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Decision Support System with AI-based Gait Estimation as Aid for Neurodegenerative Disease Patients

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Abstract: *AI-based uncertainty handling can be applied to multimodal data fusion for IMU (Inertial Measurement Units) sensor-based gait motion capture in tracking gait differences in patients with Alzheimer's disease or other medical conditions. The challenge is represented by monitoring and analyzing gait patterns in patients with Alzheimer's disease to detect changes over time and assess disease, progression, or treatment effectiveness. Machine learning models are used to enhance the accuracy of gait analysis systems, making them valuable tools in healthcare for diagnosis and rehabilitation. Thus, IMUs have evolved with multi-sensor systems, sensor fusion, and machine learning for precise gait analysis, finding applications in clinical and consumer settings. AI-based gait motion capture has advanced through deep learning and video-based methods, enabling non-invasive, markerless analysis for individual identification, and enhancing healthcare diagnostics and rehabilitation. Recurrent neural networks (RNNs) or long short-term memory networks (LSTMs), are developed and trained using historical gait data from patients with Alzheimer's disease that also include the uncertainty estimates as input features to the models. AI-based uncertainty handling integrated into gait motion capture and analysis allows continuous monitoring of gait differences in patients with Alzheimer's disease and other medical conditions.*

1. INTRODUCTION

The problem addressed in the research is the need for high-precision motion capture and gait analysis in various domains such as medicine, sports, entertainment, military, and aerospace. The existing methods using IMU sensors for motion capture suffer from measurement errors, leading to inaccurate orientation estimations and imprecise positions, especially during rapid movements. This hinders the applicability of IMU sensors in real-time trajectory assessment, bio-mechanical modeling, and gait analysis, which are crucial for rehabilitation, training, and other applications.

The approach taken in the research involves the development of dedicated criteria and a set of instructions for anomaly detection and error reduction in motion capture using IMU sensors. The goal is to enhance the accuracy and application of IMU sensors in diverse domains by leveraging a precise motion capture system.

The proposed solution involves a meticulous methodology that encompasses both hardware and software components essential for accurate gait data recording and processing. The research leverages wearable 6-axis accelerometer sensors, an Arduino Uno R3 board, and a Serial Port Expander for data collection and processing. The system design includes careful placement and

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arrangement of sensors on the lower body, optimal settings for data collection, and software components for signal processing and visualization. The MATLAB Simulink model is utilized for simulation and control of the motion capture system.

During the practical implementation phase, the gait capture system is physically assembled, rigorously tested, and calibrated to ensure accuracy and reliability. Human participants are involved in pilot studies and data collection sessions to capture diverse walking movements under various circumstances and scenarios. The collected walking motion data undergoes pre-processing and analysis using signal processing techniques to derive gait characteristics.

The results of the study involve a meticulous evaluation of gait characteristics by comparing them to established reference values and standards. Various measurements such as joint angles, cadence, stride length, and stride duration are employed to comprehensively assess gait patterns. Correlation analysis and comparison tests are conducted to examine the relationships between different gait measurements and ascertain the variations in gait parameters across different scenarios or participant groups. The customizable data filtering criteria developed in the research is a highly important aspect of the solution. It allows for the customization of multiple sub-criteria, such as the number of read values to calculate the mean value from, time intervals for data reading, and the number of comparisons, enabling destination-specific levels of precision for motion capture analysis.

In conclusion, the research addresses the problem of high-precision motion capture and gait analysis by developing dedicated criteria and a set of instructions for anomaly detection and error reduction. The approach involves a meticulous methodology encompassing both hardware and software components essential for accurate gait data recording and processing. The goal is to enhance the accuracy and application of IMU sensors in diverse domains, and the proposed solution achieves this by providing customizable data filtering criteria for high-precision motion capture analysis.

The research findings contribute to the advancement of gait analysis methodologies and hold implications for various fields such as health monitoring, age-related therapies, sports performance, rehabilitation, and assistive technology. The customizable data filtering criteria open doors to diverse precision levels in motion capture analysis, offering valuable insights for various applications and driving progress in gait capture research.

