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Hand Rehabilitation Device with Dynamometer and Tactile Stimulators

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Abstract

Hand injuries are impaired motor functions that can significantly hinder an individual's quality of life, and their daily activities are affected. The rehabilitation process is often lengthy requiring consistent and targeted therapy to restore strength and dexterity. This paper proposes a portable battery-operated hand rehabilitation device which provides effective and efficient rehabilitation in a home setting. The device is integrated into a wearable sleeve and incorporates diagnostic; therapeutic and safety functionalities aimed at promoting the recovery of hand strength and functionality. The device utilizes a combination of tactile stimulators and a hand dynamometer to measure the patient's hand strength. It features a feedback loop that determines the level of force generated by the injured hand compared to the healthy hand using a customizable reference based on hand dominance. For right-handed individuals the device sets the right hand as 15% stronger than the left and vice versa for left-handed users with ambidextrous settings available to tailor therapy. By continuously monitoring progress, the device ensures that the injured hand reaches the strength levels of the healthy hand for complete rehabilitation. A Peltier module system provides thermal therapy that enhances muscle relaxation and blood circulation through controlled heating and cooling. The safety mechanism is supported by a microcontroller, a Zener diode for over-voltage protection and an alarm system to prevent misuse. The device is powered by an AC source with a regulated battery backup to ensure uninterrupted operation. This technology offers a cost-effective, user-friendly, and adaptable approach to hand therapy, reducing the dependency on in-clinic sessions and enabling patients to regain hand strength in a more personalized and flexible manner.

Keywords

Tactile stimulators, Dynamometer, Peltier module system

Introduction

Hand injuries are among the most common musculoskeletal issues that affect individuals across various age groups and occupations. These injuries can result from a variety of causes such as

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repetitive strain, trauma, or surgical interventions leading to reduced grip strength limited range of motion and impaired fine motor skills. Traditional rehabilitation methods typically involve multiple visits to physical therapy clinics which can be time-consuming, costly, and inconvenient for patients. This challenge highlights the need for a more efficient, accessible, and cost-effective solution that can empower individuals to take charge of their rehabilitation from the comfort of their homes.

This research work aims to address this gap by developing a portable battery-operated hand rehabilitation device that provides comprehensive therapy while being easy to use. The innovative device is designed as a wearable sleeve offering both diagnostic and therapeutic functionalities. The inclusion of tactile stimulators adds a sensory dimension to therapy encouraging muscle activation and promoting neuromuscular re-education which is crucial for patients recovering from nerve damage or muscle atrophy. A key feature of the device is its adaptive approach to therapy based on hand dominance. For individuals with a dominant right hand the system assumes the right hand is naturally 15% stronger than the left and vice versa for left-handed users. For ambidextrous individuals the healthy hand’s strength serves as the reference point. Logic helps tailor the rehabilitation process ensuring that therapy is personalized and goal oriented. Additionally, the device is equipped with a Peltier module for providing temperature-controlled thermal therapy which aids in pain relief, reduces muscle stiffness and enhances blood flow. Safety has been a primary consideration in design.

The device incorporates a microcontroller-based system with Zener diode for over-voltage protection and an alarm system to prevent misuse or excessive strain on the hand during exercises. It operates on an AC power source with a regulated battery backup to ensure reliability and portability, allowing users to continue their therapy sessions without interruptions. By offering a compact, versatile, and user-friendly solution the project aims to transform the traditional approach to hand rehabilitation. It empowers patients to regain their strength and functionality more efficiently ultimately improving their quality of life and reducing their dependence on clinical therapies.

Noh et al. (2016) highlights the use of load cells as the primary sensor that accurately measures grip strength. This is essential in restoring the functionality of hand-in-rehabilitation devices. Their study highlights that load cells can offer high accuracy, reliable signal amplification, processing and effectiveness in rehabilitation applications. Rexhaj et al. (2024) investigate the HX711 amplifier module and identified as a suitable and cost-effective choice due to its simplicity, compatibility, and precision, making it highly recommended for rehabilitation systems that need to balance performance and affordability. This module plays a critical role in converting analog signals from load cells to digital values that microcontrollers can easily process, thus facilitating integration with a display or feedback system for the user. This DSP process, combined with proper noise filtration and compensation algorithms, ensures that users receive consistent feedback on their grip strength, enabling gradual, trackable improvement over time. The acquisition of signals and processing of signal in the aspect of thermal therapy and their study reveals importance of Peltier modules for controlled cooling and heating, for therapeutic applications in hand rehabilitation.

