September 2024, Vol:2, Issue:2

International Journal of New Findings in Engineering, Science and Technology

Journal homepage: *https://ijonfest.gedik.edu.tr/*

Mechatronics System Design and Implementation of a Pneumatic Hand Rehabilitation Device

Emre Tuğberk Gülnergiz[a*]

[a]*Department of Mechatronics Engineering, Istanbul Gedik University, Turkey e-mail:tugberk.gulnergiz@gedik.edu.tr*
*(*Corresponding Author)*

Abstract

This study presents the development of a mechatronic device for an additively manufactured Pneumatic Artificial Muscle (PAM) rehabilitation orthosis. Within this scope, the system's electro-pneumatic, mechanical, control, and software designs have been designed and implemented. The device, intended to directly interact with both patients and therapists within the bio-mechatronic process, is equipped with an intuitive graphical user interface (GUI). Utilizing a FlexSensor to measure hand flexion/extension angles, the device employs a solenoid valve, along with a trigger relay, for the inflation and deflation of the orthosis. During the electronic design phase, challenges such as interference and latency were mitigated through the implementation of isolations in the design. Employing a PD (Proportion-Derivative) control loop on the ATmega328 microcontroller, control parameters were determined empirically. By excluding a compressor pump inside the device, a lightweight, portable, and cost-effective system was accomplished. While potential enhancements discussed in the conclusion will be considered in future studies, the current prototype effectively fulfills the project objectives.

Keywords: Pneumatic Artificial Muscle; Hand Rehabilitation; Mechatronic System Integration

1. INTRODUCTION

When reviews in the field of robotic hand rehabilitation are examined, it is observed that a large portion of the studies involve the application of similar methods in different forms. Particularly, several complex methods have been adopted, especially in terms of power transmission and actuation techniques. The advantages and disadvantages of these methods in relation to each other and traditional physical therapy techniques have been extensively studied and presented in various works as shown in **Figure 1**.

https://doi.org/10.61150/ijonfest.2024020205

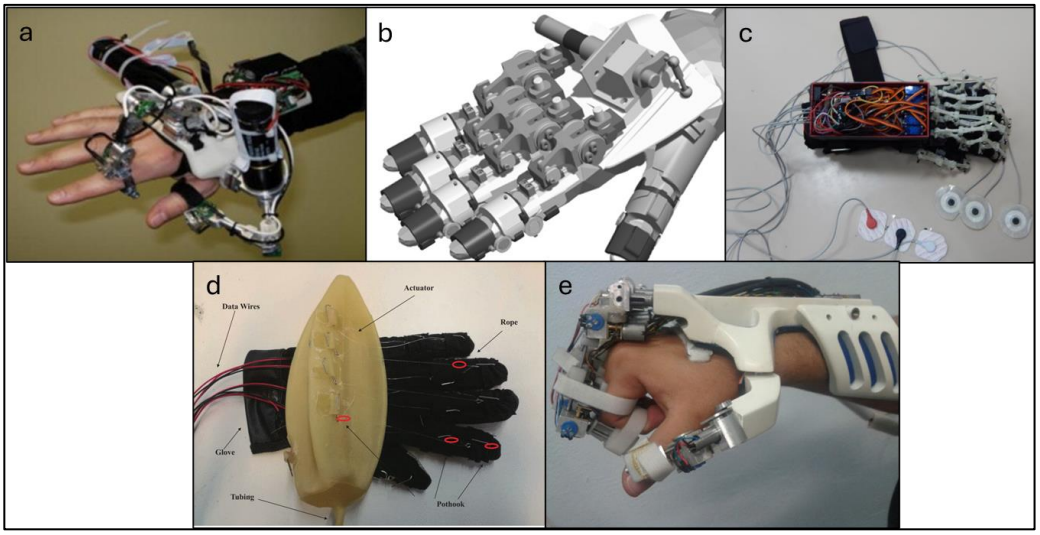

Figure 1. Some Examples of Mechatronics Hand Rehabilitation Devices [1-5].