2. LITERATURE REVIEW

Wearable inertial measurement units (IMUs) and motion capture systems have been extensively researched to analyze human walking patterns (Fusca et al., 2018). The goal is to assess motor functionality and evaluate gait. However, the lack of reliable validation for these systems necessitates the development of standardized approaches. IMUs utilize accelerometers, gyroscopes, and magnetometers to track the trajectory of body segments, while sensor fusion algorithms are employed to improve tracking accuracy. However, the adoption of motion capture systems is limited by cost and the issue of occlusion (Tsilomitrou et al., 2021).

In terms of validation, a neural network architecture has been proposed to predict trajectories and calibrate sensors, but its validation has been limited to optical systems (Kim et al., 2021). It is crucial to explore and validate these methods in diverse real-world scenarios. While research has primarily focused on validating IMUs for gait measurement, there are certain limitations such as methodological constraints and a lack of assessment regarding repeatability (Lewin et al., 2022). Although IMUs placed on the shank can detect gait events, challenges arise when it comes to detecting turning movements, as false events and missed detections can occur (Romijnders et al., 2021). Reliable detection of gait parameters has been observed in straight and slalom walking, but caution should be exercised when dealing with rotations and disruptions. Other factors, such as environmental conditions and individual differences, also need to be taken into consideration.

One study presents a calibration protocol tailored specifically for children, utilizing magneto and inertial sensors for motion tracking (Ricci et al., 2014). Another research introduces an artificial neural network-based quality control algorithm to evaluate joint orientation estimates from IMUs, which holds potential for remote patient monitoring (Lebel et al., 2016). IMU precision and accuracy in measuring running frequencies and magnitudes have been investigated, but the study was limited by a small sample size and a focus solely on running (Provot et al., 2017). Accurate indoor pedestrian tracking using low-cost sensing systems has also been explored, emphasizing the need for aesthetic improvements and enhanced knowledge input (Zizzo & Ren, 2017). Additionally, a proposed complementary filter that integrates optical and inertial technologies shows promise in detecting both small and large-scale motions but struggles with micro-motions of small amplitude and high frequency (Phan et al., 2020).

IMUs have demonstrated agreement with motion capture systems when measuring hip-joint angles, but they exhibit increased errors when assessing knee and ankle joints (Park & Yoon, 2021). In the context of a teleoperated robot system, IMUs and armbands effectively correct upper arm and forearm roll angles (Zhu et al., 2022). IMUs have proven valuable in estimating joint kinematics during movements, but challenges persist, such as sensor alignment errors and reliance on motion capture data (Potter et al., 2022). Deep neural networks based on IMU data can accurately predict locomotion intentions in amputees, underscoring the importance of subject-specific training data (Mazón et al., 2022). A human pose estimation method that combines IMUs with spatial attention and kinematic regression networks achieves superior accuracy (Liao et al., 2023). While IMU-based advancements provide valuable insights, there are still challenges that need to be addressed through further investigation to refine these techniques and expand their applications.

In a research article, the authors (Panaite et al., 2021a) unveil a few benefits. They ingeniously employ budget-friendly, wearable devices, ensuring easy accessibility for all. Multiple sensors heighten the data wealth, offering a potential source for machine learning. Moreover, the motion capture system's flexibility opens doors for future expansion. By endorsing free software, the researchers present a viable solution for rehabilitation, recreation, and technical pursuits. Nevertheless, they highlight some intriguing research gaps, like the need to scrutinize accuracy, explore diverse applications, and develop advanced algorithms.

As another possibility (Olar et al., 2020), augmented reality reigns, enhancing a robotic arm's control and precision. Empowering patients to perform tasks with newfound dexterity. Remote supervision enables healthcare professionals to offer assistance from afar, promoting a better quality of life. The findings (Panaite et al., 2021b) provide various sensor technologies for motion analysis. Marker-less motion tracking and mathematical models propel accuracy. Camera-based systems extend their use underwater and in medical imaging for real-time monitoring and motion correction.

