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Research Article

A Systematic Review of Advancement in Gait Analysis Techniques

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Abstract

The examination and the survey of how a person moves, particularly the way of life of walking and running. It entails studying and quantifying a person's gait in terms of their stride length, cadence, foot position, and movement of various body joints. Wearable technology makes it possible to monitor the gait pattern continually while moving about freely. The direction line, gait line, foot line, foot angle, principle line, step length, step breadth, and displacement value obtained from the gyro and accelerated sensors coupled to the shank and thigh are all used to analyze the gait pattern. There has been a lot of research on this method of recognizing people by the way they walk.

The two most crucial facts are that OpenPose, a 2D multi-person posture estimation library, can detect 135 critical body locations without the requirement for fiducial markers, and that smartphone cameras can detect the gait pattern without the use of physical markers. In addition, lower extremity sagittal joint angles, spatiotemporal gait parameters, and timings of gait events were independently determined for motion capture. Gait analysis systems use portable, readily available cameras to measure gait characteristics. The pace of gait, length of steps, time of steps, cadence of steps, and the period of stance are the most crucial factors. Recently, the top standard for the examination of gait was used to evaluate the schemes based on two camera usage to evaluate the framework of different gait patterns.

The precision of the examination of SCA is being increased by data scientists through the development of AI-based computer algorithms. To increase individualization, Bertillon measured the body and faces of several convicts in 1883.

More Information

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Keywords: Wearable technology; Gyro and accelerated sensors; Gait pattern; OpenPose; Smartphone cameras; Gait parameters; The gold standard for gait analysis; SCA gait analysis

Introduction

Human analysis and recognition are attractive technologies in many ways. In digital imaging, people can be analyzed based on their unique characteristics such as iris, face, hair, sweat, gait, palms and fingers. The gait pattern refers to the unique way an individual moves while walking or running [1]. This is influenced by a variety of factors, including an individual's age, gender, health, and physical ability. Gait analysis is the study of human movement, specifically the study of walking or running patterns. It involves observing and measuring various aspects of a person's gait, including stride length, cadence, foot position, and movement of different joints in the body [1]. In recent years, human gait has become of particular interest in health conditions and research because of its links to individual quality of life and personal autonomy, as well as the cognitive processes involved, as the patterns of normal walks may also be associated with neurological disorders [2]. Aberrant gait detection supports current gait analysis methods by offering quantitative measurements and technical advantages such as less invasiveness and a simplified setup. Recent advances in RGB-D devices have enabled low-cost solutions for human 3D motion analysis [3].

Detecting abnormal gait patterns can enhance current methods of human gait analysis by delivering precise, objective measurements while offering technical benefits like reduced invasiveness and a more straightforward setup. Recent developments in RGB-D technology have paved the way for affordable solutions in three-dimensional motion analysis [3].

Currently, methods for assessing the risk of falls are dependent on self-reported information or one-time assessments, which may not be the best strategy [4]. Wearable technology makes it possible to monitor the gait pattern continually while moving about freely. The WS systems employ sensors positioned on various bodily regions, such as the thighs, palms, feet, and knees. Various signals that define human gait are captured using multiple types of sensors.

According to Muro-de-la-Herran, et al. [5], this includes accelerometers in order gyroscopic gadgets, magnetic resonance imaging, sensors for force, extensometers, goniometers, active indicators, electromyography, also, etc. Step length, step length, length ratios, stance or stride width, linear dimension, and horizontal dimensions, measurements of foot, feet line, the direction line, feet angle, gait line, etc. are some of the metrics that may be included. Human locomotion is the subject of gait analysis, a discipline. Orthopedic surgery is increasingly using gait pattern analysis for both clinical and academic purposes [6]. Recognizing the pathological gait abnormalities in neuromuscular illnesses and the biomechanical imbalances that cause the injury has benefited greatly from early research. The issue of personal identification has drawn a lot of attention, especially in the security field. One of the more practical methods for enabling in-person identification at some distance without the requirement for high-quality photos is gait recognition. There are, however, a number of review articles addressing person identification, including the use of wearable sensors, silhouette photographs, and facial images [7]. A person or individual leaves behind a trail of footprints that are together referred to as a gait pattern. The action of the limbs while moving, whether it be walking or running, determines the gait pattern. As a result, it aids in the investigation of crimes. Because it can be used to estimate a person's age, sex, and height, examining and analyzing their gait pattern is crucial [8]. An unconscious behavior like walking can be utilized to recognize a person. In most situations of robbery, theft, housebreaking, etc., gait patterns can be seen. The most frequent pattern evidence in most crimes is a person's gait, which helps establish a connection between the culprit and the crime. Finding the total number of suspects associated with the crime can be useful in some circumstances. Because it has certain characteristics, such as uniqueness, Gait pattern examination holds significant forensic value [2].

