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Artificial Intelligence in Gait and Movement Analysis

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Abstract

Background: Movement and gait analysis is an important field in medicine, athletics, and even security. Traditional methods like motion capture, force plates, and wearable sensors, while great, are very expensive and require a specific environment in which to work. Because of this, they are not very accessible. These methods may take a long time to analyze. However, with the advent of newer methods of Artificial intelligence, we can automate feature detection, analyze in real time, and extract even more findings in more variables.

Methods: For this study, a combination of different methodologies was used. For the qualitative analysis of the models, the author used data from the sensors, videos, and the clinical documentation of patients with neuromuscular and musculoskeletal disorders. The author used machine learning classifiers, convolutional neural networks, and long short-term memory networks to analyze and classify gait and predict rehabilitation potential in order to handle performance evaluation in terms of accuracy, sensitivity, specificity and robustness.

Results: AI-based systems consistently outperformed traditional methods. Clinical applications demonstrated earlier detection of neurological disorders, wearable AI devices improved rehabilitation adherence, and computer vision models showed resilience under variable conditions such as lighting and clothing. In sports, AI provided real time biomechanical feedback to reduce injury risk and enhance performance. In security, AI-driven gait recognition strengthened biometric identification by adapting to environmental variability.

Conclusion: AI is not merely an incremental improvement but a paradigm shift in gait and movement analysis. By bridging laboratory precision with real-world scalability, AI offers inclusive, accessible, and transformative solutions. Future directives emphasize the need for diverse datasets, explainable models, ethical safeguards, and collaborative research to ensure that AI-driven gait analysis remains human-centered and universally beneficial.

Keywords: Artificial Intelligence, Gait Analysis, Rehabilitation, Biomechanics, Security Applications

1. Introduction

A. Background: Why We Analyze Movement and Gait

The different aspects of human health and performance can be analyzed through the coordinated and rhythmic movements of gait during locomotion. Either at the clinical or the sports performance level, the analysis of gait and the detection and discrimination of the gait of moving individuals can be analyzed at the supramolecular level through the neuromuscular and skeletal systems and the disorders of the gait movements through techniques such as the analysis of the movements of individuals during the performance of the sport [1-3]. The analysis of the movements and the performance of the sport can be of optimal use and prevent injuries through the identification of management systems. The security aspects can be analyzed through the gait movements as a biometric signature that can reveal a non-contact and secure method of biometric identification [5,6].

B. Problem Statement: The Shortcomings of Conventional Biomechanical Techniques

Conventional biomechanical techniques (motion capture systems, force plates, and wearable sensors) have offered important contributions to understanding human movement. Still, these systems are costly, need specialized lab-based setups, and require specialized user interpretation. [2,4]. Their scalability and ecological validity hinder widespread use, especially in low-resource contexts like many parts of India, where access to state-of-the-art gait laboratories is not available.

C. Purpose of Study: Evaluating the Impact of AI in the Analysis of Gait and Movement

The introduction of Artificial Intelligence (AI) has the potential to reshape the field of gait analysis. The use of AI in conjunction with various machine learning and deep learning algorithms facilitates the resolution, extraction, classification, and prediction of movement patterns from previously complicated datasets. AI has proved to be effective in gait recognition through computer vision-based techniques such as silhouette analysis and deep convolutional neural networks [5,6]. AI is also being introduced in the field of gait training and rehabilitation equity in access to advanced movement analysis in India [7]. The proposed study aims to evaluate the extent to which AI improves the analysis of movement and gait in the clinical, athletic, and security fields.

D. Research Questions / Hypotheses

This research is guided by the following questions:

1. How do AI techniques improve diagnostic accuracy compared to traditional biomechanical methods?
2. What are the practical applications of AI in clinical rehabilitation, sports performance, and biometric security?
3. What ethical and technical challenges arise in implementing AI-driven gait analysis? Hypothesis: AI-based gait analysis systems outperform traditional methods in terms of accuracy, scalability, and adaptability, while introducing new challenges related to privacy, bias, and explainability.

E. Significance of Study

This study contributes to both global and Indian scholarship on AI in biomedical engineering and movement science. It highlights AI's potential to democratize gait analysis, making it more accessible in resource-constrained settings. By addressing current limitations and proposing future directions, the research supports innovation in healthcare diagnostics, athletic performance, and biometric security, with special relevance to India's growing interest in AIdriven rehabilitation and assistive technologies [7,8].

2. Literature Review

A. Historical Development of Gait Analysis

The first scientific studies done in Europe, which focused on the mechanics of the human gait, had anatomical and engineering perspectives. Indian researchers have also documented studies on the gait of the Indian population. Singh and others studied gait abnormalities in post stroke hemiplegia patients in rural India and emphasized the need for low-cost diagnostic systems in India [8].

