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Development of an Active Orthosis and Internet of Things (IoT) Application for Lower Extremity

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ABSTRACT

The Internet of Things (IoT) technology has increasingly gained prominence in the field of sports sciences, much like in various other domains, due to its potential to enhance performance, monitoring, and control capabilities. In the context of athlete rehabilitation, IoT presents significant advantages over traditional rehabilitation systems, offering superior capabilities in real-time data collection, feedback, and personalization. This study is organized into three distinct phases, with the primary goal of developing a next-generation active lower extremity rehabilitation system that leverages IoT technology to optimize the rehabilitation process. In the first phase, a design for an active-controlled orthosis for the lower extremity will be created. The control system for the orthosis will implement the admittance control method, which is a crucial technique for regulating the interaction between the user and the robotic system. In this approach, admittance, represented as A, will be adjusted with minimal or zero deviations to control the rapid rise or lifting effect of the device. By manipulating the admittance parameter, the desired force response during rehabilitation can be precisely achieved, ensuring that the patient's movements are well-supported throughout the treatment. This approach allows the system to adapt in real time to the forces applied by the user, enhancing both safety and effectiveness. The admittance control method addresses a critical gap in the current literature by enabling the fine-tuned control necessary for rehabilitation systems that involve active participation from patients. The second and third phases of the study will focus on expanding the orthosis system to integrate adaptability and real-time data transfer capabilities. Specifically, the system will be designed to transmit rehabilitation data to mobile applications, providing a seamless interface for both athletes and sports physicians. This feature allows the system to distinguish itself from other rehabilitation devices, as it can be personalized for individual athletes. Physicians will be able to monitor the recovery progress of multiple athletes remotely via a mobile device, thus enabling them to offer real-time feedback on the patient's use of the orthosis. This function will significantly enhance the efficiency of treatment by allowing physicians to make necessary adjustments to the rehabilitation protocol without requiring in-person interaction. In addition, the system will continuously record the pressure exerted by the patient on embedded sensors. If the applied pressure exceeds a predetermined threshold set by the physician, the system will immediately send notifications and trigger vibrations to alert the athlete. This feature ensures that the rehabilitation process continues safely and effectively, preventing overexertion or injury. Ultimately, the use of IoT technology in this system allows for the continuous, real-time monitoring

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of the athlete's progress, while the adaptive feedback loop ensures that the treatment process is dynamic and responsive to the patient’s needs. Consequently, this study presents a significant advancement in athlete rehabilitation, combining cutting-edge mechanical design with the transformative potential of IoT.

Keywords: Internet of things, home based rehabilitation, exoskeleton, lower extremity

1 Introduction

The primary concern addressed in this study is the absence of integration between existing orthoses designed for issues like the low foot syndrome and athlete rehabilitation through IoT. Consequently, the study aims to develop an active lower extremity orthosis specifically targeting ankle joint rehabilitation, potentially applicable in athlete injuries and rehabilitation robotics. The original concept underpinning this work involves controlling post-injury ankle movements via user prompts to achieve optimal recovery. Previous relevant studies, forming the theoretical framework, will be detailed in the subsequent section. Subsequently, the study will undertake application trials for a lower extremity orthosis using outputs from the initial phases, comprising:

• Development of Stimulus Algorithm for Active Orthosis: Experimental testing follows the development using a threshold value and piezoelectric sensor to support walking.

• Development of IoT-based E-health Application: Aimed at enabling both athletes and healthcare professionals to monitor rehabilitation via an Android-based application. Ensuring secure data flow through new-gen IoT technology is a key focus. Forces applied to the ankle joint can be tracked using this system.

• Usability Testing: Planned assessment of system usability by both athletes and healthcare professionals with the adaptation of a usability scale in Turkish for the mobile application. Subsequent testing will involve healthy users.

The central problem statement to be addressed within the scope of these objectives is 'Can a low-cost IoT-supported lower extremity orthosis be developed?' The subsequent sub-problems are enumerated as follows:

• How can a method be devised for the use of a stimulus-supported lower extremity orthosis assuming walking as a periodic movement?

• Is the use of IoT-based mobile applications for smart orthosis systems feasible for athletes and sports physicians (physiotherapists)?

• What factors influence the usability of the mobile application? What modifications are required based on usability outcomes?

