diminished quality of life[3,4]

Assessment of gait is therefore a cornerstone of rehabilitation. Observation of walking frequently provides valuable information regarding neurological, orthopaedic, and functional impairments

Traditionally, gait evaluation was largely descriptive and dependent upon clinician experience. Although observational gait analysis remains indispensable in everyday practice, its subjective nature limits reliability and sensitivity, particularly in subtle gait abnormalities [2]

Modern gait analysis combines clinical assessment with motion capture systems, force platforms, electromyography, pressure mapping technologies, and wearable sensors to provide objective evaluation of locomotor performance[1,5]. These technological advances have transformed gait assessment from a predominantly observational skill into a quantitative scientific discipline and have improved diagnostic accuracy, treatment planning, outcome evaluation, and understanding of pathological movement patterns.

A sound understanding of normal gait biomechanics forms the foundation for interpreting both clinical observations and laboratory-derived gait data. This review discusses the principles of normal gait, methods of clinical and instrumented gait

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Biomechanical Basis of Normal Gait

Human gait is a cyclic and coordinated pattern of movement that enables forward progression of the body while maintaining postural stability and minimizing energy expenditure[3,4]. Walking requires precise integration of the musculoskeletal, neurological, sensory, and cardiopulmonary systems, and disruption of any of these components may result in gait dysfunction. The basic unit of locomotion is the gait cycle or stride, defined as the interval between two successive initial contacts of the same foot[3].

The Rancho Los Amigos terminology divides the gait cycle into eight functional intervals consisting of five stance-phase periods and three swing-phase periods. This classification emphasizes functional events during locomotion and is widely used in contemporary clinical gait analysis [3]. The gait cycle consists of two principal phases:

- Stance phase (approximately 60% of the gait cycle)
- Swing phase (approximately 40% of the gait cycle)

During stance phase, the lower extremity accepts body weight, maintains balance, and generates forward propulsion [3,6]. Initial contact and loading response are responsible for weight acceptance and shock absorption, while midstance and terminal stance maintain single-limb stability and forward progression. Pre-swing initiates limb unloading and contributes to push-off through plantar flexor activity[4]. During swing phase, the limb advances forward while maintaining adequate foot clearance and preparing for the next cycle of weight acceptance[3].

Spatiotemporal parameters provide quantitative description of walking performance and form the basis of both clinical and laboratory gait analysis[1]. Important spatial parameters include stride length, step length, step width, and foot progression angle. Reduced step length commonly occurs in Parkinson disease, painful conditions, frailty, and neurological disorders. Increased step width may reflect impaired balance, cerebellar dysfunction, or fear of falling[3,6].

Temporal parameters include stance time, swing time, cadence, stride time, single-limb support time, and double-limb support time[3]. Prolonged double-support time often indicates instability or impaired balance, while reduced single-limb support may occur in weakness, pain, or neurological impairment. Walking velocity or gait speed has been described as the “sixth vital sign” because of its strong association with functional independence, frailty, hospitalization, and survival[15]. Gait symmetry and gait variability are also clinically important because asymmetry frequently reflects neurological or musculoskeletal pathology and increased gait variability is associated with fall risk and cognitive decline in older adults[15].

Normal walking accomplishes three major functional tasks: weight acceptance, single-limb support, and limb advancement[3]. Weight acceptance occurs during initial contact and loading response and requires coordinated eccentric muscle activity to absorb impact forces while preserving stability[4]. Single-limb support during midstance and terminal stance demands adequate balance, proprioception, hip abductor strength, and postural control. Limb advancement during swing requires coordinated joint motion, limb shortening, and adequate foot clearance. Weakness, spasticity, contracture, or impaired motor control may disrupt these mechanisms and produce compensatory gait deviations such as circumduction, hip hiking, or vaulting[4,6].

To improve walking efficiency and reduce vertical and lateral displacement of the centre of mass, the body utilizes several biomechanical mechanisms collectively known as the determinants of gait[7]. These include pelvic rotation, pelvic obliquity, lateral pelvic displacement, knee flexion during stance, coordinated ankle rocker mechanisms, and knee flexion during swing. Pelvic rotation effectively lengthens the lower extremity and increases step length, while pelvic obliquity and controlled lateral displacement reduce unnecessary movement of the centre of mass[4,7]. Early knee flexion functions as a shock absorber during loading response, whereas coordinated foot and ankle rocker mechanisms preserve forward momentum and facilitate smooth progression over the supporting limb [6].

