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Integrated Platform for Gait Assessment with Plantar Imaging and Wearable Inertial Sensors

***Abstract*—A hybrid prototype system for human gait analysis was developed by combining dynamic imaging of plantar footprints with kinematic measurements from inertial sensors. The primary aim was to create a cost-effective and functional tool for evaluating biomechanical parameters in environments with limited technological infrastructure. The platform was constructed using MDF and tempered glass, featuring a wide-angle camera mounted below to capture the dynamic footprints during walking. In parallel, two custom-designed wireless inertial sensors were positioned on the subject's ankles to gather relevant motion data. Both subsystems were synchronized via timestamps to align gait events and visual information accurately. To analyze the footprints, computer vision methods were employed to segment the images and determine arch types through the Foot Concavity Index (FCI). Meanwhile, the inertial sensors provided gait metrics, including step length, cadence, and walking velocity. The accuracy of the kinematic measurements was validated by comparing them with results from the Kinovea software, showing acceptable error levels. Overall, the prototype demonstrated its potential as a compact and practical alternative for integrated gait assessment, combining morphological footprint analysis with real-time functional movement data.**

***Index Terms*—Biomechanics, Computer vision, Foot concavity index, Gait analysis, Plantar footprint,**

I. Introduction

Gait analysis and movement biomechanics have gained significant relevance in the medical and rehabilitation fields due to their impact on the detection and treatment of locomotor disorders. Understanding human gait from a biomechanical perspective requires an interdisciplinary foundation that bridges physiology, engineering, and clinical science.

Biomechanics evaluates human movement through mechanical and physical principles. In gait analysis, it enables the study of locomotor patterns and their relation to neuromuscular control. Understanding gait biomechanics is essential not only for healthcare professionals but also for the development of technologies applied to diagnosis and rehabilitation, facilitating advances in the treatment of movement disorders [1]. Gait involves cyclic movement coordinated by the musculoskeletal and nervous systems, where any disruption can affect mobility and independence, increasing the risk of falls [2].

Gait evaluation considers spatiotemporal parameters such as speed, cadence, stance and toe-off time, ground reaction forces, as well as step length and width—reflecting forward and lateral foot placement, respectively [3]. Although gait is generally automatic, factors like posture, trauma, or pathology may lead to compensatory mechanisms and functional limitations [4].

Plantar footprint reveals load distribution [5] and helps detect neurological and musculoskeletal disorders [4]. The foot's arches play a central role in absorbing impact enabling propulsion [6]; structural alterations may affect other joints such as the knee, hip and spine [2]. This is also essential in managing diabetic foot, where impaired sensation increases the risk of ulcers due to uneven pressure distribution [7].

Traditionally, the diagnosis of gait abnormalities has relied on physical and clinical examinations. However, a more comprehensive analysis requires detailed studies of movement patterns [8]. In recent years, the development of advanced technologies has facilitated both gait analysis and plantar footprint evaluation [9]. Among these technologies are approaches such as photographic imaging and optical systems like podoscopes, which highlight the footprint impression on a glass surface that is captured and analyzed using specialized software [10].

According to the Department of Physical and Occupational Therapy at CEUTEC (Centro Universitario Tecnológico of Honduras), advanced technologies for gait analysis, such as photopodoscopes and inertial measurement units, are prohibitively expensive, preventing their implementation in public hospitals and clinics. As a result, some hospitals resort to similar yet outdated methodologies that lack the technological capabilities required for proper plantar footprint analysis. This creates a significant barrier to accurate diagnosis for the population relying on the public healthcare system.

This study aims to develop an accessible and functional hybrid system that enables more accurate gait evaluation through the combination of dynamic imaging and kinematic data obtained using inertial measurement systems. This approach seeks to provide a cost-efficient alternative to traditional systems, addressing the needs of healthcare institutions with limited resources and contributing to enhanced rehabilitation and diagnostic processes for musculoskeletal and neurological disorders.

Throughout this research, the technologies used for its analysis and the design of a hybrid system to optimize data collection and processing will be examined. Although the scope of this study does not consider clinical trials, it aspires to contribute innovative solutions that facilitate biomechanical evaluation and strengthen access to more accurate and accessible diagnostic tools in the Honduran healthcare sector.