When studies on hand/finger extension are examined, it is evident that the products are largely unidirectional, lacking active exercise (type of exercise involving the patient's active movements), and feature complex designs. Therefore, based on expert advice and research findings, it has been concluded that the robotic hand rehabilitation orthosis to be developed should include the following elements: the capability for passive hand/finger extension and active hand/finger flexion exercises; a simple, user-friendly design that appeals to a wide range of users and provides tactile sensory input (skin sensation); and a low-cost manufacturing technology that can be customized as needed.

In this context, instead of traditional McKibben artificial muscles, PAM via additive manufacturing was considered. In addition to all the advantages offered by McKibben artificial muscles, flexible and custom designs for different purposes [6,7] could be rapidly and affordably produced.

As seen in the **Hata! Başvuru kaynağı bulunamadı.**, design preferences were made among designs with different geometric parameters through preliminary design and computer-aided modeling phases conducted considering biomechanical requirements, along with finite element analyses and the details have been previously published [8-10]

This paper focuses on the development of the mechatronic system, which integrates the previously designed orthosis with the necessary electronic and control components to create a functional rehabilitation device. The following sections will detail the methodology used in the development of this system, including system integration, and control mechanisms.

2. METHODOLOGY

As seen in the methodological flowchart presented in **Hata! Başvuru kaynağı bulunamadı.**, an additive manufacturing methodology was adopted to produce the preferred design according to the desired specifications as shown in **Figure** 3**Hata! Başvuru kaynağı bulunamadı.**. **Hata! Başvuru kaynağı bulunamadı.** Following the design and manufacturing phases, a complete mechatronic system integration was carried out to work in conjunction with the orthosis, thus preparing the ground for its analysis and rehabilitation studies.

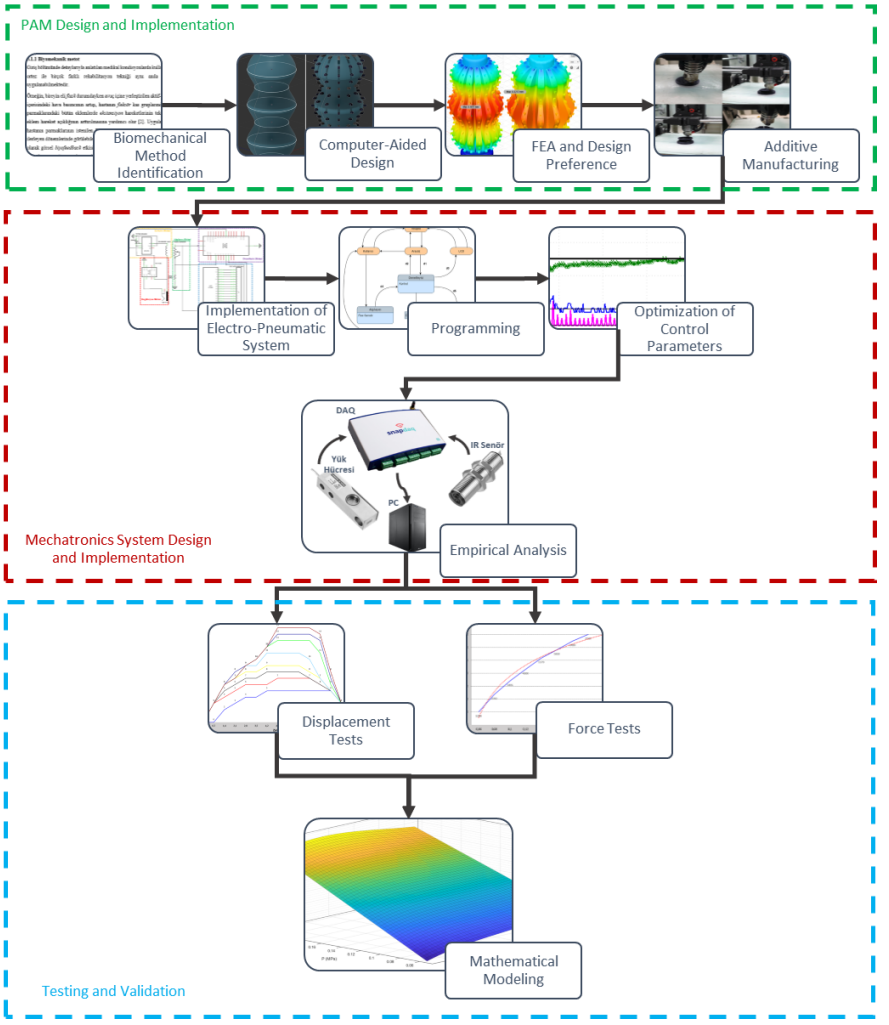

Figure 2. Methodological Flowchart.

