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Multimodal Gait Analysis Acquisition System: Challenges and Lessons Learned

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***Abstract*—Nowadays, gait data analysis has become an extremely valuable tool that, without much knowledge, provides significant support in various areas, especially in medicine. This type of analysis not only contributes to generating accurate diagnoses but also plays a fundamental role in physical rehabilitation processes.**

To harness the potential of this analysis, a multimodal system is being developed with the purpose of enhancing the storage, analysis, and synchronization of multiple modules. The imperative arises from certain constraints within prevailing devices and methods, which stem from their intricate and delicate nature. Therefore, the aim of the study involves creating an implementation that prioritizes flexibility, lightness, and autonomy, all with the ultimate aim of attaining complete self-sufficiency in future advancements.

***Index Terms*—gait, multimodal, autonomy, system, medicine**

I. INTRODUCTION

The analysis of gait over these years has been implemented in various ways; one of them is through passive reflective markers on the skin, positioned based on bony landmarks, in addition to integrating surface electrodes and/or needle electrodes for recording electromyographic activity [1].

The multimodal system helps to obtain more precise parameters through these components, such as spatiotemporal measurements, joint kinematics and kinetics, as well as dynamic electromyography. However, since these are more specialized components, they are more costly; nevertheless, they can be more accurate in measurements.[1]

With this project, the aim is to achieve optimal results based on the appropriate combination of these elements. The ongoing development of the multimodal detection system consists of five inertial sensors, two cameras, and an insole containing four pressure sensors, a gyroscope, an accelerometer, and a clock. These components independently store information, with the insole detecting points of contact during movements and angles of the moving foot. The Inertial Measurement Units (IMUs) allow for mapping movement in the x, y, and z axes, as well as the acceleration of five strategic points: on the outer part of each ankle at the lateral malleolus, another sensor at the height of each leg's lesser trochanter, and a final sensor at the lower back at the lumbar section level. The two cameras record the movements, enabling visualization of the subject from frontal and posterior perspectives. The synchronization of the sensors provides a visual guide to the subject's movement at each moment of the gait cycle.

The multimodal system entails specific challenges in terms of development, communication, storage, and synchronization. This article describes the challenges encountered in the development of a multimodal acquisition system for gait analysis. This system is part of an ongoing project for gait analysis in patients with Parkinson's disease and represents the initial attempt towards an acquisition system to predict Freezing of Gait.

The remaining content of the article is structured as follows: In Section 2, the state of the art is addressed, discussing both the history and implementation of gait analysis systems. Section 3 provides a detailed description of the adaptation of the multimodal system, from its planning phase to the challenges encountered at each stage of implementation. In Section 4, the results obtained from the creation, implementation, and testing of the proposed system are presented. Lastly, potential research paths for improvement that are planned or could be implemented in the future for this multimodal system are explored.

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II. STATE OF ART

Gait analysis refers to a set of approaches and methods used to study body movement during walking or the act of walking. This analysis can range from simple observations to sophisticated computerized measurements [10].

Its roots date back to the early 1980s when the United Technologies Corporation in Newington established a pioneering laboratory. During this era, an innovative approach emerged, involving the strategic placement of retro-reflective markers on the skin in relation to anatomical landmarks. This technique was coupled with a system of cameras, meticulously capturing and visualizing the markers' position and orientation [3].

In Colombia, in 2012, the design and implementation of a portable device were carried out. This device processed information using a PIC 18F4550 microcontroller and stored it on a microSD card. This data was then recreated in a graphical interface developed in Open GL [13].

As time has progressed and with the advent of computer systems, along with advancements in informatics, modern and sophisticated systems for the analysis of human motion have been developed, which are available today. However, the origins of gait analysis are not restricted to the boundaries of modern laboratories. They stretch back to ancient times when a deep fascination with human movement already existed. Since the inception of medical practice, observers closely scrutinized the movements of the infirm, employing this observation as a tool for diagnosing diseases and devising therapeutic interventions [7].

