Turkish Journal of Engineering

https://dergipark.org.tr/en/pub/tuje

e-ISSN 2587-1366

Development of elbow rehabilitation device with iterative learning control and internet of things

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Cite this study: Demirsoy, M. S., Hamida El Naser, Y., Sarıkaya, M. S., Peker, N. Y., & Kutlu, M. (2024). Development of elbow rehabilitation device with iterative learning control and internet of things. Turkish Journal of Engineering, 8 (2), 370-379

https://doi.org/10.31127/tuje.1409728

Keywords
Iterative learning control
Internet of things
Exoskeleton
Home-based rehabilitation

Research Article

Received: 25.12.2023
Revised: 28.01.2024
Accepted: 29.01.2024
Published: 17.04.2024

Abstract

In this study, we present a novel approach for rehabilitation devices through the design of an active elbow joint orthosis, inspired by the fundamental principles of robotic exoskeletons. The device not only enables home-based usage but also facilitates the transmission of exercise data from patients to physiotherapists via the Internet of Things (IoT) device. This approach offers the possibility of increased therapy sessions for each patient while allowing physiotherapists access to data for real-time or subsequent analyses, thereby establishing a database. This permits a single physiotherapist to manage multiple patients more effectively. The developed mobile application within this research incorporates a distinct entry interface for both patients and physiotherapists. Maximum force and position values generated during each exercise period are displayed within the application. The device enables active exercise with a single degree of freedom at the elbow joint and is equipped with force sensors to ensure safety against potential high-shear forces. Furthermore, it can be worn on the upper extremity using adjustable Velcro straps to accommodate users with varying arm circumferences. Specifically, this system amalgamates two primary components: a microcontroller operating control algorithms and IoT technology, and a smartphone application containing interfaces for physiotherapists and users undergoing therapy. The control design of the device employs a P-Type Iterative Learning Control (ILC) due to periodic exercise movements, reducing the error norm by approximately 20% during each exercise period (excluding the initial period). The controller consistently diminishes error values with each iteration, ultimately converging to zero. Throughout an exercise lasting around 3 minutes, the average error norm is recorded as 0.229^0. In essence, this study presents a pioneering approach that sets itself apart from other research by minimizing shear forces and errors through a specialized controller, all while enabling remote, home-based rehabilitation under expert supervision.

1. Introduction

Stroke is a prevalent health issue among adults in Turkey. The annual number of stroke-related deaths in the country is estimated between 35,000 to 40,000 [1]. The functionality of upper extremity joints holds significant importance, especially in fulfilling basic needs like eating, bathing, among others. Functional losses post-stroke, particularly those affecting the upper extremities, significantly impact individuals' abilities to carry out daily life activities and meet essential needs [2]. However, the rehabilitation process is laborious and costly. Despite the proven effectiveness of stroke rehabilitation when administered early, it's known that not all patients receive the necessary treatment during this period. The increasing number of cases exacerbates the challenge of meeting rehabilitation needs. Intensive sessions and targeted home-based rehabilitation are essential steps aimed at enhancing effectiveness.

Rehabilitation robots enable therapists to treat multiple patients simultaneously, reducing their workload and potentially lowering treatment costs. Furthermore, these robots possess additional functions like recording and analyzing patient performance data. Monitoring this data aims to alleviate hospital congestion and promote home-based rehabilitation. However, factors such as the high cost and lack of mobility in rehabilitation robots need consideration.

Exoskeleton robots, designed for both lower and upper extremities, can be categorized as therapeutic or assistive motion systems [3]. The effectiveness and usability of home-based exoskeleton robots hold significant importance in terms of performance. Certain criteria need to be considered to achieve optimal performance with these robots:

• Home-based exoskeleton robots should not only be structurally but also functionally ergonomic, enabling users to comfortably perform daily activities [4].

• These robots should have a stable control mechanism.

• The number of actuators and sensors should be adequate to enhance mobility effectively.

• Cost-effectiveness is essential for home-based exoskeleton robots.

• The energy requirement of the robot intended for home use should be sufficient and rechargeable when necessary [5].

The system developed in this study supports upper extremity rehabilitation using innovations in IoT technology, sensing devices, control algorithms, and mobile applications. Specifically, this system integrates two fundamental components. Firstly, a microcontroller card operating control algorithms and IoT technology, and secondly, a mobile phone application containing user interfaces for physiotherapists and patients. This study focuses specifically on the device called "MentArm", denoted as a home-based elbow joint rehabilitation kit. This research will demonstrate that the use of an active elbow joint orthosis provides more effective home-based rehabilitation compared to traditional methods. Thanks to this system, patients' therapy sessions will increase, a database will be created that provides access to data in real-time or for subsequent analysis, and will allow a physiotherapist to manage multiple patients more effectively. How does this system, which combines a microcontroller board with control algorithms and IoT technology and a smartphone application, affect the therapy processes of patients and physiotherapists?

Various robotic exoskeleton systems used in upper extremity rehabilitation have been examined based on information obtained from multiple studies. The functionality of these rehabilitation robots in the literature tends to be limited concerning upper extremity mobility. However, the shoulder exoskeleton plays a significant role in the stabilization of the upper limb in existing robots. Ball et al. developed an adjustable exoskeleton robot named MEDARM to assist therapists [6]. This mechanism utilizes an electric motor as an actuator to facilitate planar shoulder-elbow movements and transmits motion through a combination of cables and belts. This design provides the robot with an advantage against the factor of gravity, optimizing the power-to-weight ratio. The device named MEDARM, capable of independently controlling five degrees of freedom, also offers a notable advantage in adapting to different limb sizes [6].

