



Designing, Modelling and Implementation of AnkleFlexAR for Ankle Joint

Rehabilitation

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Abstract

The developed low-cost user-friendly ankle joint rehabilitation system enables patients to perform mandatory physiotherapeutic exercises by controlling four essential foot movements, which consist of dorsiflexion as well as plantar flexion and inversion and eversion. An ESP32 microcontroller forms the core of this device because it produces wireless Bluetooth connectivity and enables real time monitoring and control through an application made specifically for this system. One DC motor functions through the BTS7960 high-current motor driver to establish two-directional mechanical movement. The device contains limit switches, which track position precision while stopping movements beyond safe limits. The system provides users with two operational modes that can be run manually or by providing predefined parameters. Under predefined operation, the device runs rehabilitation sequences through either cycle-based counting (stroke-based) or time-based controls (timer-based). Therapists together with users gain control over the direction of movement through a joystick module present in the manual operating mode. All system components benefit from stable operation through the buck converter, which regulates power supply. A WTC (Wireless Transmission Component) enables uninterrupted communication between the hardware components and mobile interface system. The system exists as a non-portable device but it maintains a design suitable for stable operation in clinical and home-based environments. The system offers affordable setup and straightforward user interface features that enable healthcare providers to serve patients in diverse settings and monitor their achievements apart from permitting therapists to refine protocols as required.

Keywords: Ankle Rehabilitation, Robotic Device, Biomechanical Therapy, Wireless Monitoring, Assistive Rehabilitation.

1. Introduction

Injuries about the ankle are amongst the most common musculoskeletal injuries found in people who participate in physical activity, like sports. These injuries occur when the ankle joint is twisted, rolled, or turned in an abnormal way (mechanics), causing damage to the ligaments, tendons, bone and muscles. The most common type of ankle injury is a sprain, which occurs when the ligaments surrounding the ankle are stretched or torn due to an excessive force of sudden trauma. Ankle injuries are categorized based on the extent of the ankle sprain into grade one (mild) to grade three (severe) with complete ligament rupture or fractures. The injury commonly occurs when the ankle is forced to move beyond its usual range of motion, especially during activities such as running, jumping or sudden stop and go actions. The effects of an ankle injury go further beyond damage limited just to the foot and joint itself, greatly hindering your ability to move well, maintain balance and carry out other physical activities efficiently. If left untreated, these injuries can cause long-term issues like ankle instability or osteoarthritis. Therefore, it is very important to diagnose and treat a SLAP tear in the correct way so that further injuries are kept at a minimum. In fact, significant advances have been made in sports medicine and physical therapy for treatments of ankle injuries with a presence of limited evidence for long-term interventions, which are effective during the recovery process. The ankle joint plays a crucial role in providing stability, equilibrium, and impetus to a human's full anatomy. Created through the amalgamation of multiple articulations, an ankle serves as the

articulation between the lower leg and foot. Its primary task involves executing dorsiflexion, elevating the foot, and plantar flexion, lowering the foot [1]. Numerous individuals experience challenges related to their ankles. These issues might arise from uncomplicated causes; however, they can also serve as potential indicators of more severe underlying conditions. Afflictions affecting the ankle encompass instances, such as sprains, trauma, arthritis, osteoarthritis, tendonitis, rheumatism, and neurological complications, among various others. Enhancing the mobility of the ankle joint can contribute to the promotion of healthier joint surfaces and a reduction in discomfort. In the initial stages of the functional recuperation of the ankle, it is advisable to incorporate exercises that target the range of motion, especially following an acute sprain or instances of chronic instability [2]. An ankle sprain arises when there is an injurious twist, roll, or turn of the ankle, leading to harm. This results in ligaments being stretched beyond their typical range of motion. In the context of ankle arthritis, performing dorsiflexion and plantar flexion exercises. The utilization of robotic structures offers potential advantages, including cost reductions associated with labor-intensive movement-based rehabilitation treatments, along with the broadening of the spectrum of exercises that can be performed. This expansion facilitates patients in sustaining their mobility through continuous therapeutic interventions [3].

