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Review Article

Gait Disorders in Parkinson's Disease: Assessment and Management☆

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SUMMARY

Gait disorder, a major cause of morbidity in the elderly population, is one of the cardinal features of Parkinson's disease. Owing to the characteristics of these gaits varying widely from festination to freezing of gait, analysis can be hardly identified in the clinical setting. Instrumented gait analysis has been widely used in a traditional gait laboratory. Recently, wireless monitoring systems have become highly informative by allowing long-term data collection in a variety of environments outside the labs. The quantitative analysis of gait patterns is probably the first step to a successful management of an individual patient. The presence of abnormal gait usually indicates advanced stages of disease and is often associated with cognitive impairment, falls, and injuries. Besides pharmacological and surgical treatments, parkinsonian gait can benefit from a variety of interventions. Assistive devices prevent patients from falls, and cueing strategies help them decrease episodes of freezing. Therefore, a multidisciplinary team approach to the optimal management is essential for an elderly patient with Parkinson's disease.

1. Introduction

Parkinson's disease (PD) is the second most common neurodegenerative disorder, affecting about 1% of adults over 60 years of age[1]. This figure increases from 3% to 5% in people aged above 85 years[2]. The prevalence rate of PD in Taiwan is similar to that reported in Western countries, and in the areas studied, and the incidence was twice as high in the urban area as in the rural area[3]. Primary features include resting tremor, rigidity, bradykinesia, and loss of postural reflexes. Progressive loss of postural reflexes eventually develops in most patients with PD, leading to gait difficulties and balance problems. Typical gait disorders of PD include stooped posture, freezing of gait (FOG), festination, shuffling steps, and falling. FOG, defined as an episodic inability to generate effective steps in the absence of any known cause other than parkinsonism or high level gait disorders, is most commonly experienced during step initiation and turning but also when faced with obstacles, doorways, stress, and distraction[4]. The FOG phenomenon is believed to be related to lesions in the striatum, the frontal lobe, and frontal basal ganglia projections. It is estimated to affect around 7% of people with early disease and 60% of people with advanced disease, leading to impairment of quality of life, mobility, and independence[5]. In this article, we determine the current status of laboratory-based gait-analysis technology, introduce gait analysis using wireless sensors, review the current evidence on gait analysis of patients with PD, and provide a comprehensive outlook for the treatment of gait disorders in patients with PD.

Effective treatment, specifically for gait disturbance in PD, requires reliable tools for determination of the severity of gait disorders and assessment of the efficacy of interventions. At the present time, instrumented gait analysis is carried out primarily in one of two ways[6]. The first method is performed in a standard gait laboratory by using specialized technology with full analysis of the motion of all body segments and is expensive and requires cumbersome equipment to be attached to the patient; however, this method produces well-quantified and accurate results over short distances. The second method is newly developed and uses wearable sensors with a long-term monitoring system; the equipment involved is light, small, and inexpensive and can be carried for long periods and distances to quantify gait parameters (Table 1).

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2. Laboratory-based gait analysis

Human gait analysis can be divided into three fields: kinematics, kinetics, and electromyography (EMG). The kinematics of the human gait records the movements of the major joints of the lower extremity in the human gait. Gait kinetics highlights the study of forces and actions involved in the production of human movements and often requires the orientation of all the leg segments obtained from gait kinematics. The EMG of the human gait focuses on detecting and analyzing muscle activity during walking.

A standard gait laboratory, usually located in a hospital or a research center, will usually have four systems for evaluating gait:

- A video system, which records images of the patient while walking.
- A motion-capture system, which digitally tracks the patient's movements.
- Force plates, which are used to measure ground-reaction force.
- An EMG system, which is used to record muscle activity during gait.

Video recordings are used to augment observational gait analysis and provide a degree of quality control of the motion-capture data. Slow-motion and even frame-by-frame playback can be used as an adjunct to observational gait analysis, enabling quick or subtle movements to be more readily detected. Viewing the patient from multiple angles simultaneously can also be helpful in understanding the patient's movement patterns. Basic gait parameters, including cadence, stride length, and speed, can be obtained from a video recording of the subject walking across a known distance bounded by two adhesive tape lines on the floor.