Gait analysis requires understanding not only visible movement patterns but also the forces and muscular activity responsible for locomotion[1,3]. Kinematics describes movement without consideration of the forces producing that movement. During normal walking, coordinated motion occurs at the hip, knee, ankle, and pelvis throughout the gait cycle[3]. The hip progresses from flexion at initial contact to extension during terminal stance before returning to flexion during swing. The knee flexes during loading response to absorb impact forces, extends during stance, and flexes again during swing to facilitate limb advancement[4]. The ankle undergoes controlled plantarflexion following initial contact, progressive dorsiflexion during stance, and rapid plantarflexion during push-off before returning to neutral during swing[3].

Kinetics examines the forces responsible for movement[6]. Ground reaction forces generate external moments around the hip, knee, and ankle joints that must be counteracted by coordinated muscular activity. Hip extensors stabilize the trunk during weight acceptance, quadriceps eccentrically control knee flexion during loading response, and plantar flexors generate substantial propulsive power during terminal stance and pre-swing[4,6]. Reduced ankle plantar flexor power generation is a major contributor to impaired propulsion and increased energy expenditure in stroke gait [1].

Electromyographic studies demonstrate highly coordinated muscle activation patterns during walking[8]. Hip extensors are active during early stance, dorsiflexors maintain toe clearance during swing, quadriceps stabilize the knee during loading response, and plantar flexors regulate tibial progression and generate push-off power[3,4]. Hamstrings decelerate forward limb progression during terminal swing and assist preparation for weight acceptance. Abnormal muscle activation patterns, including spasticity, co-contraction, and impaired timing, are common in neurological disorders and contribute significantly to pathological gait deviations[8].

A comprehensive understanding of gait biomechanics is essential for recognizing pathological gait patterns, interpreting instrumented gait analysis data, and developing targeted rehabilitation interventions in PMR practice[1,3].

Clinical Gait Analysis

Clinical gait analysis remains the foundation of locomotor assessment in Physical Medicine and Rehabilitation because it combines biomechanical observation with functional interpretation and rehabilitation planning[2,3]. Although advanced gait laboratories provide objective quantitative data, bedside observational gait assessment continues to play a major role in routine clinical practice due to its accessibility, low cost, and immediate applicability.

Evaluation begins with detailed history taking, including onset and progression of symptoms, falls, pain, fatigue, assistive device use, and functional limitations[3]. A focused neuromuscular examination should assess posture, joint range of motion, muscle strength, tone, coordination, balance, sensory function, and limb alignment.

Observational gait analysis is performed from anterior, posterior, and lateral views while assessing spatiotemporal symmetry, stance and swing phase transitions, trunk and pelvic movements, arm swing, foot clearance, heel strike, and compensatory strategies[2]. Physiatric gait assessment emphasizes interpretation of the relationship between impairments, compensations, and functional limitations rather than merely describing visible abnormalities.

Recognition of compensatory mechanisms is particularly important because many gait deviations are secondary adaptations. Circumduction, hip hiking, and vaulting commonly compensate for impaired foot clearance, while trunk lean in Trendelenburg gait may partially compensate for hip abductor weakness [4,6].

Characteristic pathological gait patterns provide valuable diagnostic clue as illustrated in Table 1.

Table 1: Pathological Gait Patterns

Gait pattern	Key features	Common causes
Hemiplegic	circumduction, hip hiking, equinus	stroke
Parkinsonian	shuffling, festination, reduced arm swing	Parkinson disease
Steppage	high stepping, excessive hip & knee flexion	foot drop
Trendelen-burg	pelvic drop, trunk lean	hip abductor weakness
Cerebellar	broad base, instability	cerebellar lesion

Simple clinical tools such as the Timed Up and Go Test, 10-Meter Walk Test, 6-Minute Walk Test, and smartphone-based video analysis improve assessment reliability and facilitate outcome monitoring[5,10]. Despite its limitations, clinical gait analysis remains indispensable because it provides functional context that cannot be fully captured by laboratory-derived numerical data[2].

Instrumented Gait Analysis and Modern Gait Lab

Instrumented gait analysis objectively quantifies locomotor function using motion capture systems, force platforms, electromyography, and plantar pressure analysis[1,3]. Modern gait laboratories integrate biomechanics and rehabilitation medicine to generate detailed analysis of pathological movement patterns.

Three-dimensional motion capture systems utilize reflective markers and infrared cameras to produce kinematic data describing joint motion throughout the gait cycle[11]. Kinematic analysis allows precise evaluation of abnormalities such as stiff-knee gait, crouch gait, pelvic obliquity, and abnormal ankle kinematics.

