The Applications of Wearable Sensors for Gait Analysis

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U.S. Airman on treadmill during gait-analysis, Joint Base Charleston, Jan. 8, 2013 (U.S. Air Force photo).

Abstract

Wearable sensors have transformed gait analysis by providing portable and affordable devices for monitoring human movement in real-world environments. This review focuses on the applications of wearable sensors, such as Inertial Measurement Units (IMUs), accelerometers, gyroscopes, and foot pressure sensors, in healthcare, rehabilitation, and robotics. These sensors capture critical information about gait dynamics, enabling accurate diagnosis and real-time intervention for movement disorders like cerebral palsy and Parkinson's disease. The integration of artificial intelligence and machine learning enhances predictive capabilities, allowing for more personalized treatment options. Another significant application of wearable sensors is in robotics, particularly in the design of exoskeletons and prosthetics that mimic natural gait. This review also discusses areas of interest, such as sensor placement and future directions for research.

Introduction

The development of wearable sensors has given researchers a convenient, accessible, portable, and practical approach to gait analysis in real-world applications. Portable sensors such as inertial measurement units (IMUs), accelerometers, gyroscopes, and foot pressure sensors enable researchers to understand human motion more easily and accurately (Tao et al., 2012). Collecting data using labmonitored systems can be challenging, time-consuming, and expensive. In contrast, wearable sensors are not only more affordable but also easier to use and transport, contributing to their growing popularity. Furthermore, advancements in artificial intelligence have enhanced the capabilities of these sensors, particularly in the healthcare sector, where continuous monitoring is essential for effective treatment. The early detection of neurodegenerative diseases has become easier, ultimately improving patient health and treatment outcomes (Liu et al., 2021).

These wearable devices are user-friendly and effective outside the lab. By integrating sensors such as inertial measurement units (IMUs) and pressure sensors, they provide continuous insights into an individual's walking patterns, including step length, joint angles, and movement speed (Prasanth et al., 2021). Furthermore, the incorporation of Artificial Intelligence (AI) in these sensors has enhanced the accuracy of predicting conditions such as cerebral palsy and detecting neurodegenerative disorders, facilitating earlier and more precise diagnoses (Gage et al., 1996; Kahlon et al., 2023). This review will explore various applications of wearable technology in gait analysis, highlighting their roles in medical and rehabilitative settings as well as prospects for future development.

Gait Cycle Phases

The gait cycle is typically divided into two main phases: the stance phase and the swing phase. Each of these phases consists of sub-phases that together illustrate the movement of the lower limbs during walking. The stance phase, which accounts for approximately 60 percent of the gait cycle, begins with initial contact when the foot first touches the ground, commonly referred to as heel strike (Gage et al., 1996; Tao et al., 2012). The swing phase, comprising the remaining 40 percent of the gait cycle, starts with the initial swing, during which the foot leaves the ground, and the leg moves forward (Gage et al., 1996; Tao et al., 2012). These phases and sub-phases describe the complete cycle of walking, providing a structured way to understand the complex movements involved in human gait (Gage et al., 1996; Tao et al., 2012; Díaz et al., 2019; Kahlon et al., 2023).

Phases of Stance:

Initial Contact: This is the moment when the foot touches the ground. This marks the start of the stance phase.

<u>Loading Response</u>: Immediately after initial contact, the body begins to absorb the impact, and the body weight starts to shift onto the limb.

<u>Midstance</u>: The body starts to move forward, with the foot fully in contact with the ground. This phase is important for the overall balance of the body.

<u>Terminal Stance</u>: The heel begins to lift off the ground as the body continues moving forward, shifting weight to the other foot.

<u>Pre-swing</u>: This is also known as toe-off, the final part of the stance phase, where the toes push off the ground to initiate the swing phase.

Phases of swing:

<u>Initial Swing</u>: The foot leaves the ground, and the leg starts to move forward.