A. *State of the Art*

Gait analysis, as a discipline of biomechanics, allows for the evaluation of body movement patterns during locomotion. According to Moro et al., gait analysis is not only used to monitor patients with certain pathologies but also plays a key role in personalizing rehabilitation treatments [11]. It can be performed using laboratory-based systems, inertial sensors, or portable devices suitable for ambulatory and outdoor environments [12].

Gait analysis enables the detection of movement alterations that may indicate underlying health issues. It not only supports patient monitoring and personalized treatment planning but also contributes to improving the accuracy and effectiveness of interventions. Given the variety of available methods to evaluate movement, these systems can be adapted to different needs and contexts.

This technological diversity makes gait analysis accessible across a wide range of situations and patient profiles, including those in resource-limited settings. Motion capture systems are essential for kinematic gait analysis and are widely implemented across industries such as film, gaming, and medicine. These systems include mechanical, optical, and sensor-based technologies that provide precise data for monitoring human movement patterns [13]. The use of infrared markers and portable sensors has improved analysis accuracy, allowing for the evaluation of basic activities like walking and supporting complex rehabilitation processes [11].

Motion capture systems are a fundamental component of biomechanical analysis, serving as the core of data acquisition capabilities. These systems enable the precise identification of human movement patterns and, even through basic activities such as walking, allow for detailed and continuous monitoring of a patient's condition over time.

1) Inertial Measurement Units (IMUs).: IMU sensors calculate linear acceleration and angular velocity through accelerometers and gyroscopes, generating relevant human motion data [14]. They are known for their portability and real-time data capture capabilities [4], making them key components in the development of accessible biomechanical assessment tools, especially in mobile or low-cost systems.

Sensors are essential devices for motion capture, as they detect physical changes during data collection and analysis. In this context, inertial measurement units (IMUs) serve as a gateway to the development of advanced systems, enabling practical and real-time data acquisition in an accessible manner.

2) Image Processing.: Image processing is essential for the dynamic analysis of plantar interaction with the ground. Techniques such as contrast enhancement, segmentation, and edge detection optimize image quality and facilitate the identification of morphological and biomechanical alterations [10]. These methods allow for precise calculation of pressure distribution, contributing to a more complete understanding of gait [5]. Moreover, recent developments in deep learning have introduced convolutional neural networks that enhance the segmentation of plantar pressure images, significantly improving diagnostic accuracy and biomechanical evaluation [15].

Image processing is essential for capturing the interaction between the foot and the ground during gait, as it enhances image quality and enables the detection of deformities or alterations in plantar pressure. Various applied techniques not only improve the accuracy of biomechanical analysis but also allow for the identification of edges, contact areas, and pressure distribution for more detailed assessments.

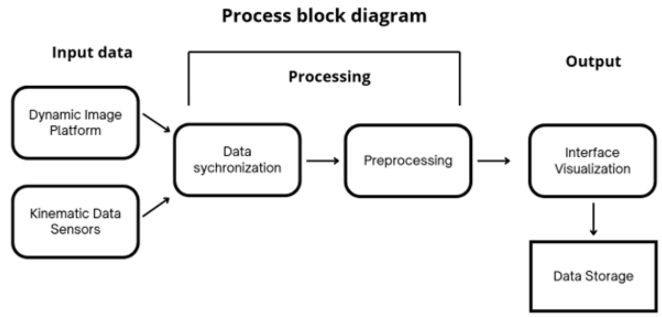

Fig. 1. Block diagram of the proposed hybrid system for gait analysis

3) Platforms for Gait Analysis.: Various visual data acquisition technologies have been applied to enhance footprint analysis, including pressure platforms, infrared systems, and podoscopes [3]. These methods are non-invasive, and facilitate early diagnosis of postural deformities, contributing to the design of customized insoles and treatment strategies for conditions such as diabetic foot or lower-limb abnormalities [8]. Photo-podoscopes offer a natural method of analyzing plantar footprints, revealing how pressure is distributed across the sole of the foot during walking [5]. Technologies such as baro-podoscopes have been developed to measure plantar pressures with high precision [10].

