Distinction Task 2.3: Comprehensive Literature Review – Synthesis, Gap Analysis and Research Direction

1. LiDAR Applications in Gait Analysis

1.1 Paper 1 - Development and Validation of 2D-LiDAR-Based Gait Analysis Algorithm

Key Literature Artifacts

The paper presents an innovative gait analysis tool that utilises compact 2D-LiDAR technology. The approach employs an object-tracking algorithm and undergoes validation with young, healthy participants. It compares the performance of 2D-LiDAR to a stereo camera, using motion capture as the reference standard. The findings reveal a significant advantage of 2D-LiDAR, with mean absolute errors of 46.2 ± 17.8 mm, surpassing the stereo camera. Gait parameters measured by 2D-LiDAR demonstrate strong agreement with motion capture results ($r = 0.955$ for step length, $r = 0.911$ for cadence), emphasizing its capability to simultaneously track multiple targets.

Main Gaps

- The limited ability of the 2D-LiDAR sensor, even when coupled with the inertia-based object tracking algorithm (IoTA), to predict whole-body motion analysis due to its exclusive acquisition of depth data within a two-dimensional plane.
- This initial study, focusing on protocol development and validation, exclusively enrolled young and healthy participants.
- The implications of gait parameters for clinical outcomes in diverse medical or surgical contexts were not definitively established.

High-Level Summary of Unique Contributions

Our research focuses on the early detection of gait disorders through the analysis of gait parameters, particularly targeting the elderly population. The primary objective is establishing a definitive correlation between these gait parameters and clinical disorders. The study involves a proof-of-concept phase, incorporating a survey conducted among individuals with various gait disorders. The choice of utilizing 2D LiDAR is based on its commendable attributes of accuracy, efficacy, and affordability, making it an optimal selection for our research endeavours. Furthermore, we aim to address the limitation posed by the 2D LiDAR sensor, which exclusively captures depth data in a two-dimensional plane. To overcome this limitation, we plan to demonstrate the 2D LiDAR's potential by showcasing its capability to generate three-dimensional point cloud models.

1.2 Paper 2 - Gait-Based Person Identification using 3D LiDAR and Long Short-Term Memory Deep Networks

Key Literature Artifacts

This paper presents an innovative approach to gait recognition by employing a real-time multi-line 3D LiDAR system in conjunction with a Long Short-Term Memory (LSTM) based technique. In tackling the difficulties associated with gait identification, the research generates a Point Cloud Gait dataset involving 30 participants utilizing an omnidirectional 3D LiDAR (HDL-32E). The fundamental methodology involves the integration of a 2D CNN and an LSTM model, each comprising four layers. Comparative experiments conducted with a 3D CNN and GEINet underscore the challenges associated with LiDAR data, particularly in the resolution of Gait Energy Image (GEI). Despite these challenges, the LSTM-based approach outperforms the 3D CNN, achieving a notable 60% accuracy in gait recognition.

Main Gaps

- Focus limitation on overall person identification through gait recognition without specific emphasis on individual gait aspects such as step length, stride length, cadence, etc.
- While the paper introduces an innovative LSTM-based gait recognition system using real-time multi-line LiDAR, it underscores the significant cost and computational burden associated with 3D LiDARs due to their volumetric data.
- Lack of clarity regarding the demographics and representation of different age groups in the study, despite the dataset collection from 30 individuals.

High-Level Summary of Unique Contributions

In the research paper, the authors leveraged the potency of a 3D CNN architecture coupled with 3D LiDAR, achieving a notable classification performance of approximately 60%. Recognizing the computational heaviness associated with this setup, our strategy involves a shift towards utilizing 2D LiDAR to construct three-dimensional point cloud models, a concept that will be substantiated through a proof of concept.

Furthermore, our study extends beyond mere individual identification, placing a distinct emphasis on extracting intricate gait features such as step length, stride length, stance duration, and more. Given our specific focus on detecting gait disorders among the elderly, we plan to ensure the inclusivity of a diverse demographic, encompassing individuals with various gait disorders alongside a cohort of gold-standard control groups without any discernible issues. This comprehensive approach aims to broaden the applicability and impact of our research within the realm of gait analysis and disorders.

