WIRELESS INSTRUMENTED ANKLE FOOT ORTHOSIS (AFO) FOR GAIT CYCLE MONITORING: A PRELIMINARY STUDY

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Abstract— Ankle Foot Orthoses are used for rehabilitation after ankle injuries or pathologies, but their effectiveness and recovery time can be affected by improper patient use. To address this issue, an instrumented Ankle Foot Orthosis can assist doctors in monitoring the patient's gait cycle, enabling the development of a personalized rehabilitation plan. In this paper, an Ankle Foot Orthosis capable of monitoring the gait cycle and the deformation of the orthosis is proposed and preliminary analyzed. The system consists of two force sensors to detect ground contact, a strain gauge bridge to measure orthosis deformation, and an inertial module to analyze the gait cycle. An Arduino Nano is used to acquire these signals after electronic conditioning. The microcontroller transmits data to a low-power Bluetooth module, which communicates with a LabVIEW program where the data is displayed in real time and stored in a text file. After characterizing the entire system, a PCB board is developed and mounted onto the orthosis using a support printed with a 3D printer.

Keywords—Ankle-Foot-Orthosis, AFO, Braces, Instrumented AFO, Gait-Cycle-Monitoring

INTRODUCTION

Nowadays, the prevention, diagnosis, and monitoring of gait cycle pathologies are crucial. Electronic sensors play a key role in this process. People with gait cycle disorders often use assistive medical devices, such as an Ankle-Foot Orthosis (AFO) or a crutch. The sensorization of these devices can help doctors quickly and accurately determine whether rehabilitation is effective.

In the state of the art, several instrumented assistive medical devices have been developed to monitor specific gait cycle parameters, such as ankle or crutch movement [1,2], Ground Reaction Force (GRF) [3], or orthosis deformation [4]. For instance, Hamid et al. [5] developed an active AFO system by placing a force sensor under the foot. This setup allows for the identification of the gait cycle phase, enabling the movement of the active system to assist patients with foot drop pathologies [6]. Rescio et al. [7] designed an instrumented insole that measures foot temperature. Several studies have demonstrated a correlation between foot temperature and diabetic pathologies, such as foot ulcers. Therefore, this insole can help prevent or diagnose these conditions.

Svensson et al. [8] attached a Wheatstone bridge with strain gauges to an optimal position on the orthosis to measure deformation during hill walking. They demonstrated that deformation is greater during uphill walking than downhill walking. Tanino et al. [9] used two strain gauge bridges to measure torque during walking. To identify the gait cycle phase, Aminian et al. [10] placed a force sensor on the heel and toe of the foot. This configuration allows the detection of initial and final ground contact, providing information about gait cycle time and several other parameters. They also placed a gyroscope system on the shank, which, combined with a force sensor (which functions as a footswitch), measured spatio-temporal gait parameters. Betz et al. [11] used an inertial module to investigate the ankle inversion angle with two types of orthoses, one designed to protect against ankle inversion.

To ensure comfort wireless communication of the measured data is usually adopted respect to wired communication. In this regard, proper power management is also crucial, making low-power communication the best option. The entire system can be considered an IoT-based system. After data acquisition, the information can be sent to a cloud database. For example, Shefa et al. [12] designed and developed an IoT-based AFO. They placed an Electromyography (EMG) electrode and an inertial module on the shank, which communicates with a microcontroller. The data is transmitted via Wi-Fi to a cloud platform, where it is initially stored and pre-processed. Then, a Machine Learning model analyses the information. Finally, the data is sent from the cloud platform to a doctor's device, allowing for diagnosis or the creation of a prevention plan.

Force and deformation sensors, as well as electromyography electrodes, can be printed directly onto the orthosis using innovative printing techniques, such as Aerosol Jet Printing [13], Photonic Curing [13], and Piezo Jet Printing [14]. Cantù et al. [15] printed multi-EMG electrodes on the 3D surface of an orthosis using Aerosol Jet Printing (AJP), demonstrating the device's ability to detect gastrocnemius muscle activity during a sit-to-stand task. This study highlights the efficiency of AJP in designing customizable orthoses with specific parameters for monitoring a patient's particular pathologies.

For the validation of the inertial module and sensors, a gold standard is the 3D tracking of human motion [16] using an optical system. Lancini et al. [17] used a Smart-DX vision system with eight infrared video cameras. These cameras acquire data from a retroreflective spherical marker. This system is used to validate the inertial module, while a load platform is used to validate the force sensors.