Ruiz et al., (2024) study reveals that Peltier modules provide an effective solution for temperature modulation, enabling targeted cooling to alleviate inflammation and heating to promote circulation and muscle relaxation and both crucial in injury recovery. Peltier modules work by utilizing the Peltier effect, where electrical current flows through a junction of two dissimilar conductors, causing one side to cool while the other heats. The combination of load cell data and DSP enables the device to switch between cooling and heating modes effectively, creating a responsive therapy tool. The system's ability to adapt temperature based on grip strength is particularly advantageous, as it aligns therapeutic feedback with the user's progress, enhancing the personalization of the rehabilitation process. Vizza et al. (2023) examined the final component of rehabilitation system is user feedback, specifically through an LCD interface. Their study reveals the importance LCD displays for real-time feedback, highlights that clear data visualization and provides progress tracking in user engagement and therapeutic efficiency.

Methodology

The Development of the System

The hand rehabilitation system was developed using a carefully selected combination of hardware and software components to measure grip strength, deliver thermal therapy, and provide real-time feedback to the user, facilitating an effective and interactive recovery process. The primary materials used include a 12V DC power supply, a load cell, an HX711 amplifier, an Arduino microcontroller, a MOSFET for power regulation, Peltier modules for heating and cooling, and an LCD display for user feedback. The load cell is the key sensor responsible for measuring the force exerted by the user during grip exercises, which is crucial for assessing hand strength. The small analog signals generated by the load cell are then amplified and digitized by the HX711 module, which is widely regarded for its precision in weight measurement applications.

This digital signal is sent to the Arduino microcontroller, which serves as the main processing unit for the system, interpreting the grip strength data to control the thermal therapy process and manage the user interface on the LCD display. The MOSFET acts as an efficient switch that allows the Arduino to regulate power flow to the Peltier modules based on the user's grip strength, ensuring that thermal therapy is applied accurately without unnecessary energy consumption. The Peltier modules themselves are responsible for delivering either heating or cooling to the user's hand as required; cooling is used to relieve inflammation and relax the hand muscles, while heating promotes circulation and assists in the recovery of tissues.

Finally, the LCD display plays an essential role in providing the user with real-time feedback by displaying their current grip strength, target levels, and the status of the thermal therapy, which enhances user engagement and motivation during the rehabilitation process. The system's method of operation involves the load cell measuring grip strength and transmitting this data through the HX711 to the Arduino, where it is processed and compared against target levels. Based on these measurements, the Arduino determines whether the thermal therapy should be in cooling or heating mode, and it adjusts the Peltier modules accordingly via the MOSFET. This real-time adjustment allows the system to deliver personalized thermal feedback based on the user's progress, while the LCD display continuous updates to keep the user informed, creating an interactive and responsive rehabilitation experience tailored to their needs. The diagram of the system is shown in Figure 1.

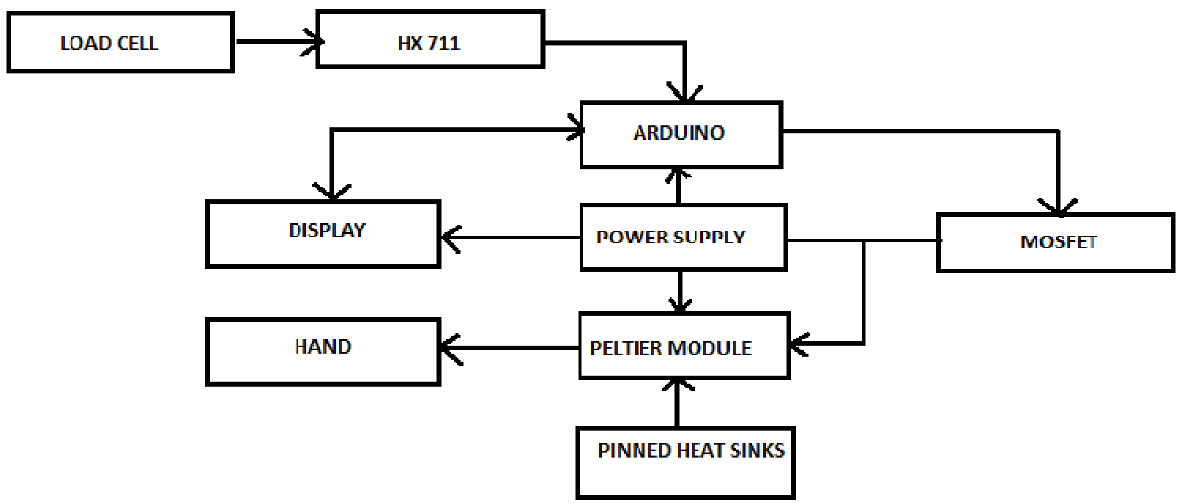

Figure 1. Block diagram of hand rehabilitation system

Force Measurement and Grip Strength Calculation

The load cell is the key sensor in this device, measuring the force exerted by the hand when the user applies pressure. When a user grips the sensor, the load cell's resistance changes, which results in a voltage output. This output is then amplified by the HX711 amplifier to a readable digital signal for the Arduino. To calculate the force applied by the user (i.e., the grip strength), Equation 1 is used.