To identify a potential suspect, the trajectory of the line, the motion line, the heel line, the heel angle, the primary line, the stride length, and the step width must all be calculated and analyzed from an individual's gait pattern. Analysis of gait patterns is mostly utilized for personal identification. By making an educated guess about a person's age, sex, height, and weight, one can identify them personally [8] (Figure 1).

1. **The direction line:** This line is straight. The way a person is moving in or walking can be ascertained with the aid of a hypothetical line traced down the middle.

2. **The gait line:** The dotted line across the inner side of the foot groove corresponds to the gait line of a healthy person.

3. **The foot line:** From the second foot to the heel's midpoint, this line extends. Shows the angle at which the foot is positioned.

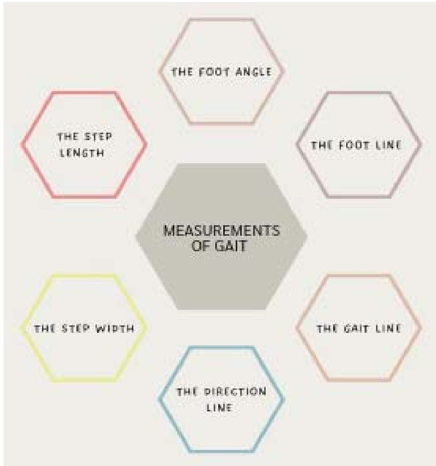

Figure 1: Measurements of gait.

4. **The foot angle:** The foot angle is the angle formed by the straight line that leads and the foot line. The usual foot angle is between 30 and 32 degrees.

5. **The step length:** The separation between the first foot strike and the second foot strike. Both left and right steps are equal during a typical gait.

6. **The step width:** Your two heels should be apart when you're standing in pairs. The distance between the two heels' axis as well as the lines that cut through them is used to estimate stride length. Adults typically walk 1 to 3 feet (3 to 8 centimeters) in their stride [8].

Different tools and techniques used for the analysis of gait patterns

Wearable sensors for gait analysis: The increased interest in gait analysis and eagerness to learn the uniqueness of human locomotion has led to a constant evolution of techniques in gait analysis [9]. Earlier, the analysis of gait patterns was done with the use of markers and optical cameras. They calculated the 3-dimensional arrangement of body parts during motion [10]. As the need for an abundance of workspace, difficulty in applying in outdoor or non-traditional surroundings added drawbacks [11]. Countermeasures had to be taken.

Modern wearable sensors include electromechanical systems based on foot-switches and electro-goniometers. These devices showed high accuracy in measuring joint angles in the sagittal plane [12]. A more recent method is wearable inertial and magnetic sensors [13] (Figure 2).

Wearable magnetic sensors: The displacement value collected from the gyro and accelerated sensors connected to the shank and thigh were used in calculating the 3D angles of the knee during motion [14,15]. Magnetic sensors were utilized due to the error that occurred in the calculation of knee joint displacement [16]. Advanced mathematical techniques, such as transform-based methods, have also been explored

Figure 2: Wearable sensors for gait analysis.

to improve the modeling and analysis of biomechanical data [17].

The errors raised in accelerated and gyro sensors were compensated by magnetic sensors. The correlation with the camera system was present. In locations where high magnetic interference was present, the ferrous materials affected the magnetic sensors which in turn restricted their usage. This was overcome by the attachment of a magnetic source. This helped eradicate the interference of magnetism [18].

The tilt angle from the lower body parts was calculated using the acceleration data instead of exterior sources, such as magnetic fields or cameras. The rotation of the abdominal region in the horizontal plane was measured using gyro technology. Problems did arise in the usage of acceleration sensors to measure inclined angles [19].

There are magneto-resistive sensors based on the magnetoresistive effect. In the absence of magnetic flux, the current can be observed flowing through the InSb plate. The magnetic force will deflect the current path if the magnetic flux is adapted. Due to the deflection, the distance of the current flow increases which causes an increase in resistance. Based on the tilt angle correlated with the magnetic field direction, the sensors are able to calculate the changes in the body parts [20-22].

Electromyography (EMG)

This method calculates the muscle action in the lower body. The electrodes in EMG act as a kind of sensor. They provide timing and intensity of muscle contraction by detecting voltage potential.