Influential historical figures such as Aristotle, Hippocrates, and Galen accorded significant importance to the study of human movement, particularly gait analysis. Aristotle, in particular, delved into the concept of the center of gravity and the laws governing motion and levers. He is considered a precursor to Newton's laws of motion and believed that the ability to walk was a unique gift to humans, stemming from their divine nature [7].

The driving force behind these endeavors was the recognition of a substantial deficiency in the content of diagnostic rehabilitation studies during that era. Consequently, researchers embarked on a mission to enrich the value of these studies by generating comprehensive information that transcended mere observation. Their focus shifted towards collecting data related to subjects' positioning, pressure distribution, and orientation during motion [3]. This complex process is facilitated through the utilization of periodic gait signals, commencing with data captured during walking, which is then segmented into distinct gait cycles based on two precisely defined events: heel strike and toe-off, as shown in Figure 1 [4].

However, these measurements based on periodic signals are commonly referred to as kinematic measurements. They are executed using cameras connected to computers, outlining the movements of the major lower limb joints in three dimensions. The primary kinetic measurement involves the force exerted under each foot while walking, and by amalgamating this data, joint moments and powers can be calculated [5].

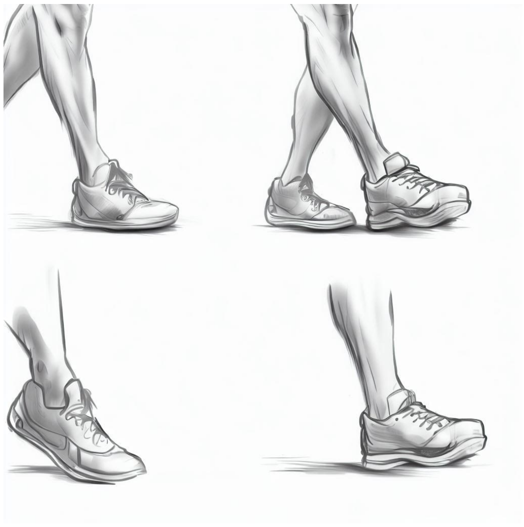


Fig. 1. Gait cycles: based on heel strike and toe-off [8]

A recent study explores the characterization of normal gait and the identification of pathological deviations induced by neurological diseases, with a specific focus on the angular kinematics of the knee in the sagittal plane. To provide a standardized framework for anatomical descriptions, the study adopts the anatomical position, wherein an individual stands erect, feet together, and arms resting at their sides with palms facing forward. This position, combined with reference planes and terminologies depicting relationships between various body parts as illustrated in Figure 2 [9], allows for the comparison and contrast of different gait patterns.

Additionally, thanks to the advancement of technology and informatics, highly sophisticated systems have been created to analyze human movement. These systems have become essential in the clinical field for understanding and treating various conditions. Significant progress has been made in conditions such as cerebral palsy, spina bifida, neuromuscular diseases, among others. These advancements have allowed for a deeper understanding of the underlying mechanisms of these conditions, the identification of evolving patterns over time, and improvements in treatment guidance and objective evaluation [11], [12].

The authors of the study introduce an innovative unsupervised approach based on Dynamic Time Warping (DTW) to identify distinct normal gait profiles that represent the typical behavior of healthy subjects. This approach utilizes raw descriptions of gait signals. Furthermore, the methodology presents the potential to quantitatively assess the impact of therapies on gait rehabilitation [4], providing valuable insights into the effectiveness of such interventions.

These types of measurements prove exceptionally valuable for monitoring clinical progress. If interventions occur between assessments, monitoring effectively transitions into outcome evaluation. Assessing changes in these technical biomechanical measures typically yields greater clinical insights [6].