$F = (Vout - Vzero)\ SF = S(Vout - Vzero)$ - (Eq. 1)

Where:
- F = Force applied (in Newtons or pounds)
- $Vout$ = Voltage output from load cell
- $Vzero$ = Baseline output voltage
- S = Sensitivity of the load cell

After converting the analog signal to digital values, Arduino processes the data and calculates the current grip strength. This value is displayed on the LCD screen to keep the user informed about their progress. The grip strength is also used to adjust the intensity of the Peltier modules during therapy.

Dominant and Non-Dominant Hand Logic

The logic for the device adapts to both dominant and non-dominant hands during rehabilitation. Typically, a dominant hand (e.g., right hand) is about 15% stronger than the non-dominant hand. The user is rehabilitating the right hand the device calculates the strength of the left hand based on the assumption that the right hand is 15% stronger. Thus, the device assumes the left-hand strength to be 25.5 N if the right hand is 30 N. The therapy for the left hand will be adjusted to target this value for recovery.

For example:
If the right-hand strength is measured as:
Fr=30 N

The left-hand strength is calculated as:
$Fl = Fr - (0.15 \times Fr)$
$Fl = 30\ N - 4.5\ N = 25.5\ N$

For users who are ambidextrous or rehabilitating their non-dominant hand the system uses the dominant hand's strength as the target for rehabilitation. If the left hand is injured and the user is ambidextrous the device will set the target strength to match that of the dominant hand (the stronger hand). This ensures that the rehabilitation goal is to match the strength of the healthy hand. For instance, if the dominant right hand has strength of 30 N, the non-dominant left hand should eventually match this value as it recovers.

Tactile Feedback Via Peltier Modules
The device uses Peltier modules to provide thermal stimulation during rehabilitation. These modules work by transferring heat from one side to the other when power is applied. The MOSFET controls the power to the Peltier modules, switching between heating and cooling effects. In heating mode, the Peltier modules can heat the hand to relax muscles and improve blood circulation, which is beneficial for recovery. In cooling mode, cooling can help reduce swelling and inflammation in the injured hand. The device does not require a temperature sensor because the heating or cooling intensity is pre-programmed for specific stages of rehabilitation based on user feedback. The heating or cooling intensity is controlled through the MOSFET, adjusting the power sent to the Peltier modules. The control algorithm ensures that the user experiences an optimal level of thermal therapy during each session.

Feedback Mechanism and LCD Display
The LCD display provides real-time feedback to the user, including the current grip strength, displayed in Newtons or pounds, the target strength based on the dominant hand or healthy hand for non-dominant users, rehabilitation progress through a visual representation of the user's progress toward their goal, and the Peltier module status, showing whether the module is in heating or cooling mode. This feedback is important for user motivation and helps the patient track progress over time. The device provides feedback during each session to ensure that the therapy is aligned with the user's recovery goals.

Safety Mechanisms
Safety is a critical aspect of the rehabilitation device. The system includes mechanisms to ensure that both the force exerted by the hand and the thermal therapy from the Peltier modules are within safe limits. These include force thresholds, where if the measured force exceeds the safe threshold, such as when the patient exerts too much pressure, the device will automatically reduce the applied force or stop the therapy session. Temperature limits are also included. Even though no temperature sensor is used, the intensity of the thermal therapy is pre-programmed to avoid

overheating or overcooling the hand. The user will be able to adjust the intensity based on their comfort level.

Results and Discussion

The hand rehabilitation system designed for improving hand strength post-injury was tested and evaluated through several stages of the project, with a focus on the effectiveness of its components, user feedback, and overall performance. The system combines a load cell, HX711 amplifier, Arduino microcontroller, MOSFET, Peltier modules, and an LCD display to offer comprehensive rehabilitation experience. The following results highlight the system's functionality and performance based on the components.

Load Cell and Strength Measurement

The load cell was successfully calibrated and used to measure the pressure exerted by the user during gripping. The HX711 amplifier facilitated the conversion of the analog signal from the load cell to a readable digital value for the Arduino. Upon calibration, the load cell accurately measured small variations in force, with a minimum accuracy of 0.1 kg. The system could provide real-time strength data on the LCD display. Testing showed that the system consistently tracked strength levels and displayed them without significant delay, making it easy for users to monitor their progress.