Photo-podoscopes are another key component of image and motion capture systems. Through plantar footprint analysis, they enable a better understanding of how foot structure influences gait patterns, thereby complementing dynamic analysis. These tools provide insights into how foot structure influences gait patterns and serve as a complement to dynamic analysis.

II. Method

This research adopts a methodological process composed of three main phases: data acquisition, processing, and visualization. This approach ensures proper integration of the different components of the hybrid system and allows for the design and execution of functional tests for synchronization, capture, and processing among the various elements, as shown on Fig. 1, the block diagram illustrates the system's workflow from data acquisition to processing and visualization.

As part of this work, a low-cost hybrid system was designed and implemented for the functional and morphological analysis of human gait, combining computer vision with inertial sensors. The system includes a custom-designed optical pressure platform for dynamic plantar footprint capture in video format, and two inertial measurement sensors placed on the patient's ankles. The data from both sources are synchronized for further clinical use by healthcare professionals in diagnosing movement disorders.

The hybrid system begins with data acquisition from two sources: a dynamic image platform that captures plantar footprints in real-time, and the inertial measurement units (IMUs) placed on the body to collect kinematic data. A synchronization process ensures both data types align temporally. The synchronized data is then preprocessed using tools like OpenCV, and noise-reducing filters to enhance its quality. Finally, the processed data is visualized through a graphical user interface (GUI) and can be exported for clinical analysis.

Materials. The hybrid gait analysis system comprises several phases in its complete structure. It requires various materials that enable the construction of the platform, as well as the integration and design of the inertial sensors and the image capture system. The system consists of three main parts, each containing its own essential components.

The physical platform was built using an MDF board and a tempered glass surface, with LED strips placed around the glass to enhance the visualization of the plantar footprint. For dynamic image capture, a smartphone was used as a wireless webcam through the Droid Cam application, which connects to a computer via a local IP address for real-time streaming. Kinematic data acquisition is carried out using an inertial measurement unit (IMU) consisting of an ESP-32 micro-controller, and GY-BMI160 accelerometer and gyroscope module, powered by a 3.7V battery, The components were mounted to protect and integrate the electronic parts into custom enclosures which were designed and fabricated using 3D printing technology.

III. Results and Discussion

The prototype integrates two essential subsystems: the visual footprint capture system and the kinematic data capture system using inertial sensors (IMU). Both systems operate in a coordinated and synchronized manner, enabling the simultaneous collection of visual and kinematic data through timestamps. This integration allows for the alignment between each recorded kinematic parameter and the specific moments of the gait cycle captured visually. This hybrid system can combine visual and kinematic information within a single biomechanical analysis, which could be useful in clinical contexts.

A. Design and Construction of a Platform for Plantar Footprint Analysis.

The initial design of the physical platform was carried out using SolidWorks, as shown on Fig. 2, where a structure was modeled to provide stability, resistance to the patient's weight, and the capacity to integrate a video camera. The structure was built with MDF (medium-density fiberboard) and covered with 0.87 cm thick tempered glass.

Structural simulations were conducted in SolidWorks to assess the platform's resistance and stability under simulated loads of up to 150 kg. The simulations included three main types of analysis:

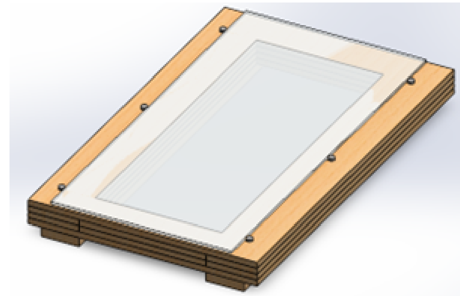

Fig. 2. Digital design of the platform for gait analysis.

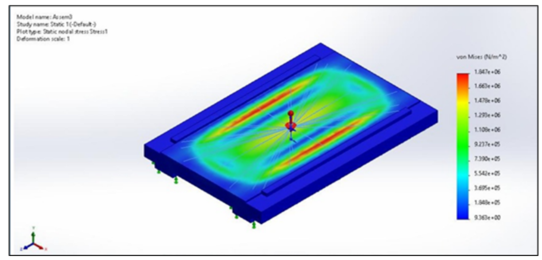

Fig. 3. Platform static stress analysis results in SolidWorks.