In this paper a novel instrumented AFO capable of monitoring the gait cycle and the deformation of the orthosis is proposed and preliminary analyzed. While previous studies have focused on monitoring isolated gait cycle parameters—

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such as GRF, orthosis deformation, foot temperature, or muscle activity—this research presents an integrated approach that combines multiple sensing technologies within a single instrumented AFO. Unlike previous works that analyze either ground contact force or orthosis deformation, this study combines force sensors, strain gauges, and an inertial module to provide a comprehensive assessment of both gait cycle dynamics and orthosis behaviour.

Furthermore, this study implements a low-power Bluetooth communication system to transmit real-time data to a LabVIEW interface, allowing for immediate visualization and storage without reliance on cloud-based processing. Unlike previous designs that integrate rigid electronics onto orthoses, this work develops a custom PCB and a 3D-printed support, ensuring seamless integration, reduced weight, and improved patient comfort. While previous works have focused on specific pathologies (e.g., foot drop, diabetic foot monitoring), whereas this study's system can be adapted for various rehabilitation scenarios, improving personalized therapy through detailed gait analysis.

By integrating multiple sensing modalities, real-time wireless communication, and practical design improvements, this research advances the field of instrumented AFOs beyond existing solutions, offering a more effective and adaptable tool for rehabilitation monitoring.

GAIT CYCLE

In the gait cycle, there are several parameters to monitor. This section summarizes the theory behind the parameters that are the focus of this work.

The gait cycle is defined as the time interval between the initial contact of the foot with the ground and the subsequent contact of the same foot with the ground [18]. Gait Cycle has two important phases:

a. Stance Phase: The foot is in contact with the ground, making up about 60% of the total gait cycle.
b. Swing Phase: The foot is in the air and lasts for the remaining portion of the gait cycle.

During the gait cycle, both movement and kinetics parameters can be monitored.

A. Movement Parameters

During the gait cycle, the ankle can perform two types of movements [18]:

a. Plantar/Dorsiflexion: As shown in Fig. 1, this movement allows an ankle range of approximately -20 to 20 degrees. The AFO reduces this range because it is designed to limit excessive ankle movement.

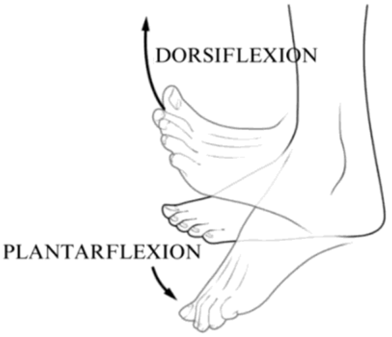

Fig. 1. Plantar Flexion and Dorsiflexion

b. Inversion/Eversion: This movement, as shown in Fig. 2, reaches a maximum angle of 2 degrees during the gait cycle.

Fig. 2. Inversion and Eversion

B. Kinetics Parameters

The GRF is a measure of the impact with the ground by the foot. It can be obtained using a foot sole with force sensors [19] or a force platform [20]. The measurement of deformation in an orthosis can be correlated with the torque during the gait cycle.

WIRELESS AFO DESCRIPTION

The AFO is an external medical device designed for patients with injuries or neuromuscular dysfunction, helping to improve the gait cycle. There are several types of AFOs, as shown in Fig. 3, such as the Posterior Leaf Spring AFO (PLS-AFO), which is used for patients with drop foot pathology. This AFO helps the patient control plantar flexion, and in this case, the ankle angle is wider than that of a healthy person. In this work, the PLS-AFO TO4302 orthosis, developed by Tenortho (Italy), is used to be instrumented. The proposed measurement system consists of two force sensors to detect the stance and swing phases, a strain gauge bridge to measure orthosis deformation, and an inertial module to determine position (Fig 3). The signals are then acquired by a microcontroller and transmitted via Bluetooth to a LabVIEW program, where the data is displayed in real time.