The software carrying the system's operating algorithm was integrated into the system with a user interface, and the parameters of the preferred controller type were determined using this system through empirical methods. After the completion of system integration, parallel experimental analyses were conducted alongside finite element analyses, the details of which have been published previously [8-10], and a mathematical model was established based on these analyses.

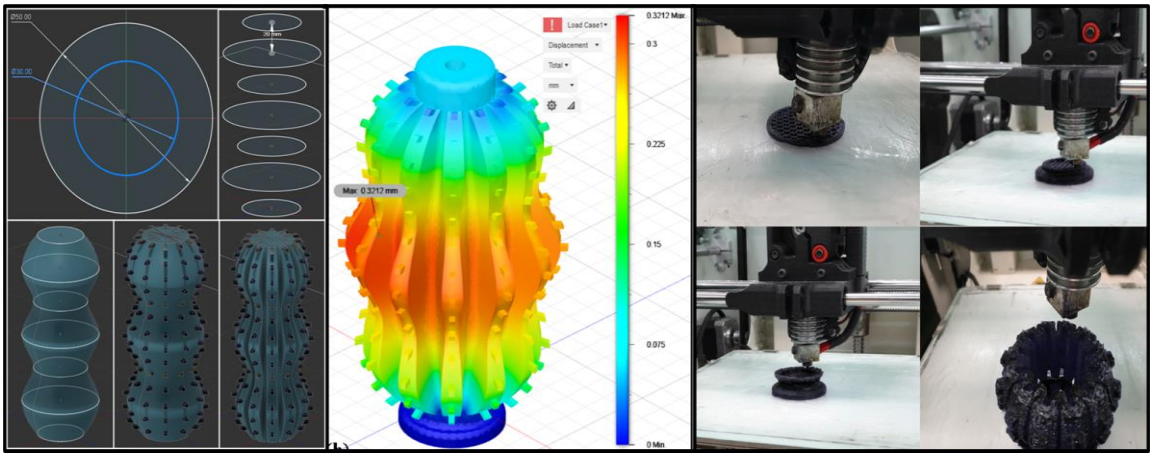

Figure 3. The Design, Analysis, and Production Phases of The Orthosis [8-10].

The implementation process of the bio-mechatronic system was generally divided into 5 sections: actuator unit, I/O unit sensor unit, control unit, therapist, and patient. The Data Flow Diagram (DFD) and the bio-mechatronic sub-systems are presented in Figure 4. In the Input/Output unit, an LCD screen is used as an output, while the Graphic User Interface (GUI) is used as an input and output tool. These input/output tools will facilitate the control of the rehabilitation device for the therapist. The actuator unit includes components such as the trigger relay, solenoid valve, and pneumatic orthosis necessary for the device to perform mechanical work. In the system's sensing unit, a flex sensor is included to analogically measure hand extension and flexion amounts. The control of all units and the data processing are carried out on the Atmega328 central controller.