Advancing in prosthetics (Rosca et al., 2020), the research models and simulates a 3D prosthesis. A lifeline for amputees, the design's adaptability caters to diverse patients. Offering a wide array of movements akin to real limbs, this solution addresses existing limitations while being cost-effective and comfortable. In another pursuit (Olar et al., 2021), the research sets its sights on replicating natural biomechanics. The result: a low-cost, reliable, and forceful motion system. The synthesis of joint movements reaches new horizons.

Wearable IMUs and motion capture systems hold great potential for gait analysis and motor functionality assessment. Challenges such as validation, occlusion, and accuracy persist, but innovative approaches, like neural networks and sensor fusion algorithms, offer promise. This research is needed to address limitations and refine these technologies for diverse applications.

The previous works mentioned in the provided text encompass a wide range of research and development efforts in the field of motion capture systems, particularly focusing on the use of IMU sensors and wearable technology for gait analysis and motion tracking. These works have contributed significantly to the advancement of various applications in domains such as medicine, sports, entertainment, military, and aerospace. In this detailed analysis, we will discuss the pros and cons of the previous works, highlighting their contributions, limitations, and potential for future advancements.

Pros of Previous Works:

1. Diverse Applications: The previous works have demonstrated the versatility of IMU sensors and motion capture systems in diverse applications such as rehabilitation in medicine, optimizing training exercises in sports, motion capture for video animation in entertainment, enhanced training and ergonomics in the military, and potential use in aerospace for training astronauts. This highlights the broad impact and potential of these technologies across different industries.
2. Real-time Trajectory Assessment: The utilization of IMU sensors for motion capture enables real-time trajectory assessment and bio-mechanical modeling, benefiting rehabilitation and training. This real-time assessment provides immediate feedback and monitoring, which is crucial for applications such as rehabilitation and sports training.
3. Sensor Fusion Algorithms: The use of sensor fusion algorithms to improve tracking accuracy is a significant advancement. By integrating data from accelerometers, gyroscopes, and magnetometers, these algorithms enhance the precision of motion tracking, leading to more accurate gait analysis and motion capture.
4. Neural Network-based Quality Control: The introduction of an artificial neural network-based quality control algorithm for evaluating joint orientation estimates from IMUs holds potential for remote patient monitoring. This technology has the potential to empower patients to perform tasks with newfound dexterity and enable healthcare professionals to offer assistance from afar, promoting a better quality of life.
5. Wearable IMUs and Motion Capture Systems: The development of wearable IMUs and motion capture systems holds great potential for gait analysis and motor functionality assessment. These technologies offer promise for addressing challenges such as validation, occlusion, and accuracy, paving the way for advancements in motion capture and gait analysis methodologies.

Cons of Previous Works:

1. Measurement Errors: One of the major challenges highlighted in the previous works is the presence of measurement errors, leading to significantly inaccurate orientation estimations, especially when the sensors are moved rapidly. This limitation can affect the precision and

reliability of the captured motion data, impacting the accuracy of gait analysis and motion tracking.

2. Cost and Occlusion: The adoption of motion capture systems is limited by cost and the issue of occlusion. The cost associated with acquiring and implementing motion capture systems may pose a barrier to widespread adoption, especially in resource-constrained settings. Additionally, occlusion can hinder the accurate tracking of body segments, affecting the overall quality of motion capture data.
3. Methodological Constraints: Previous research has highlighted methodological constraints and a lack of assessment regarding repeatability when validating IMUs for gait measurement. These constraints can limit the reliability and reproducibility of gait analysis results, impacting the overall utility of IMU-based motion capture systems.
4. Environmental and Individual Variability: Challenges arise when dealing with environmental conditions and individual differences in gait patterns. Factors such as environmental conditions and individual differences need to be taken into consideration to ensure the robustness and generalizability of gait analysis results across diverse scenarios and populations.
5. Data Anomalies and Filtering: The presence of data anomalies and the need for effective data filtering criteria have been highlighted as important considerations. Anomalies in the captured data can complicate the gait measurement process, necessitating the development of robust data filtering criteria to ensure the accuracy and reliability of motion capture analysis.