The electromechanical elbow rehabilitation robot developed by Vanderniepen focuses on executing specific joint movements and preventing excessive force. It requires personalized braces to accommodate the unique characteristics of each patient's extremity [7]. This device features a smaller spring in its actuation mechanism compared to other similar systems, making it more suitable for anterior loads. Moreover, the device boasts a prominent actuation system in terms of rapid accessibility and adjustability as shown in Figure 1 [7].

Figure 1. Vanderniepen home-based exoskeleton device [7].

ULERD stands out in home-based rehabilitation due to its lightweight and portable design. Specifically designed to support elbow joint movements, it employs two degrees of freedom with passive rotational potentiometer sensors. The device is optimized in terms of mass and power balance, using an aluminum frame and brushless DC motors [8].

Ripel et al. [9] developed an active elbow orthosis inspired by the principles of robotic exoskeletons. This orthosis determines the patient's movement activity using a force sensor and transmits this data to an actuator to control the device.

Zhang et al. [10] NEEM device is a reinforced elbow exoskeleton system designed to provide maximum comfort and safety. Featuring dual linkage, it offers an enhanced robot-human interaction zone, optimizing interaction comfort through its compact structure.

Recent studies have focused on developing elbow rehabilitation devices for home use, aiming to facilitate effective rehabilitation outside traditional clinical settings. Ceccarelli et al. [11] introduced L-CADEL v2, a specific therapeutic device designed for elbow movement, highlighting advancements in devices tailored for elbow rehabilitation. Wu et al. [12] developed a device beneficial for individuals with mild to moderate elbow joint symptoms, emphasizing a home-use elbow rehabilitation system that integrates a smartphone and cloud database to potentially execute elbow joint rehabilitation programs at home. Additionally, Said et al. [13] introduced a smart elbow brace aiming to reduce rehabilitation costs outside hospitals, alleviate therapist workload, and encourage patient adherence to programs.

Erin et al. [14] have devised an Android application grounded in the IoT to facilitate real-time operations. This application transmits accelerometer data to the cloud environment. Through software crafted in the Python environment, real-time data is fetched from the cloud, initiating a classification process that effectively identifies individuals' movements. Delays encountered during the research process have been pinpointed, and the classification process has been observed to function seamlessly.

Studies in the literature often do not completely focus on devices exclusively designed for home use but predominantly tailor them for clinical environments. Factors such as high cost and the requirement for domestic electrical power can limit the usability of these devices at home. Limitations like the lack of remote expert control further restrict their use in home settings. The MentArm device stands out as a home exercise device with stability in its control mechanism. Its capability to enable exercise under remote expert control, its low cost, compatibility with home energy requirements, and its iterative learning-based controller all contribute to its usability at home, filling the gap observed in the literature.

2. Material and method

In the design process, the concept of function can be defined as the relationship between the inputs and outputs of the intended system to be designed. In a large and complex design problem, breaking down the entire function into sub-functions simplifies the process of finding a solution. The detailed flowchart of the MentArm device is illustrated in Figure 2.