<u>Mid-swing</u>: The leg continues its forward motion, passing underneath the body, while the knee begins to extend.

<u>Terminal Swing</u>: The leg decelerates, preparing the foot for the subsequent gait phases, starting from initial contact as the knee fully extends and the foot is positioned to touch the ground.

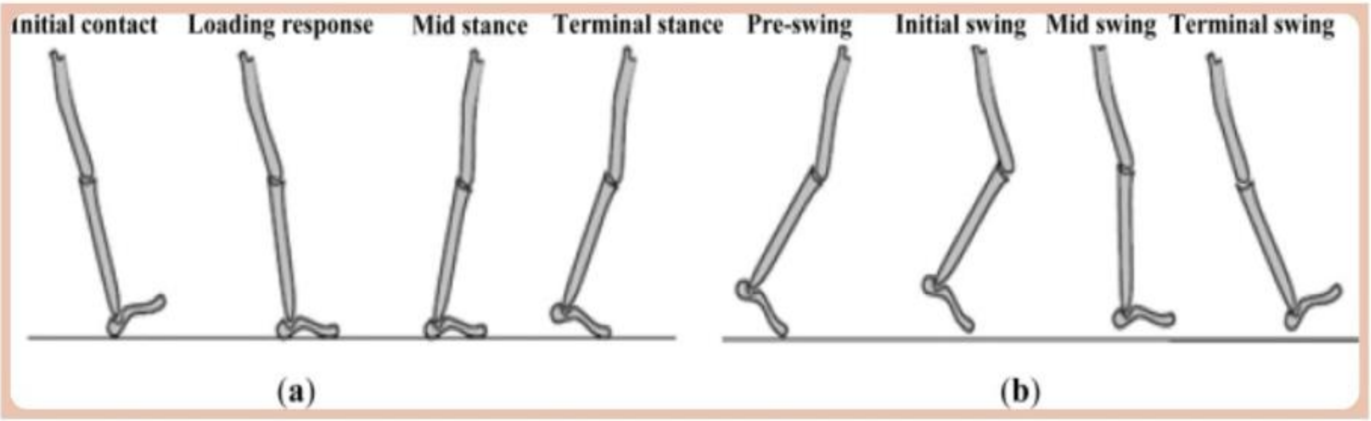

Fig 1: Gait phases in a normal gait cycle. (a) Gait phases of the stance period; (b) Gait phases of the swing period (Tao et al., 2012).

Accelerometers and IMU Sensors

Accelerometers and other types of Inertial Measurement Unit (IMU) sensors used for gait analysis are reliable tools for capturing kinematic data such as acceleration, angular velocity, and the orientation of body segments in real time. These sensors are primarily attached to the lower limbs or torso and play a crucial role in detecting important gait events, including heel strikes and toe-off events (Tao et al., 2012).

Their clinical applications are valuable, as they can potentially identify abnormal movement patterns that may indicate the onset of neurological or musculoskeletal disorders before they worsen (Liu et al., 2021).

An IMU typically combines an accelerometer with a gyroscope, which are usually attached to the foot, shank, and thigh to measure linear acceleration and angular velocity. When integrated with other sensors, IMUs enhance gait detection and provide more accurate real-time data, making them valuable for clinical, robotics, and research applications (Prasanth et al., 2021; Kahlon et al., 2023).

Furthermore, accelerometers and IMUs are portable and are increasingly used outside laboratory settings to monitor various variables and joint angles, facilitating real-world applications (Roberts et al., 2017). These portable sensors are particularly significant for clinical diagnostics and rehabilitation, as they offer a simple method for tracking and understanding gait and balance dynamics by measuring critical events such as heel strikes and toe-offs (Díaz et al., 2019). Not only are these sensors advancing methods of gait analysis, but they also promise more personalized and timely interventions in healthcare.