Future Directions and Potential Advancements:

Despite the limitations and challenges identified in the previous works, there are several potential advancements and future directions that can address these limitations and further enhance the capabilities of IMU-based motion capture systems:

1. Error Reduction and Precision Enhancement: Future research can focus on developing advanced error reduction techniques and precision enhancement algorithms to mitigate the impact of measurement errors and improve the overall accuracy of motion capture data.
2. Cost-effective Solutions: Efforts to develop cost-effective motion capture systems and wearable IMUs can help address the cost barrier associated with the adoption of these technologies, making them more accessible for a wider range of applications and settings.
3. Validation and Standardization: Continued research into validation methods and standardization approaches for IMU-based motion capture systems can contribute to improving the reliability and reproducibility of gait analysis results, addressing methodological constraints and enhancing the overall utility of these systems.
4. Environmental Adaptability: Advancements in motion capture technologies that can adapt to diverse environmental conditions and accommodate individual variability in gait patterns will be crucial for ensuring the robustness and applicability of these systems across different scenarios and populations.
5. Customizable Data Filtering Criteria: The development of customizable data filtering criteria, as mentioned in the previous works, can open doors to diverse precision levels in motion capture analysis. Future research can focus on refining and optimizing these criteria to cater to specific application requirements and resource management needs.

In conclusion, previous works have made significant contributions to the field of motion capture systems and IMU-based gait analysis. While they have demonstrated the potential of these technologies in various domains, some challenges and limitations need to be addressed. Future research and advancements in error reduction, cost-effectiveness, validation, environmental adaptability, and customizable data filtering criteria hold promise for further enhancing the capabilities and applicability of IMU-based motion capture systems. These advancements have the potential to drive progress in gait analysis methodologies and contribute to the development of innovative solutions for healthcare, sports, rehabilitation, and assistive technology applications.

3. BENCHMARK DATASET

The benchmark dataset in this research utilizes data collected from wearable inertial measurement units (IMUs) and motion capture systems. These systems employ accelerometers, gyroscopes, and magnetometers to track the trajectory of body segments, enabling the assessment of motor functionality and gait analysis. The dataset encompasses gait characteristics such as joint angles, cadence, stride length, and stride duration, derived from the recorded acceleration data. The dataset is meticulously evaluated by comparing the gait characteristics to established reference values and standards, and correlation analysis is conducted to examine the relationships between different gait measurements. This benchmark dataset serves as a fundamental basis for the advancement of motion capture and gait analysis methodologies.

The paper presents a comprehensive study on the development and implementation of a lower body motion capture system using IMU sensors. The study aims to enhance the precision of synthesized motion from captured data and explores the potential applications of this technology in various domains such as medicine, sports, entertainment, military, and aerospace.

The methodology employed in the study is meticulous and encompasses several key phases. The research begins with a thorough review of existing literature to understand the state of the art in motion capture systems and to identify the gaps and opportunities for improvement. The design phase involves the creation of a complete system design, including both hardware and software components essential for accurate gait data recording and processing. This includes the placement and arrangement of 6-axis accelerometer sensors on the body, integration with the Arduino Uno R3 board, and the development of optimal settings and parameters for data collection and processing.

The software components are developed in parallel with the hardware design, with a focus on choosing suitable frameworks and programming languages to effectively fulfill the required functions. The Arduino Integrated Development Environment (IDE) plays a central role in programming the Arduino Uno R3 board, and the software architecture takes into account signal processing methods necessary for extracting relevant gait parameters from the accelerometer data.

The practical implementation phase involves the physical assembly of the motion capture system, rigorous testing, and calibration processes to ensure the accuracy and reliability of the system. Pilot studies and data collection sessions are conducted with human participants, capturing diverse walking movements under various circumstances and scenarios. The collected walking motion data undergoes pre-processing and analysis using signal processing techniques, including filtering the data to remove noise and artifacts, standardizing, and calibrating the data for consistency across all participants.

The results of the study are meticulously evaluated by comparing gait characteristics to established reference values and standards. Multiple measurements, such as joint angles, cadence, stride length, and stride duration, are employed to comprehensively assess gait patterns. Correlation analysis is conducted to examine the relationships between different gait measurements, and comparison tests are employed to ascertain the variations in gait parameters across different scenarios or participant groups.