Surface electrodes are for general muscle activity information. Wire electrodes on the other hand are for specific information on a particular muscle. Wire electrodes are inserted with the use of a hypodermic needle [23]. EMG sensors are also used in the evaluation of walking performance in individuals having disabled functioning in the lower body [24,25].

Sensing fibres

This fabric is a hybrid of fabric and sensing technology. It comprises electronic components, yarns with sensing technology attached to regular fabrics, and electronics made of fabrics. It is more flexible and comfortable in the measurement of an individual's locomotion and posture. The application of piezoelectric or piezo capacitive materials helps in giving sensing abilities to the fabric [26,27]. The addition of carbon polymers onto stretchable fabric will produce a good quality sensing material [28].

Flexible goniometer

The relative rotation between body segments can be easily identified by calculating the physical signal from the bodily changes. It comprises strain gauges, mechanically flexible, optical fiber, and an inductive goniometer. Flexible goniometers are applied to use since the early 1980s [29].

Currently, flexible electro goniometers are commercially available in the market to measure the spinal motion and posture of individuals [30]. The surveillance of joint locomotion is done through a newly developed optical fiber goniometer [31]. The longitudinal displacement is measured using a mechanical flexible goniometer, and the measurement is done during joint locomotion [32].

Force sensors

The gait measurement was done by the force sensors connected to the footwear. The 3D vector GRF is dependent on the process happening between the foot and the ground. Easy addition of piezoelectrics, strain gauges, capacitive transducers, and force transducers can be done [33]. A wearable force sensor based on photoelastic triaxial force transducers was invented to measure the ground reaction force [34].

The source of the controlled magnetic fields influences the changes in induced voltages in accordance with the object's orientation and position. A fixed transmitter is responsible for providing the magnetic fields in the ETS. The receivers which are fixed to the moving item pick up the magnetic force fields [35,36].

Non-wearable sensors for gait analysis

Wearable sensors are limited to a point. Wearable sensors are widely utilized in the entertainment industry. In the case of criminals, the sensors have to be worn later to analyze if the individual is the actual culprit. Non-Wearable sensors on the other hand gives quick and efficient result with mostly the help of cameras. Recent technological advancements have driven growth in this sector. Semi-subjective methods are Extra-Laboratory Gait Assessment, Performance-oriented by Tinetti, Walking Scale, and major methods like Image Processing and Floor Sensors [37] (Figure 3).

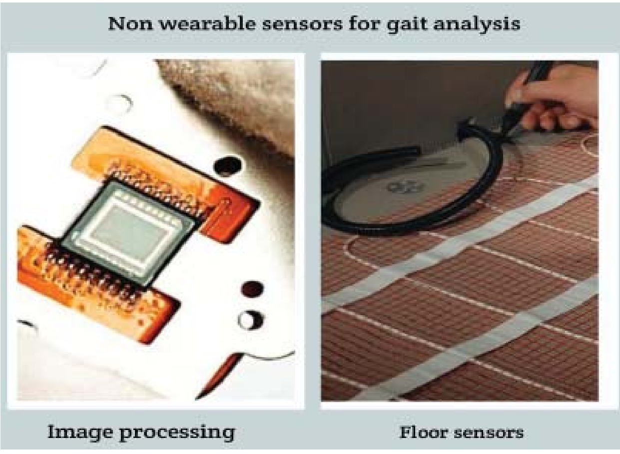

Figure 3: Non wearable sensors for gait analysis.

Image processing

It is a system made of digital or analog cameras with apt lenses to capture gait patterns. It is one of the methods to calculate the motion changes. Threshold filtering is a method that converts images into pixels, black and white. Color grading and background segmentation are also analyzed [38].

The system is capable of providing the apt breakdown and analytical results for thigh and knee to be currently utilized in the field of medicine [39]. New analysis shows good and promising results in gait recognition [40]. This IP method has become very important in the present age. The sub-methods coming under this are Camera Triangulation, Time-of-Flight Systems, Structured Light, Infrared Thermography [41,42].

Floor sensors

In this system, sensors are placed on the floor. They may be working as instrumental or force sensing. The force sensors and moment transducers help in the monitoring of gait data. One type of platform senses force while the other senses pressure. They find the pressure predominantly and then calculate the force vector. The arrangement of the system is in such a way that platforms are separated from coded systems. Only the patterns from foot pressure can be measured. It is coded so that other types of particle pressure may be avoided automatically [43].