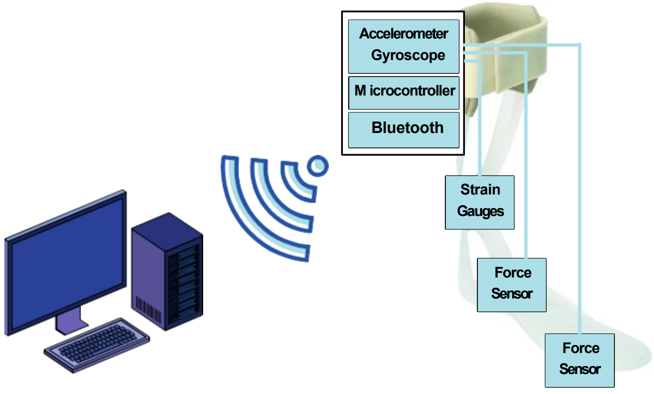

Fig. 3. Measurement System

A. Forces

For the identification of stance and swing phases, Force Sensitive Resistors (FSRs) are used, positioned as shown in Fig. 4. One sensor is placed on the heel of the AFO, while the other is positioned on the toe. The first sensor detects the initial contact with the ground, marking the start of the stance phase, while the second sensor detects the beginning of the swing phase [21].

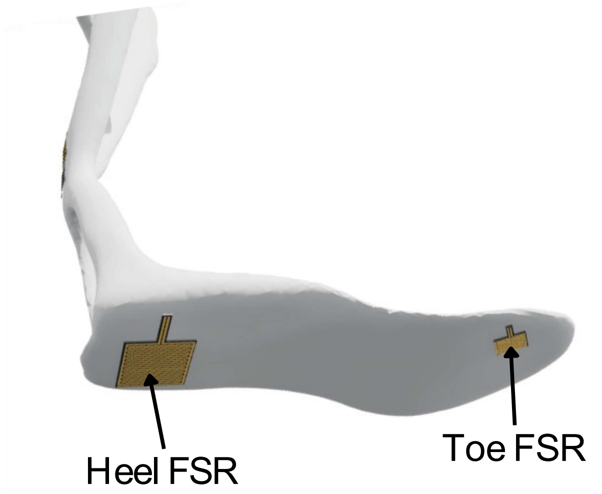

Fig. 4. Force sensor positioning

For signal conditioning, a current preamplifier circuit (shown in Fig. 5) is used to convert current into voltage.

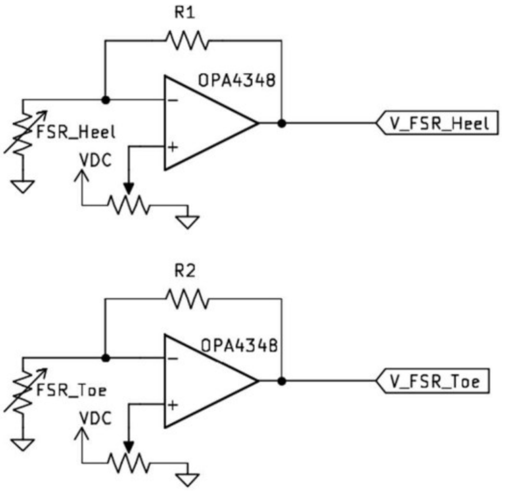

Fig. 5. Preamplifier Current

B. Strain

To measure the deformation of the AFO, four strain gauges (each with a resistance of 120 Ω and a gauge factor of 2) are positioned as shown in Fig. 6. Their orientation is chosen to form a Wheatstone Bridge. Specifically, two strain gauges experience compression while the other two undergo extension, or vice versa. One strain gauge in compression and one in extension are fixed on the external part of the orthosis, while the other two are attached to the internal part. The sensors are thus placed diametrically opposite to each other. For maximum deformation variation, the sensors are attached using a glue specifically designed for strain gauges.

During the gait cycle, plantar/dorsiflexion causes a deformation of the AFO, making it possible to use strain gauge data to determine the ankle angle.