• Is the use of Internet of Things (IoT) technology for data flow suitable for this wearable device? Are there any instances of this technology's usage in medical devices?

The first phase of the study focuses on active orthosis control, presenting a gap in the literature despite prior studies. This includes devising methods for utilizing active orthoses, deriving load and motion values for joint control post-injury. Additionally, an emphasis is placed on developing user-compatible models supporting volunteer effort, potentially through admittance control. The absence of advanced control applications for active orthoses is noted in the literature, primarily relying on simple open-close control or neural network-controlled orthoses, indicating the novelty and prospective direction of this study. The second phase of the thesis involves tele-rehabilitation development using IoT-based applications for home-based system usage. While literature exists on IoT in health systems, no instances of IoT-supported studies for athlete rehabilitation were found, marking this study as unique in filling a gap in the literature and pioneering an IoT-based lower extremity orthosis. The research assumptions include biomechanical modeling simplification, assuming user stability, and app usability. Limitations encompass the lack of user testing, constituting the primary constraint for behavior tests.

Within the literature, devices developed for rehabilitation and ankle treatments can be categorized based on degrees of freedom, control types, actuator types, exercise variations, measured parameters, sensor and mechanism structures. Various devices have been classified according to the parameters specified, showcasing their features and historical development concerning their place in the literature. While some facilitate straightforward exercises, others have been specialized through tailored control algorithms to respond to greater needs and elevate the standard of treatment. Developed robots can broadly be categorized into three main groups: passive mechanisms (which do not consume electrical energy), electrically powered passive devices, and intelligent robotic devices, as identified by Yıldırım [1].

Passive devices primarily aim to reduce spasticity. These devices typically cannot perform biomechanical measurements and are generally adjusted to the maximum allowable joint angle, held for a predetermined duration. Through exercises created in this manner, a reduction in spasticity is anticipated. However, for functional improvements, there is a need for specialized test algorithms in intelligent devices. The objective of such robots is not solely to reduce spasticity but also to increase muscle strength, enhance neuronal control, and measure biomechanical parameters. Intelligent devices are utilized not only for recovery but also for measurement, assessment, and diagnostic purposes [2]. Devices developed by researchers such as Neubauer et al. and Ren et al. have led to significant advancements in robotic rehabilitation of the ankle by employing intelligent control strategies and diverse rehabilitation methods [3]-[4].

Ayas et al. developed a parallel-platform ankle rehabilitation device in 2017, designed with 2 degrees of freedom. The system utilized fuzzy logic-based adaptive admittance control within its controller structure. The device operates with a DC electric motor as its actuator, capable of conducting active, passive, isotonic, and isometric exercise rehabilitations. However, it is physically cumbersome, heavy, and impractical for easy patient use in home-based rehabilitation due to its non-portability. The visual representation of the device developed by Ayas is shared in Figure 1 [5].

Figure 1: Device developed by Ayas [5]

Meijneke et al. have developed an exoskeleton named 'Achille' aimed at reducing the metabolic cost of human walking. Figure 2 illustrates the lower extremity treatment device related to Achille AFO. Upon examination, the Achille exoskeleton comprises a backpack and two active AFOs [6]. Each active AFO is powered by a series elastic actuator (SEA) consisting of a ball screw, an electric motor, and a leaf spring. Motor movement is tracked using an incremental encoder, while an absolute encoder is utilized for measuring ankle position angles.

Figure 2: Achille AFO [6]

During the development of active AFOs, various types of actuators have been employed to generate assisting torque. The most crucial criterion in actuator selection is to provide the necessary torque and support to the patient within the walking cycle. While delivering this support, the chosen actuator should also impose a weight and size that are tolerable for the patient and fall within acceptable dimensions, avoiding additional burden beyond the tolerable limits [6-8].

2 Materials and Methodology

Within this section, the systematic approach followed in the design of the developed therapeutic support orthosis is discussed. One of the most significant challenges in creating an original product in design and requirement determination is finding the most suitable path to the optimal solution.