The force received from feet to the ground is Ground Reaction Force. The GRF separates FS and IP-based systems [44]. These tools provide a premonition to the kind of gait issue the patient may be suffering from. As the reaction and initial force are inversely proportional, the expert determines the value of foot pressure at that instance. The specialists are getting positively aided with this analysis and are able to give satisfactory diagnoses.

Gait analysis techniques using smartphones & software

In criminal investigations or legal procedures, forensic gait analysis involves the application of gait analysis methods. It entails comparing the stride of an unidentified person to that of a suspect or witness who is a known party.

The application of forensic gait analysis is applicable to situations involving eyewitness testimony, crime scene evidence, or surveillance film. The height, weight, gender, and other physical attributes of the person seen in the video or any supporting evidence can be determined by forensic specialists by examining gait patterns.

Generally, we are not always equipped with high-end technologies to monitor, record or overall analyze gait patterns.

In order to solve this problem there are various simple techniques that if applied to the videos taken from a smartphone camera, can easily analyze the specific gait pattern, some of them are capable enough to monitor and differentiate gait patterns even if the video footage has crowded background

Recording of the footage: For the proper analysis of the gait, the footage should contain as much data as within them

Three-dimensional video capture involves using single or multiple cameras to record video from various perspectives,

The angle of videography - for gait analysis as it is focused majorly on the legs movement we consider these angles for videography

- wide-angle footage
- low angle footage
- sagittal plane footage from left and right sides [45].

lightning & scaling of the scene: These smartphone cameras now come with inbuilt light enhancement features during video recording & also can easily detect the gait pattern without any help of physical markers, however on research conducted on 320 lux intensity of light was quite enough for the recording of the gait pattern.

The scale of the backdrop is taken into account when recording the gait since it aids in the analysis of the length of the step, regular walking habits, and duration of the gait. So we scale a few background walls, poles, or even the floor in order to precisely calculate these values [46].

In the cases where we get footage from CCTV or from other sources, its edited version with increased exposure can be used for analysis which can solve the lighting problem.

And the scaling problem can be solved by measuring the height & length of structures present in that footage physically.

Camera settings—including focus, white balance, exposure, ISO, and shutter speed—should be adjusted based on the recording environment, however, framerate and quality should be kept at the maximum supported by the device

Analysis of the recorded footage through AI software

1. **Openpose-based markerless gait analysis:** Both top-down and bottom-up methods may be used to create human poses. Because it is quicker and has a lower error rate than the top,bottom-down approach [47] involves estimating key points and creating a relationship between them to generate the pose. The ability of OpenPose [48], to recognize 135 important body points without fiducial markers makes it an advantageous tool for obtaining anatomical joint coordinates in the lower extremities.

Openpose's operational parameters include spatiotemporal gait characteristics such step time, step length, gait speed, stance time, swing time, and double support, as well as timings of gait events at heel-strikes and toe-offs [46].

2. PoseNet: TensorFlow, a well-known machine learning framework developed and maintained by Google, is used to program this artificial intelligence, which is written in Python. PoseNet Perceives 17 fundamental focuses: the nose, ears, shoulders, hips, knees, elbows, and ankles PoseNet is compatible with both GPUs and CPUs. It offers two operational modes: a posture detector for many individuals and a pose detector for one person, which is quicker and easier to use but only works with one subject in the image. One of the most appealing advantages of this skeletal tracking technology is its capacity to operate almost independently of the number of patients being analyzed concurrently [49].

3. Nuitrack: It is a confidential shut-source application. It is an artificial intelligence that is based on deep learning. It supports face tracking, gesture recognition, and 3D full-body skeleton tracking across platforms. 19 distinct points are observed by Nuitrack: It doesn't follow the feet, but it does follow the hands [49].

4. The Skeleton Tracking SDK from Cubemos is a closed-source, exclusive application that uses the distribution of the OpenVINO toolset from Intel. It is a machine learning-based artificial intelligence. A scene with up to five individuals should only employ this real-time, cross-platform, multi-person, 3D full-body posture estimator.

Cubemos is aware of the following 18 fundamental parts of the body: the eyes, nose, ears, wrists, hips, elbows, ankles, and spine. As a result, it is unable to offer data on the hands, feet, or specific rotations. Both CPUs and GPUs may be used by it.

The Skeleton Tracking SDK from Cubemos, an Intel partner, is designed for usage with Intel hardware [49].