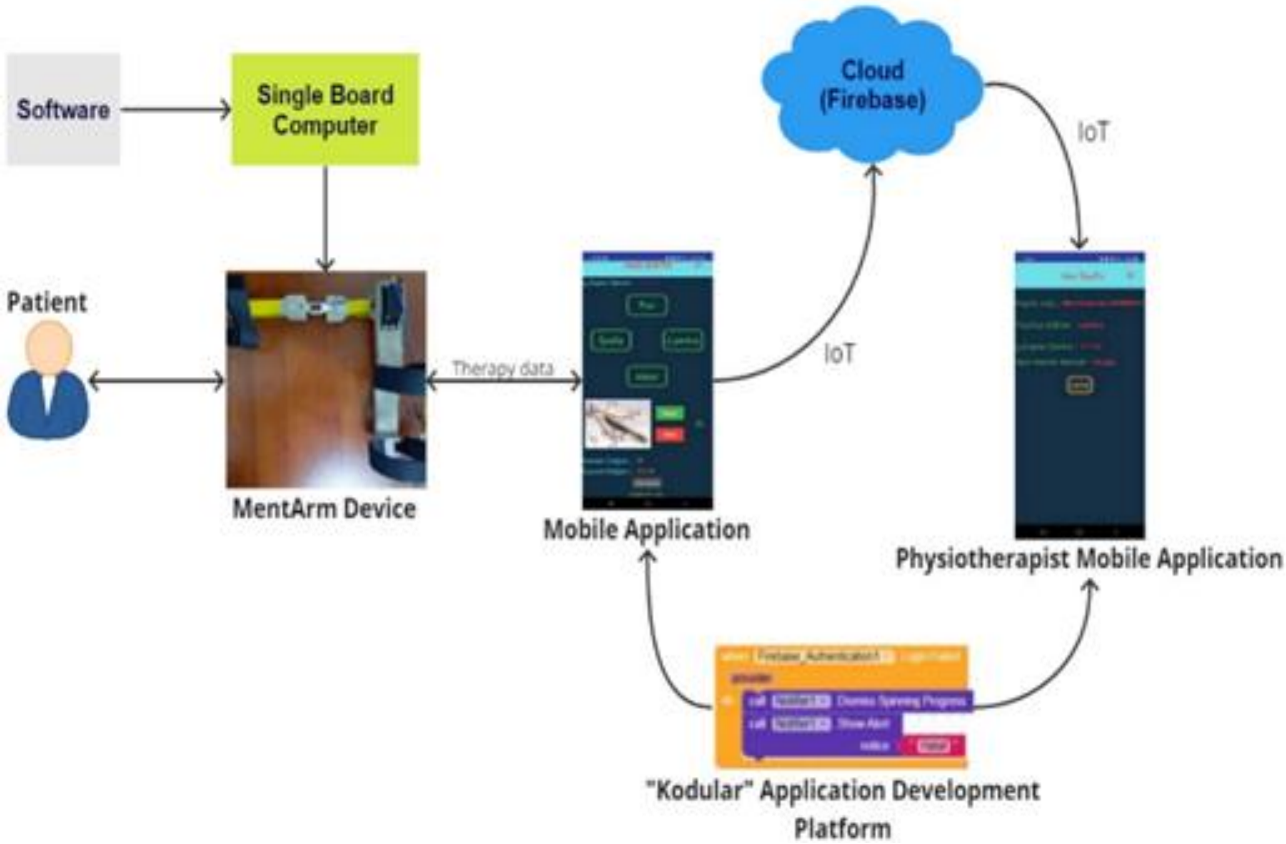


Figure 2. Flowchart of the MentArm device.

2.1. Functional structure and mechanical design

The full functionality of the elbow rehabilitation device is illustrated in Figure 3, according to the design criteria. The system boundary is delineated by axis lines in the diagram. Energy input into the system is denoted as E, while the outgoing energy from the system is represented as E’. The designed rehabilitation device operates through a combination of electrical energy and muscle power. As the device is suitable for both active and passive rehabilitation, muscle power can be considered part of the energy input. The electrical energy supplied to the actuator in the elbow region is transformed into mechanical energy, resulting in frictional losses during this conversion process. Additionally, users may support the device using their own muscle power, which could lead to muscular fatigue during exercises. The entry of patients into the system is denoted as H, while the output of rehabilitated individuals is indicated as H'. The system's operation is governed by the input from the control unit, designated as K, while the actuator output and movement of the system are symbolized as K'.

The functionality defining the elbow rehabilitation device developed within the scope of this study explicates the system's intricacies through detailed sub-functions. In this context, the device's sub-functions encompass attaching the device to the arm, executing elbow exercises, adjusting device operating parameters via the mobile application, and establishing communication between the mobile application and the device. Figure 4 visually illustrates these specified sub-functions.

The ease of wearing the device is a fundamental requirement, achieved through the use of Velcro straps, facilitating effortless application. This approach enables individuals with diverse conditions or arm issues to easily don the device. Accordingly, different sizes (small, medium, large, etc.) for the upper and forearm parts of the device can be produced to suit various body measurements. Additionally, a custom-sized device can be designed based on specific measurements taken from the individual's arm, enabling its production through three-dimensional (3D) printing. The connections for the upper and forearm should be adjustable or produced in different sizes. Moreover, it necessitates a microcontroller for adjusting and monitoring exercise tasks. Furthermore, a dedicated mobile application needs to be developed to visualize the acquired data and establish an Internet of Things (IoT) connection to transmit data to the physiotherapist.

The mechanical design ensures the prevention of excessive force effects and adaptability to different users. In Figure 5, the mechanical design of the device (a) and its manufactured form (b) are depicted. This design mitigates the risk of arm injury to the user and includes a force sensor for safety purposes, thus alleviating some constraints in actuator selection. Moreover, it diverges from conventional designs by not integrating a spring element found in previous studies. This design allows users to engage solely in active rehabilitation, ensuring secure flexion and extension movements at the elbow-arm joint.

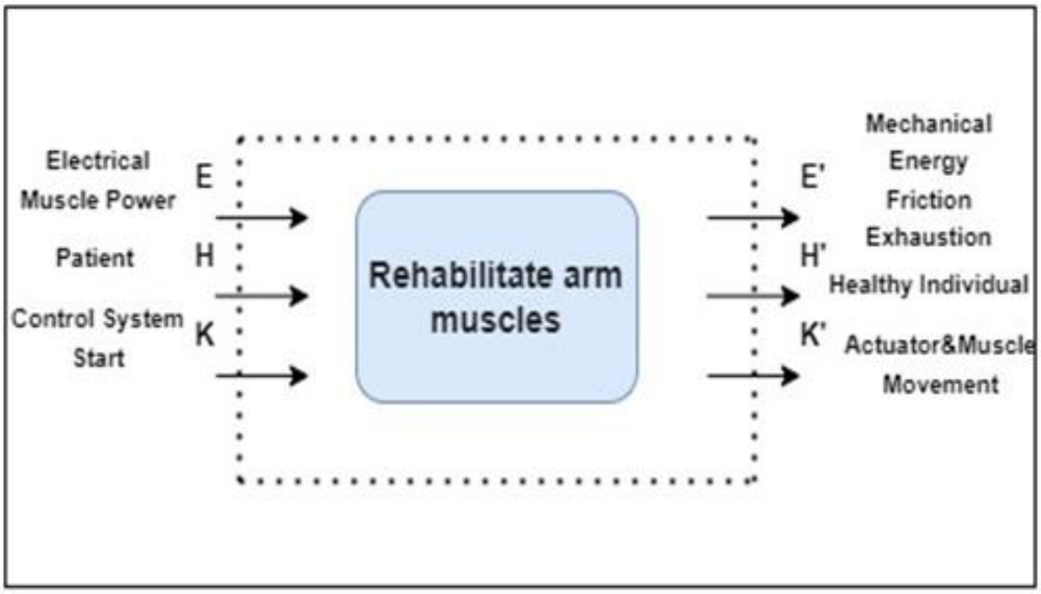


Figure 3. The entire function of MentArm.