The study's findings provide valuable insights into the system's accuracy and reliability, serving as a fundamental basis for the advancement of motion capture and gait analysis methodologies. The authors also discuss the implications of the findings for various fields, including health monitoring, age-related therapies, gender differences in gait patterns, and walking mechanics. The customizable data filtering criteria developed in the study opens doors to diverse precision levels in motion capture analysis, contributing to advancements in the field of gait capture.

4. RESEARCH METHODOLOGY

The research methodology employed in the study involved a comprehensive approach to developing a gait capture system. The process began with an extensive review of existing research, followed by the design, implementation, testing, and analysis of the system's performance. The methodology encompassed both hardware and software components essential for accurate gait data recording and processing. Careful consideration was given to the placement and arrangement of 6-axis accelerometer sensors on the body, taking into account the biomechanical nuances of walking. The integration of these sensors and data collection was simplified using the Arduino Uno R3 board and a Serial Port Expander.

The software components were developed in parallel with hardware design, with a focus on choosing suitable frameworks and programming languages that could effectively fulfill the required functions. The Arduino Integrated Development Environment (IDE) played a central role in programming the Arduino Uno R3 board, offering a user-friendly interface for firmware creation, development, and uploading. The software architecture took into account signal processing methods necessary for extracting relevant gait parameters from the accelerometer data. This involved employing filtering techniques to eliminate noise and artifacts, segmentation algorithms for identifying specific steps, and feature extraction approaches to measure gait characteristics. A graphical user interface (GUI) or visualization component was developed to present and analyze gait data in a user-friendly manner, enabling real-time monitoring of gait parameters, visualization of gait patterns, and comparison across multiple trials or participants.

The practical implementation phase involved the physical assembly of the gait capture system, rigorous testing, and calibration processes to ensure the accuracy and reliability of the system. Pilot studies and data collection sessions were conducted with human participants, capturing diverse walking movements under various circumstances and scenarios. The collected walking motion data underwent pre-processing and analysis using signal processing techniques, and the findings were compared with established gait analysis methods and existing literature to validate the accuracy and efficacy of the gait capture technology.

The methodology was thoroughly documented, providing comprehensive information about the system's capabilities and limitations. This documentation served as a record of the system implementation process, and the results yielded valuable insights into the system's accuracy and reliability, serving as a fundamental basis for the advancement of motion capture and gait analysis methodologies.

The paper focuses on developing a lower body motion capture system using IMU sensors for applications in various domains such as medicine, sports, entertainment, military, and aerospace. The methodology involves a comprehensive review of existing research, system design encompassing hardware and software components, and meticulous testing and analysis of the system's performance. The results include detailed evaluations of gait characteristics, comparison with established norms, and the successful implementation of data filtering criteria to enhance motion capture accuracy. The customizable data filtering criteria hold promise for diverse precision levels in motion capture analysis, contributing to advancements in gait analysis methodologies and various fields.

The data circuit in the system involves the flow of sensor data from the inertial measurement unit (IMU) sensors, specifically the 6-axis accelerometer sensors (SEN0386), to the Arduino Uno R3 board for processing and then to a PC for further analysis and visualization (Figure 1).