- **Static stress analysis:** This simulation, as shown in Fig. 3, allowed the identification of areas on the platform where the internal stresses were most concentrated. The results indicated that maximum stress levels did not exceed 1.4 MPa, which is well below the yield strength of both the glass and MDF. Most of the structure remained within regions represented by cool colors (blue), suggesting that the stress induced by the load was low and uniformly distributed.
- **Strain analysis:** This analysis aimed to evaluate the deformability under load, as illustrated in Fig. 4. The MDF, due to its lower stiffness, absorbed most of the deformation, while the glass exhibited a more rigid structural behavior, with significantly less deformation. This distribution is ideal, because it allows the MDF to function as a damping base without compromising the integrity of the transparent observation component.
- **Maximum displacement analysis:** This analysis quantified the structural displacement under applied load, as shown in Fig. 5. A maximum displacement of approximately 1.9 mm was observed at the edges of the MDF base under a 150 kg load, while the glass component exhibited minimal deformation. This level of displacement does not pose a structural risk nor compromise the system's functionality, remaining well within acceptable limits for support structures intended for image capture.

In all simulations, the safety factor exceeded 100, indicating a high level of resistance to the applied loads. This value reflects a wide safety margin, especially considering that the simulated weight surpassed the average real load for most patients.

These results supported the choice of tempered glass and

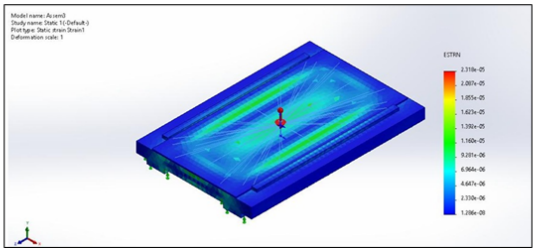

Fig. 4. Platform strain analysis results in SolidWorks.

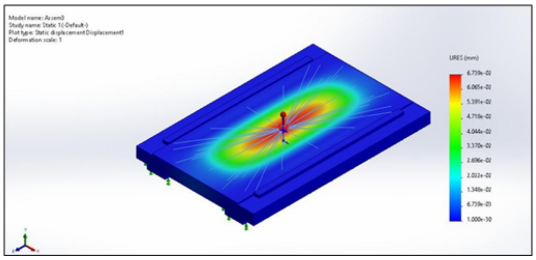

Fig. 5. Platform maximum displacement analysis results in SolidWorks.

stacked MDF sheets, offering an optimal balance between structural rigidity, transparency, and economic accessibility.

To enhance the visual capture of plantar footprints, a green LED strip was installed around the perimeter of the tempered glass surface. The choice of this lighting was based on experimental tests that showed a significant improvement in footprint contrast, without causing relevant interference during digital image processing. As for the angular camera, its optimal position was determined through empirical testing, selecting the location that maximized the visibility of the gait pattern and allowed clear capture of both footprints in a single frame.

B. Visual Capture System.

Visual capture was carried out using an angular camera installed at the bottom of the platform, as seen in Fig. 6. Its placement was determined through empirical testing, selecting the position that offered the greatest visibility of the gait pattern and allowed for clear recording of both plantar footprints in a single frame. This camera was connected to a GUI developed in Python, enabling real-time processing of each video frame.