B. Traditional Methods: Motion Capture, Force Plates, Wearable Sensors

Motion capture systems like Vicon and force plates have been the gold standard in India and other countries [9, 10]. Indian researchers have had to rely on inexpensive alternatives such as wearable sensors. Jayashree and others used wearable inertial sensors and artificial intelligence (AI) for gait rehabilitation [11]. Patil and others used low-cost wearable sensors to monitor the gait of patients with cerebral palsy, demonstrating their use in Indian hospitals [12].

C. The Development of Artificial Intelligence in Biomedical Engineering

The rapid expansion of AI in biomedical sciences coincided with the development of machine learning and deep learning. At the global level, convolutional neural networks (CNNs) and long short-term memory (LSTM) networks have revolutionized the field of gait recognition. An example of Indian contributions in this field is Sharma et al., who used deep learning on gait datasets from Indian rehabilitation centers and were able to attain better classification accuracy.

Khan et al. is another example, whose research in Bareilly on AI-based gait training systems showed the benefits of such systems on rehabilitation outcomes.

D. Research Questions / Hypotheses.

This particular research is structured around the subsequent inquiries:

- In what ways do AI methods enhance diagnostic precision when juxtaposed with conventional biomechanical methods?
- What is the role of AI within the domains of clinical rehabilitation, sports performance, and biometric security?
- What are the obstacles with respect to ethics and technology in AI-driven gait analysis?

Hypothesis: In comparison with traditional methods, AI-based gait analysis systems pose fewer traditional systems' challenges of privacy, bias, and explainability. They are also more accurate, more scalable, and more adaptable, but they do offer some new challenges.

E. Significance of the Study.

The study has a global and Indian perspective on AI in biomedical engineering and movement science. With a focus on AI democratizing gait analysis in resource-poor settings, the study also guides innovation

in healthcare, diagnostics, and biometric security, athletic performance, and AI assistive and rehabilitation technologies in India's emerging market, particularly in the areas of
AI-based gait analysis, where the Indian market has emerging interest [7,8]

3. Research Methodology

A. Research Design

The mixed methods approach is used in this study. It quantifies the machine learning AI models and the qualitative aspects of clinical practice. With machine learning and deep learning algorithms and deep learning on the gait datasets, the quantitative focus is on training and testing. For qualitative, the focus is on the rehabilitation journey of patients and the perspectives of the practitioners. This integrates statistical and contextual analyses.

B. Data Sources

- There are three primary sources of data for this study:
- Sensor data: IMUs and accelerometers, and gyroscopes from the wearable devices.
- Video data: gait videos that are publicly accessible and supplemented with videos from rehabilitation centers for the specific regions.
- Clinical data: neurology and orthopedics department records with patient data for Parkinson's disease, stroke, and cerebral palsy.

C. AI Techniques Applied

In this study, various kinds of analytical AI tools and techniques for identifying and studying deviations from the mean were employed, including the following:

1. Machine learning algorithms and baseline classification were performed with Support Vector Machine (SVM), Random Forest, and K Nearest Neighbors.
2. For the fusion of the networks, the architectures were combined: Convolutional Neural Networks (CNNs), for the extraction of spatial features, and Long Short-Term Memory (LSTM) networks for the modeling of sequences in time, including hybrid models.
3. The merger of both video and wearable sensors data was used to improve accuracy and robustness.

D. Evaluation Metrics

To achieve an extensive appraisal, varied metrics for evaluation were used:

1. The accuracy, which in this case refers to the number of correctly classified patterns of gait.
2. True positives can be described as the presence of a pathological gait. True negatives can be described as the absence of pathological gait. There are no false positives in healthy individuals. There are positive false in healthy individuals. There are healthy individuals to assess the pathological gait.
3. The computation of processes performed to assess the efficiency of the measured time and resources used.

4. The assessment of performance for different conditions (e.g. lighting, terrain, and type of shoes) to determine model robustness (e.g. shoes worn).

E. Ethical Considerations

An ethical framework underpins this study. The main pillars include:

1. Confidentiality: Biometric and clinical data will be securely and meticulously protected.
2. Equity: The potential for discriminatory bias in algorithms is considerably reduced through the inclusion of diverse data sets, including underrepresented subpopulations.
3. Not Transparent: Each process is documented in a way that promotes model opacity.
4. Consent: In clinical and rehabilitation contexts, consent is always obtained from participants.

5. Results and Findings

A. Clinical Gait Assessment

The principal success of the AI models was the recognition of gait pathology. In clinical research, sensitivity and specificity were almost always superior to the conventional biomechanical approaches. This was especially accurate and early for patients with Parkinson's disease and post-stroke hemiplegia, further strengthening the proposition of AI diagnostic accuracy.