2. Background

Ankle injuries, coupled with their significant impact on morbidity and disability, have become a major concern for both medical and athletic communities. The ankle joint is a complex structure that connects the tibia, fibula and talus bones with multiple surrounding

ligaments and tendons to provide stability during weight bearing activities[4]. Injuries occur when the ankle joint is twisted, rolled, or turned in an abnormal way (mechanics), causing damage to the ligaments, tendons, bone and muscles. Sprain the most common type, that which occurs when the ligaments surrounding the ankle are stretched or torn due to an excessive force of sudden trauma. Ankle injuries are categorized based on the extent of the ankle sprain into grades 1 (mild) to grade three as shown in figure. 1, with complete ligament rupture or fractures[5]. Ankle injuries, especially in the context of advanced medical science and technology, are understood through a more nuanced perspective that incorporates biomechanics, regenerative medicine, precise surgical techniques and state-of-the-art rehabilitation practices[6][5].

2.1 Classification of Ankle Injury:

1. Ankle Sprain occur frequently and they are caused by overstretching of the collagen structures, which support and stabilize the ankle joint complex. Usually involves the lateral ligamentous complex on the outside of the ankle.
2. Ankle Strain occurs when stress is applied on the ankle joint muscles and tendons. Commonly for overstretching or overuse.
3. Fractures occur where one or a few of the bones of the ankle (foot tibia, fibula and talus) experience a break.
4. Achilles Tendon Injury causes substantial pains due to tear or inflammation in the Achilles tendon.

Recent developments, in particular devices should be able to easily diagnose, treat and rehabilitation problems around the ankle joint in the recent times[7]. The prime objective

of these innovations is to enhance the outcomes, shorten the period and even minimize the re-injuries. Some noteworthy progresses include Wearable Devices and Smart Technology such as Smart Ankle Braces[8]. Current solutions lack affordable, programmable devices for precise ankle rehabilitation. This study introduced Ankle FlexAR for Ankle Joint rehabilitation. This device provides controlled mechanical treatment through four essential movements (Dorsiflexion, Plantarflexion, Reversal and Eversion) basic for lower leg restoration. These developments restore the range of motion. Controlled practices strengthen the surrounding muscles and tendons; improve security and decreasing the risk of future injuries. The device delivers exact and slow movement through programmed protocols, ensuring no excessive pressure is put on the damaged region[9]. The ankle joints are vital in terms of motion and locomotion support, standing and maintaining balance in the human body. Conditions of trauma, surgery as well as conditions for example sprains, fractures, torn ligaments and even neurological conditions can lead to compromises.

2.2 Significance of the Study

Ankle injuries are common among athletes and physically active populations which leads to a major public health concern, causing morbidity, disability, and significant economic burden from long-term recovery time and risks of re-injury[10]. This study introduces Ankle FlexAR, a great budget friendly rehabilitation device that provides accessible ankle injury treatment by giving programmable control over four precise movements (dorsiflexion, plantarflexion, inversion, and eversion) through low- cost components e.g. ESP32 microcontroller, DC motors, and BTS7960 drivers. The device allows both clinical and home based rehabilitation with operation that are dual mode (manual joystick and

mobile app control), safety features (limit switches, emergency buttons), and heat therapy reducing dependency on therapist along with supporting SDG 3 (Good Health and Wellbeing) in limited resource in areas like Pakistan and implements practical biomedical engineering innovation to improve and fastens the recovery process, prevent chronic complications.

3. Materials and Methods

This research project investigates the design and development of ankle flexAR for ankle joint rehabilitation, methodology illustrates in figure.1. This innovative technology aims to provide a safe and effective solution for ankle to move in four directions also effective to heal the injury like strain sprain these problems are very common among Globe. The methodology employed this project comprise various components.

