Clinical Application and Challenges of Wearable Sensors in Freezing of Gait Monitoring in Parkinson's Disease

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Abstract. Parkinson's disease (PD) is the second common neurodegenerative disorder in the world. Freezing of Gait (FOG) is one of the most harmful symptoms of PD. Traditional assessment methods, such as questionnaire surveys and non-wearable monitoring devices are limited by patients' subjective cognitive, clinicians' experience, and the suddenness and fluctuations of FOG. In recent years, wearable sensors have become a new way for real-time FOG monitoring in various scenarios for a long term. This study reviews the characteristics of PD-FOG and its limitations of traditional assessment. It explores the advantages and necessities of wearable sensors in FOG real-time monitoring. This study also analyzes three of the common sensors in a broad vision, which present both values and challenges of them. In addition, current challenges in sensitivity, specifically, stability, security and disconnection of wearable monitoring technology are discussed. Overall, FOG monitoring based on wearable sensors has had a range of achievements, but further developments are needed to improve its performance and comfort before a perfect clinical transformation.

Keywords: Wearable sensors, Parkinson's disease, Freezing of gait monitoring.

1. Introduction

Parkinson's disease (PD), as the second most common neurodegenerative disorder in the world, its prevalence rate continues to rise with the aging of the population. Freezing of gait (FOG), as a typical motor complication in the middle and advanced stages of PD, exhibits an increasing incidence rate, which exceeds 50% in the advanced stage, and usually causes misdiagnoses of PD [1]. It significantly increases patients' fall risk through sudden gait arrest and difficulty in initiating movement, as well as triggers psychological issues including social isolation, anxiety and depression due to limited activity ability and neuropsychiatric symptoms, which seriously damage the quality of life and individual survival ability of patients [2]. Consequently, it has become one of the leading causes of disability in PD patients.

However, significant limitations still exist in the clinical assessment currently. Traditional diagnosis relies on subjective tools like the Unified Parkinson Disease Rating Scale (UPDRS) and Freezing of Gait Questionnaire (FOG-Q). Due to the influence of patients' memory and the differences in evaluators' experience, it is difficult to accurately capture the sudden and fluctuating characteristics of FOG [3]. Non-wearable monitoring devices like motion capture systems can provide objective data, whereas they are limited by laboratory scenarios, complex operations and high costs, making them unsuitable for long-term monitoring [4]. These limitations directly lead to a lack of precise data support for FOG diagnosis and treatment and restrict the formulation and optimization of individualized therapeutic regimens.

With the advancement of telemedicine and wearable sensor technology, wearable sensors have provided new solutions to real-time and long-term FOG monitoring [4]. Their portability, non-invasiveness, and ability to collect multi-dimensional physiological information such as human motion, dynamics and electromyographic signals, enable objective and quantitative assessment of symptoms.

This study aims to provide theoretical support and technical reference for improving PD-FOG diagnosis and management. Specifically, this study first introduces the characteristics of PD-FOG and the limitations of traditional assessment. This review also discusses working principle, applications, and significance of three major types of wearable devices such as inertial measurement unit (IMU) sensors, pressure sensors, and surface electromyography (sEMG) sensors. Current challenges and future development for clinical transformation are also analyzed.

2. Clinical Needs and Value

The characteristics and hazards of FOG in patients with PD reflect the urgency of precise monitoring. The demand gap caused by the limitation of traditional assessment can be met by wearable sensor technology.

2.1. The FOG Movement Characteristics of PD

2.1.1 The symptoms and scenarios of FOG

FOG is a characteristic gait disturbance in PD, that can significantly impair patients' mobility and increase the risk of injury. As its name suggests, FOG gives patients the sensation that their feet are temporarily 'glued' to the ground. During these episodes, patients are unable to initiate or continue walking normally. Patients may be completely unable to take steps or may only take short steps. They may perceive their feet or toes as stuck to the ground, and in the same case, experience tremors in one or both legs [5]. FOG can occur in diverse situations, such as turning, passing through narrow spaces, or under stress, making it difficult to detect or predict accurately.