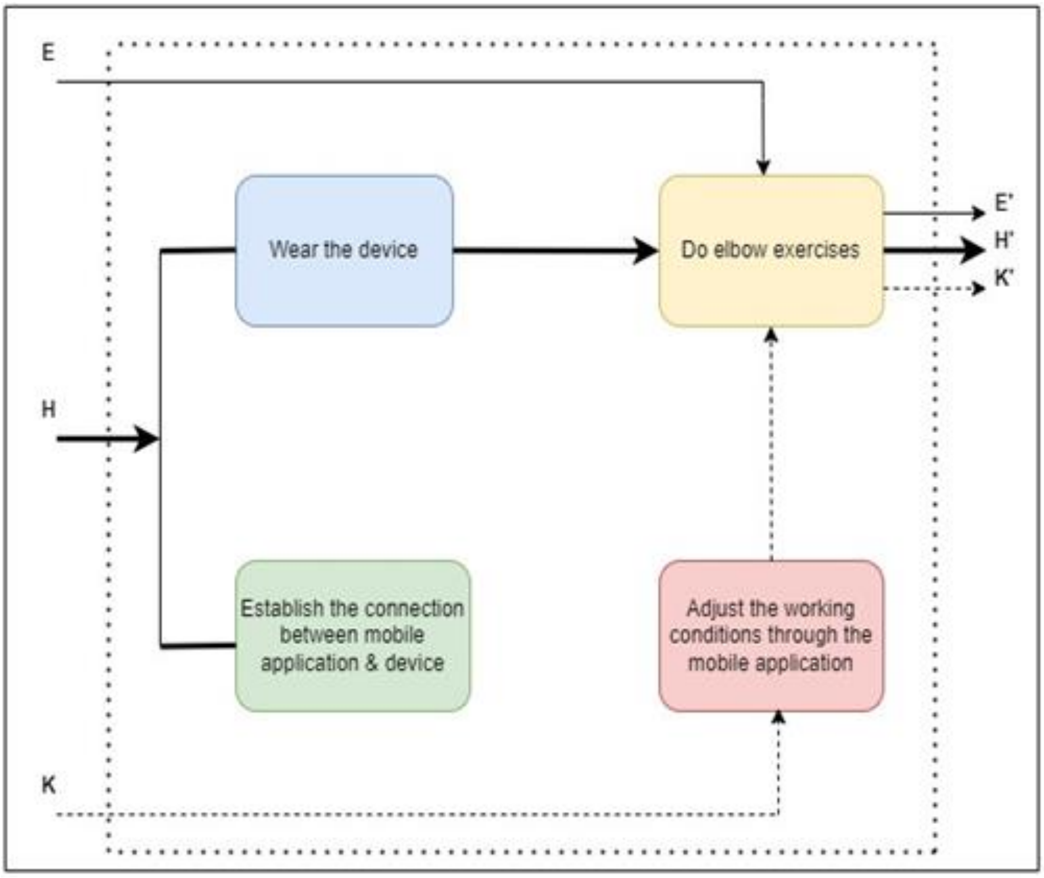
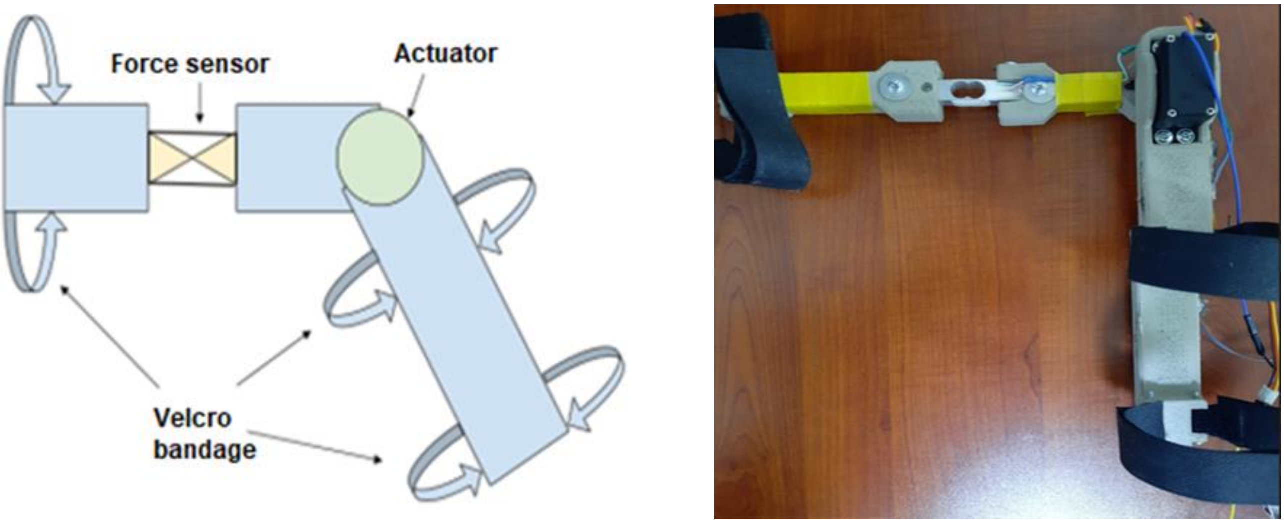


Figure 4. Sub-function of MentArm.