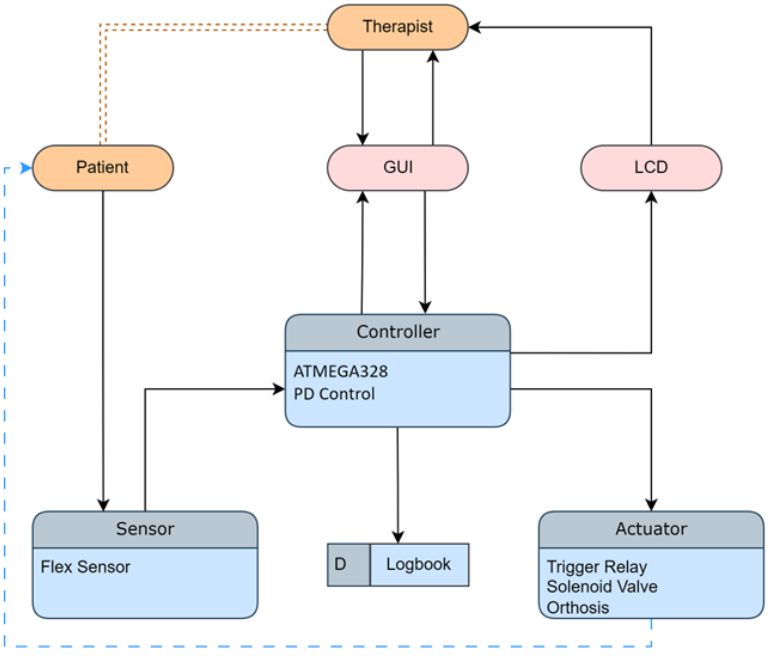

Figure 4. DFD of the Bio-Mechatronic System.

2.1 Electronic Design

The main sensing element used in the closed-loop control of the rehabilitation device is a flex sensor. The 4.5" long sensor is long enough to measure the cylindrical grasping movement of a normal human hand and can operate without the need for an additional amplifier circuit, using only an input resistor. The flex sensor in the system's sensing unit measures hand aperture in real-time and sends it to the controller. The controller then processes the data according to the control algorithm and sends relevant triggers and/or information to the actuator and the I/O units. Although a relatively simple power/control mechanism would suffice to meet the requirements described in the introduction section, the structure of the control algorithm, as discussed in the next section, has brought along some physical application challenges. To overcome these challenges, a few additions have been made to the electronic design. As seen in Figure 5, while all components in the circuit operate with direct current, a voltage regulation unit has been added to the circuit due to the voltage differences between the components. However, as also shown in the same figure, the MP1584 integrated voltage regulator in the circuit is used not for supplying all components operating at 5V but only for powering the triggering relay.

Although the 1.8-amp output current of the MP1584 voltage regulator would be sufficient to power all 5V components in the circuit, this approach has been taken as the relay and solenoid valve are inductive elements. The rapid switching of inductive elements in the circuit leads to the generation of reverse EMF (electromotive force), interference on the electronic circuit, and high voltages due to induction currents.

These parasitic effects and fluctuations on the load negatively affect various parts of the system, including the USB interface used for communication with the central processor and the LCD screen controller communicated via the I2C protocol. For these reasons, only the inductive elements have been powered by the MP1584 (Figure 5), and additionally, the trigger relay has been opto-isolated , and the I2C controller has been protected with a flyback diode and decoupling capacitor. The ATmega328 has been chosen as the main controller of the system due to its 16MHz clock speed and 32 KB ISP flash memory [11].

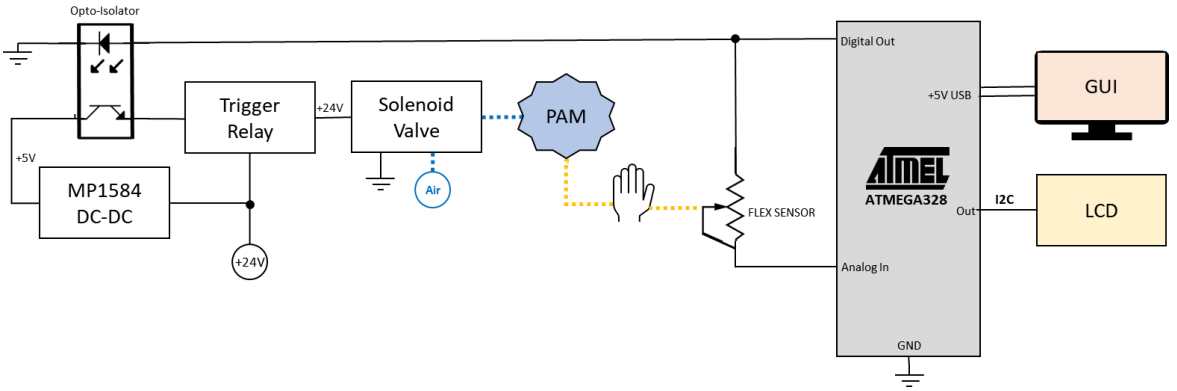

Figure 5. Electronic Circuit Diagram.

2.2 Control

Although the relay and solenoid valve used to activate the orthosis are digital components, the flex sensor used as the main sensor in the system provides analog outputs according to the degree of bending. In similar cases, the widely preferred PD control technique has also been chosen in this study as shown in Figure 6.