2.1 Hardware Design

Within this section, the selected materials for the design of the developed lower extremity orthosis and their purposes of use will be discussed. Ultimately, the hardware of the designed system will be delineated. The developed lower extremity orthosis comprises six components: an orthosis, a programmable board, a Bluetooth communication module (4), a DC vibration motor (1), a piezoelectric pressure sensor (3), and a mobile application (6). Powering the design components of the orthosis was achieved through a DC power source, namely a battery, which guided the selection of design equipment. A design model capable of maintaining the foot and ankle joint in the correct position in the intended geometry for the patient undergoing treatment was realized.

This orthosis provides the desired environmental conditions for rehabilitation by maintaining the foot in the desired geometry during the treatment process. Materials used in the fabrication of the developed orthosis have been modelled to be composite, semi-flexible, or different material alloy types, ensuring strength without compromising human health or causing harm to the skin [9]. Flexibility has been imparted to the device through Velcro straps (5), enabling adaptation to anatomical structures of different individuals. The developed design utilized an Arduino Uno (2) microcontroller board for programming. The preference for this board was driven by its small dimensions in response to increasing demands for wearable technologies, its ability to operate on low voltage, and its capacity to provide low-power desired voltage outputs. The hardware components of the developed lower extremity orthosis assembled into a device are depicted in Figure 3. To facilitate comprehension of its physical components, they are represented as follows. The system structure and connections were assembled according to parameters defined for the user's specific criteria.

Figure 3: The Hardware Components of the Developed Orthosis

The piezoelectric sensor model has been used to grant the device functionality according to the parameters set during exercise stages, enabling the desired level of monitoring and progression. It features a surface area of approximately 35mm in diameter with positive (+) and negative (-) wiring connections. It possesses a voltage sensitivity of 5V/μƐ and can operate within temperatures ranging from approximately -20°C to +60°C. It is capable of producing values within the range of 0 to 1000.

2.2 Software Design

A mobile application with an APK extension has been developed for the control and monitoring of the designed orthosis. This application has been created to serve exercises to be performed in a home setting, a necessity heightened due to recent pandemic situations. Developed using the MIT App Inventor platform, this application offers different interfaces for use by both the patient and the doctor. Real-time data transmission has been enabled through the Internet of Things (IoT) [10]-[11]. Data generated based on parameters defined during patient exercises is transmitted to the cloud via IoT, and the application developed for the physiotherapist pulls this data [12]. Figure 4 displays the patient interface screen of the developed application.

Figure 4: Patient Screen Mobile Application Interface

The patient initially wears the orthosis on their foot and opens the application, entering personal information and establishing Bluetooth pairing between the device and the application. Starting the weight-bearing exercises while maintaining a standing position, the patient begins to exert pressure on the foot. The pressure generated at the heel during this exercise is measured by the sensor and transmitted to the Arduino board where the program is written. Analog sensor data received here is utilized to alert the user via vibration based on device operating conditions. Simultaneously, these real-time data during the exercise are sent to the application via the HC-05 Bluetooth module [13]. These transmitted data to the patient screen are then transferred in real-time to the cloud in the Firebase platform. The data sent to the cloud is instantly accessible to the doctor through the dedicated application. This process ensures that exercises conducted in a home setting are supervised and controlled by the doctor. Figure 5 illustrates the system's data flow.

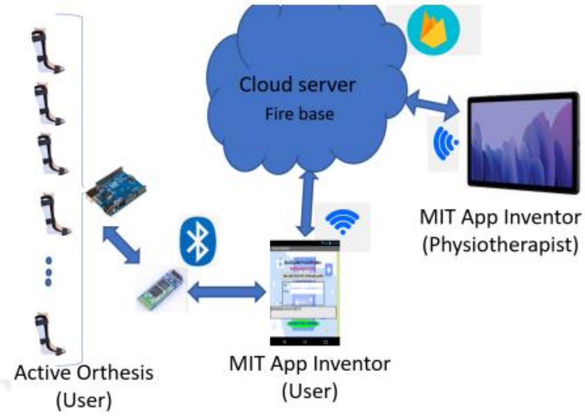

Figure 5: Data Flow Diagram

2.3 Manufacturing and Controller Design

A piezoelectric sensor is positioned in the insole area to gauge the pressure on the sole. The program board (Arduino Uno), DC power supply, Bluetooth module, and the actuator related to the design are positioned in the midfoot transition area. The device's straps allow for personalized adjustments of the orthosis. Its absence of articulated structures enhances both device and user safety. During exercises, the DC vibration motor delivers vibration alerts to the midfoot transition area, aiming for effective and efficient use. The physical dimensions of the components used in the structure of the developed orthosis are provided in the appendix [14]. Figure 6 displays the assembled device.