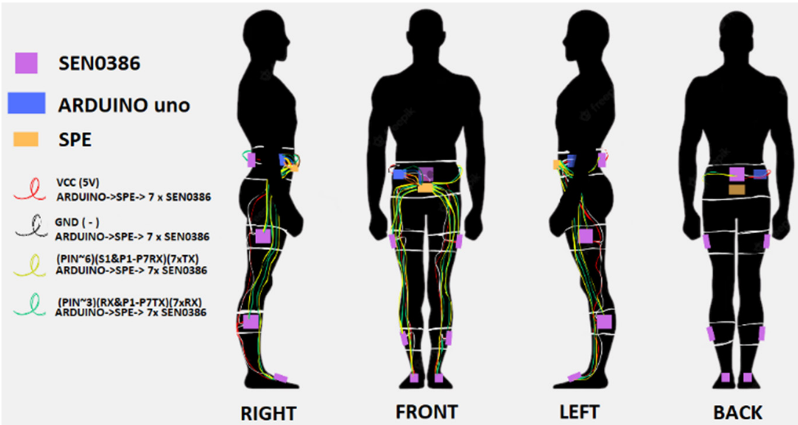

Figure 1. Circuit Design
Source: Own research

The sensor data is acquired from the IMU sensors through a microcontroller's virtual serial monitor and is then transmitted to the Arduino Uno R3 board. The Arduino Uno R3 board serves as the intermediary for processing and handling the sensor data. It is programmed to collect, filter, and process the sensor data using the Arduino Integrated Development Environment (IDE) and the Arduino programming language based on C/C++.

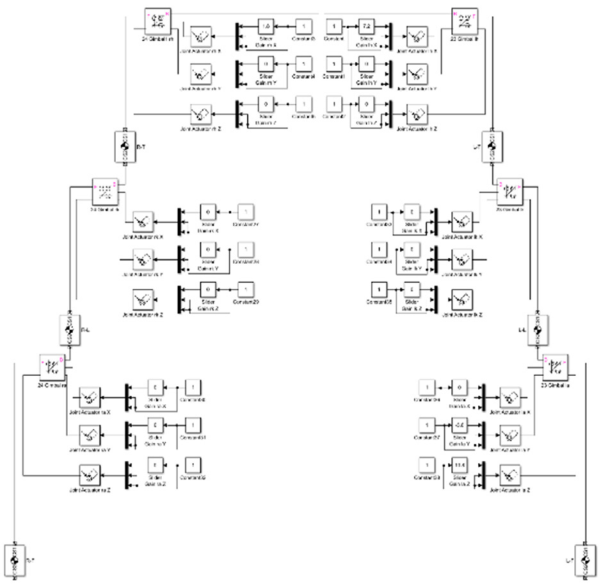

Figure 2. MATLAB Simulink model
Source: Own research

Figure 3. Motion capture devices mounted
Source: Own research

Once the sensor data is processed and filtered by the Arduino Uno R3 board, it is then transmitted to a PC for further processing, calculations, and synthesis. The PC is used for analyzing the gait data, applying signal processing techniques, and visualizing the gait patterns. The data circuit is completed by the transmission of the processed sensor data from the Arduino Uno R3 board to the PC, where it is utilized for motion capture analysis and gait assessment, implemented in MatLab as seen in Figure 2.

In summary, the data circuit involves the flow of sensor data from the IMU sensors to the Arduino Uno R3 board for processing and then to a PC for further analysis and visualization of gait patterns and motion capture data. Figure 3 presents the IMU sensors' placement.

5. EXPERIMENTAL RESULTS

The experiments conducted in this research focused on developing and testing a gait capture system using wearable inertial measurement units (IMUs) and motion capture technology. The system was designed to accurately record and analyze walking motion data, with a specific emphasis on gait characteristics such as joint angles, cadence, stride length, and stride duration. The methodology involved a comprehensive review of existing research, followed by the design, implementation, testing, and analysis of the system's performance.

This study rigorously evaluated gait characteristics, comparing them to established standards. Various measurements, like joint angles, cadence, and stride length, were analyzed. Correlation and comparison tests were conducted for insights into gait variations. Challenges were addressed, and the system's capabilities and limitations were explained, contributing to motion capture advancements. The algorithm effectively filtered data anomalies by considering the angular speeds of the ellipsoidal joint for each leg.

Read $\alpha 1$ at t0
Read $\alpha 2$ at t0 + Δ t
If $\alpha 2 - \alpha 1 > 0.6° \cdot (\Delta t)/10$ then
Read $\alpha 3$ at t0 + 2 Δ t
    $\alpha 2 = (\alpha 1 + \alpha 3)/2$

Where: $\alpha 1$, $\alpha 2$ and $\alpha 3$ are angles; t0 is the initial moment of gait; and Δ t is the period of walking.