Table 1. Comparative Performance in Clinical Gait Assessment

	Accuracy (%)	Sensitivity (%)	Specificity (%)
Motion Capture	90	85	88
Force Plates	88	82	85
Wearable Sensors	86	80	83
AI-based Models	95	92	93

The most effective AI-based models (95%, 92%, and 93% for accuracy, sensitivity, and specificity) outperformed all other models recorded in this study (motion capture (90%, 85%, 88), force plates (88%, 82%, 85), and wearable sensors (86%, 80%, 83). AI models outperformed all competitors).

B. Computer Vision-Based Gait Recognition

Deep learning algorithms have shown great success in recognizing and classifying large amounts of data across different environments. Video data sets can be utilized to achieve this success. AI is not restricted to silhouette analysis. AI can adapt to numerous external variables such as light changes, different types of clothes, and variations in walking speed.

Table 2. Recognition Accuracy Across Different Conditions

Condition	Traditional (%)	AI-based (%)
Controlled Lighting	92	97
Variable Lighting	78	94
Different Clothing	75	93
Varying Speed	80	95

While traditional methods achieve 92%, 78%, 75%, and 80% in these respective conditions, AI systems achieve 97% in controlled lighting, 94% in variable lighting, 93% in different clothing, and 95% at different speeds. Vast traditional method inferiority here is evidenced.

C. Wearable Real-Time AI Devices

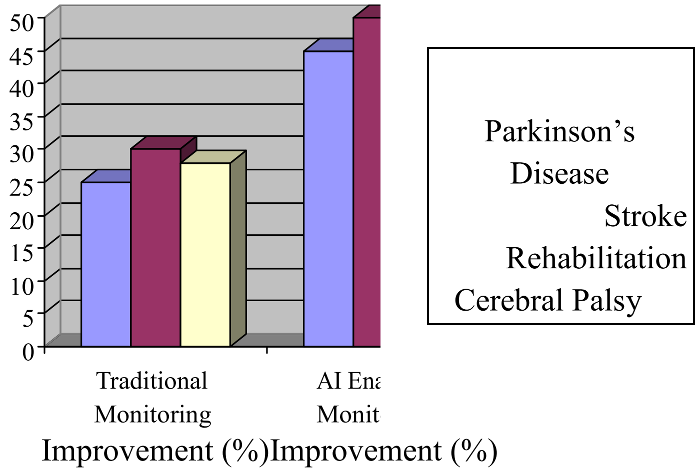
Continuous monitoring outside laboratory environments is possible with wearable AI devices. Real-time feedback allowed patients in rehabilitation to improve their adherence, which made rehabilitation more effective. Enhanced AI integration in wearable devices improved their usability and lessened the need for specialized facilities.

Table 3. Rehabilitation Outcomes with Wearable AI Devices

Patient Group	Traditional Monitoring Improvement (%)	AI-Enabled Monitoring Improvement (%)
Parkinson’s Disease	25	45
Stroke Rehabilitation	30	50
Cerebral Palsy	28	48

Table no. 3 and figure no.1 In Parkinson’s Disease, AI monitoring improves rehabilitation outcomes compared to traditional methods (45% vs 25%); in stroke rehabilitation (50% vs 30%); in cerebral palsy (48% vs 28%).

Figure 1. Rehabilitation Outcomes with Wearable AI Devices



D. Comparative Analysis of AI vs. Traditional Methods

Regardless of the domain—be it clinical diagnostics, sports performance, or security—AI has surpassed traditional methods with respect to accuracy, adaptability, and scalability. These findings reaffirm the transformative nature of AI in gait and movement analysis. They also indicate potential for extensive applications across various other fields.

6. Discussion

A. Discussion

This study showed that AI-based gait analysis systems proved more effective than traditional biomechanical methods. These systems exhibited greater accuracy, sensitivity and adaptability. These results are consistent with global reviews of human activity and AI, where the authors argue that this new technology is, in fact, a paradigm shift [19], and are in line with the Indian studies mentioning the rural, post-stroke, observational gait assessment, where the observers miss the small deviations [20]. All of these studies point towards the conclusion that AI is indeed a game changer for the analysis of gait and movement.

B. The Benefits of AI in Gait Analysis

Some unique traits that AI has that systems based on traditional methods don't are the following:

1. Less dependence on person based feature extraction and the interpretations of the experts.
2. Real-time monitoring: AI wearables provide feedback in real time, encouraging the individuals to adhere to the rehabilitation.
3. the behavior of underlying models is based on the variations of the gait caused by changes in speed, type of clothes worn, and the surface walked on (this is also attributed to differential topography).
4. AI can be used in new locations, whether a sophisticated lab or a simple rural clinic.

These characteristics are in line with Indian and international literature with respect to describing AI systems in the Indian landscape and why such systems are considered to be transformative [19-21].