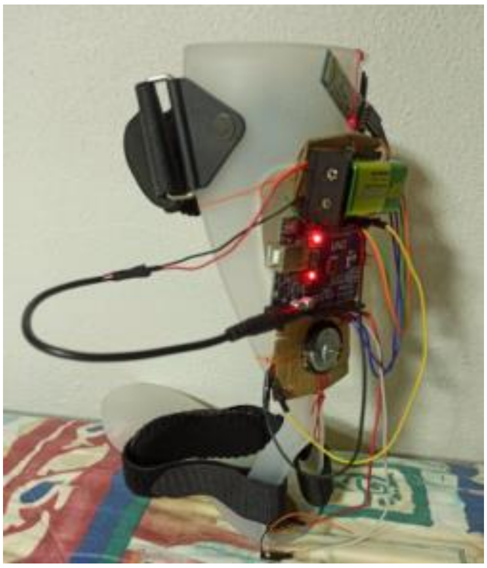

Figure 6: Assembled Foot Orthosis

In the scope of this implemented study, the system incorporates an admittance control structure for system control. The mechanical equation of this control structure, the inverse of impedance control, is demonstrated in Equation (1) [15]. X represents the rotation position of the motor, F represents the pressure force on the heel ankle, and A represents the admittance control value.

$$A = \frac{X}{F} \tag{1}$$

Here, X represents the motor's rotational position, while F denotes the pressure stress at the ankle heel region. The variation of motor position concerning the pressure stress at the heel is considered as the admittance error value.

The developed device depicts system measurement data in red, corresponding to the system outputs displayed in blue. The measurement range of the sensor used is 10 bits, which means it operates within the range of 0-1023 values, while the system output, the actuator's working range, is 8 bits, namely 0-255 values. The linearity of the system's response within these measurement and response ranges has been observed. Figure 7 illustrates the system's measurement and response responses.

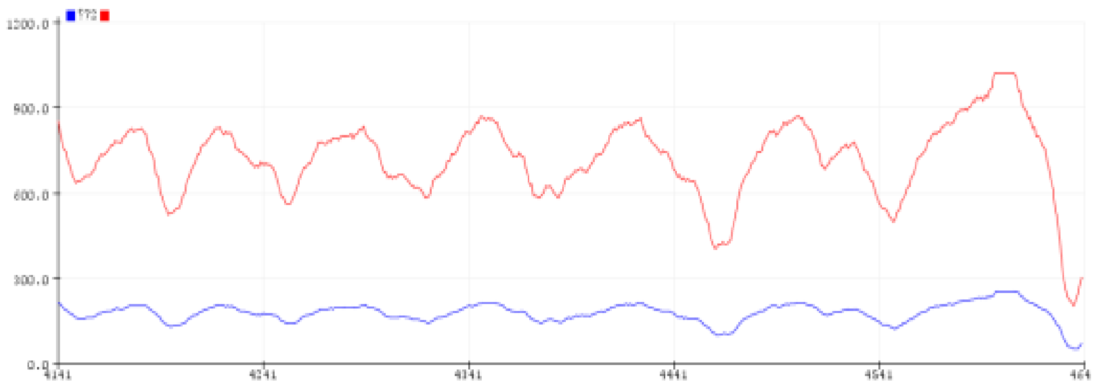

Figure 7: System Controller Output

During the walking step phase, the measurement values corresponding to the maximum output of the actuator's operating range are shown in Figure 8. Here, the system response reaching the desired range at the maximum level corresponds to the maximum pressure force generated in the ankle joint's heel area.