During the practical implementation phase, the gait capture system was assembled and tested, and data collection sessions were conducted with human participants. The collected walking motion data underwent pre-processing and analysis using signal-processing techniques to derive gait characteristics (Figure 4). The results were meticulously evaluated by comparing them to established reference values and standards, and correlation analysis was conducted to examine the relationships between different gait measurements.

Figure 4. Visual Simulation
Source: Own research

The findings provided valuable insights into the system's accuracy and reliability, serving as a fundamental basis for the advancement of motion capture and gait analysis methodologies. The data filtering criteria, which were applied to the motion data, successfully filtered out anomalies and contributed to the system's overall success in accurately measuring and recording gait data. The customizable nature of the data filtering criteria allows for diverse precision levels in motion capture analysis, opening doors to various applications in health monitoring, age-related therapies, walking mechanics, and more.

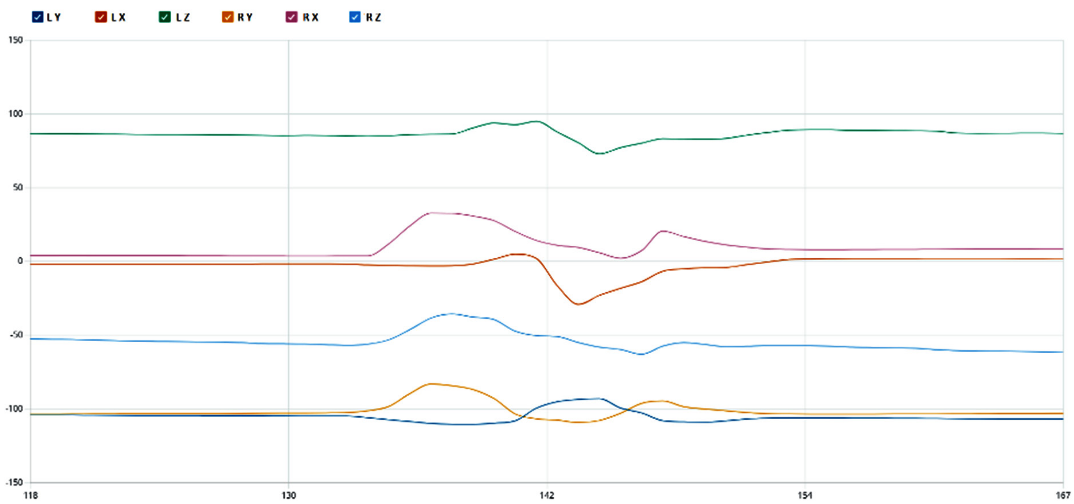

Figure 5. Data diagram
Source: Own research

In summary, the experiments and results of this research demonstrated the successful development and testing of a gait capture system, providing valuable insights into gait analysis methodologies and their implications for various fields (Figure 5).

The study utilized 6-axis accelerometer (SEN0386) sensors placed on the body, and the integration of these sensors and data collection was simplified using the Arduino Uno R3 board and a Serial Port Expander. The system design also encompassed the creation of wiring diagrams, ensuring secure and reliable connections while minimizing signal interference and noise. The software components were developed in parallel with hardware design, with careful consideration given to choosing suitable frameworks and programming languages that could effectively fulfill the required functions.

During the practical implementation phase, the system demonstrated its ability to accurately record and display walking motion data. The results encompassed detailed descriptions of the acquired gait data, statistical analyses, and comparisons with established norms. Gait parameters were compared to reference values, and their correlations with participant characteristics were thoroughly explored. Furthermore, the clinical relevance of the findings was discussed by juxtaposing the results with relevant thresholds, that are customizable by all sets of parameters.

6. CONCLUSION

In conclusion, the research has made significant strides in advancing gait analysis methodologies, with implications for health monitoring, age-related therapies, and walking mechanics. The customizable data filtering criteria offer diverse precision levels in motion capture analysis, addressing hardware resource management. The findings hold promise for therapeutic, sports, rehabilitation, and assistive technology applications, driving progress in gait capture research. Future research could focus on refining the data filtering criteria, exploring its applications in diverse domains, and collaborating on ethical considerations to further foster advancements in the field of gait capture.

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