(a) (b)

Figure 5. (a) Mechanical design of the device and (b) Manufactured device.

2.2. Biomechanical model design

The human arm exhibits various axes of movement in its different joints. The shoulder, elbow, and wrist serve as the primary centers enabling this motion. This study aims to determine the center of the single-degree-of-freedom elbow position using a biomechanical model and develop a suitable exoskeleton model. Specifically, the study focuses on the uniaxial movement at the elbow joint in the human arm model, where the elbow joint axis is represented by the ϕ axis. In the constrained human arm model, movement is restricted to flexion and extension along a single axis at the elbow joint. The ϕ angle allows movement in the x and y planes in the elbow region. I_{u1} and I_{u2} represent the upper arm section from shoulder to elbow, while I_{f1} and I_{f2} denote the forearm section between the elbow and wrist joints. m_u and m_f represent the masses of the upper arm and forearm, assuming their concentration at the midpoint of these sections. Figure 6 illustrates the constrained human arm model.

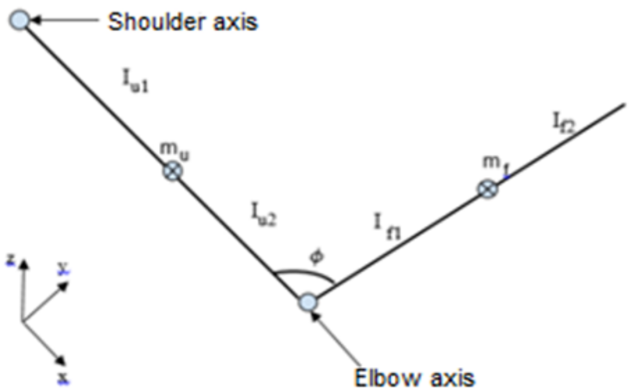


Figure 6. Constrained human arm model.

In Equation 1, J and C represent inertia and Coriolis effects, respectively. F_h and G_h stand for friction and gravitational effects, respectively. Here, h_h denotes the externally applied force [15].

$$J(\ddot{\phi}) + C(\dot{\phi}) + F_h(\dot{\phi}) + G_h(\phi) = g(\phi) - h_h \quad (1)$$

The difference in the angle of the elbow joint between the exoskeleton model and the constrained human arm model has been reasonably determined.

2.3. Mobile application and IoT design

A mobile application has been specifically developed to facilitate the device's use at home, ensuring users exercise under expert supervision. This application was designed using the Android application development platform called 'Kodular'. It was meticulously crafted to offer a user-friendly interface for both patient users and expert physiotherapists. Additionally, it integrates the widely used IoT (Internet of Things) technology for data transfer. Patient users' data are stored in the cloud via IoT, allowing physiotherapists to access this data from their mobile applications by pressing the 'getir' button in the doctor's menu. Figure 7 showcases the interface of the mobile application (MentArm).

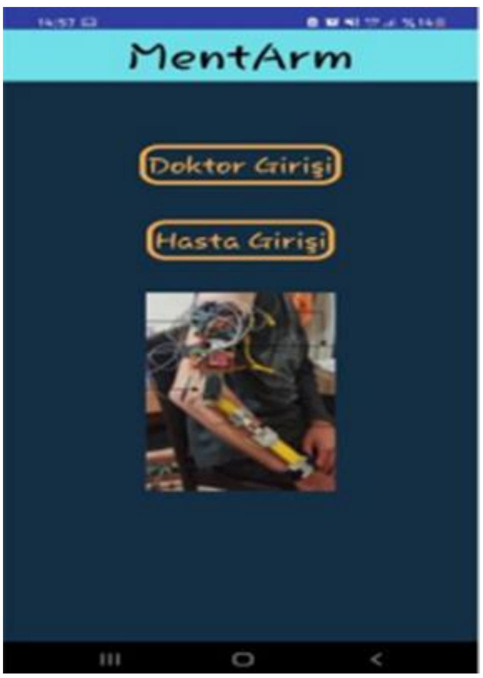


Figure 7. Mobile application home interface.

Users receiving therapy will encounter the exercise screen after logging in. Initially, they need to establish a connection with the device via Bluetooth on this screen. Once the connection is established, they will press the relevant button to select one of the four exercises available. These exercises are respectively labeled as 'far,' 'contra,' 'near,' and 'ipsila.' 'Far' represents the far movement, 'contra' denotes the opposite movement, 'near' explains the close movement, and 'ipsila' signifies the movement in the same direction. The panel displays force and position values after each reference signal period. Upon initiating the exercise by pressing the 'Start' button, the timer begins measuring the duration. To conclude the exercise, users can utilize the 'Finish' button. If the force value falls within the range of +10 to -10 N, no specific value is displayed. However, if it exceeds these limits, a warning message appears on the screen, and the exercise is terminated. This termination is implemented to prevent potential excessive force and ensure user safety. Figure 8 illustrates the interface for users undergoing therapy.