The current clinical solution for motion sensing is to use a camera-based optical motion-capture system, which consists of synchronized cameras, markers attached to the patient's body, and computer software that acquires marker motion during walking. The marker position data are highly accurate and can be used for further kinematic and kinetic analysis of human gait. Although effective, this technique is time consuming and expensive.

Force plates measure the force applied to the ground by the feet as the patient walks over them. They measure not only the downward force exerted by a person while walking, but also the braking and acceleration force and force directed mediolaterally. The number of force plates varies according to the laboratory. Information is then integrated with the motion-capture system to assess the mechanics of the movement. Treadmills can be used to allow gait to be observed for longer times and at higher speeds than can be achieved on a gait laboratory walkway. Equipping treadmills with force sensors and high-speed cameras to capture details invisible to the naked eye may permit the analysis of both the kinematics and kinetics of gait.

The EMG system is used to track the activities of muscles during gait, a process referred to as "dynamic EMG". The analysis of EMG can be done on several levels. The most basic level determines if the activity of a muscle is phasic, with clear on and off periods, or is nearly constant, either on or off, indicating an absence of useful control. The next level of analysis determines if the timing and intensity of the EMG during a phase of or the entire gait cycle informs neurological control and muscle integration. If the patient's posture or movement dynamics are abnormal, it follows that the mechanics of movement will be altered; hence, the activity of the muscle driving that movement will also be altered. Muscle activity can be effectively assessed only in conjunction with a motion-capture system or force-plate data.

A lengthy hospital stay in order to monitor and adjust a patient's treatment contributes to increased costs and morbidity because of the hospitalization itself. Another disadvantage of the standard gait laboratory method is that the monitoring process is carried out in a controlled environment in which the patient feels safe. Many patients experience the most severe episodes of freezing gait while at home, possibly because of distraction or inattention to walking.

3. Gait analysis using wireless sensors

Recent advances in gait analysis include portable digital monitoring systems, data gathering by the patients themselves, and wearing sensors both in and outside the home. Portable technology may be more suitable than complex and time-consuming laboratory-based methods. This option is supported by a rapidly increasing body of literature reporting the successful detection of gait disturbances in individuals through the use of relatively low-cost, portable devices that can be widely applied. Examples include the application of body-fixed sensors (e.g., accelerometers, gyroscopes) to further quantify gait parameters.

An accelerometer is the most common type of inertial sensor. Its ability to measure changes in speed along its sensitive axis makes it suitable for measuring motion status in the human gait. By attaching these accelerometers to the lower limbs, the velocity of the feet or legs during the gait can be determined in order to perform a gait analysis. A gyroscope is an angular rate sensor

Table 1
Comparison of laboratory-based gait analysis versus ambulatory gait analysis.

Technology	Equipment	Advantages	Disadvantages
Laboratory-based gait analysis	Optical motion measurement systems and force platform, which are linked to a computer	1. Widely accepted as 'gold standard' 2. Good at measuring position 3. Well-quantified and accurate results over short distances	1. Limited number of consecutive strides can be measured 2. Poor at measuring acceleration 3. Requires camera and markers to be seen 4. Long set-up times 5. Walking during varying circumstances cannot be investigated 6. Expensive and cumbersome equipment attached to the body
Ambulatory gait analysis	Inertial sensors consisting of either accelerometers, gyroscopes or a combination, attached to parts of the body, which are linked to a tiny computer capable of recording data and online signal processing	1. Portable, low-cost and light-weight 2. Good at measuring acceleration 3. Suitable for measuring brief, high speed events 4. Can be used indoors and outdoors regardless of lighting conditions 5. Continuously monitored over long periods of time	1. System should be adjusted to the walking style of each user 2. Poor at measuring position 3. Validation required to demonstrate real-world performance 4. Initial training period of the machine–human interface warranted

based on the concept of measuring the rotational inertia, which can be applied to measure the angular velocity of the feet or legs while walking and to determine the reorganization of the various gait phases. During gait analysis, a gyroscope is often combined with an accelerometer to construct a complete inertial sensing system.

Compared to a motion-capture system, accelerometers have certain limitations: they measure acceleration but are poor at computing the precise position because of the problems of integrating data with baseline drift. The determination of the orientation of an accelerometer system in an inertial frame is difficult, and it limits the application of this technique for calculation of joint kinetics.