2.1.2 The temporal characteristics of FOG episode

Bastiaan et al. (2004) analyzed FOG incidence in patients with PD, suggesting that the frequency of FOG episodes is relatively low during the early stages of the disease [6]. However, FOG frequency tends to increase as the disease progresses to late stages. While this relationship remains debated, some studies suggest that high FOG frequency in advanced stages may be influenced by levodopa therapy [7].

2.2. The Limitation of Traditional Assessment of FOG

2.2.1 Suddenness and volatility

Because FOG episodes occur in diverse and unpredictable situations, symptoms may not manifest during clinical observation. Some patients may not recognize their experiences as FOG, which complicates clinical assessment. Additionally, patients' attention and emotional state can affect the occurrence and presentation of FOG episodes. Medication effects further contribute to variability in symptoms. These factors collectively present significant challenges for accurate clinical diagnosis.

2.2.2 Limitation in assessing severity

Although several questionnaires have been developed to assess FOG severity, these tools rely heavily on patient self-report, which can be influenced by cognitive impairment, emotional state, and self-awareness. Recent studies have demonstrated that these subjective assessments may lack reliability [8].

2.3. The Significance of Wearable Sensors in the Diagnosis and Treatment of PD

2.3.1 The necessity of real-time monitoring

Limited motion detection, insufficient real-time communication and reduced efficacy of medication in late-stage patients complicate PD management. These factors create a gap between clinicians' assessment and patients' actual symptoms. Therefore, real-time monitoring is essential. Real-time monitoring can help reduce missed detections caused by environmental limitations and enable timely adjustment of therapeutic regimens.

2.3.2 Improve the accuracy of assessment

Wearable sensors capture kinematic, dynamic and physiological data, allowing detailed characterization and quantification of FOG episodes. They can also detect subtle movements that are imperceptible to clinicians. Currently, artificial intelligence techniques, including cloud computing and machine learning, are incorporated to enhance the effectiveness and accuracy of continuous monitoring.

2.3.3 Clinical value

(1) Therapeutic value

Neuropsychiatric symptoms, such as depression and anxiety, are common in PD and may accompany FOG. Non-invasive therapies, such as repetitive transcranial magnetic stimulation (rTMS), have been proved to alleviate depression and may influence FOG symptoms [9]. However, the long-term psychological impacts of these interventions remained to be fully investigated [10].

(2) Socioeconomic value

As a kind of telemedicine, wearable sensors can reduce reliance on outpatient services, optimize medical resource allocation, improve patients' quality of life and self-management, and enable continuous long-term monitoring of disease progression.

3. The Technology and Clinical Application

Some wearable sensors have been used to monitor FOG. These sensors can quantify and rate the symptoms, and can be directly applied in clinical scenarios such as treatment effect evaluation and remote risk warning.

3.1. The core Composition and Working Principle of Sensors used for FOG Monitoring

3.1.1 IMU

An IMU typically contains an accelerometer, a gyroscope and a magnetometer. These components measure three-dimensional acceleration, angular velocity, and magnetic field direction, respectively. IMUs are typically attached to patients' ankles and mid-thighs [11]. By capturing spatio-temporal gait parameters, IMUs can identify FOG characteristics, including sudden reductions in walking speed, abrupt decreases in angular velocity of limb swing and rapid directional changes. IMU sensors provide doctors with real-time, dynamic information on patients' motor condition, including the frequency, duration, and severity of FOG episodes. These data enable telemedicine applications and assist clinicians in developing personalized treatment plans for each patient. IMU sensors can be integrated into various wearable devices, including wristbands, insoles, and waist-mounted devices.