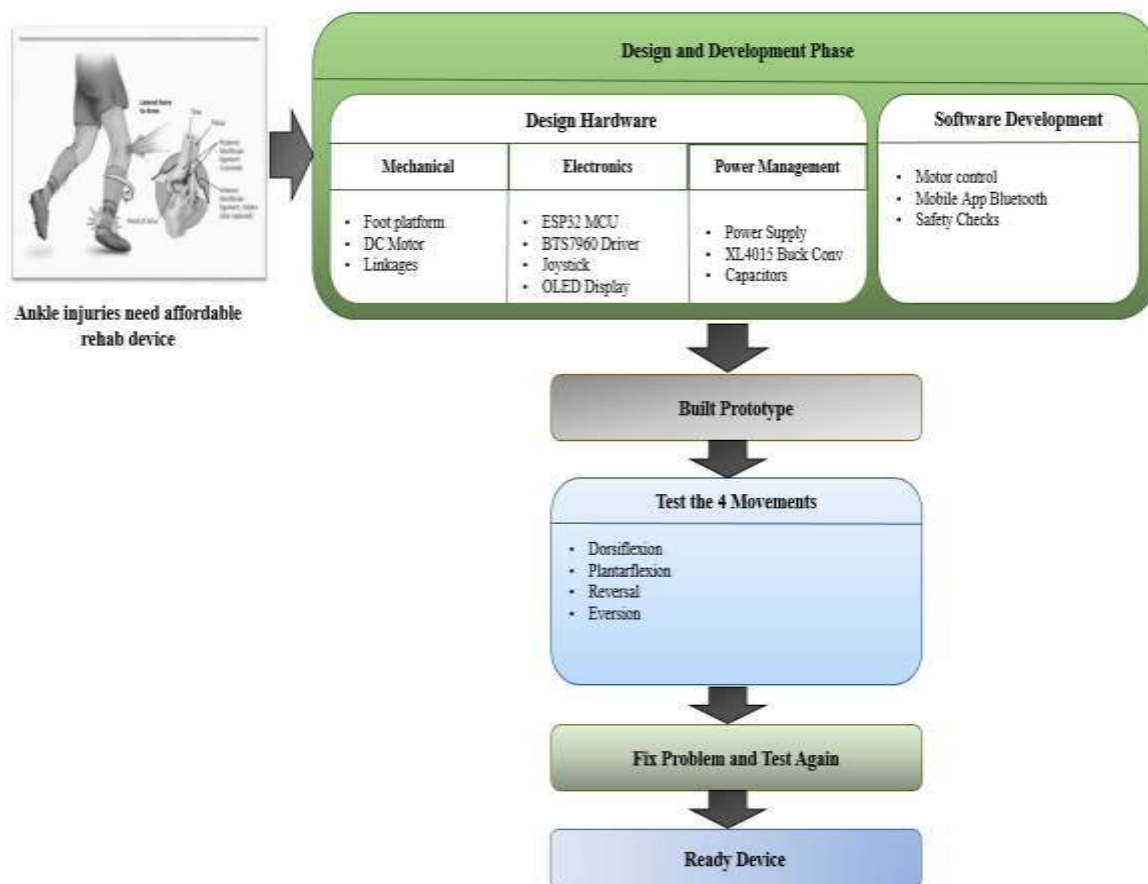


FIGURE 1. FLOW CHART OF ANKLE FLEXAR FOR ANKLE JOINT REHABILITATION

3.1 Materials

DC motor serves as an electromechanical tool, which transforms direct electrical power to produce mechanical rotational movement and their ability to deliver smooth motion outputs. Compatible with ESP32 and BTS7960. Figure.2 ESP32 microcontroller delivers low-cost dual core with Wi-Fi and Bluetooth capability alongside advanced processing features. This device finds broad application in biomedical and IOT systems for real-time wireless data processing and communication purposes. 3 inch SH1106 OLED show little high contrast 128x64 screen with SH1106 driver and fast serial interface figure.3, furnishes

patients with constant on developments and directed activities. Joystick module enables users to operate motion through two directional control points (X and Y-axes) by using a stick or lever or lever containing potentiometers together with a pushbutton, a control interface for human operation enables ankle movement directions. Up/down for dorsiflexion and plantarflexion. Left/right for inversion and eversion. Where ESP32 receives analog signals from joystick stick movement. Press buttons (10mm) are mechanical switches that open or close an electrical circuit when squeezed, utilized as client input interface to control the gadget beginning or halting recovery works out, changing settings and resetting. BTS7960 is a powerful H-bridge engine driver intended for controlling DC engines. Utilized to control motor simulating ankle joint movements practices like dorsiflexion, plantarflexion, or eversion/reversal of the lower leg. XL4015 Buck Converter figure. 4, enables efficient conversion of a high input DC voltage into a low output DC voltage (5V/3.3V) for ESP32, joystick, sensors and HC-05 Bluetooth in embedded biomedical systems. 12V @ 20A Power Supply gives a steady result of 12V DC with a greatest current of 20A, normally used to control high-power frameworks, guarantees that all parts of the gadget, particularly those requiring high current (like engines or warming components), get satisfactory power. Without framework shakiness or power interferences. Perfboard (Huge) figure.5, punctured board with pre bored openings used to make custom electronic circuits permits simple binding and mounting of parts, utilized to fabricate and arrange restoration gadget circuit giving steady stage to motor drivers, sensors and wiring. 1000 μ F @ 25V Capacitors (6 Units) figure.6, capacitor are parts that store electrical energy briefly with 1000 μ F capacitance and 25V rating, assist with streamline voltage vacillation and lessen power supply swell giving stable voltage to