2. Smart Sensor Systems for Seated Environments

2.1 Paper 3: Developing a Mixed Sensor Smart Chair System for Real-Time Posture Classification

Key Literature Artifacts

This study presents a groundbreaking sensor-equipped smart chair for real-time monitoring and classification of workers' sitting postures. Combining six pressure sensors in the seat cushion and six infrared reflective distance sensors in the seatback, the system, guided by a k-Nearest Neighbour algorithm and ergonomic literature analysis, achieves a remarkable overall posture classification accuracy of 0.92. Outperforming single-sensor systems, the mixed-sensor approach demonstrates superior accuracy (0.92 vs. 0.59 and 0.82) and reliability, as indicated by F1 scores ranging from 0.83 to 0.97, highlighting its efficacy in diverse real-time posture classifications.

Main Gaps

- The research focuses exclusively on the classification of sitting positions, primarily emphasizing sitting posture, and neglects the consideration of other bodily parameters such as the force exerted by the hands during standing up or the strength employed by an individual on the chair handles when sitting up.
- The experimentation process relies solely on the implementation of a single Machine Learning Algorithm, KNN (k-nearest Neighbour).

High-Level Summary of Unique Contributions

Our proposed smart bench module within the framework will be tailored to address the gaps identified in existing research. The primary goal will be to enhance the study's comprehensiveness by expanding the focus beyond sitting posture, ensuring a more holistic evaluation of body dynamics and associated parameters. This expansion is deemed crucial for acquiring a thorough understanding of various aspects, including the force exerted by the hands during standing up or the strength applied when sitting up.

Furthermore, in the experimentation phase, we are committed to avoiding the limitation of relying on a single machine-learning algorithm. Instead, we will advocate for a more comprehensive approach involving the incorporation of multiple algorithms. This diverse array of algorithms will facilitate a robust performance comparison, enabling a nuanced exploration of the strengths and limitations inherent in different machine-learning techniques. Through these planned enhancements, our proposed smart bench module aims to contribute to a more nuanced and holistic understanding of human posture dynamics in real-time scenarios.

2.2 Paper 4: Designing a Testing Device for Athletes Assessing Trunk Control in Seated Environments

Key Literature Artifacts

This study introduces a novel testing device to evaluate athletes' responses to propulsion determinants. The device features a seat within a sensor-equipped aluminium frame, employing force sensors and ropes to assess propulsion and trunk control. Tests include simulated bench press, pulling, and unpredictable balance perturbations. Key findings indicate increased trunk Range of Motion and angular velocity during balance control tests with rising perturbation stimuli acceleration. No significant directional differences suggest that these results could serve as an index for seated athletes' trunk control.

Main Gaps

- The study is based on results obtained from only one athlete with a high level of impairment. This small sample size limits the generalizability of the findings and hinders the ability to draw statistically significant conclusions.
- The study mentions that no statistical analyses were performed due to the small sample size. The absence of statistical testing makes it challenging to determine the significance and reliability of the observed results.
- Although the balance control test results suggest that trunk range of motion (ROM) and angular velocity can be used as an index of trunk control, the study acknowledges the need for further tests comparing different levels of impairment.

High-Level Summary of Unique Contributions

The investigation proficiently evaluates force production and balance control using simulated exercises, providing valuable insights into the role of muscular strength in conditions related to muscle strength disorders. The findings illuminate the specific muscles that play a vital role in generating force through the foot. This information holds considerable relevance and will significantly contribute to the objectives of our ongoing research study, enhancing our understanding of the intricate relationship between muscular strength and associated disorders.

To address the gaps in current research, our project will expand our participant pool to include individuals with diverse impairment levels, enhancing the generalizability of our findings regarding the interplay between force production, balance control, and impairment. Additionally, our study will incorporate rigorous statistical analyses to derive meaningful and statistically significant conclusions. Furthermore, our research will conduct additional tests comparing various levels of impairment, providing a nuanced understanding of how trunk range of motion (ROM) and angular velocity function as indices of trunk control.