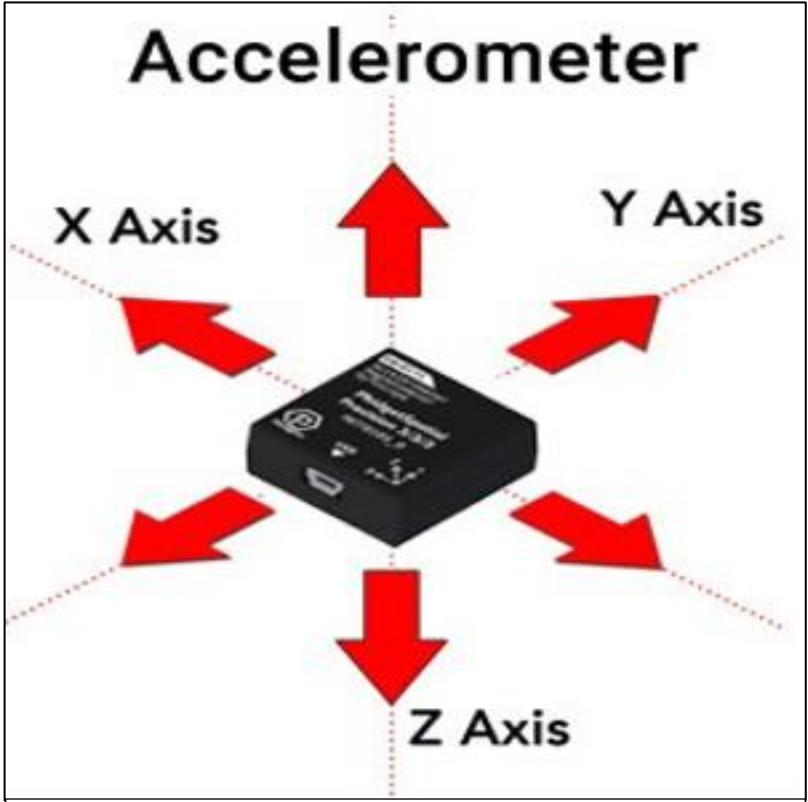

Fig. 2: Diagram of an accelerometer showing measurement along X, Y, and Z axes. Reprinted from Phidgets (Phidgets, n.d.).

Foot Pressure Sensors

Foot pressure sensors are utilized in gait analyses to measure how forces are distributed across various points of the foot while walking. These sensors are typically embedded in insoles and are effective for assessing the pressures on the foot during the stance phase of the gait cycle (Tao et al., 2012). Clinicians use them to diagnose conditions that may lead to diabetic neuropathy or gait abnormalities due to aging, enabling a more personalized rehabilitation program (Liu et al., 2021; Prasanth et al., 2021). For instance, foot pressure sensors can detect abnormal pressure distributions and gait irregularities. These abnormalities may be early indicators of neuromuscular disorders or conditions such as cerebral palsy. Identifying these patterns aids in designing devices or surgical interventions aimed at improving foot stability (Gage et al., 1996). When combined with biomechanical tools, foot pressure sensors provide a comprehensive gait analysis, particularly concerning the generation and absorption of forces during the stance phase (Roberts et al., 2017; Díaz et al., 2019). Unlike accelerometers and inertial measurement units (IMUs), which provide data on acceleration, angular velocity, and orientation, foot pressure sensors measure the actual forces exerted on the foot during ground contact. Together, these tools offer a more complete understanding of gait dynamics (Tao et al., 2012; Liu et al., 2021).