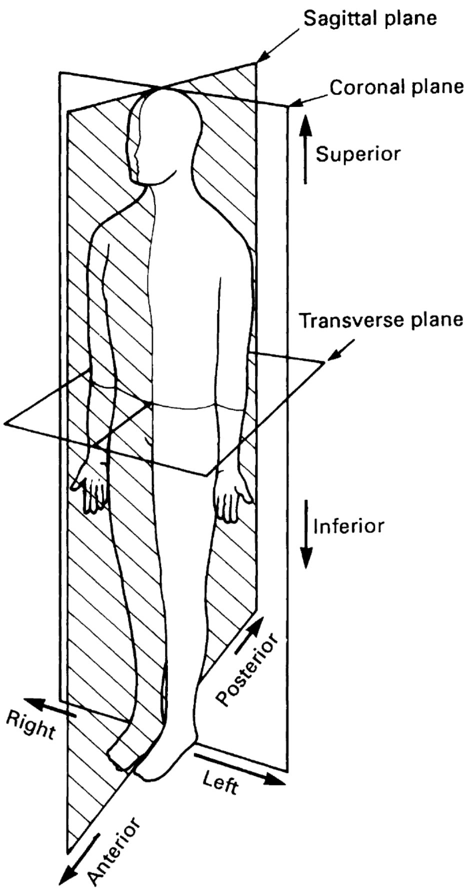


Fig. 2. The anatomical position, with three reference planes and six fundamental directions. [9]

Nevertheless, the multimodal gait analysis approach presents a series of limitations and challenges. Firstly, the comprehensive evaluation of the system is confined to controlled environments, which restricts its applicability in real-world situations where conditions can vary significantly. This, in turn, can make operating the devices more challenging, potentially requiring substantial training for users to obtain precise results. The need for improvement in both the insoles and IMUs design to address limitations related to battery life and storage capacity is evident. Lastly, while the system can capture accurate data regarding movement patterns and pressure points, its predictive capability based on this data is still under development. These limitations highlight critical areas where further work and development are required to fully harness the potential of the multimodal gait analysis approach.

III. PROPOSED MULTIMODAL SYSTEM

In this section, it is presented the proposal for the multimodal system designed for gait analysis. In this context, the challenges faced and the knowledge gained throughout the entire process of developing and implementing this system are also described.

A. System test via the path travelling

In the process of test planning using the multimodal system, four main routes have been established. These routes are designed to guide test subjects through a progression from simple and short paths to more complex challenges that involve avoiding a static obstacle positioned in the center of the pathway.

In the first route, whose layouts can be observed in Figure 3, participants are directed to move linearly from point A to point B. This phase allows us to gather gait patterns, identify foot support points, assess inclinations, and determine whether the movement between the two points is direct or if deviations occur.

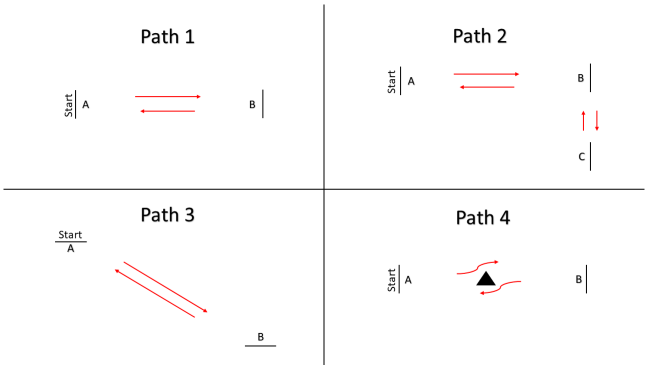


Fig. 3. Pathways for gait analysis

In the second route, a turn is introduced to the movement observed in the first trajectory. This addition enables the analysis of gait patterns during turns to a specific side, in this case, the right side.

In the third route, a diagonal path is proposed. This trajectory aims to explore gait habits in situations where an additional incline must be encountered in the direction of movement.

Finally, in the fourth route, movements are examined in scenarios where an obstacle requires a change of direction in a more confined space.

The selection of these four routes has been strategically designed to encompass a variety of challenges and movements, ranging from linear paths to turns and evasions. This comprehensive approach to test planning will enable us to attain a complete perspective of gait patterns and movements in various contexts and scenarios.