3.1.2 Pressure sensor

A pressure sensor consists of a receptor, a transducer and a measuring circuit. It operates based on the piezoresistive or piezoelectric effect. When force is applied to the receptor, the transducer converts the resulting deformation to electric signals. The measuring circuit amplifies and filters these signals. Plantar pressure distributions of patients with FOG, including pressure concentration and temporal patterns, can thus be assessed. Even subtle abnormalities can be detected using pressure sensors. This is beneficial for the early detection of FOG, as minor gait abnormalities may otherwise be overlooked in the early stages. Moreover, continuous monitoring of plantar pressure changes can assist clinicians in evaluating the therapeutic effects and guiding rehabilitation training. Pressure sensor arrays have been proposed for wearable applications. These flexible sensors can be embedded in customized insoles for individuals and fully integrated with pre-made insoles [12, 13].

3.1.3 sEMG sensor

An sEMG sensor is composed of surface electrodes, a signal amplifier, filters and a microprocessor. The electrodes are attached to the skin surface to record electric signals generated by muscle concentrations. These signals are subsequently amplified and filtered by the amplifier and filters, respectively. The microprocessor analyzes and processes the recorded signals. The relationship between sEMG activity and gait has been widely documented in the literature. A new study measured EMG activity in the quadriceps and hamstring muscles, demonstrating a signal reduction in preceding

FOG episodes [14]. In other words, sEMG signals can be used to predict FOG episodes and trigger timely alerts. Due to its miniaturized electrodes and flexible conductive wires, the sEMG sensor has been integrated into wearable devices. During rehabilitation, the sensors provide real-time feedback in muscle activity, allowing therapists to adjust training accordingly. This enables timely adjustments to treatment protocols. In clinical research, sEMG can be used to further investigate the pathophysiological mechanism underlying FOG.

3.2. Quantify Symptoms and Ratings

Traditionally, FOG is assessed using questionnaires such as FOG-Q and NFOG-Q, which rely entirely on patient self-report. Using IMU sensors, Wang et al. (2024) proposed a gait normality index to quantify abnormal gait patterns. The Double-Hurdle Model has also been developed to quantify FOG using spatio-temporal gait parameters [15]. While the integration of multimodal sensors and advances in AI, algorithms such as deep learning and Convolutional Neural Networks (CNN), have made objective FOG quantification increasingly feasible [16].

3.3. Evaluation of the Therapeutic Effect

Patients receiving levodopa treatment alternate between the ON and OFF states. The temporal variability between these states can be used to predict FOG severity, which reflects fluctuations in the therapeutic effect [17]. The Double-Hurdle Quantification Model demonstrated that FOG symptoms are associated with reduction in gait speed and increased variability of gaits, which can be exacerbated during medication wearing-off periods [15, 18].

3.4. Risk Warning

Following the collection and analysis of FOG data, the development of risk warning systems has emerged as an important research area. In wearable devices, a vibrotactile simulator can be activated within 50 milliseconds upon recognition of a FOG episode [19].

4. Challenges

Despite progress in sensor technology, several key obstacles hinder the clinical translation of FOG monitoring.

4.1. Technical Difficulties

4.1.1 Insufficient sensitivity and specificity

Currently, FOG monitoring systems that rely on a single sensor are prone to errors and omissions. The primary reason lies in the complexity and individual variability of FOG symptoms. Data collected from a single IMU sensor is inevitably influenced by environmental noise and movement artifacts. Moreover, the limited range of measurement also leads to incomplete data during complex motion [20]. Pressure sensors are further limited by cross-talk among pressure matrix elements and by low sampling rates [13]. A study evaluated a FOG monitoring system based on a wearable sensor and reported a lack of universality when applying a global threshold. When user-specific parameter optimization was applied, the system had the performance of 88.6% sensitivity and 92.4% specificity; however, using a global threshold reduced performance to 78.1% sensitivity and 86.9% specificity [21].

4.1.2 Insufficient stability

At the hardware level, some sensors with high accuracy are characterized by overly large dimensions and excessive weight. Such designs may cause gait compensation in patients. For example, when sensors are tied on the ankle, the uneven weight distribution can change patients' gaits patterns. This affects the authenticity of the monitoring data. Moreover, sensor signals are susceptible to interference from external environments such as magnetic fields, humidity and physical obstructions. Such interference directly affects the continuity of monitoring.