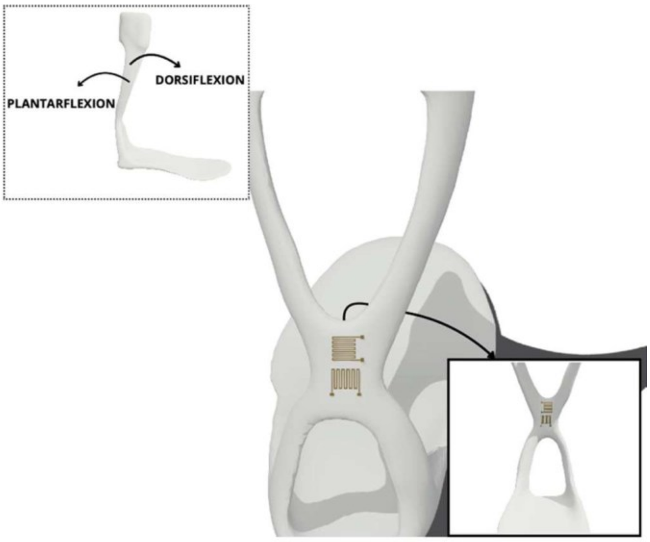

Fig. 6. Strain Gauge Sensor positioning

The signal conditioning circuit is shown in Fig. 7. The differential potential is measured by an Instrumentation Amplifier, and subsequently, the signal is amplified and filtered. The second stage of the circuit needs to adjust the signal to cover the entire range of the microcontroller's Analog-to-Digital Converter.

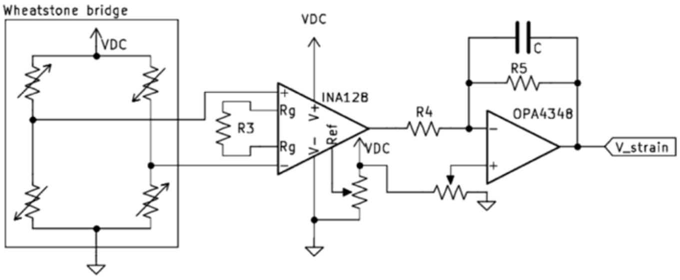

Fig. 7. Signal Conditioning

C. Movement Analysis

The monitoring of movement during the gait cycle is performed by the Inertial Module LSM6DSR (3-axis digital accelerometer and 3-axis digital gyroscope) . This module includes an accelerometer, a gyroscope, and a magnetometer, and it communicates with the microcontroller using the SPI protocol. The resolution is limited by a 32-bit data length. The entire system is shown in Fig. 8b, the board is placed inside a box and fixed to the orthosis using a two-support 3D-printed mount. The acceleration values are used to measure the yaw, pitch, and roll angles, while the gyroscope values can be used to examine gait abnormalities [22].

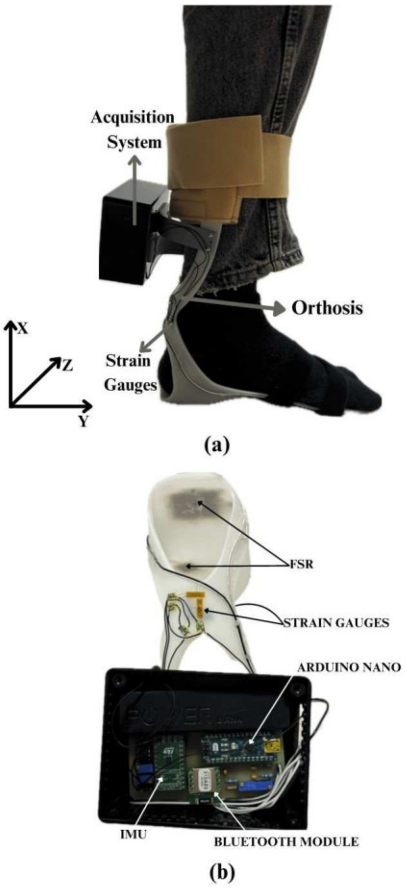

Fig. 8. (a) Electronic Board Positioning (b) Electronic System

D. Wireless Communication

Strain, force, and IMU signals are acquired by an Arduino Nano microcontroller. Subsequently, the data are sent to the Bluetooth module Parani ESD200 via serial communication. A LabView program then receives this data and, using appropriate software, displays all information in real time. The Parani module uses low-power communication and can transmit data up to 30 meters.

