# Gait Analysis in Neurorehabilitation

Subjects: Engineering, Biomedical

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Gait analysis can be performed through laboratory systems, non-wearable sensors (NWS), and/or wearable sensors (WS). Using these tools, physiotherapists and neurologists have more objective measures of motion function and can plan tailored and specific gait and balance training early to achieve better outcomes and improve patients' quality of life.

gait analysis | neurorehabilitation | neurological disorders | wearable sensors | non-wearable sensors

## 1. Introduction

Gait and postural impairments are the most frequent symptoms of neurological diseases (ND), including acquired brain injury (stroke and traumatic brain injury (TBI)) as well as neurodegenerative disorders, including Parkinson disease (PD), cerebellar ataxia (CA), and multiple sclerosis (MS). These impairments often reduce the quality of life of people affected by ND, limiting the activities of daily living [1]. Altered gait patterns in stroke survivors include a decreased stance phase and prolonged swing phase on the paretic side, in addition to a reduction of walking speed and shorter stride length [2]. In TBI, the pattern of gait is quite similar to stroke, depending on the degree of injury (i.e., mild, moderate, and severe). Generally, there is a reduction in speed walking, with important difficulties in walking in tandem and in maintaining balance [3]. In neurodegenerative disorders, such as PD, gait alterations are influenced by rigidity and postural instability, both affecting the forward limb propulsion and the spatiotemporal gait parameters, including speed and step length [4]. In MS, the individuation of a single pattern of gait alteration is more complicated due to the several localizations of demyelination plaques, above all pyramidal (in 42%) and/or cerebellar (in 25%) [5]. According to Benedetti et al. [6], MS patients may show a decrease in walking speed, shorter strides, and prolonged double support intervals, accompanied by spasticity, ataxia, fatigue, and muscle weakness. All these gait abnormalities can be objectively investigated through gait analysis systems and other technologies able to capture movements during walking.

Gait analysis can be defined as the set of procedures that are needed to observe, record, analyze, and interpret human locomotion [7]. In fact, digital-based technologies are fundamental to provide kinetic, kinematic, and muscle activation information that are not detectable by clinical observation alone [8]. Observational gait assessment methods, including common rating scales, have been widely used by physiotherapists to investigate gait and balance as well as motor function in clinical practice. Clinical gait assessment investigates the person's ability to

walk and “how” they walk, considering also the fatigue level during gait [9]. For example, clinical tests for acquired brain injury patients usually include the 10-min walking test (10 MWT), Functional Ambulation Scale (FAC), or Motor Assessment Scale (MAS) [10], while in PD patients, the Unified Parkinson’s Disease Rating Scale (UPDRS) and Hoehn and Yahr scale are both used to stage the severity of the disease as well as to evaluate motor symptoms (including dyskinesia, resting tremor, muscle stiffness, and postural control) [11]. In SM patients, the Expanded Disability Status scale is commonly used to classify patients according to motor disability, whereas CA gait skills are often assessed with the scale for the Rating and Assessment of Ataxia [12][13].

Despite their common use in the clinical context, these scales have been criticized since they lack specificity, responsiveness, and/or reliability, and they also require high levels of expertise from clinicians. For these reasons, observational gait assessment tools and clinical scales may be useful for unidimensional or unspecific gait evaluation, but they are not appropriate for multidimensional gait analysis that is performed by gait-related technologies. These devices are classified as non-wearable (NWS) (i.e., laboratory-based motion capture systems, plates, and platforms) and wearable sensors (WS) (i.e., magnetometers, accelerometers, and force sensors) [14] (see **Figure 1**).