engine driver and microcontroller. 104 Capacitors (4 Units) figure.7, clay capacitors with a capacitance worth of $0.1\mu\text{F}$ (100nF), normally utilized for separating and commotion concealment, used to filter out high-frequency noise ensuring clean and stable operation for motor control, sensor readings, or communication between components. Pin Terminal Block Connectors (3 units) figure.8, Terminal block connectors are utilized for simple and secure wire associations with 2-pin screws connections, consider simple and safe associations between the power supply and the engine driver or among sensors and the microcontroller guarantees a steady bind free association. 3-Pin Terminal Block Connector (1 Unit), Like the 2-pin connector yet with three screw terminals for parts that require three wire associations, regularly utilized for sensors, modules like temperature sensors and actuators giving protected secluded circuit association. Female Header Strip figure.9, a line of attachments for simple removable associations with male pins, utilized to make measured associations between framework parts permitting simple connection of microcontrollers or sensors to principal circuit. Male Header Strip figure.10 comprises of a line of pins embedded into female header attachments, utilized related to female strips for associations between control board, sensors and engine driver and microcontroller. DS18B20 Temperature Sensor figure.11, computerized temperature sensor with high accuracy over 1-wire interface, utilized to screen lower leg or heating elements ensuring heat during restoration does not surpass safe levels. 12V 10 Watt 50°C Warmer, warming component intended to give intensity to a particular region, ordinarily fueled by a 12V DC source, utilized to give heat treatment to the lower leg, advancing blood flow and helping with muscle unwinding. IRF520 Double MOSFET Module figure.12, a double MOSFET module incorporates two MOSFET semiconductors utilized for controlling electrical flow

to parts, used to control power to high-power components like the motor or heater allowing precise switching for safe rehabilitation exercises.

3.2 Methods

3.2.1 Operation of Ankle FlexAR

This microcontroller is the fundamental "mind" of the gadget. It can deal with different errands like controlling engine development, perusing sensor information, and overseeing client input from buttons or a joystick. 1.3 Inch SH1106 OLED could show boundaries like development points, force applied, or temperature readings, engine drivers handle high power engines securely.

3.2.2 Ankle FlexAR Control System

This device is intended to address lower leg wounds (injuries, strains, and cracks) by giving designated treatment through controlled development and natural The direct actuator servo engine will perform controlled developments for dorsiflexion, plantarflexion, inversion movements, DS18B20 temperature monitoring, SH1106 OLED display, joystick or buttons for manual or automated modes, BTS7960 drivers with 12V warmer via IRF520 MOSFETs.

3.2.3 Working Mechanism for Healing

Dorsiflexion and plantarflexion developments assist with lessening firmness without overemphasizing the injury. Warm Treatment: The radiator gives calming warmth to further develop dissemination and advance tissue fix. Input: The joystick and OLED show

guarantee the client can modify treatment power in light of torment resistance. Slow presentation of inversion and eversion developments to reinforce encompassing muscles and tendons. Adaptable reach through application.