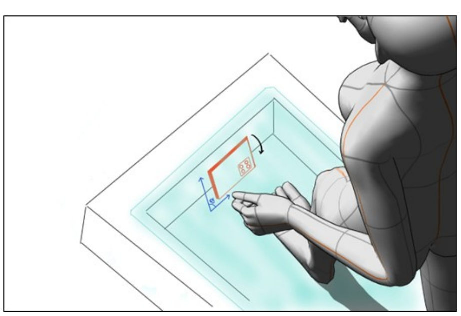

Fig. 6. Camera placement in the platform

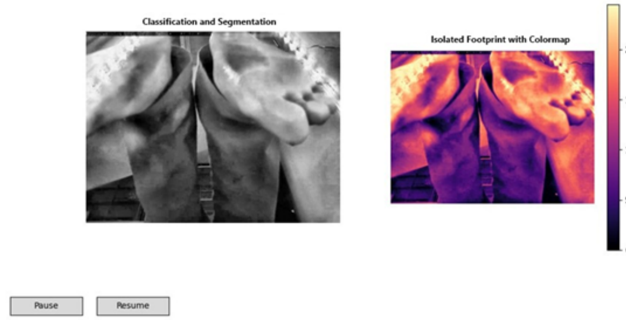

Fig. 7. Color map for footprint segmentation and processing.

Each image was processed by prioritizing the green channel of the RGB color space, as this component corresponded to the green LED lighting used on the platform, which helped improve the contrast of the plantar footprints. Subsequently, the images were converted to grayscale and subjected to processing techniques that included contrast enhancement using Contrast Limited Adaptive Histogram Equalization, bilateral filtering to reduce noise without affecting the edges, and adaptive thresholding to eliminate reflections caused by LED lighting.

Once the image quality was enhanced, adaptive binary segmentation was applied to isolate the plantar footprints. Morphological operations were then used to refine the generated masks, prioritizing the regions corresponding to the patient's feet, automatically identified as the most prominent areas in the processed image. Based on this segmentation, a color map was generated to intuitively visualize the spatial distribution of footprint intensities, providing an additional visual tool for the clinical analysis of plantar contact, as shown on Fig. 7.

During the analysis, the GUI allows the selection of a region of interest to calculate the Foot Concavity Index (FCI) and classify the foot type as flat, normal, or high-arched. The Chippaux-Smirak Index (CSI) is calculated over this area, which corresponds to the ratio between the midfoot and forefoot widths. This metric enables automatic classification of the patient's arch type as flat, normal, or high arch. This index is obtained by dividing the midfoot width by the forefoot width, comparing the narrowest and widest parts of the footprint. A foot is classified as flat when the index ranges between 45.1% and 100% [16]. This is calculated directly through a Python function.

C. Kinematic Capture System.

The kinematic system consists of two GY-BMI160 inertial sensors, each coupled to an ESP-32 microcontroller. These devices were housed in ergonomic casings designed in SolidWorks and manufactured using 3D printing. The casings feature integrated straps to secure them to the ankle, ventilation to prevent component overheating, and a structure that allows the patient to maintain freedom of movement during testing.

Fig. 8. Approximate placement of IMUs. (R) and (L) indicating right and left ankle.

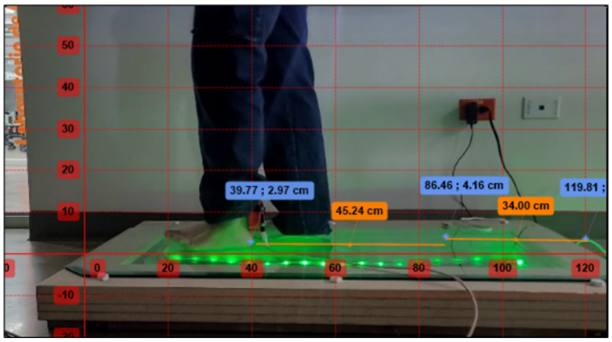

Fig. 9. Step analysis in Kinovea.

After multiple field tests, the optimal location for the sensors was determined to be the ankles, as shown on Fig. 8, as this position offered stability during gait and minimal interference with the natural movement pattern. From this location, the sensors recorded acceleration along the X, Y, and Z axes, as well as angular velocity, allowing the identification of key gait cycle events such as step initiation and termination.

The collected data was digitally processed using filtering techniques to reduce noise and improve signal accuracy. Based on these signals, the system calculated relevant biomechanical parameters such as step length, step duration, cadence, and walking speed, enabling a quantitative analysis of the patient's gait performance. Furthermore, by using two independent sensors, it was possible to distinguish between the movement patterns of the left and right legs, adding greater depth to the analysis.