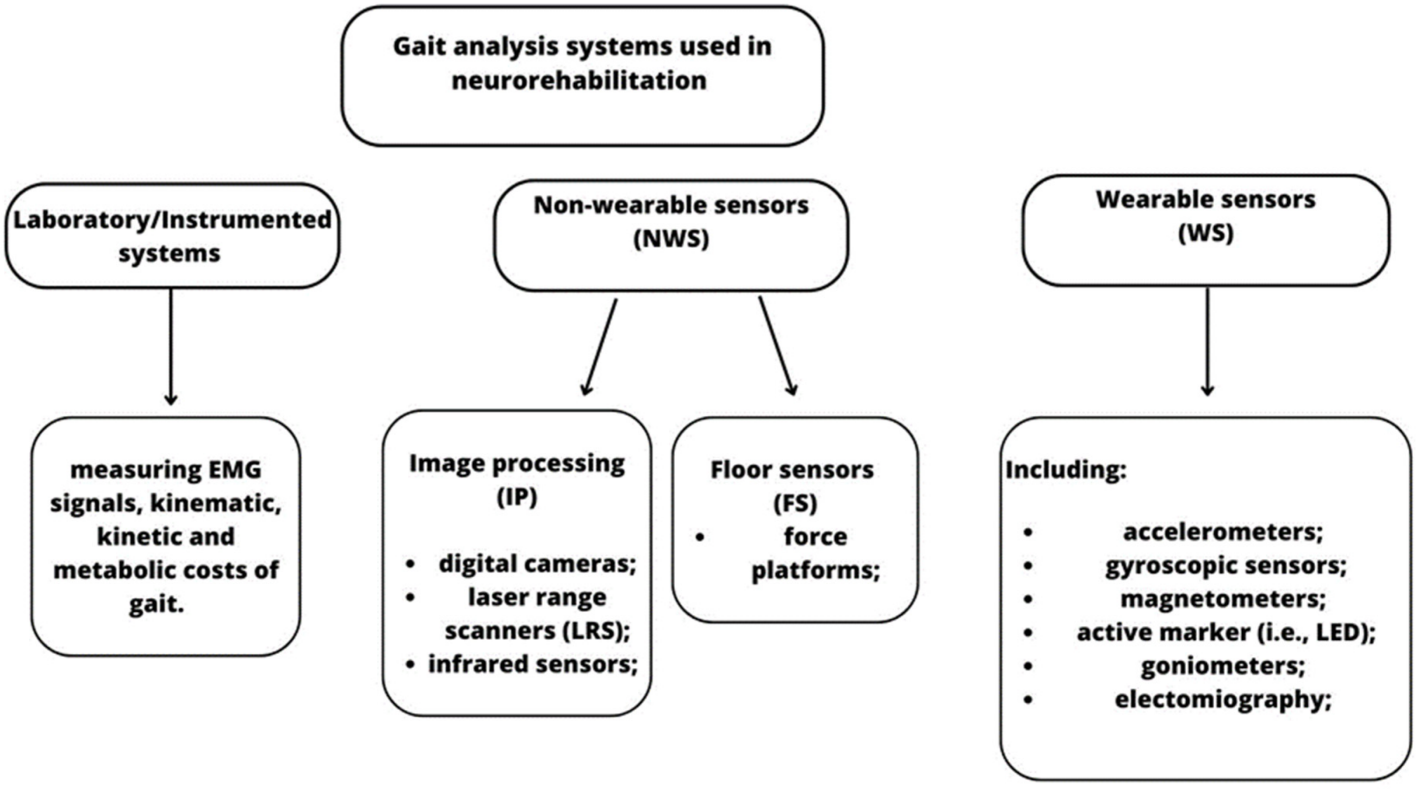


**Figure 1.** Classification of the main NWS and WS technologies used in gait analysis for neurological patients.

Notably, NWS and laboratory systems are considered the gold-standard for the detection of accurate movements; however, they are expensive and are not easy to adapt to everyone, also requiring specific spaces and staff. On the other hand, WS are more suitable than NWS due to free-living gait assessment that can continuously monitor patients in their real-life setting where natural dual-tasking or social interactions occur [15].

## 2. Neurodegenerative Disorders

Neurodegenerative disorders cause progressive neuronal loss that consequently worsens postural control and gait ability over time [16]. In this way, some specific features of gait patterns can occur for each pathology, and clinicians should consider them during the rehabilitation path because they could require different types of motor training (**Table 1**).

**Table 1.** The technologies used to perform gait analysis in PD, MS, and CA, and their clinical implications, revealed by the selected studies.

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | Non-Wearable Sensors | Wearable Sensors | | | |
| [15] | X | X | Three-dimensional gait analysis in laboratory, including optometric system, a dynamometric platform, and ad hoc software. | PD with 1.5–2 H&Y stage | Reduced gait speed and step length, showing bilateral extra rotation of knee, ankle, and foot. |
| [16] | | X | Triaxial accelerometer-based device placed on the fifth lumbar vertebrae and a double-sided tape. | PD with 1–3 H&Y stage | NA |
| [17] | | X | Instrumented force-sensitive insole placed in patients' shoes, with eight pressure-sensitive sensors. | PD with 2–3 H&Y stage | Stride-to-stride variability due to bradykinesia, loss of muscle synergies in the lower limb, and lack of rhythmicity. |
| [18] | X | X | Motion-capture based gait analysis compared to mobile sensor (inertial sensors) gait analysis, which were | PD with 1–4 H&Y stage | Reduced gait speed, stride time, and length; increased duration |