Force-plate sensors can be embedded into footwear for ambulatory measurement of gait, allowing the capture and analysis of the gait over long periods of time and while the patient is in a natural (noncontrolled) environment.

Quantitative ambulatory assessment tools, in combination with sophisticated analysis software, may pave the way to successful measurement of gait rhythmicity, stride time variability, and the coordination during turning. Overall, the advantages of this method over laboratory-based techniques are that it can more readily be applied to large cohorts and that it can be integrated into a spectrum of ecologically relevant tasks that an individual may encounter in daily life.

4. Current evidence on gait analysis in PD

Quantitative gait assessment tools have been shown to differentiate PD patients from controls; many also track disease progression and are apparently sensitive to dopaminergic treatment. PD patients who were off dopaminergic therapy walked more slowly and with shorter stride length, comparable cadence, and longer double support times than healthy control subjects[7]. Hence, these parameters could be used to monitor treatment response of gait disorders in PD.

Owing to the episodic and unpredictable nature of FOG, it is notoriously difficult to study in the laboratory. Patients with FOG have a higher temporal variability and asymmetry of strides compared to patients without FOG[8]. Analysis during a FOG episode shows that the stepping rhythm suddenly jumps into high frequency (4–5 Hz), and that floor reaction forces are dysregulated[9].

A previous study using wireless portable sensors showed the feasibility of discriminating FOG from locomotion or volitional standing by using the frequency spectra of shank vertical linear acceleration[10]. In the mild form of FOG, it was described as “forward shuffling with small steps” because the foot was still moving forward at the time of initial contact. More severe cases were accompanied by high-frequency components in the 3–8-Hz band of vertical leg movement, a reflection of the “trembling in place” observed during FOG. In the most severe cases, patients cannot move forward at all.

Time-frequency analysis has been reported to be an appropriate approach to detect brief and subtle FOG episodes in patients with PD. Before the FOG episode occurs, there is an increase in the dominant frequency in the 0–3-Hz band (festination), followed by decreased power in the 0–3-Hz band and increased power in the 3–8-Hz band during the FOG episode. This approach detected even very brief FOG with acceptable sensitivity (75–83%) and specificity (>95%)[11].

A comparison study of the clinical and objective measures of FOG in PD showed that “percent time FOG”, defined as cumulative duration of FOG/total duration of the walking task, is a more reliable metric of severity than the number of freezing events for both clinical and objective measures.[12] Owing to the large degree of variability introduced by clinicians, clinical ratings should be used with caution.

5. Current evidence on treatment of gait disorders in PD

A recent study showed that dopaminergic medications and deep brain stimulation surgery provided similar improvements in balance and gait tasks[13]. Lack of synergistic effect of these treatments suggests that both therapies improve balance and gait by influencing similar neural pathways. Levodopa decreased gait variability and had positive effects on gait stability in persons with PD. PD-related gait problems may also be managed using varieties of nonpharmacological therapies[14–21]. A twice weekly progressive resistance training program for 10 weeks appeared to be effective to improve balance and gait function (initial stride length and velocity) in people with PD[14]. Rehabilitation program of robot-assisted gait training was probably more effective than conventional physiotherapy to improve walking speed, and benefits are maintained for a month[15]. In a randomized, double-blind, sham-controlled study, Benninger et al found that 50-Hz repetitive transcranial magnetic stimulation of the motor cortices in eight sessions over 2 weeks appeared a short-lived “on”-state improvement in activities of daily living but failed to improve motor performance and functional status for the long run[16]. In another study, transcranial direct-current stimulation of the motor and prefrontal cortices improved gait in PD by some measures for a short time and improved bradykinesia in both the on and off states for longer than 3 months[17]. In a small case series study, electroconvulsive therapy was reported a safe and effective therapeutic option in L-dopa-resistant patients with PD with predominantly axial “on” phenomena[18]. In a Cochrane Systematic Review published in 2010, patients with PD who received treadmill training were more likely to improve their impaired gait in gait speed, stride length, and walking distance, but not gait cadence. However, it was not known how long such improvements last[19]. From tango to tai chi, training appeared to reduce balance impairments in patients with PD, with probable additional benefits of improved functional capacity and reduced falls[20,21].