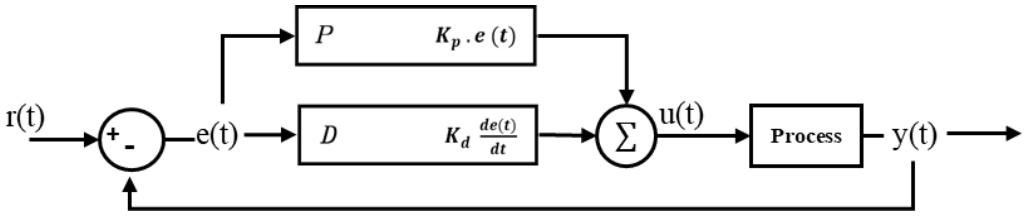

Figure 6. Control Diagram.

For the determination of the K_p, and K_d coefficients of the controller, empirical methods used in the literature [12-15] were reviewed concerning Rise Time, Overshoot, Settling Time, and Steady State Error. In this context, the coefficients presented in the study by Heidari et al. [16] were initially considered as the starting point for coefficient determination. Later, the final values of the coefficients were determined through experimental methods as shown in Figure 7.

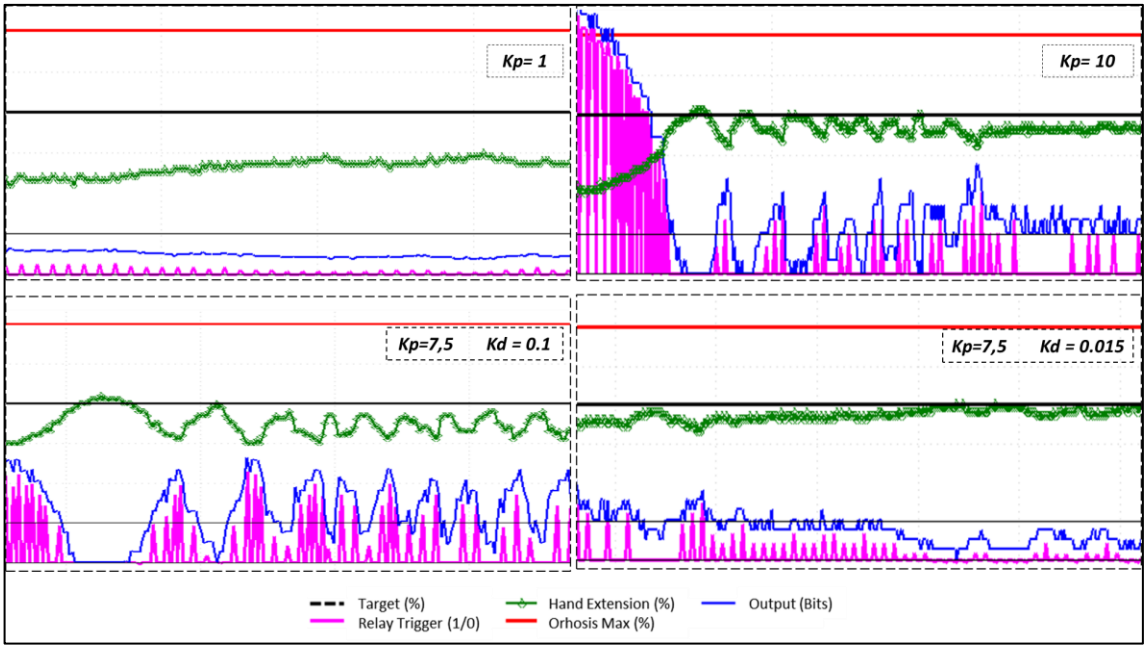

Figure 7. Controller Tuning.

2.3 User Interface

The graphic user interface (GUI) of the system, consisting of 4 main sections, is presented in Figure 8. In the Calibration section, the therapist must "reset" the system before starting the session. After the patient has put on the orthosis in its deflated state, pressing the "Calibrate" button will save the current angle value read by the sensor as the base angle value for the controller. This allows the system to record the patient's joint degree in flexion enabling to work based on this reference. Then, the therapist will select the size of the orthosis worn by the patient as the pneumatic orthosis can be manufactured in different diameters and parameters for various patient groups (young, elderly etc.). This selection will be saved and the predefined maximum expansion angle parameter for the selected orthosis will be used as a limit during the process.