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | Non-Wearable Sensors | Wearable Sensors | | | |
| | | | integrated in the mid-sole of the athletic shoes. | | stance phase time accompanied by a synchronic decreasing duration of swing phase time. |
| [19] | X | X | Gait assessment through an optoelectronic (48 retroflected markers), inertial, and a smartphone-based capture system. | PD with <3 H&Y stage | NA |
| [20] | | X | Wearable device compared to Opti Track system, using an error state Kalman filter algorithm. | PD | NA |
| [21] | X | | Stereophotogrammetric system (Vicon Motion Systems Ltd., Oxford, UK) and reflective markers to estimate joints' angles. | MS with a score of ≤5–6 | MS patients showed reduced gait speed, which correlated with a decrease in cadence, step length, and swing time, and an increase in stance time. Additionally, authors found an increased pelvic tilt, which negatively correlates with the 6MWT. |

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | Non-Wearable Sensors | Wearable Sensors | | | |
| [22] | X | X | Wireless AS200 system, comprising three line-scanning camera system and 11 active infrared markers attached on body's patient, with a 2-mm accuracy. | MS with a mean score of 3.6 in EDSS | MS patients manifested changes in variability of movement gait patterns due to fatigue, altered motor coordination linked to additional activity of the antagonists, or insufficient strength produced by the agonists. |
| [23] | X | | Walkway sensor and machine learning (XGB) process to distinguish MS patients' degree of severity based on their gait features. | MS with a mean score of 2.11 in EDSS | Step time and step width were considered as the most important variables to distinguish level of severity of MS subjects. |
| [9] | X | X | SMART-E stereophotogrammetric system (BTS, Milan, Italy) with eight infrared cameras (for acquiring kinematic data). Sensorized pathway with 2 piezoelectric force platforms (for acquiring kinetic data), 22 retro-reflective spherical markers for lower-body segments, and 15 markers for the upper body, placed on specific anatomic sites. | Spino-CA autosomal dominant (type 1 and 2) and Friedreich's ataxia as recessive ataxia | Loss of lower limbs control during gait and of ability to stabilize a walking strategy over time. CA patients definitively lack a stable gait control behavior since the cerebellum functions of motor behavior and |

Legend: PD (Parkinson's disease), H&Y (Hoehn and Yahr scale), EDSS (Expanded Disability Status Scale), 6MWT (6-Minute-Walking Test), SARA (Scale for the Assessment and Rating of Ataxia).

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | Non-Wearable | Wearable Sensors | | | |
| [27] | | | | | developing new motor patterns are altered. |
| [24] | | X | Triaxial accelerometer. | Spino-CA with a mean score of 3.9 for stance and gait in SARA | Gait velocity, cadence, step length, step regularity, and step repeatability are strongly correlated with disease duration. [28] |
| | | | Seven inertial sensors while | | |

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | NWS | WS | | | |
| [29] | X | | A 10 m walkway with a pressure sensitive mat. Spatial–temporal parameters were registered using GaitRite mat, which contains a total of 13,824 sensors. | Post-stroke patients (both ischemic and hemorrhagic) | Most useful gait parameters are step length, swing time, and stance time. In addition, authors stated that asymmetry time values are not reliable parameters to assess gait in post-stroke patients. |
| [27] | | X | Inertial Measurment Unit (IMU) system (Xsens Technology B.V., Enschede, The Netherlands, Hengelo) composed of seven inertial sensors. | Post-stroke patients | NA |

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | NWS | WS | | | |
| [28] | | X | Kinect v2, which included an 8-core Intel® in addition to an ad hoc application designed to register the 3D position and orientation of the 25 human joints provided by the Kinect v2. | Post-stroke patients (both ischemic and hemorrhagic) | Results indicated that patients with a higher fall risk manifested lower gait velocity and cadence, a shorter stride and step length, and higher double support time. Additionally, the risk of falling was related to increased trunk and pelvic obliquity and tilt, and to decreased hip flexion–extension and ankle height variation. |
| [30] | X | | Odonate 3D motion capture system in a mobile terminal and a workstation. This innovative a binocular depth camera combined with an artificial intelligence system to capture, analyze, and calculate gait parameters automatically. | Post-stroke patients | Alterations were found in spatial–temporal and kinematic parameters; thus, this new system can perform an objective gait assessment in five minutes, also in a home-based setting. |
| [31] | | X | Five synchronized IMUs. | Severe TBI patients | Severe TBI patients present serious difficulties in maintaining balance during gait, especially movements of the head, which are the most impaired, probably related to vestibular dysfunctions due to traumatic events. Additionally, authors suggested to assess gait through dynamic balance skills during curved trajectories as in Figure-of-8 Walk Test. |

## References

| Reference n° | Gait Analysis System | | Technology Description | Neurological Disorder | Clinical Implication |
|---|---|---|---|---|---|
| | NWS | WS | | | |
| [32] | | X | Three IMUs were attached with elastic straps over both lateral ankles to detect gait phases and over the fifth lumbar vertebrae. | TBI | TBI patients manifest great imbalances in dynamic balance, especially in antero-medial weight shifting, when compared with healthy control subjects. |


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