Figure 8. Exercise interface for users undergoing therapy.

In Figure 8, the user undergoing therapy is depicted with details including their name, exercise type, duration, and a cloud-stored error message triggered in case the predefined force limits are exceeded, facilitated by IoT. These data are accessible to physiotherapists through the mobile application when they press the 'fetch' button, displayed on the panel. The real-time monitoring screen, where exercise data is transmitted via IoT to the Firebase cloud platform, allowing instantaneous observation of data, is illustrated in Figure 9.

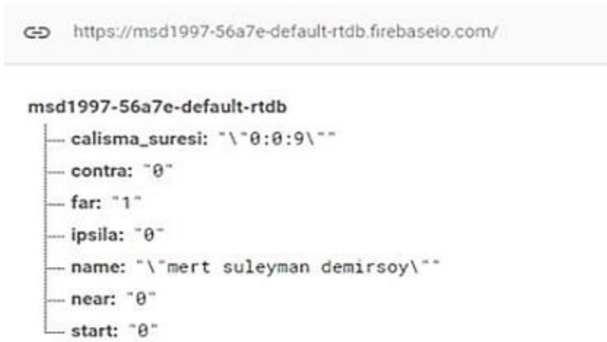


Figure 9. Firebase real-time database.

This allows the data to be collected, and processed, and the condition of the therapy-receiving user to be recorded in a cloud environment (Firebase) through IoT communication.

2.4. Controller design

Controller design involves the management mechanisms employed to ensure that a system or device exhibits the desired performance. This design tracks and analyzes variables within the system and intervenes when necessary to achieve the desired behavior. Controllers are typically built upon a feedback loop; they monitor the current state of a system compare this information, and initiate corrective actions to align with the desired state.

For the controller design of the device, a P-type iterative learning control will be utilized, aiming to settle into the stable region with minimal error and in the shortest possible time.

Iterative learning control is a novel method designed for systems performing periodically repeated operations. The simple proportional structure of P-type iterative learning control (ILC) does not demand detailed knowledge of system dynamics. The principle behind this controller involves retaining output and error values from the previous cycle in memory to approach the reference signal in the subsequent cycle. Initially, for the first cycle, output signals and error values for each sampling are set to 0 in memory. In subsequent cycles, the output signal values and error values from the previous cycle are stored and utilized. Each ILC attempt starts from a fixed initial position, and the positional error occurring in each attempt is used to update control parameters, enhancing the accuracy of subsequent attempts. In this system, a structure that does not rely on system dynamics is formulated mathematically, as shown in Equation 2.

$$u_{k+1} = u_k + \gamma e \tag{2}$$

Equation 2 represents the current output signal u_k of the system. γ denotes the learning gain, a continuous scalar value influencing the convergence rate of the system, and the amount of error. This learning gain is chosen as a value between 0 and 1, considering system dynamics and error tolerance. As this gain value approaches 0, the system converges slower to the reference signal but reduces the error. Conversely, as the gain value approaches 1, the system approaches the reference signal faster but increases the error amount. The new output value (u_{k+1}) is determined by multiplying the learning gain (γ) with the error value (e) in the formula shown in Equation 2 and adding it to the previous output value. This method enables the system to approach the reference signal slowly or rapidly depending on the chosen learning gain.

The block denoted by C in Figure 10 represents the proportional controller, with the proportional gain value (k_p) determined as 0.5 based on experimental tests. The ILC block possesses a memory feature. The value obtained from the proportional controller 'u' is added to the value from the ILC controller and transmitted as u_k for the motor. Figure 10 illustrates the block diagram of the P-type ILC.

In Figure 11, a graph illustrating the sinusoidal reference signal tracked by the P-Type ILC controller applied to the servo motor is presented. The experimental test results have led to the selection of a proportional control gain (k_p) of 0.5 as the controller parameter. Additionally, the learning gain (γ) for the ILC controller is set at 0.4. As represented in Figure 11, due to choosing a learning gain closer to 0, it is evident that the error magnitudes are reduced, albeit resulting in a longer time to precisely reach the reference signal. This observation highlights a decrease in error magnitudes from the 1st to the 4th period compared to previous periods.

The sinusoidal waves consist of 100 samples per period. Initially, the presence of a high overshoot is attributed to the proportional controller's coefficient and the learning gain value. However, the system rapidly approaches the reference signal and stabilizes in approximately 12 samples.