3. Role of Machine Learning in Gait Analysis

3.1 Paper 5: Computer Vision and ML-Based Gait Pattern Recognition for Fall Prediction

Key Literature Artifacts

This study uses computer vision techniques and lower limb variables to find the most effective machine learning algorithm for classifying gait patterns in healthy individuals. It explores the feasibility of employing these techniques to distinguish various gait patterns associated with falls on flat ground. Utilizing the Kinect Motion system, spatiotemporal gait data from three walking trials (normal gait, pelvic-obliquity-gait, and knee-hyperextension-gait) is recorded for seven participants. Four classification methods—CNN, SVM, KNN, and LSTM—are applied to categorize different gait patterns. SVM achieves the highest accuracy at 94.9 ± 3.36%, followed by KNN at 94.0 ± 4.22%, while CNN and LSTM show accuracies of 87.6 ± 7.50% and 83.6 ± 5.35%, respectively.

Main Gaps

- The study lacks detailed information on the selected features for gait pattern recognition, impeding transparency and replicability in machine learning studies.
- The study doesn't include clinical studies for the sensor system to distinguish gait differences between flat-fallers and non-flat-fallers, raising doubts about its practicality in identifying and classifying pathological gaits in individuals with specific health conditions.
- The study uses four classification methods (CNN, SVM, KNN, LSTM) but lacks detailed evaluation metrics, such as precision, recall, and F1 score, hindering a nuanced understanding of classification accuracy.

High-Level Summary of Unique Contributions

The researchers directed their attention to measuring joint angles, specifically emphasizing hip angles calculated through computer vision-marked joint lines. This methodology introduces a fresh viewpoint distinct from conventional approaches, showcasing inventive techniques in gait analysis. Moreover, the researchers effectively showcased that machine learning algorithms accurately identified three distinct gait patterns. This achievement implies the possible applicability of their methodology in the impartial classification of diverse gait abnormalities.

Our study will specifically compare gait patterns between those prone to falls and those not prone to falls. This analysis aims to reveal the system's ability to predict and distinguish gait patterns associated with fall risks, providing crucial insights for clinical decision-making. Additionally, our research will comprehensively assess model performance using various metrics like precision, recall, and F1 score. This thorough approach ensures a nuanced understanding of the classification accuracy of our machine-learning models. We will also optimize the machine learning models' parameters through hyperparameter tuning, a vital step for achieving optimal accuracy and generalizability.

3.2 Paper 6: Identification and Interpretation of Gait Analysis Features and Foot Condition by Explainable AI

Key Literature Artifacts

This study addresses complex gait data using ML for feature extraction and foot condition identification. SVM and RF eliminate low-variance features, and SVM, RF, KNN, LREGR, and MV algorithms are compared. KNN and MV achieve top average accuracy (0.86) in classifying foot conditions, with KNN having the maximum average recall (0.97). Both KNN and MV demonstrate the highest average F1 score (0.86), indicating a robust and clinically relevant relationship between features and foot conditions.

Main Gaps

- The study relies heavily on LIME for interpreting black-box models. Exploring additional interpretability methods or discussing LIME's limitations would enhance model prediction understanding.
- Despite emphasizing the need for physiological relevance confirmation with physicians, the study lacks details on validated features. More information on confirmed physiological relevance is crucial for clinical applicability.
- The study mentions good predictions from all algorithms but lacks a detailed comparison of their strengths and weaknesses. A more in-depth analysis of each model's performance, especially in distinguishing foot conditions, is needed for practical insights.

High-Level Summary of Unique Contributions

The researchers effectively tackled the necessity for automating feature selection in foot condition identification, streamlining diagnostics, and easing the workload for clinicians. Recognizing the hurdle of class imbalance, the researchers appropriately addressed the issue, evaluating various models, including Random Forest, for their effectiveness in handling imbalanced data. They crafted an advanced machine learning pipeline integrating feature elimination techniques and diverse classification algorithms.