B. Integration of modules

Development was a key aspect, as a motion capture system was employed to perform gait analysis. This system involves strategically placing markers on specific points of the foot's sole, enabling the detection of body segment movements. In this case, sensors capture the pressure exerted by the person on specific areas, providing information about position, applied force, and even potential foot deformities. Subsequently, with the help of gyroscopes and accelerometers, it can determine the continuous flow of gait, you can see the insole used in

Figure 4, highlighted in the yellow rectangle. However, none of these data would be truly useful without the inclusion of the clock in the system. The clock plays a crucial role in data synchronization, allowing us to identify which foot is stepping at a given moment and which of the two feet is in a supporting position.

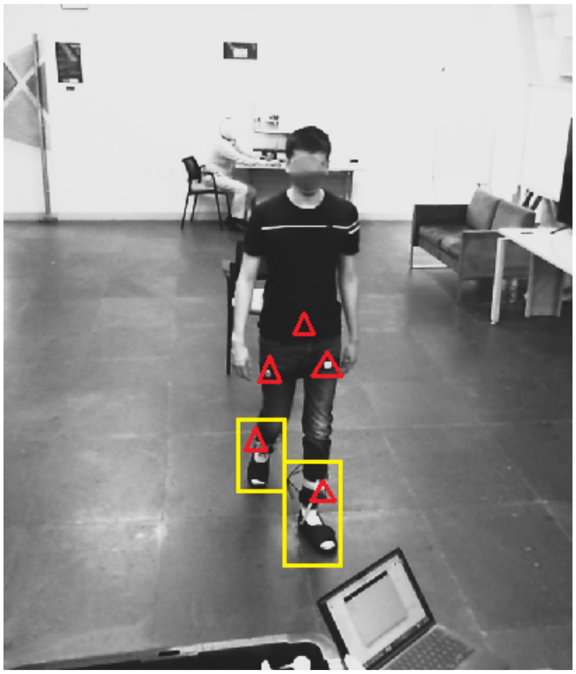
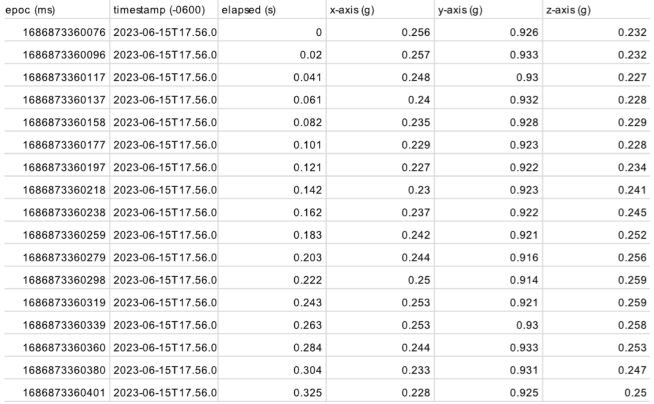


Fig. 4. Physical location of the modules. In this image, the IMUs' positions are indicated by red triangles, and the location of each insole is marked by yellow rectangles.

The detection process was initiated through the implementation of a module designed to streamline sensor development. During the initial phase, the hypothesis was that a greater number of sensors would yield more precise data detection. However, a challenge arose when attempting to incorporate an excessive amount of sensors, as their placement began to overlap, consequently compromising the reliability of the data.

IMUs are positioned in a specific manner, allowing us to store information in a standardized way. This enables us to properly process the data collected by each IMU, as can be seen in Figure 4, where the position of the IMUs is highlighted in the red triangles, including position along the x, y, and z axes, as well as acceleration. All of this is done through the Metabase application [2], which provides data in the following format: epoch (ms), timestamp (-06000), elapsed (s), x-axis (g), y-axis (g), and z-axis (g), this information can be seen in Figure 5

The cameras offer a visual guide to the subject's movements at every stage of the journey. As a result, during data processing, one can ascertainn the position of each IMU, the insole, and the corresponding image for each frame of the recording.