New filming techniques for gait pattern analysis

Modern systems that measure the gait metrics frequently have substantial prices, as well as training and setup requirements (1). An accessible, alternative without the usage of markers is gait analysis devices, which employ portable, commercially available cameras. (2) The evaluated camera-based gait analysis structures are now only partially capable of providing reliable gait characteristics. (3) These relatively easy techniques are utilized for examination of gait whether the available designs are modified, and the technique of the camera develops. (4) A thorough gait study can highlight irregularities and abnormalities in gait behavior, enabling medical experts to gauge the likelihood of disease or injury. (5) When measured correctly, the measurement of the framework offers valuable distinctive medical details. (6) The most important gait analysis variables, as stated by Springer and Seligmann, are walking speed, stride length, stride period, rhythm (steps taken by a person per minute), and stance period. (7) The changes related in the step framework with age are related to an expansion in step period and wideness of steps, as well as a reduction in the symmetry of gait and the length of step (8) [49].

The GAITRIte system (GS): A movable device used for automatic evaluation of the characteristics of gait, is one of the most convenient and holds top quality for the examination of gait. According to studies, the utilization of GAITRIte is reasonable and authentic. However, because it requires expensive equipment that is not usually available in clinical settings, its use is limited. In addition, since only step parameters can be recorded, whole-body step analysis is not possible [50].

According to a recent study, gait analysis with Microsoft Kinect is both effective and inexpensive [8,9]. According to studies, Kinect is a reliable measuring tool only for measuring certain steps. There is an examination of evidence utilizing the GAITRIte method as a backing system, the Kinect was established to be applicable for calculating average stride length or stride length in combination with other common measurements (the correlation from Spearman coefficient i.e., 0.94 for the standard length of stride and 0.75 for the standard length of per stride). It is extra difficult to determine more accurate results based on individual strides (SCC 0.74 length per stride and 0.43 stride length per stride), which makes it more difficult to determine more complicated gait metrics such as symmetry of gait. Clark et al. This study also showed that the justifiability Kinect system had for complex step factors was limited. New devices that use relatively new and extensive data techniques like smartphones have progressed because some current techniques are costly, require a lot of areas, do not apply, or require a lot of training. In the submitted examination, the methods based on the two-camera utilization for calculating distinct characteristics of gait were testimonies averse to the gold quality of the analysis of the gait. [51].

Three different technologies were used for gait analysis: the pressure-sensitive pavement system and number 40; GAITRIte-System, GSand#41, Motognosis Labs software, and the Xbox One Kinect sensor (Microsoft Kinect System, MKS).

The examination and the check of how a person moves, particularly the way of life of walking and running. It entails studying and quantifying a person's gait in terms of their stride length, meter, bottom position, and movement of colorful body joints. Wearable technology makes it possible to cover the gait pattern continually while moving about freely. The direction line, gait line, bottom line, bottom angle, principle line, step length, step breadth, and relegation value attained from the gyro and accelerated detectors coupled to the cutter and ham are all used to dissect the gait pattern. Extensive research has been conducted on this method of identifying individuals by their gait.

The two most pivotal data are that OpenPose, a 2D multi-person posture estimation library, can descry 135 critical body locales without the demand for fiducial labels, and that smartphone cameras can descry the gait pattern without the use of physical labels. In addition, lower extremity sagittal joint angles, spatiotemporal gait parameters, and timings of gait events were singly determined for stirring prisoners. Gait analysis systems use portable, readily available cameras to assess gait characteristics. The pace of gait, length of way, time of way, a meter of way, and the period of station are the most pivotal factors. Lately, the top standard for the examination of gait was used to estimate the schemes grounded on two camera operations to estimate the frame of different gait patterns. The perfection of the examination of SCA is being increased by data scientists through the development of AI- grounded computer algorithms. To enhance individual identification, Bertillon measured the bodies and faces of several convicts in 1883.

Ultramodern systems that measure the gait criteria constantly have substantial prices, as well as training and setup conditions. (1) An accessible, indispensable without the operation of labels is gait analysis bias, which employs movable, commercially available cameras. (2) The estimated camera-grounded gait analysis structures are now only incompletely able of furnishing dependable gait characteristics. (3) These fairly easy ways are employed for examination of gait whether the available designs are modified, and the fashion of the camera develops. (4) A thorough gait study can punctuate irregularities and abnormalities in gait gestures.