Assistive devices that help patients with PD to remain ambulatory and prevent falls include wheeled walkers and specialized canes[22,23]. While a cane or a wheeled walker may stabilize patients and increase confidence, patients immediately walk with a slower gait and shorter stride length when walking with a wheeled walker[24], suggesting that these ambulatory assistive devices should be used with caution in clinical practice for gait rehabilitation.

6. Treatment of FOG

FOG is a heterogeneous symptom that can be divided into dopaminergic-sensitive, dopaminergic-resistant, and dopaminergic drug-provoked categories. For patients with dopaminergic-resistant FOG, other therapeutic options might be considered. Medications classified as IA by level of evidence showing clinical benefit to FOG include levodopa, dopamine agonists, and monoamine oxidase type B inhibitors[25]. The use of methylphenidate for gait impairment in PD remains controversial[26,27]. A preliminary study showed that intravenous amantadine may be effective in FOG that is resistant to dopaminergic drugs, suggesting that amantadine may exert its benefit independent of a dopaminergic mechanism[28].

The most well-known nonpharmacological and nonsurgical treatment of FOG is the use of cueing strategies, which involve the use of external temporal or spatial stimuli to facilitate movement. External visual, auditory, or somatosensory cues improve gait in people with PD, even among drug-naïve patients[29]. Attentional strategies include instructions to take big steps and offer an alternative to external cues; they rely more on cognitive mechanisms of motor control and are internally generated.

During motor planning, cues are believed to activate the premotor cortex, which is followed by suppression of pathological activity in the subthalamic nuclei, leading to improved motor performance in PD[30]. FOG significantly improved in PD patients with both visual and auditory cues, with more benefit from visual cues[31]. A recent study has shown that visual cues are beneficial only when the lower limbs can be seen, suggesting that these cues focus attention on the lower limbs to compensate for a proprioceptive processing deficit in PD[32]. An open-label study also provided evidence of the ability of a laser light visual cue to overcome FOG and reduce falls in PD patients[33].

Auditory cues target not only dopaminergic gait dysfunction (stride length), but also stride-to-stride fluctuations in gait, potentially increasing mobility and reducing gait instability and falls[34]. The Apple iPod-Shuffle has been reported to be a cost-effective and an innovative platform for the integration of individual auditory cueing devices into clinical, social, and home environments and has been shown to have an immediate effect on gait, with improvements in walking speed, stride length, and freezing[35].

Persons with PD appear to have been able to benefit from attentional cues and to combine attentional and auditory cues, but they did not derive additional benefit from such a combination[36]. In more complicated environments, paying attention to cueing might adversely affect gait; for example, when a simultaneous task—such as avoiding obstacles—must be executed[37]. In the above studies, external cueing appears to improve walking under both single- and dual-task conditions in people with PD. Attentional cues can also improve walking in people with PD, but controversies still exist regarding the efficacy of cognitive strategies to improve dual-task walking.

7. Prognosis and future perspectives

Understanding how gait is influenced by PD is perhaps the most important task before us. A major challenge ahead is that gait analysis remains an academic discipline with little acceptance by clinicians. Advances in the gait analysis technology will hopefully bring a decrease in the cost and also facilitate improvements in the intelligent gait analysis system, which integrates multiple wearable sensors with small volumes, low power, and wireless data transfer. In the prospective smart home, gait analysis using wearable sensors can play an important role as a medical tool for the prevention and treatment of gait disorders. Further work regarding walking aids and cueing apparatus is required to determine the most effective devices in the community setting.

8. Conclusion

Gait should be assessed in every PD patient as part of a basic evaluation at initial and follow-up examinations. An individualized approach is needed in all cases to identify problems and determine a treatment plan. Gait is best managed with a multidisciplinary team of physical therapists, occupational therapists, gerontologists, neurologists, and psychologists. Effective treatment may reduce the need for medications and improve the quality of life. Studies of cue strategies vary in terms of cueing modality, training duration, tests used for outcome assessment, and duration of follow-up. Currently, intervention results in benefit to most outcomes over the short term. Future research is warranted to determine the strategies that provide the greatest and most sustained benefits for gait disturbance in PD.

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