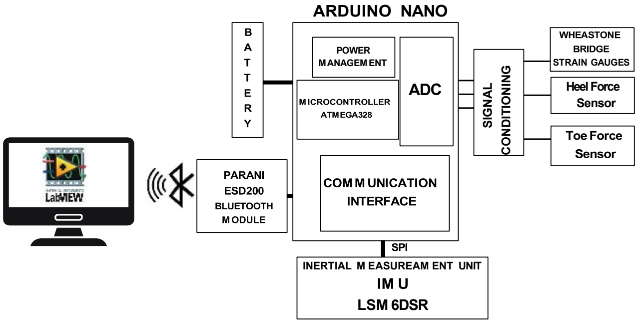

Fig. 9. Hardware Architecture

E. Software Architecture

The operating logic of the microcontroller firmware is as follows: when the Arduino is powered on, it enters an initial state where the inertial module and the Bluetooth module are configured. Subsequently, when the LabView program starts communication with the microcontroller, the state transitions to the data transmission phase. In this phase, each data value is sent in two separate transmissions because the Bluetooth module can only send 16-bit data at a time, whereas the stored information is 32-bit. To send all data the module needs 18 communications.

The LabView software is designed to display the ankle inversion/eversion in real-time using a gauge, with all signals also displayed in real-time in separate plots. This data can also be stored in a text file (as shown in Fig. 10).

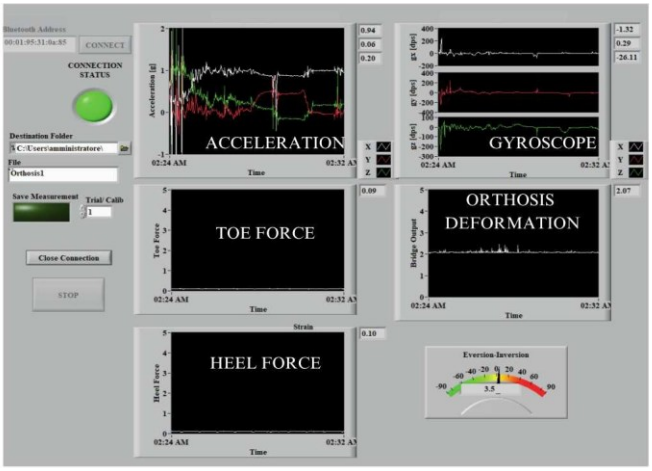

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Fig. 10. LabView Display

RESULTS

A. Force Sensor

For the validation of the force sensor, a dynamometer is used to test the effective detection of contact with the ground (as shown in Fig. 11). A Force is applied to a plastic foot, and the resistance from the two-force sensor is recorded using a multimeter. The results show a decrease in the resistance of the Toe Force Sensor from 2 MΩ to 1541 Ω with a 30 N load (Table 1). This characterization is also performed on the Heel Force Sensor. These results are used to design the conditioning circuit to achieve the maximum performance of the system.

Fig. 11. Dynanometer Testing

TABLE I. RESISTANCE VALUE

	LOAD			
Sensor	**0 N**	**10 N**	**30 N**	**50 N**
Toe Force	2 MΩ	4.79 kΩ	1.541 kΩ	1.2 kΩ
Heel Force	1.5 MΩ	3.13 kΩ	1.21 kΩ	782 Ω

B. Gait Cycle Monitoring

In these preliminary results, the orthosis is worn by a subject performing a 5-meter walk. Before the walk, sensors calibration is required. Specifically, the Wheatstone bridge is calibrated to achieve the balance condition. The University Research Ethics Committee (CERA) of the University of Brescia approved this testing procedure.

Fig. 12 shows the deformation of the orthosis during one gait cycle, and these results are consistent with the classic gait cycle plot [23]. The output signal exhibits a variation of 165 mV for each gait cycle, and it can be observed that the stance phase lasts for 77% of the gait cycle, while the swing phase accounts for the remaining 23%.

By using a system composed of two inertial modules—one placed on the shank and the other on the foot—it is possible to correlate the orthosis strain with the plantar/dorsiflexion ankle angle. After this correlation, one of the two inertial modules can be removed, and the ankle angle can be measured using only strain gauges.

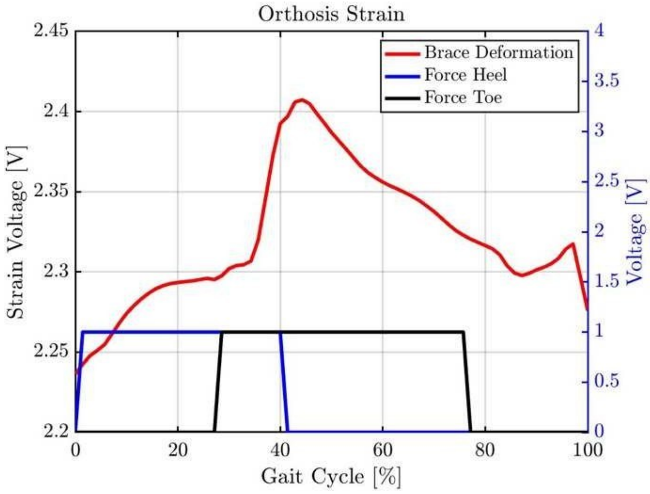

Fig. 12. Deformation of the orthosis during the gait cycle. The strain gauges have a sensitivity of 50 ± 0.53 µm/m per Volt. Force sensors are used in a binary (on/off) mode to detect foot contact.