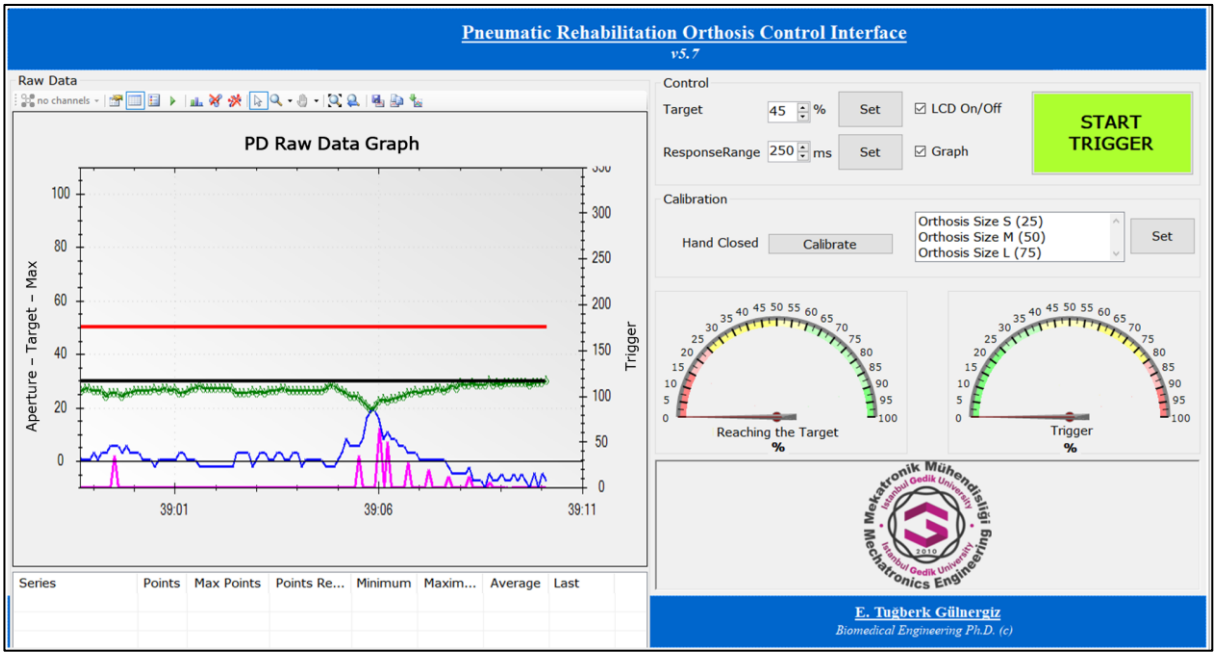

Figure 8. Graphical User Interface (GUI).

In the Control section, the therapist can adjust the “Target” and “Response Range” values. Additionally, he or she can control the LCD screen, view the raw data graph, and start or stop triggering. The Response Range parameter is crucial for the controller and generally determines the response sensitivity of the device. If it is determined that the output from the control loop is greater than the previously set "Response Range," the relay is triggered.

This range, which directly affects the system's behavior, has a default starting value but can be easily and instantly adjusted by the therapist. The "Target" value represents the percentage of hand aperture that the therapist aims to achieve during that therapy session. This percentage is calculated using the base value set in the calibration section and the limit value that can be reached by the selected orthosis size. For example, the hand being as closed as it was in the initial state represents 0%, while the hand being fully extended to the maximum angle the orthosis can inflate represents 100%.

Additionally, the "Start/Stop Triggering" button under the same group allows the therapist to perform system adjustments/calibrations without triggering any pneumatic actuation during therapy sessions and shut down the system when the session is complete. The user interface provides two dial gauges to the therapist, displaying the triggering amount and the percentage of reaching the target. Additionally, since this system is a prototype, there is a graph screen in the interface where all raw data is shown and logged into the logbook.

3. RESULTS AND DISCUSSION

The completed rehabilitation device is presented in Figure 9. As this system is a prototype, further optimization steps are needed for commercialization or mass production.