Sensor Placement

Accurate and appropriate sensor placement is crucial for effective gait analysis. Incorrect sensor positioning can lead to errors in data interpretation (Liu et al., 2021; Kahlon et al., 2023). Typically, sensors like accelerometers, gyroscopes, and foot pressure sensors should be situated on the feet, ankles, thighs, and/or lower backs to capture joint angles, step lengths, and ground reaction forces (Tao et al., 2012). A common method involves using insoles equipped with pressure sensors placed in footwear, along with inertial measurement units (IMUs) attached to the lower back, to monitor the dynamics of various gait phases (Liu et al., 2021). Additionally, IMUs placed on the foot, shank, and thigh have demonstrated improved detection of angular velocity and acceleration, allowing for real-time characterization of gait (Prasanth et al., 2021). In clinical applications, combining sensors on the pelvis and lower limbs with reflective markers allows for detailed analyses of joints and muscles in cases of pathological gait (Gage et al., 1996). Although these sensor placements vary depending on their specific applications, their functions are similar; they consistently provide kinetic data relevant to real-world and clinical scenarios (Díaz et al., 2019).

Recent findings support that foot-placed IMUs are a valid alternative for collecting temporospatial gait variables. For Instance, Mach et al. (2025) found that RunScribe foot-mounted IMUs showed strong correlations and excellent reliability for step rate (SR) and stride length (SL) when compared to shank-placed MyoMotion sensors. However, Napier et al. (2021) emphasize that the validity of IMU data can also be affected by contextual factors such as footwear, running speed, and the exact sensor location. These findings highlight that while foot-placed sensors are promising, careful attention to placement and testing conditions remains essential for accuracy.

Table 1: Summary of Wearable Sensors and Their Clinical Applications in Gait Analysis

Authors	Sensor Type	Sensor Model	Placement	Behavior Analyzed
(Tao et al. 2012)	IMU (Accelerometer, Gyroscope)	Triaxial accelerometer, Gyro	Foot, Calf, Thigh	Gait kinematics, joint angle, gait phases
(Bamberg et al. 2008)	IMU (Accelerometer, Gyroscope)	Shoe-integrated system	Foot	Gait analysis, foot orientation, and position
(Prasanth et al. 2021)	IMU (Accelerometer, Gyroscope)	Inertial measurement unit (IMU)	Shank, Foot	Real-time gait analysis, gait phases, and events
(Prasanth et al. 2021)	Pressure sensors	Electric conductive rubber	Knee	Knee adduction moment
(Kahlon et al. 2023)	IMU (Inertial Measurement Unit)	Xsens MVN, APDM Opal IMU	Shank, Thigh	Gait kinematics, angular velocity, acceleration
(Zexia He et al. 1995)	Pressure Sensors, Motion Sensors	Custom wearable system with 6 pressure-sensitive electric conductive rubber sensors	Knee	Gait parameters, Rehabilitation for knee osteoarthritis
(Díaz et al. 2019)	IMU (Inertial Measurement Unit)	Triaxial Lumbar, Accelerometer, Gyroscope	Ankles	Gait variability, balance, range of motion analysis

Health Care Applications

Recent advances in technology have led to the emergence of wearable sensors that provide detailed gait analysis. These sensors enable healthcare professionals to measure disease progression and tailor treatments for conditions such as Parkinson's disease and stroke (Tao et al., 2012; Liu et al., 2021). Furthermore, wearable sensors allow for continuous monitoring of patients diagnosed with neurological or musculoskeletal disorders, helping to detect gait abnormalities at early stages and refine interventions (Prasanth et al., 2021).

Gait analysis can assist surgeons in performing multiple corrective procedures in a single session using automation and robotics, thereby reducing recovery time and improving patient health (Zexia et al., 1996). Wearable sensors are valuable tools for detecting gait changes in conditions like Parkinson's disease and multiple sclerosis, providing crucial information for planning rehabilitation strategies (Roberts et al., 2017; Kahlon et al., 2023). Finally, continuous monitoring through wearable sensors offers objective feedback that enhances the rehabilitation of individuals with balance and gait disorders, particularly those recovering from neurological conditions (Díaz et al., 2019).