The ankle angle variation for eversion/inversion is shown in Fig. 13 using only one inertial module. The angle variation is within a 4.98-degree range, and the plot is consistent with the typical plot of a healthy patient [24]. Figure 14 shows a Gyroscope plot for the three directions. Analyzing the Y signal, it is possible to evaluate the plantar flexion and dorsiflexion.

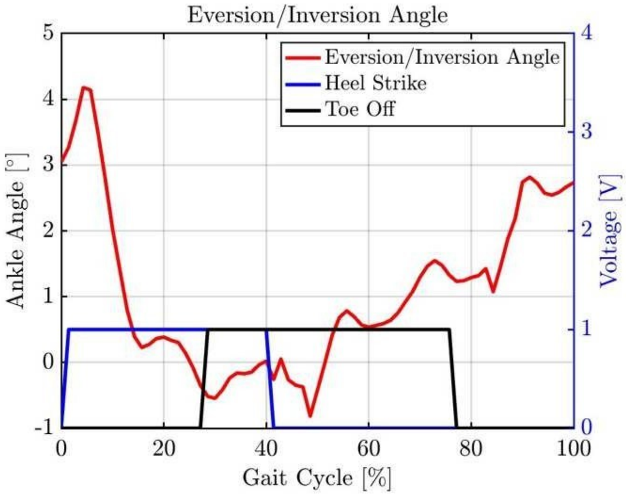

Fig. 13. Eversion/Inversion ankle angle with a ±0.2° measurement uncertainty

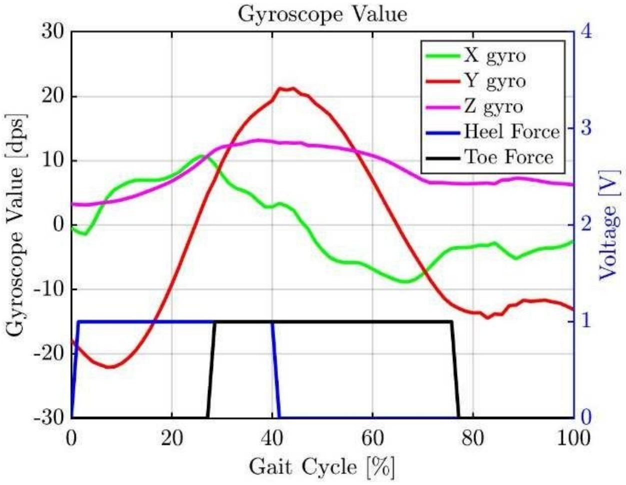

Fig. 14. Gyroscope plot with a ±1.71 dps measurement uncertainty

CONCLUSION AND FUTURE DEVELOPMENTS

In this work, a wireless instrumented AFO for monitoring the gait cycle is designed and developed. The system includes an inertial module, deformation sensors, and force sensors to monitor movement, orthosis deformation, and the detection of gait phases, respectively. The acquired signals are transmitted via Bluetooth communication to LabView software, which allows for data storage and real-time display. This research introduces an integrated instrumented AFO that combines force sensors, strain gauges, and an inertial module to monitor both gait cycle dynamics and orthosis deformation—a capability not addressed simultaneously in previous studies. Unlike existing systems that focus on isolated parameters, this AFO provides comprehensive real-time data transmission via low-power Bluetooth to a LabVIEW interface, ensuring immediate visualization and storage without cloud dependency. Additionally, a custom PCB and 3D-printed support enhance wearability and usability, making it a more practical solution for personalized rehabilitation compared to prior designs.

For future developments, miniaturization is important to improve patient comfort during data acquisition and to reduce measurement errors. Finally, for system validation, a 3D capture system will be used, and a sufficient number of patients will participate to allow for statistical analysis.

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