Kinetic analysis evaluates the forces responsible for movement using force plates embedded within the walkway[6]. Ground reaction forces permit calculation of joint moments and powers, enabling identification of abnormal loading patterns and impaired propulsion[1,6].

Dynamic electromyography provides information regarding muscle activation timing, co-contraction, and spasticity during walking[8]. EMG is particularly useful in neurorehabilitation because it helps distinguish primary spasticity from compensatory muscle activation and may guide botulinum toxin injection planning.

Instrumented gait analysis is especially valuable in cerebral palsy, stroke rehabilitation, movement disorders, amputee rehabilitation, and complex orthopaedic conditions where mere observational assessment may be insufficient[1,13]. However, gait labs remain expensive, require specialized expertise, and may not be available in resource-limited settings[5,16].

Clinical Applications in Rehabilitation

Gait analysis plays a central role in rehabilitation medicine because locomotor dysfunction directly affects independence, participation, safety, and quality of life[1,3]. Beyond diagnosis, gait analysis assists physiatrists in identifying biomechanical impairments, understanding compensatory strategies, selecting interventions, and monitoring rehabilitation outcomes.

In stroke rehabilitation, gait analysis helps identify asymmetry, weakness, spasticity-related deviations, and compensatory pelvic movements[5]. Instrumented assessment may differentiate abnormalities caused by weakness, spasticity, contracture, or impaired motor control, thereby guiding orthotic prescription, gait retraining, functional electrical stimulation, and botulinum toxin therapy[3,8]. In cerebral palsy, gait analysis assists in differentiating primary abnormalities from compensatory mechanisms and plays an important role in surgical planning and postoperative evaluation[13]. In Parkinson disease, gait analysis identifies reduced stride length, gait variability, freezing episodes, and impaired turning[5]. Wearable technologies allow home-based monitoring of mobility fluctuations and fall risk[16].

Biomechanical gait assessment is also important in amputee rehabilitation, osteoarthritis, sports injuries, and geriatric rehabilitation[6,14]. Among older adults, reduced gait speed and increased gait variability are strongly associated with frailty, falls, hospitalization, and mortality[15]. Importantly, gait analysis should not be viewed merely as a technological exercise but as a tool for rehabilitation decision-making. Effective interpretation requires integration of biomechanical findings with patient goals, functional limitations, cognition, endurance, and participation restrictions. The ultimate objective of gait analysis in PMR is to improve safe, efficient, and meaningful mobility through individualized rehabilitation interventions[1,3].

Emerging Technologies and Limitations

Recent technological advances have expanded gait analysis beyond specialized laboratories and improved accessibility in routine rehabilitation practice. Wearable inertial sensors containing accelerometers and gyroscopes enable continuous gait monitoring in real-world and facilitate home-based assessment [5].

Markerless motion capture systems utilize computer vision and artificial intelligence to analyse movement directly from video recordings, reducing equipment costs and improving accessibility[11]. Machine-learning algorithms are increasingly being used to identify disease-specific gait signatures, predict falls, monitor rehabilitation progress, and support intelligent prosthetic control systems[16]. Virtual reality platforms and robotic gait-training systems combine task-specific practice with objective movement analysis and have become useful adjuncts to neurorehabilitation programs.

Despite these advances, important limitations remain. Comprehensive gait laboratories are expensive, require specialized expertise, and may not be readily available in many rehabilitation settings, particularly in low- and middle-income countries[1]. Marker-based systems are susceptible to soft-tissue artifacts, and laboratory walking conditions may not fully reflect real-world mobility patterns.

Future developments are expected to focus on wearable technologies, artificial intelligence, tele-rehabilitation, cloud-based analytics, and low-cost markerless systems capable of delivering laboratory-quality gait assessment in routine clinical practice.

Conclusion

Gait analysis has evolved from subjective clinical observation to a multidisciplinary science integrating biomechanics, engineering, and rehabilitation medicine. Understanding normal gait biomechanics is essential for recognizing pathological movement patterns and interpreting quantitative gait data. Clinical gait analysis remains indispensable for rehabilitation physicians, while instrumented assessment objectively evaluates spatiotemporal, kinematic, kinetic, and electromyographic abnormalities and assists rehabilitation planning and outcome assessment.

Advances in motion capture systems, force platforms, electromyography, wearable sensors, and artificial intelligence have enhanced the precision and clinical applicability of gait evaluation. As these technologies become increasingly accessible, gait analysis will continue to play an important role in personalized rehabilitation, evidence-based clinical decision-making, and optimization of functional outcomes.

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