The device, excluding the orthosis, has a total weight of approximately 500 grams and has been produced in a compact and portable form. A computer is required for the operation of the device. While some summary data can

be accessed directly through the LCD screen during the system's operation (Figure 10), the device does not have any input method for adjustments, making it impossible to operate independently from a computer. In future studies, the LCD screen on the device will be replaced with a TFT LCD Touch Screen, allowing the device to function as a standalone system for basic rehabilitation and exercises.

Figure 9. The Final Prototype

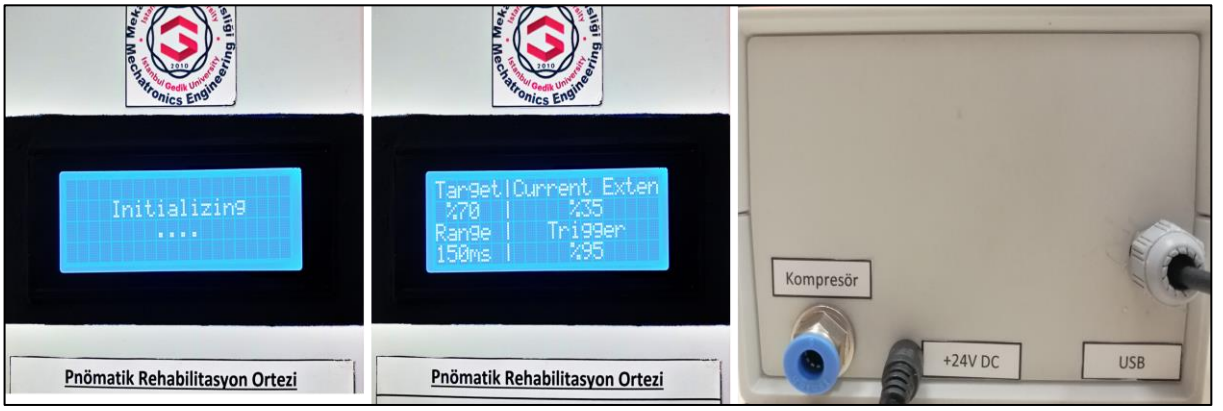

Figure 10. LCD Screen and Connections

Similarly, the device's electrical and compressed air supplies are expected to be provided from external sources as shown in Figure 10. Although the maximum operating pressure of PAM orthoses produced by additive manufacturing is 0.2 MPa, due to the size and weight of compressors that can meet this requirement, they have not been included in the system. In future studies, it is possible to produce a version of the device with a built-in compressor motor.

As shown in Figure 11, the device tests have been successfully completed with different orthoses. The approximate total hardware cost of the prototype, which is around $100, makes this device quite accessible for patients, therapists, and institutions. Thanks to its simple design, patients can acquire this device to perform daily hand exercises without therapist supervision if they choose to do so.

Figure 11. Testing of the Prototype

The integrated logbook in the system has been prepared to provide meaningful data to both patients and therapists. These data will be beneficial for tracking the progress of patients during the therapy process. Additionally, for potential commercialization and mass production, adding retrospective data analysis and patient tracking features to the software would be advantageous.

The control parameters of the system have been determined through experimental methods. Although the current performance of the controller in reaching the target is deemed sufficient, future studies plan to adopt a more systematic approach to extract the parametric model of the system.

4. CONCLUSION

In this study, a mechatronic device has been developed for an additively manufactured PAM rehabilitation orthosis. The device, which will interact directly with the patient and therapist in the bio-mechatronic process, has been integrated with an easy-to-use GUI. The device uses a flex sensor to measure the flexion/extension angles of the hand, and a solenoid valve, in series with a trigger relay, is used for inflating and deflating the orthosis. During the electronic design of the device, issues such as interference and latency were addressed by adding isolations to the design. The device applies a PD control loop on the ATmega328 microcontroller, and the control parameters were determined using an empirical method. Although the improvements mentioned in the discussion section will be included in future studies, the prototype currently meets the project objectives.

Acknowledgements

This study was conducted as part of a master's thesis under the supervision of Assoc. Prof. Dr. Savaş Dilibal. Previous publications related to the thesis are presented in the bibliography.

Funding

There is no financial interest in this study.

Declaration of Competing Interest

There is no conflict of interest in this study.

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