Green Blue camera. SCA was downloaded on a Google Pixel 2 mobile phone which runs on Android. (3) GS dimension was started from the contact of the first pressure on the mat. The videotape record feature of MKS and SCA started when the actors arrived at the filming point. At the end of each walking period, the experimenters checked if the structures were measured rightly. Eventually, actors entered a brief assessment of their gait pattern grounded on GAITRIte data. The training lasted about an hour for the actors. All exploration procedures were approved by all the codes of conduct commissioned, then the data protection authority of Charité (4) (Figure 4).

GS data is used to help inventors acclimatize to the

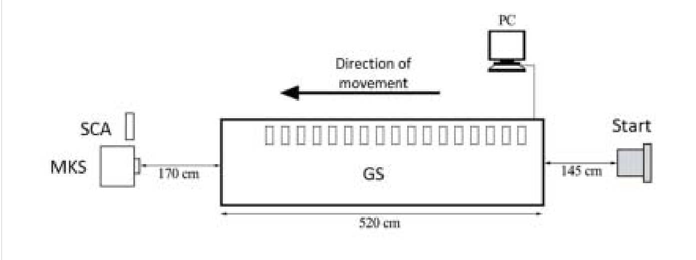

Figure 4: Experimental setup.

Comparative Table 1: Evolution of Gait Analysis Techniques.

Feature	Conventional Methods	AI - Based/Modern Systems
Technology Used	Optical motion capture , force plates , EMG , goniometers	Deep learning, computer vision, wearable IMUs, smartphones
Setup Requirement	Lab-based, requires markers and controlled environment	Portable, markerless, adaptable to real-world settings
Cost and Accessibility	High cost, limited to research/ clinical labs	Lower cost, accessible via smartphones and open-source tools
Measurement Parameters	Kinematic/kinetic data, joint angles, muscle activity	Spatiotemporal features, skeletal tracking, pose estimation
Marker Requirement	Requires reflective or physical markers	Markerless, relies on visual keypoints and AI models
Examples of Tools	GAITRite, Vicon, EMG sensors	OpenPose, PoseNet, Nuitrack, Cubemos, Kinect

conditions of methodical step analysis, utilized primarily in drug and physical remedy. MKS and SCA algorithms then are progressed afterward and grounded on the presented exploration. In particular, this exploration will be utilized as an initial foundation to strengthen the important information and wisdom experience for the further progression of the SCA examination. The scientists that are dealing with data are continuing to progress in Artificial Intelligence grounded computational styles to ameliorate the delicacy of SCA gait examination. Compared with the step analysis performed with the use of the Microsoft Kinect camera, which has been utilized successfully in former studies with multiple groups that have been targeted, the step analysis performed with the smartphone camera is a fully new system. Before further exploration, the underpinning of artificial intelligence must first be explained [51,52] (Table 1).

Conclusion

Forensic gait analysis has a lengthy history and has been employed in court cases for more than ten years in several nations. The study of gait patterns by Murray et al. has demonstrated that each person's gait is distinctive and affected by their personality. Compared to other biometrics, gait recognition has the benefit of being effective in situations where other biometrics may be concealed or require the subject's cooperation. It could aid law enforcement in the early detection of suspects and the suppression of more criminal activities.

As with any biometric identification technology, it is crucial to take into account the limitations and potential downsides of gait recognition. For forensic applications, the accuracy and dependability of gait recognition methods may require more investigation and confirmation. It is also essential to follow ethical and legal standards when applying gait recognition in legal proceedings.

With technological advancements and continued research, gait recognition holds significant potential in forensic investigations. Its ability to capture an individual's unique movement pattern makes gait recognition a promising biometric identification technique, which is impacted by their personality. As with any forensic technology, gait recognition should be applied responsibly to ensure reliability and effectiveness in legal contexts, in conjunction with other evidence, and in accordance with legal and ethical norms.

Despite notable progress in gait analysis technologies, numerous challenges and gaps persist, especially in relation to forensic applications. Upcoming studies should aim to enhance the precision and dependability of gait recognition systems in practical settings, including low-light situations, blocked scenes, or instances where individuals are dressed in loose or obscuring attire.

It is also necessary to create standardized protocols for forensic gait analysis to guarantee uniformity and admissibility in court cases. Integrating multimodal biometric systems—such as those combining gait, voice, facial, or postural identifiers—can enhance reliability and reduce false positives.

Additional efforts are needed to enhance AI and machine learning algorithms to recognize subtle differences in gait caused by age, injury, or emotional condition, and to evaluate how these differences affect identification precision. Furthermore, broadening datasets that include varied populations and actual walking situations will be essential for training and validating models.

Future studies should enhance gait recognition in low-light, obstructed scenes, and create standardized forensic protocols.

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