The research project will try to improve the understanding of black-box models by exploring interpretability methods beyond LIME and addressing its limitations. Engaging in detailed discussions with physicians, the project seeks to establish a clearer connection between confirmed physiological features and foot conditions, enhancing clinical applicability. Additionally, a thorough analysis of classification algorithms will be conducted to distinguish foot conditions, presenting a comprehensive comparison of strengths and weaknesses for a profound understanding of practical implications.

4. Clinical Correlations of Gait Patterns in Neurological Disorders

4.1 Paper 7: Gait Analysis and Clinical Correlations in Early Parkinson's Disease

Key Literature Artifacts

This study employs 3D gait analysis to assess spatiotemporal and kinematic parameters in early-stage Parkinson's disease (PD) individuals. Comparing 44 early PD patients with a control group, the methodology utilizes a dynamometric platform with piezoelectric sensors for three-dimensional data capture, analyzing key parameters such as cadence, stride duration, stance duration, step length, limb and swing velocities, and average velocity. The findings reveal distinctions in cadence and stride duration, significant differences in swing phase and duration, and spatial parameters, as well as statistically distinct velocities in PD patients compared to healthy subjects.

Main Gaps

- The study does not include an analysis of falls, a critical aspect in PD research. Investigating the relationship between gait characteristics and falls could provide valuable information for fall prevention strategies in early PD.
- While motor parameters are extensively discussed, the study could benefit from a more comprehensive exploration of non-motor symptoms and their correlation with gait abnormalities.
- While the study identifies correlations between gait parameters and disease-related factors, there is a call for further physiological validation of these findings.

High-Level Summary of Unique Contributions

The study accurately identified significant differences in temporal parameters such as cadence, stride duration, and stance duration, as well as spatial parameters including velocity, step width, stride length, and swing velocity between PD patients and healthy subjects. The study provided valuable insights into the potential clinical implications of gait analysis in early PD, emphasizing the importance of identifying and distinguishing gait abnormalities in the early stages for timely medical treatment and rehabilitation.

We will conduct a thorough analysis of falls to understand their relationship with gait characteristics, informing fall prevention strategies. Additionally, our research will extend beyond motor parameters to explore correlations between non-motor symptoms and gait abnormalities in early PD. Collaborating with physicians, we aim to provide physiological validation for identified correlations, enhancing the reliability of our findings.

4.2 Paper 8: Early Signs of Gait Deviation in Duchenne Muscular Dystrophy

Key Literature Artifacts

This study quantitatively assesses early gait abnormalities in Duchenne muscular dystrophy (DMD) patients using a six-camera motion capture system in a Gait Analysis Laboratory. Participants walked barefoot on a 10-meter walkway with a force platform measuring foot-ground reaction forces. Notably, no reduction in range of motion or walking velocity was observed in DMD patients. However, significant differences were identified in pelvis orientation, range of pelvis tilt, and various joint motions at the hip, knee, and ankle joints, providing valuable insights into gait alterations in DMD.

Main Gaps

- The papers did not present the demographics of the study participants, potentially lacking information on age distribution and diversity within the DMD and control groups.
- The study primarily focused on biomechanical aspects of gait but did not extensively explore the functional implications for daily activities.
- The papers lacked a robust exploration of the clinical correlation of the observed gait disorders.

High-Level Summary of Unique Contributions

The papers focused on early-stage Duchenne muscular dystrophy (DMD) patients, revealing strength reductions in specific muscles, prolonged Gowers' and walking times, and distinctive gait alterations. Increased cadence compensated for reduced step length, while pelvis orientation and joint motions exhibited significant variations. Kinetic analyses highlighted reduced joint moments and powers. These insights provide a foundation for targeted rehabilitation interventions in the early stages of DMD.

Our research will address the identified gaps by ensuring a comprehensive presentation of participant demographics, including diverse age distributions within the Duchenne muscular dystrophy (DMD) and control groups. Unlike prior studies primarily focusing on biomechanics, our investigation takes a holistic approach, thoroughly exploring the functional implications of gait abnormalities in daily activities. Additionally, we prioritize a robust clinical correlation, establishing meaningful connections between specific gait parameters and their clinical impact.