epoc (ms)	timestamp (-0600)	elapsed (s)	x-axis (g)	y-axis (g)	z-axis (g)
1686873360076	2023-06-15T17.56.0	0	0.256	0.926	0.232
1686873360096	2023-06-15T17.56.0	0.02	0.257	0.933	0.232
1686873360117	2023-06-15T17.56.0	0.041	0.248	0.93	0.227
1686873360137	2023-06-15T17.56.0	0.061	0.24	0.932	0.228
1686873360158	2023-06-15T17.56.0	0.082	0.235	0.928	0.229
1686873360177	2023-06-15T17.56.0	0.101	0.229	0.923	0.228
1686873360197	2023-06-15T17.56.0	0.121	0.227	0.922	0.234
1686873360218	2023-06-15T17.56.0	0.142	0.23	0.923	0.241
1686873360238	2023-06-15T17.56.0	0.162	0.237	0.922	0.245
1686873360259	2023-06-15T17.56.0	0.183	0.242	0.921	0.252
1686873360279	2023-06-15T17.56.0	0.203	0.244	0.916	0.256
1686873360298	2023-06-15T17.56.0	0.222	0.25	0.914	0.259
1686873360319	2023-06-15T17.56.0	0.243	0.253	0.921	0.259
1686873360339	2023-06-15T17.56.0	0.263	0.253	0.93	0.258
1686873360360	2023-06-15T17.56.0	0.284	0.244	0.933	0.253
1686873360380	2023-06-15T17.56.0	0.304	0.233	0.931	0.247
1686873360401	2023-06-15T17.56.0	0.325	0.228	0.925	0.25

Fig. 5. Data capture of a IMU.

C. Data Dictionary

The data dictionary represents a fundamental resource that provides a comprehensive description of the variables recorded during gait analysis tests. This valuable dataset not only includes critical information, such as the date and time of data recording, but it is also organized into two main sections: sensors on the left foot and sensors on the right side.

Sensors on the left foot's insole, identified with labels like LI5, LI6, LI7, and LI8, are positioned at specific points on the left foot and measure pressure at each of these points. Additionally, the gyroscopic and accelerometer sensors located on the left side, labeled as LAccelX, LAccelY, LAccelZ, LGyroX, LGyroY, and LGyroZ, record acceleration and angular velocity in the X, Y, and Z axes of the left side.

Simultaneously, sensors on the right side, named as RI5, RI6, RI7, and RI8, perform pressure measurements at contact points on the right foot. The gyroscopic and accelerometer sensors situated on the right side, identified as RAccelX, RAccelY, RAccelZ, RGyroX, RGyroY, and RGyroZ, capture acceleration and angular velocity in the respective axes.

In addition to these foot-specific sensors, our system also employs Inertial Measurement Unit (IMU) sensors, which are numbered according to their position and orientation. These additional sensors are responsible for gathering crucial data, such as acceleration and angular velocity in multiple axes. Each of these IMU sensors is labeled with the corresponding number and associated variables, such as 2AccelX, 2AccelY, 2AccelZ, 2GyroX, 2GyroY, and 2GyroZ.

It's important to note that before conducting each test, the number and position of these IMU sensors are meticulously recorded. This is done because these devices may rotate or be replaced to ensure accurate communication and reliable data capture. The exact placement of these IMU sensors is visually represented in Figure 4 , where they are highlighted with triangle markers for easy identification and proper configuration.

D. Communication

In terms of communication, the intention was for these sensors to connect via Bluetooth, aiming to eliminate the need for a cable connected to the module at all times, thereby providing greater freedom of movement for the user. While this strategy had its undeniable advantages, several difficulties were encountered that needed effective resolution to ensure optimal functionality and precise data synchronization.

One of the challenges lay in establishing and maintaining a stable Bluetooth connection between the sensors and the acquisition module. Wireless interference, physical obstacles, and signal fluctuations could all impact the consistency of data transmission, potentially compromising the integrity of the obtained results.