During the testing phase, the kinematic data acquisition system stored the collected information for later export in a .csv file format. The sensor data was subsequently analyzed by comparison with motion analysis software, specifically Kinovea. A side-view video recording was used to capture the subject's steps, with key gait events manually annotated in the video, starting from a resting position.

The analysis focused on the right foot, identifying the onset of the swing phase and measuring the distance traveled until heel strike occurred again. This allowed for the measurement of two complete steps, as shown in Fig. 9.

Once both the sensor data and the reference values obtained through Kinovea were available, a percentage error was calculated to assess the system's accuracy. This error was determined by comparing the sensor measurements against the Kinovea-derived reference values. It is important to note that while Kinovea provides reasonably accurate results, it is subject to user-dependent variability and perspective limitations inherent to manual video annotation.

The percentage error was calculated using Microsoft Excel. For the first step, an error of 14.34% was obtained, while the second step showed a slightly lower error of 13.31%, indicating a minor improvement in performance.

D. Data Synchronization and Integration in a GUI.

The integration between the visual and kinematic systems was achieved through a synchronization strategy based on timestamps. Each image captured by the angular camera was tagged with a timestamp, as was each sample collected by the inertial sensors. This allowed both data sets to be chronologically aligned.

This synchronization enabled coordinated analysis of the patient's gait behavior, identifying which visual event corresponded to specific values of acceleration or angular velocity. Temporal alignment was particularly useful for studying phases of the gait cycle such as stance, toe-off, and swing, as it provided biomechanical context from multiple data sources.

To facilitate user interaction with the system, a GUI was developed in Python using libraries such as OpenCV, Matplotlib, and NumPy. This interface automates the loading of the latest recorded video along with the corresponding kinematic data files (in .csv format), linking them automatically via the timestamps.

Once loaded, the system processes each video frame in parallel with the sensor data allowing for synchronized visualization. The interface offers interactive features such as playback pause, region of interest selection over the plantar footprints, automatic calculation of the FCI, and the option to perform the calculation manually.

The system generates a series of files as the final output of the analysis, which support the documentation, interpretation, and record of the biomechanical study performed. Each of these elements is an integral part of the workflow, corresponding to the data captured for each patient or session.

E. Discussion and Future Directions

Although this option was not implemented in the final prototype, an interface for dynamic image acquisition within the system was successfully developed. Therefore, it is recommended to consider this approach as an alternative for future work, offering a compact solution within the same enclosed environment.

It is also suggested to conduct a more robust static analysis of the platform system, with the goal of increasing its height and width. This would allow the user's step to be more natural and not restricted by the current physical dimensions of the prototype.

Additionally, validation from professionals in biomechanics, orthopedics, or physiotherapy is required to determine whether the use of computer vision provides clinical and functional value compared to traditional methods for plantar footprint analysis.

Finally, it is recommended to improve the robustness of the graphical user interface, particularly in file synchronization and data visualization—especially visual data, which is affected by interference in real-time input due to Wi-Fi signal fluctuations.

IV. Conclusions

Gait analysis is a fundamental tool for biomechanical assessment, particularly in identifying locomotor impairments that can significantly impact a patient's quality of life. However, access to advanced gait analysis technology remains limited in countries like Honduras due to the high cost of specialized systems.

This work presents a functional and low-cost hybrid system for gait analysis, integrating dynamic plantar footprint imaging and kinematic data collected via inertial sensors. The system was designed with affordable materials and local adaptability in mind, aiming to offer a practical alternative for healthcare professionals.

Field testing helped determine the optimal camera position—under the platform with a slight tilt—as well as the ideal placement of the inertial sensors, with the ankles identified as the most effective location for capturing gait data without interfering with the patient's natural movement.

It is recommended to improve the platform´s dimensions to allow a more natural gait and avoid movement limitations. Additionally, the use of anti-reflective glass and a stable Wi-Fi connection is advised to enhance image quality and ensure reliable data acquisition. Finally, improvements to the GUI are suggested, particularly for synchronizing and displaying real-time data effectively.

V. Acknowledgements

We would like to thank the FabLab at UNITEC Honduras for their support in the fabrication of various system components. We also express our gratitude to Geovanny Fortín and Fávell Núñez for their guidance throughout the development process.

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