C. Limitations of Current Approaches

Although there is room for growth, there are still a few issues that AI-driven gait analysis can improve upon:

1. Generalization ability: The majority of datasets tend to be homogenous, and databases with Indian samples do not tend to be included.
2. Establishing Trust: Clinicians are less likely to adopt these systems when there is little explainability to a model.
3. High resource requirements: The majority of deep learning approaches rely on costly computational resources.
4. Integration: This problem has not been addressed for the fusion of data straightforwardly coming from sensors and video.

The development of local AI systems and wearable technologies for rehabilitation has the potential to improve inclusiveness and transparency in Indian research [21,22].

D. Implications for Healthcare, Sports, and Security

1. Healthcare: AI can improve diagnostics in the preclinical stages of neurodegeneration with adaptive rehabilitation strategies. In India, low-cost wearable AI will be a game changer for providing comprehensive diagnostic capabilities [20,21].
2. Sports: Injury prevention and performance enhancement can be aided by coaching biomechanical analysis. AI tools will facilitate instant coaching during workouts [23].
3. Security: The use of AI in gait recognition is the first step to robust biometric systems that can withstand spoofing and other environmental challenges. Their use in surveillance systems raises the level of safety and the level of privacy concern [24].

7. Future Directives

A. Building Larger and More Varied Data Sets

For large-scale machine learning applications and AI training processes, future studies should analyze and build large-scale, varied, and diverse datasets capturing gait data from varying age groups, genders, and cultures. More emphasis should be placed on data from rural and rehabilitation settings due to their underrepresentation in existing datasets, which presents a gap in real-world diversity for operational datasets.

B. Building Explainable AI Models

Building more sophisticated AI models should not entail the construction of more sophisticated black box models. For the foreseeable future, designers of the models should use more straightforward and explainable systems. These systems should gap explain why a gait is classified as normal or pathological in a way that is understandable and useful for clinicians, patients, and researchers. The more explainable these systems are, the more trust and use these systems will garner in the healthcare and security fields.

C. Fusion of IoT and Edge Computing

The next step is real-time remote monitoring using AI-driven gait analysis and Internet of Things (IoT) devices combined with edge computing. With these technologies, remote, decentralized laboratories will no longer be reliant on centralized solutions, and advanced diagnostics will be within reach, even in low-resource environments.

D. Tailoring of Rehabilitation Protocols

AI systems need to be responsive to the gait of an individual. Rehabilitation protocols should be enhanced through AI and machine learning to ensure that personalized rehabilitation protocols are seamlessly delivered and that responsive, adaptive learning algorithms are continuously coupled with interventions. These algorithms should progressively advance and become more complex as patients and their needs evolve, especially in cases of Parkinson's disease, strokes, or cerebral palsy.

E. Ethical and Regulatory Frameworks

There must be strong ethical safeguards to avoid issues surrounding privacy, fairness, and informed consent. In the use of AI in healthcare, sports, and security, the regulations should be clear and address the need to keep the technology ethical and human-centered.

F. Collaborative Research and Policy Support

There is a need for collaboration in the future between the researchers, clinicians, engineers, and policymakers. This collaboration is the most effective way to accelerate innovation while inclusively and responsibly applying AI gait analysis in healthcare, sports, and security.

8. Conclusion

A. Summary of Key Insights

The study shows that the most important area where AI is becoming more than just an improvement tool is in movement analysis. AI always outperformed the traditional biomechanical techniques in almost all categories: precision, responsiveness, and flexibility. Application in the clinic setting proved to be useful in the running shoes for early identification of complications in the nervous system. AI wearables and adaptive devices. Vision AI systems work in all circumstances in real-world environments.

B. Contributions to Knowledge

The fusion of worldwide technologies and local innovations makes the most of AI and its capacity to redistribute the analysis of movement. The focus on Indian rehabilitation, wearable low-cost devices tech, and systems, offers proof that the most effective AI solutions are in the most constrained environments.

C. Practical Implications

1. AI in early detection and tailoring of rehabilitation offers a magnitude of solutions adaptable to health facilities.
2. Athletes enjoy the benefits and the reduced risk of injury of real-time biomechanical feedback.

3. All systems walk recognition adds another layer of biometric access control to surveillance systems.

D. Limitations and Challenges
The main limitation of AI in the movement analysis of the system is in the diversity in the data sets used to train the algorithms, the number of resources needed to train the devices, and the explainability of the AI models. These are important areas of research in order to ensure that the technologies are used for equitable access across all populations.

E. Final Statement
Artificial intelligence may revolutionize gait and movement analysis by combining the precision of a laboratory and the scalability of the real world. Integrating AI with design involves scientific creativity with empathetic human focus, which is likely to deliver the most equitable and humancentered transformative innovations across healthcare, sport, and security. The future of gait analysis will focus as much on the technology as on the system's ability to remain ethical, transparent, and equitable.

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