One of the main issues was that the Bluetooth range of the initial insole module was limited, which proved inadequate for effectively storing sensor data. When reaching the range limit, there was a significant loss of data and intermittent connectivity issues, rendering the tests being conducted unusable. This limitation enabled the exploration of solutions to extend the Bluetooth communication range, ensuring a seamless and reliable transfer of the collected data.

On their own, IMUs, when required to connect via Bluetooth, generate interference and delay in real-time data transfer. Therefore, the option was chosen to store data directly within the devices from the beginning of each trial until the end of the session. This approach helped mitigate synchronization issues during the course and enabled us to obtain cleaner and more accurate data.

E. Storage

The most fitting storage solution was to integrate a micro Secure Digital (SD) card module. This module would not only enable us to gather real-time data but also prevent data losses and potential interferences with other systems. This measure would contribute to establishing a more robust and stable database, thereby facilitating its subsequent analysis. This decision was driven by the fact that the insole module, unlike the IMUs, lacked storage capacity upon connection to the device it was linked to. Moreover, the incorporation of the SD modules helped decrease the interference that arose within the multimodal system.

By implementing the micro SD card module, the limitations posed by the insole module's storage capacity were effectively addressed, significantly improving the overall performance of the data collection and analysis process. This strategic solution not only ensured the integrity of the data but also enhanced the efficiency and reliability of the multi-sensor gait analysis system.

To carry out the data storage process, a procedure was implemented in which each frame of the video is converted into an image. This was applied to both the front and rear cameras. Furthermore, the information captured by the gyroscope and accelerometer of each IMU was included, as well as the pressure and gyroscope units of the insole. The time stamp of all devices was also recorded.