At the software level, current FOG detection algorithms are challenged by imbalanced datasets, which limit their ability to adapt to the diverse characteristics of patients across different age groups [22].

4.2. Disconnection of Monitoring and Treatment

Currently, most FOG monitoring technologies are limited to the recording and identification of symptoms. As a result, there remains a significant gap between FOG data collection and clinical treatment. As most sensors mainly capture motion signals, it is difficult to correlate these data with other factors like levodopa blood concentrations, or stimulation parameters of the deep brain stimulation (DBS) devices. This one-dimensional approach to data collection makes it difficult for clinicians to accurately identify the triggers of FOG episodes, thereby limiting their ability to adjust treatment strategies effectively.

4.3. Ethical and Regulatory Challenges

4.3.1 Privacy risk

Wearable sensors, as mobile device-based technologies, process user data automatically, which can reveal a significant amount of private information. Compared with audio and video recording equipment, the protection of motion sensor data is still inadequate [23]. As a result, sensitive information such as users' location, activity patterns, gender, and age may be at risk of disclosure [24].

4.3.2 Data security

Remote monitoring is generally classified as a form of telemedicine. The Internet of things (IoT) serves as its core medium. However, the IoT environment significantly limits the application of high secured and computationally complex algorithms of high security [25]. Without proper data management, risk such as data misuse and cybercriminal attacks may arise [26]. Therefore, there is an urgent need for security standards and regulators.

5. Future Development

In the future, it is necessary to break through the limitations of wearable sensor technology and achieve widespread clinical application.

5.1. Technical Innovation

5.1.1 Multi-parameter fusion

Multi-parameter fusion offers a promising solution to overcome the limitations of single-signal monitoring. It involves integrating motion signals (inertia, pressure), physiological signals (electromyography, electroencephalogram), biochemical signals (concentration of dopamine in the blood), and psychological signals (voice emotion). By establishing a multi-dimensional FOG characterization system, both the pathogenesis and treatment plan can be understood more comprehensively.

5.1.2 AI predict model

AI technology can extract key features of FOG from patient-specific data. Personalized monitoring models can be established based on patients' historical data and individual characteristics.

5.1.3 Equipment innovation and upgrading

Miniaturization, concealment, and multi-functional integration will be the key to enhance patient acceptance and promote clinical adoption. Advances in micro-electromechanical systems (MEMS) and flexible electronics technologies, sensors can be integrated into daily wearable items, such as insoles, socks, and belts [27, 28]. Such designs reduce the gait interference caused by traditional equipment, enable seamless monitoring of FOG, and enhance long-term compliance with device use.

5.2. Clinical Application Expansion

Future FOG monitoring is expected to extend beyond traditional clinical short-term assessments to broader applications, including home-based long-term monitoring, rehabilitation guidance, and community screening, thereby enabling comprehensive management of PD-FOG. Cloud-based data sharing could allow hospitals, community health centers, and families to jointly access patient information, facilitating tiered diagnosis and treatment.

6. Conclusion

Wearable sensors provide significant advantages for PD-FOG monitoring offering real-time, objective, and portable assessments. IMUs, pressure sensors and sEMG sensors enable quantitative evaluation of gait abnormalities, therapeutic response, and potential risk events, thereby addressing limitations of traditional clinical assessment. By long-term monitoring, it can also achieve a dynamic assessment and relieve the pressure on the outpatient department in order to optimize medical resource allocation.

Despite these advances, there are still some inevitable problems and challenges in clinical transformation. There is still insufficiency in sensitivity and specificity for patients, lack of stability in motion monitoring, gap between data and clinical treatment, and insecurity in data and privacy.

Future development should focus on comfort, accuracy and safety. First of all, researchers should manage to reduce the size of sensors in order to fix them in clothes and improve the comfort level. Second, do more research in flexible fabric electrodes, which may help us figure out a kind of measuring tool like a second skin. Third, transdisciplinary convergence can further enhance the comprehensive strength of this technology. At the same, ensuring the accuracy of data. Additionally, the supervision measures must be established before general application.

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