Strength Comparison Logic

One of the key features of the system was the strength comparison logic, which was based on hand dominance. In the case of a right-handed individual, the right hand was considered the reference for strength, being 15% stronger than the left hand. Conversely, for a left-handed individual, the left hand was treated as the stronger hand. This logic enabled the system to adjust the target strength and rehabilitation goals for each hand individually, creating a personalized therapy approach. Users reported that this dynamic adjustment helped them focus on rebuilding strength in their injured hand based on their dominant hand's performance.

Thermal Therapy Performance

The Peltier modules controlled through MOSFETs by the Arduino provided thermal feedback to the user's hand during the rehabilitation process. The system switched between cooling and heating modes depending on the strength level measured by the load cell. Cooling: When grip strength was below the target, the cooling function was activated to reduce inflammation and promote muscle relaxation. The Peltier module efficiently transferred heat away from the user's hand, providing noticeable cooling effects (Table 1).

As the grip strength approached or exceeded the target, the heating function was activated to enhance blood circulation and improve tissue healing. The heating mode was effective, and users felt the warmth promoted comfort and flexibility. Testing confirmed that the thermal feedback was responsive and adjusted to the user's strength level as intended providing a therapeutic effect based on individual needs.

Table 1. Thermal therapy performance

Time (s)	Grip Strength (kg)	Thermal Mode (Cooling/Heating)
0	0.00	Cooling
5	0.50	Cooling
10	0.80	Cooling
15	1.00	Cooling
20	1.50	Cooling
25	1.80	Cooling
30	2.00	Cooling
35	2.50	Cooling
40	3.00	Heating
45	3.50	Heating
50	4.00	Heating
55	4.50	Heating
60	5.00	Heating
65	5.00	Heating
70	4.80	Heating
75	4.20	Heating
80	3.50	Cooling
85	3.00	Cooling
90	2.50	Cooling
95	2.00	Cooling
100	1.50	Cooling
105	1.20	Cooling
110	1.00	Cooling
115	0.80	Cooling
120	0.60	Cooling

LCD Display Feedback

The LCD display offered immediate, clear feedback, displaying the current grip strength, target strength, and status of thermal feedback (cooling or heating). Users were able to easily interpret the information and understand their progress. This visual feedback helped keep users motivated and informed throughout the rehabilitation process.

System Responsiveness and User Experience

The system demonstrated fast and reliable responses. The Arduino processed grip strength data and adjusted thermal feedback in real-time. The MOSFETs responded promptly to control the Peltier modules, ensuring smooth transitions between heating and cooling. User feedback highlighted that the system was comfortable to use, with the thermal therapy being soothing and the strength measurement encouraging consistent effort during the rehabilitation process. Additionally, users appreciated the real-time feedback provided by the LCD display, which kept them informed of their progress (Figure 2 and 3).

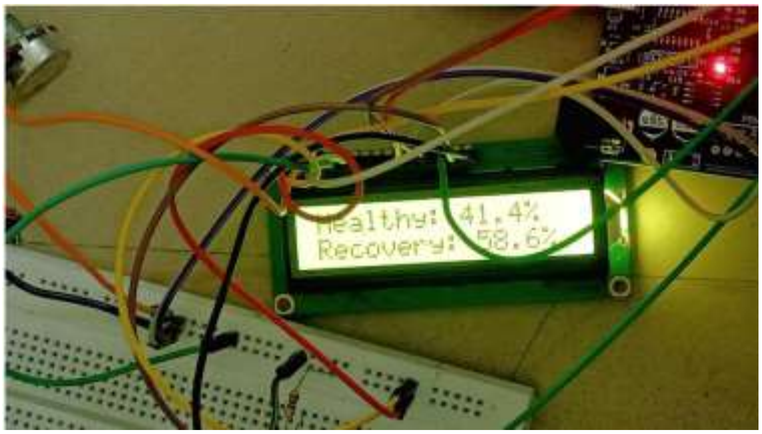

Figure 2: Results of a hand recovery

Figure 3: Results of an injured hand

Conclusion

In this work a hand rehabilitation system was designed and developed to aid in the recovery of hand strength post-injury. The system integrates several key components including a load cell, HX711 amplifier, Arduino microcontroller, MOSFETs, Peltier modules, and an LCD display, to provide a comprehensive rehabilitation experience. The system not only measures the grip strength of the user but also offers personalized thermal feedback such as cooling and heating based on the strength level. The system was intended to promote recovery by giving users real-time data on their progress and utilizing thermal therapy to enhance healing. The hand rehabilitation system successfully integrates strength measurement and thermal feedback into a cohesive rehabilitation tool. The results from testing showed that the system met its objectives, offering both effective grip strength measurement and personalized thermal therapy. The system demonstrated great potential in assisting users with hand rehabilitation, providing them with real-time feedback and motivating them to continue with their exercises. With further refinement and additional features such as mobile integration and customizable thermal settings the system could become an even more powerful tool for hand injury recovery.

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