5. Advancements in Gait Analysis Using Wearable Sensors in Real-World Outdoor Environments.

5.1 Paper 9: Analyzing Gait in the Real World Using Wearable Movement Sensors

Key Literature Artifacts

This study seeks to close the gap between controlled laboratory studies and natural field-based behaviour by introducing a methodology employing traditional wearables for outdoor tracking. Using a foot-mounted inertial sensor, GPS receiver, and barometric altitude sensor, subjects' movements are monitored both indoors and outdoors. Leveraging strap-down navigation and sensor fusion algorithms, the study identifies four frequently repeated walking paths, revealing significant variations in foot clearance, stride length, and stride width.

Main Gaps

- The study highlights differences in gait parameters based on footwear, but it doesn't deeply explore the implications.
- The study primarily focuses on indoor movements. Exploring the impact of environmental factors, such as different terrains (e.g., uneven surfaces, stairs), weather conditions, or crowded spaces, on gait analysis could provide a more comprehensive understanding.
- The paper notes that not all foot displacements are related to walking. Further refinement in the algorithm to distinguish between walking and other movements (sitting, standing) would enhance the accuracy of gait analysis.

High-Level Summary of Unique Contributions

The paper introduced a movement reconstruction algorithm using inertial sensors to analyze frequently repeated walking paths over 10 days. It reconstructed over 48,000-foot displacements, identifying four paths that traversed at least 300 strides over three days. Significant differences in spatiotemporal gait parameters between athletic shoes and sandals were observed. The method demonstrated utility for scientific intervention comparison and reduced data variability using frequently visited paths.

Our research aims to enhance gait analysis by delving into the nuanced implications of footwear on spatiotemporal parameters. Going beyond the indoor focus of previous studies, we will comprehensively explore outdoor scenarios, considering diverse terrains, weather conditions, and crowded spaces. Addressing algorithmic limitations, we will refine movement classification, employing advanced signal processing or machine learning techniques.

5.2 Paper 10: Gait Phase Estimation of Unsupervised Outdoors Walking Using IMUs and a Linear Regression Model

Key Literature Artifacts

This study introduces an experimental protocol for unsupervised outdoor gait phase estimation using body-worn inertial measurement units (IMUs). Key findings include a minimum normalized gait phase estimation error of 1.81%, a maximum of 2.48%, and an average of 2.21 ± 0.258%. The results indicate potential applications in controlling human-assistive devices, rehabilitation tools, and clinical gait analysis without relying on fixed thresholds or sensor-embedded insoles in outdoor settings.

Main Gaps

- The variability in estimation accuracy among subjects suggests a potential underrepresentation of diverse gait patterns, and efforts to include a more extensive range of subjects would enhance the study's robustness.
- The study's linear regression model simplifies gait phase estimation, and more advanced techniques may be required for accurate real-time predictions, especially in diverse outdoor conditions.
- The study focuses on outdoor gait events (HS and TO) but lacks a comprehensive exploration of various gait patterns, especially in diverse outdoor conditions, limiting the generalizability of the proposed methodology.

High-Level Summary of Unique Contributions

The research introduces a robust algorithm for outdoor gait phase estimation using a 2-IMU setup, eliminating the need for subject-independent thresholds. It explores controlling a 2-DOF prosthesis based on PCA-based gait phase estimation, addressing limitations in previous designs. The methodology allows unsupervised outdoor experiments, representing natural gait variations. The innovation extends to real-time gait phase estimation and wearable assistive device control, showcasing potential applications beyond traditional lab settings.

Our research project aims to address gaps by diversifying the subject pool and enhancing accuracy in gait pattern representation. We plan to advance gait phase estimation beyond linear regression, exploring techniques for real-time predictions in varied outdoor conditions. Additionally, the study will comprehensively investigate diverse gait patterns in outdoor scenarios, moving beyond basic events (Heel Strike and Ends at Toe Off). This approach ensures broader applicability for our methodology, aligning with our project's focus on gait analysis for disorders in outdoor environments using Lidar sensors and machine learning.

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