This approach allows us to visualize the subject throughout the entire course of each test and access the data collected by the devices at specific moments during the test. This information is correlated with the corresponding video frame, as shown in detail in Figure 6.

```
Data Point 2           6AccelY: 1.057
2AccelX: −0.15         6AccelZ: −0.107
2AccelY: 1.0           6GyroX: 0.0
2AccelZ: 0.085         6GyroY: 0.122
2GyroX: −5.244         6GyroZ: −1.585
2GyroY: 1.707          LI5: 62.522
2GyroZ: −0.122         LI6: 9.245
3AccelX: −0.296        LI7: 84.443
3AccelY: 0.93          LI8: 42.603
3AccelZ: 0.109         LAccelX: −0.44
3GyroX: −0.305         LAccelY: 10.2
3GyroY: 1.037          LAccelZ: 8.39
3GyroZ: 0.061          LGyroX: 0.12
4AccelX: 0.199         LGyroY: −0.03
4AccelY: 0.905         LGyroZ: 0.03
4AccelZ: 0.003         RI5: 0.0
4GyroX: −1.585         RI6: 0.0
4GyroY: 2.378          RI7: 0.0
4GyroZ: 0.427          RI8: 0.0
5AccelX: −0.058        RAccelX: 3.28
5AccelY: 1.021         RAccelY: 3.12
5AccelZ: 0.081         RAccelZ: 0.51
5GyroX: 0.427          RGyroX: −1.77
5GyroY: −0.244         RGyroY: 1.18
5GyroZ: 2.317          RGyroZ: 0.17
6AccelX: 0.185
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Fig. 6. Data storage.

F. Synchronization

For synchronization, a pivotal component among our modules is the clock, given its critical role in attaining precise alignment between individual units. Given that each insole incorporates its own autonomous module, the clock's significance is paramount. Nonetheless, encountered a substantial hurdle in sourcing an appropriate library for this device. As time progressed, the libraries employed for reading clock data underwent updates, a development that inadvertently hindered our progress. These updates triggered the deactivation of the clock's backup battery functionality, resulting in the freeze of the clock at the specific time and day when the primary power source was disconnected.

To tackle this challenge, the approach revolved around sourcing a clock module that was compatible with the most up-to-date libraries. This deliberate decision was aimed at enabling a seamless transition to the backup system when the primary power source was disconnected. This ensured uninterrupted power supply to the device without any disruption to the time or date, effectively preventing any instances of clock desynchronization.

After reaching a point of having a functional minimum viable product, efforts were channeled into implementing refinements to enhance its operational efficiency. This optimization drive also encompassed the incorporation of specific safeguards. These precautions were designed to prevent a scenario where, in the event of a failure in one module, the others would cease functioning as well. This proactive approach enabled the identification of any issues prior to commencing tests, facilitating the pinpointing of problematic modules.

Upon achieving the successful integration and synchronization of these components, avenues for system improvement were explored. A connection with Alexa was introduced, enabling the system to be activated from a designated distance.

Synchronizing the IMUs presented a streamlined process, as these devices seamlessly harmonized with the date and time of the connected device. This capability obviated the necessity for an extra clock, as with each trial and connection establishment, the IMUs underwent automatic updates, consequently streamlining the synchronization procedure.

With both data sources accessible, a comparison was initiated by aligning the recorded time intervals. This method facilitated the creation of a robust foundation for analysis, affirming the coherence and precision of the captured data. Additionally, to ensure data integrity, images acquired from the cameras were employed to corroborate and fortify the outcomes generated by the IMUs.

Ultimately, the combination of temporal information provided by the IMUs and the visual images from the cameras contributed to establishing reliable synchronization and validating the consistency of the collected data. This meticulous approach not only enhanced the integrity of the analysis but also solidified the accuracy of the outcomes, thereby enriching our understanding of human gait and its comprehensive assessment.

IV. RESULTS

The multimodal system successfully achieves its objectives related to the storage, analysis, and synchronization of multiple modules. The comprehensive evaluation of system functionality is restricted to controlled environments due to the complexities of device operations, making user manipulation a challenging task.

Multiple tests were conducted with participants of various genders, heights, and weights, allowing us to build a broad and diverse database. These tests were performed in two different scenarios, with the same paths and measurements maintained throughout.

In the initial tests, the insole prototype was quite basic, meaning the multimodal system lacked a battery to supply power. As a result, the connection was manually established, requiring the collaboration of two people and simultaneous action. Over time, significant improvements were introduced, enabling the multimodal system to maintain a cleaner and more accurate database.

However, certain limitations related to data storage capacity persist, relying on a micro SD card. Moreover, power consumption remains an ongoing challenge, with the battery's duration per charge currently extending to only four hours of continuous use. To address these limitations, efforts are being made to enhance the design of both the insoles and IMUs, aiming to prolong battery life and expand storage capacity. According to test results, the insole demonstrates the capability to capture precise information about movement patterns and pressure points in each foot. This achievement fuels the desire to further refine visualization methods and develop a predictive model based on observed gait patterns.

V. CONCLUSION AND FUTURE WORK

The success of the multimodal system can be attributed to the strategic placement of sensors, which prevents them from overlapping and ensures they are located in areas where the foot does make contact with the sensors. Furthermore, it effectively met the objectives related to storage, analysis, and synchronization of multiple modules by transitioning certain modules to data collection via SD cards, thereby reducing interference. The integration of batteries into the modules has also extended the system's operational lifespan, enabling us to conduct a variety of tests.

Despite the many successes of this multimodal system, the functionality of the system can only be thoroughly evaluated within a controlled environment due to the intricate nature of the device operations, making user manipulation less straightforward. Another limitation pertains to data storage capacity, which relies on a micro SD card. Furthermore, power consumption presents an additional challenge, as the current battery life is limited to four hours. Finally, power consumption presents an additional challenge, as the current battery life is limited to four hours. Efforts can be focused on finding an alternative for power consumption that is expected to last at least a full day of continuous use.

Future developments will focus on expanding the data storage capacity of the multimodal system, facilitating the retention of substantial amounts of information.

Furthermore, efforts will be directed towards enhancing the battery life per charge, with the ultimate goal of achieving nearly a full day of continuous usage. Additionally, there is a pursuit to redesign the templates to ensure comfortable long-term use, making the multimodal set accessible for users of all kinds.

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