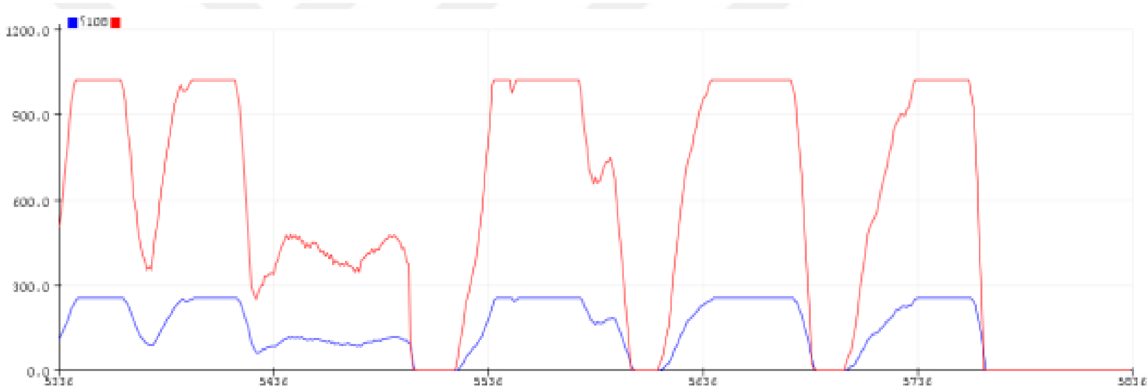

Figure 8: System Phase Response During Walking

3 Results and Discussion

The final structure of the orthosis was designed with minimal connections and using materials that don't pose a threat to human health. Care was taken to ensure the chosen materials were easily accessible and not specialized or custom-made, resulting in a low-cost device. Hardware elements selected for the device were those that wouldn't disrupt communication networks and had minimal magnetic and disruptive effects on the selected electronic components. Consequently, this conceptual study demonstrates the feasibility of developing a wearable, lightweight, cost-effective device capable of meeting rehabilitation exercise needs in a home environment. This device allows both active and passive exercises, ensuring an anatomically correct posture without causing harm to any nerve or muscle structures. It can be used in the treatment of individuals with weakened nerve and muscle cells, aiding in the recovery of lost functions and in athlete rehabilitation.

In this realized orthosis model, standard and commonly available hardware equipment have been preferred. This offers a significant advantage in terms of the device's production and procurement. The adjustable Velcro straps on the device provide flexibility, enabling usage for individuals with different anatomical structures. The absence of any hinged connection on the device ensures both the device's security and the patient's safety in unexpected circumstances. Upon examining similar devices and applications developed so far, this device stands out for its user-friendly, easily accessible, portable, and wearable features, providing significant advantages for home rehabilitation. A low-cost piezoelectric sensor has been used to measure pressure on the ankle heel region. For the control output of the device, a DC actuator has been chosen due to its low cost and capacity to perform at the desired level. Its low cost and compact size contribute to reducing the device's overall cost and ensuring portability. However, when considering the device's drawbacks, despite its suitability for the specified concept, a more robust orthosis structure, a stronger stimulating actuator, and a more sensitive sensor with a wider measurement range for force measurement need to be selected to make it more suitable for patient use. By establishing these criteria and obtaining experimental data, it appears feasible to create a more functional device within this concept. To further enhance its rehabilitation capabilities, additions based on specific needs can be made to the device. For instance, a hinged connection can be added to the joint for ankle plantar flexion and dorsiflexion movements, providing different stimuli.

The mobile application developed for device control and activation is user-friendly and compatible with smartphones, an integral part of the modern age. The interfaces created have been designed to be understandable by the general public. The application accommodates both patient dashboard panels and physiotherapist panels. Modifications can be made to the application based on specific needs, and different operating parameters can be added.

4 Conclusions

The realized device's data flow benefits from the Internet of Things (IoT) technology, which has become increasingly popular and utilized in various fields recently. Leveraging the IoT technology, a cloud network developed on the Firebase platform ensures real-time and rapid data flow. Sustainable and wearable kits have been preserved by choosing cheaper hardware equipment that can perform similar functions, which is one of the most significant parameters in the device's manufacturing cost.

5 Declarations

5.1 Competing Interests

There is no conflict of interest in this study.

5.2 Authors' Contributions

Emre YILMAZ: Developing ideas or hypotheses for the research and/or article, planning the materials and methods to reach the results, taking responsibility for the experiments.

Mert Süleyman DEMİRSOY: Organizing and reporting the data, taking responsibility for the explanation and presentation of the results.

Muhammed Salih SARIKAYA: Taking responsibility for the creation of the main part.

Mustafa Çağrı KUTLU: Taking responsibility for the literature review during the research.

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