FIGURE 2. ESP32 MICROCONTROLLER

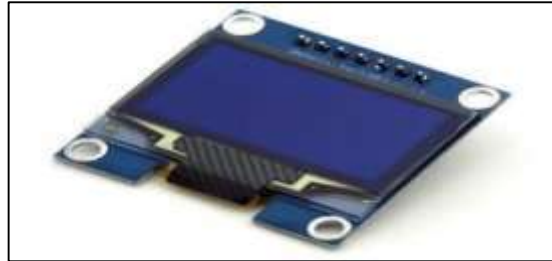


FIGURE 3. LED DISPLAY



FIGURE 4. BUCK CONVERTER



FIGURE 5. PERF BOARD



FIGURE 6. 1000µF CAPACITORS



FIGURE 7. 104 CAPACITORS



FIGURE 8. 2-PIN TERMINAL BLOCK CONNECTORS



FIGURE 9. FEMALE HEADER STRIP



FIGURE 10. MALE HEADER STRIP



FIGURE 11. DS18B20 TEMPERATURE SENSOR



FIGURE 12. IRF520 DOUBLE MOSFET MODULE

4. Results and Discussion

DC Motor integration, single high-torque DC motor to carry out its core actuation function by creating mechanical foot movements across four rehabilitation positions show in which include dorsiflexion show in figure.13, together with plantar flexion as well as inversion illustrate in figure.14 and eversion in figure.15. The BTS7960 H-bridge motor driver ensures stable operation by handling sufficient current (up to 43A) during changing load circumstances when attached to the motor. The foot displacement mechanisms of the device convert rotational motor movements into proper angular foot deformations through its lever-based linkage structure. The positioning of limit switches provides essential safety boundaries for each movement duration to prevent harmful movements throughout rehabilitation exercise procedures. Operating modes can be selected from two options through the mobile application illustrate in figure.16 via Bluetooth (ESP32) including the stroke-based control and time-based control protocols. Stroke-based control allows the system to perform specific directional sequences where every cycle involves single-direction movements from dorsiflexion to plantar flexion. A joystick-based manual control system in the device provides users or therapists with direct motion direction control through four different options. Ankle movement control of Ankle FlexAR device is designed to assist and monitor ankle joint rehabilitation by controlling ankle movements through a DC motor mechanism. The system integrates a joystick for user input, an ESP32 microcontroller for processing, and a BTS7960 motor driver for motor control generating controlled ankle motions with all recorded values within therapeutic safety margins.



FIGURE 13. SHOWS THE DORSIFLEXION MOVEMENT OF ANKLEFLEXAR



FIGURE 14. SHOWS THE INVERSION MOVEMENT OF ANKLEFLEXAR



FIGURE 15. SHOWS THE INVERSION MOVEMENT OF ANKLE FLEXAR

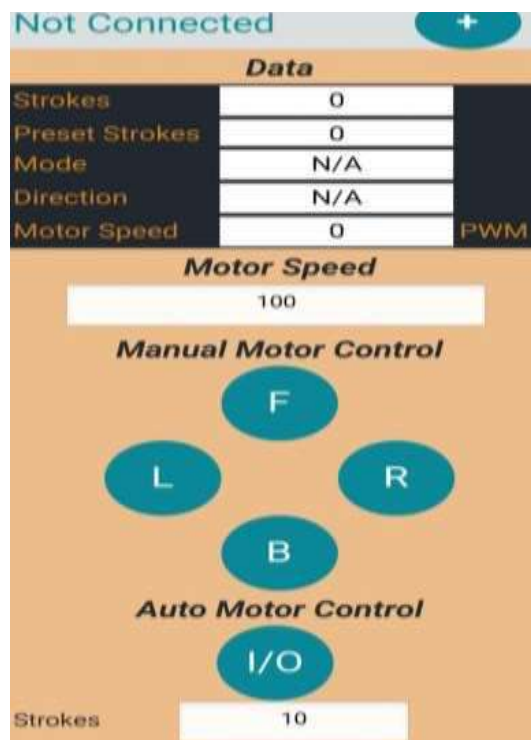


FIGURE 16. MOBILE APPLICATION FOR DEVICE CONNECTION

5. Conclusion

The Ankle FlexAR device shows encouraging clinical results for helping patients during the recovery from ankle traumas by improving joint movement capability. The Ankle FlexAR achieves its goal of assisting ankle joint patients by implementing strategic designs and modeling approaches to help them recover their ankle strength and movement control. Effects measured through early testing show that Ankle FlexAR helps patients develop better muscle coordination skills and joint stability. Future research focuses on developing improved design aspects for the device to serve diverse clinical needs by enhancing comfort and adjustability and usability. The development process of control algorithm emphasizes creating individual rehabilitation programs, which adjust to different levels of injuries and their specific characteristics. Various clinical studies with numerous patient populations remain active to confirm the device's treatment success and develop improved therapy sequences toward better outcomes. Ankle FlexAR functions through its controlled mechanical system, which guides patients during ankle movements between dorsiflexion and plantarflexion. Medical assistance from this device stimulates patient muscle involvement to strengthen muscles and expand joint flexibility capabilities. Medical professionals can use the adjustable features to configure treatment protocols based on patient recovery needs thus facilitating better therapeutic outcomes. The Ankle FlexAR device brings forward a modern approach to ankle physical therapy, which proves its worth in clinical practice. The Ankle FlexAr presents strong potential to restore ankle function, accelerate recovery, and minimize future complications resulting from ankle injuries. The Ankle

FlexAR shows potential for becoming a vital medical device in contemporary rehabilitation practices since it assists patients with gaining.

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