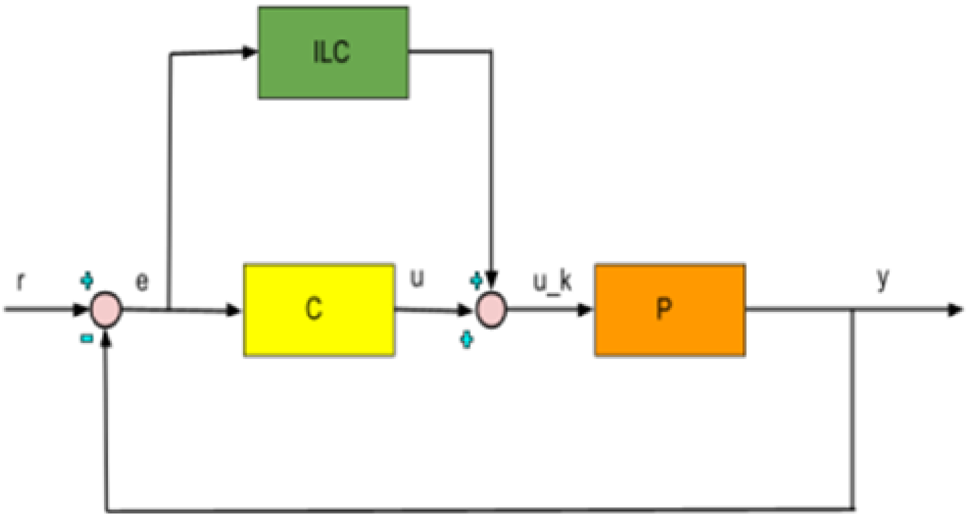


Figure 10. P-Type ILC block diagram.

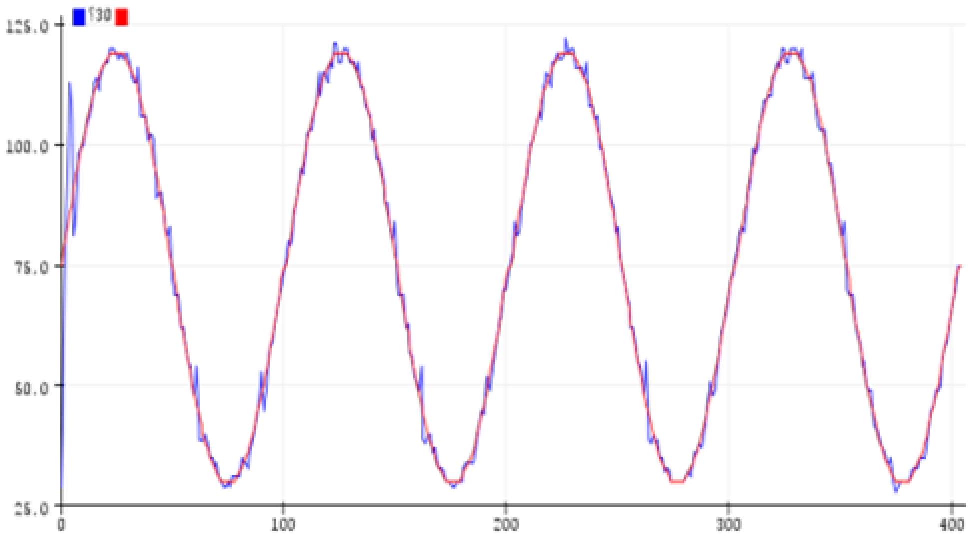


Figure 11. The input-output signal graph with P-Type ILC controller (The vertical axis of the graph represents an angle in degrees, while the horizontal axis shows the number of samples. The red line illustrates the sinusoidal reference wave, and the blue line depicts the system's instantaneous position.)

3. Results and discussion

The device introduces a novel approach to active elbow joint rehabilitation by adopting the fundamental principles of robotic exoskeletons. Additionally, the integration of a mobile application and IoT technology, facilitates the transfer of exercise data from patients to physiotherapists, optimizing the treatment process. The MentArm system increases home usability and flexibility of therapy sessions while aiding physiotherapists in analyzing patient data and formulating more effective treatment methods. Furthermore, the device's user-friendly mobile interface assists patients in monitoring their exercise routines and recording data. The strengths of this study encompass home usability, integration of a mobile app interface, and IoT for effective monitoring of patient data and enhancing physiotherapist accessibility. However, weaknesses such as actuator wear and data security need attention. Data privacy remains crucial as the communication follows an open path, necessitating end-to-end encryption for the data. The long-term effects of device usage, its effectiveness across different patient groups, and user experience require in-depth analysis.

The integration of mobile applications and IoT technology is emphasized, focusing on the swift and comprehensive transmission of patients' exercise data to physiotherapists, aiming to optimize the treatment process. The mobile application developed within the scope of the study successfully transferred patient exercise data to a database (Firebase) via IoT technology and seamlessly transmitted this data to the physiotherapist panel of the mobile application. Recent IoT-based studies demonstrate the rapid and accurate transfer of data through IoT, which has gained popularity, especially in object communication [16-20]. The tests conducted in this study revealed no data loss or delays. Consequently, the patient users' data was swiftly transferred from the cloud environment (Firebase) to the physiotherapists' application. Based on the results of exercise tests conducted in home settings, physiotherapists could remotely monitor this process. Tests on the device control system were performed using admittance, classical PID, and model-based ILC controllers. The admittance controller was deemed unsuitable for the device due to it generating an angle value against force. Therefore, classical PID and ILC controllers were found to be appropriate for the control system design. In the study by Demirsoy et al., [21] a PID controller was used in the device, explaining position errors as an average value. However, as the PID controller could not reduce errors to zero due to the system's nonlinearity, this study preferred a P-type ILC controller.