Automation and Robotics Applications

IMUs and foot pressure sensors have become crucial in automation and robotics, particularly in the development of exoskeletons and prosthetics. The biomechanical and kinematic data generated by these sensors provide essential information that informs the design and control algorithms of robotic assistive devices, enabling more natural and responsive movement patterns. As a result, these robots enhance the mobility of individuals with abnormal gait (Tao et al., 2012). These sensors allow exoskeletons to synchronize their joint movements and behaviors with those of humans, making rehabilitation and industrial applications more accurate and smoother (Liu et al., 2021). The real-time biomechanical data collected from these sensors enables robotic systems to make precise adjustments to their assistance patterns, which helps reduce user fatigue and improve mobility for patients with gait impairments (Prasanth et al., 2021). Furthermore, these technologies provide adaptive control in clinical applications for children with spinal impairments, increasing the effectiveness of assistive devices (Kahlon et al., 2023). By integrating biomechanical parameters such as walking velocity and stride length into robotic systems, real-time adjustments can be made, enhancing the adaptability of these devices (Roberts et al., 2017). Overall, wearable sensors significantly improve the synchronization and responsiveness of robotic systems, benefiting individuals with gait impairments.

Key Findings

Wearable sensors have proven highly effective in capturing gait dynamics across various applications. IMUs are known for their portability and convenience, allowing for the classification of gait phases even outside laboratory settings (Tao et al., 2012). These sensors are particularly useful in both clinical and non-clinical environments, as they provide accurate data for monitoring gait abnormalities, especially in patient populations suffering from neurodegenerative diseases (Liu et al., 2021).

Utilizing IMUs and foot pressure sensors offers a comprehensive understanding of gait dynamics, with the capability to take real-time measurements, making them well-suited for developing medical devices and enhancing rehabilitation techniques (Prasanth et al., 2021). Gait analysis is mainly employed in clinical applications; however, it also provides insights into joint dynamics and muscle activity, which are valuable for developing robotic systems that mimic natural human gait (Gage et al., 1995). Gait parameters such as walking velocity and stride length are essential for understanding both healthy and pathological gait, as well as for interpreting their roles and significance in human locomotion (Tao et al., 2012; Roberts et al., 2017).

Moreover, the correct placement of sensors enables detailed analysis of joint movement and balance, making these systems crucial for comprehensive gait analysis (Díaz et al., 2019). The extensive evidence suggests that wearable sensors are increasingly being utilized to improve gait analysis, diagnostics, rehabilitation, and other assistive technologies (Gage et al., 1995; Tao et al., 2012; Díaz et al., 2019; Prasanth et al., 2021; Liu et al., 2021; Kahlon et al., 2023).

Future Directions

The focus of gait analysis using wearable sensors is on integrating machine learning and advanced algorithms to enhance data precision and provide real-time feedback (Tao et al., 2012; Prasanth et al., 2021). This integration could further refine gait analysis in clinical settings and assist in the detection of subtle gait abnormalities (Prasanth et al., 2021). A key development goal is to make sensors smaller and more energy-efficient, which would improve portability and comfort. This enhancement would allow for wider applications beyond clinical settings, integrating these sensors more seamlessly into everyday life (Díaz et al., 2019). Overall, future developments should prioritize the systematic evaluation of wearable sensors to assess their reliability and validity across diverse clinical settings and populations. This will ultimately enhance their diagnostic precision and therapeutic applications (Tao et al., 2012; Díaz et al., 2019; Prasanth et al., 2021; Kahlon et al., 2023).

Conclusion

Wearable sensors have brought a new era in gait analysis by providing a portable and affordable means of monitoring human movement. These sensors have numerous applications in healthcare, recreation, and robotics. They are particularly valuable for studying gait dynamics and can be used for real-time interventions. Wearable sensors play a crucial role in both diagnostic and therapeutic procedures for motion disorders, personalized rehabilitation, and overall improved patient outcomes. With ongoing technological advancements—especially in real-time data processing and sensor integration—wearable sensors are likely to become increasingly important in both clinical settings and everyday life. Furthermore, continued research and implementation of wearable technology will enhance robot-human interaction, improve assistive technologies, and ultimately provide a better quality of life for individuals with gait disorders.

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