In this study, P type ILC controller was used to reduce error values and design a more stable system. The controller design was evaluated by considering the outcomes of the final device for the first four iterations. A total of 400 samples were used with a sampling frequency of 100 per iteration. The norm of the error between the reference signal and the device's motion was measured as 2.997343316^0 in the initial iteration. Subsequent iterations showed a decrease in error norms, measuring 1.422597331^0, 1.192201225^0, and 0.933405898^0, respectively. These results indicate an approximately 20% reduction in steady-state errors in each iteration with the P-type ILC utilized, showcasing how controller parameters can diminish errors to near-zero levels over increased iterations. However, Demirsoy et al., in their study designing a PID controller, found the error norm to be constant at 1.755^0. This means that the error throughout the entire exercise is 1.755^0. With the P-type ILC, controller we developed to reduce the error and approach it to zero as much as possible, the error norm decreases and approaches zero in each period. In Figure 12, it can be observed that the iterative learning controller converges toward the reference signal in each iteration, reducing the error. As the number of iterations increases, the error in the system response continues to decrease based on the parameters chosen for the controller. Figure 12 displays a graph illustrating the norm of errors obtained from comparing the data collected over 400 samples (4 periods) with the reference signal.

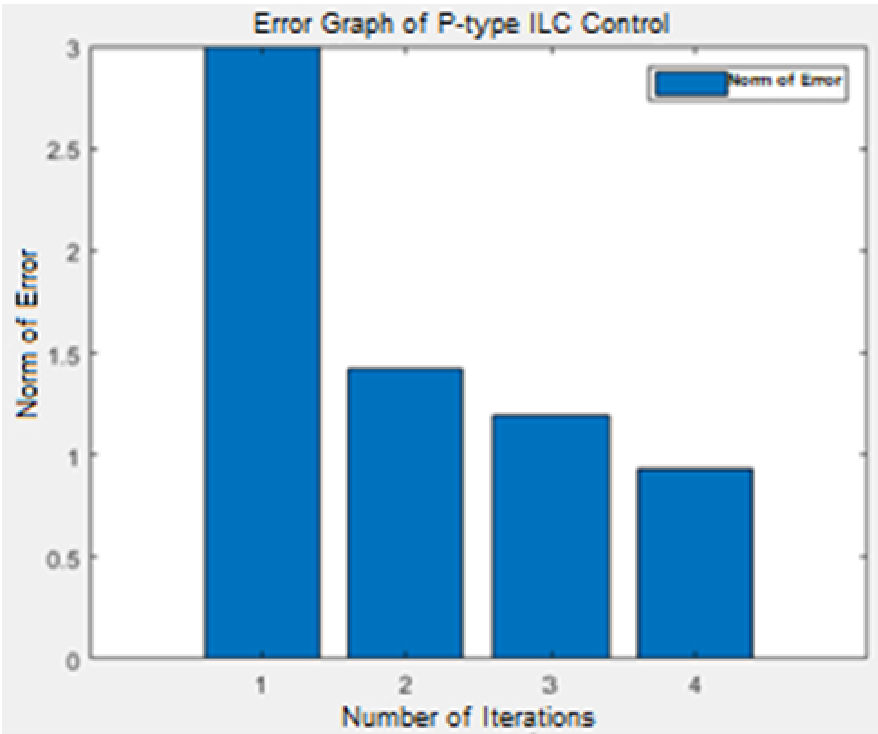


Figure 12. Column graph of error norms by iteration count.

The available data suggests the device's potential to offer effective and reliable rehabilitation in a home setting. As a result of this study, a prototype for a low-cost, portable, and remotely controlled home-based elbow rehabilitation device has been successfully designed and produced. In this way, it differs from other studies; Remote, home-type rehabilitation can be performed under expert control. In addition, there are fewer cutting forces and errors during the rehabilitation process with the controller used.

When looking at the existing studies, the distinctions of our study from the literature are outlined below:

- Real-time exercise data can be monitored through the development of an Android-based application.
- The Internet of Things (IoT) method has been incorporated into our study, allowing individuals' exercises to be continuously monitored by expert doctors, irrespective of their location.
- The developed Android application has the capability to offer 4 different personalized exercise options for patients.
- The device created is cost-effective and suitable for home use.
- The utilized controller has achieved significantly low error rates.

4. Conclusion

These results substantiate the problem and hypothesis of the study. Additionally, deductions for the target audience include expert-controlled home rehabilitation processes, a stable control methodology, and data transmission accuracy. The findings contribute to the existing literature by providing insights into the use of ILC controllers in elbow rehabilitation devices, potentially reducing positional errors to near-zero levels.

Following the evaluation of results, the study identified areas for improvement, particularly in refining control algorithms within the system and integrating additional features into the IoT system. Future studies could focus on the long-term efficacy of the MentArm system. The exercise data obtained with this device will be collected in the cloud and will serve as a repository for developing home type exercise devices, thus contributing to future studies. Additionally, broader clinical trials on diverse patient groups and increased user feedback on the device's user-friendly design could be obtained. Moreover, research into improving control algorithms using a metaheuristic optimization method and technological advancements to make the device more economical and accessible could be pursued.

Author contributions

Mert Süleyman Demirsoy: Investigation, Methodology, Software, Writing-Original draft preparation. **Yusuf Hamida El Naser:** Conceptualization, Methodology, Data curation, Validation. **Muhammed Salih Sarıkaya:** Investigation, Software, Writing-Reviewing and Editing. **Nur Yasin Peker:** Software, Visualization and Editing. **Mustafa Kutlu:** Conceptualization, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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