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TALUS: PROTOTYPE OF A PORTABLE CONTINUOUS PASSIVE MOTION PHYSICAL THERAPY DEVICE FOR ANKLE TRAUMA

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Abstract

Excessive stretching or rotation during daily movements can cause joint traumas that impair quality of life. These traumas are common in ankle joints, which bear the weight of the body, and can present as sprains, dislocations or fractures, causing pain and limited movement. Physiotherapy methods and technologies are used to restore optimum neuromusculoskeletal function. Continuous passive motion is a method used to prevent joint stiffness and calcification in joint surgery cases by providing repetitive movement of the joint. Physical therapy devices utilizing this technology allow for controlled repetition, speed, power, and angle. In this study, a prototype called Talus was developed that can deliver continuous passive motion physiotherapy at an adjustable angle, in real time or autonomously, after ankle joint trauma or surgery, and record application and patient information. Nextion was utilised to input patient information, determine movement angles, select the operating mode, and display recorded patient and treatment data. The information was recorded and the servo motors on the relevant axes were controlled using Arduino Mega. Talus allows for personalised treatment to be administered at home.

Keywords: Ankle joint, Continuous passive movement, Range of motion, Rehabilitation device

TALUS: AYAK BİLEĞİ TRAVMALARI İÇİN TAŞINABİLİR SÜREKLİ PASİF HAREKET FİZİK TEDAVİSİ CİHAZI PROTOTİPİ

Özet

Günlük hareketler sırasında aşırı gerilme veya dönme sonucu oluşan eklem travmaları yaşam kalitesini bozabilmektedir. Vücudun ağırlığını taşıyan ayak bileği eklemlerinde sık görülen bu travmalar burkulma, çıkık veya kırık şeklinde ortaya çıkarak ağrıya ve hareket kısıtlılığına neden olabilmektedir. Çeşitli fizyoterapi yöntemleri ve teknolojilerini kullanımı ile bu semptomlar geriletilerek optimum nöromüsküloskeletal fonksiyonun geri kazanılması kolaylaştırılmaktadır. Bu yöntemlerden biri, eklemin tekrarlayan hareketini sağlayarak eklem sertliğini ve kireçlenmeyi önlemek için eklem cerrahisi vakalarında da uygulanan sürekli pasif harekettir. Sürekli pasif hareket fizik tedavi cihazlarının teknolojisi kontrollü tekrar, hız, güç ve açıya izin vermektedir. Bu çalışmada ayak bileği eklemi travması veya cerrahisi sonrasında sürekli pasif hareket fizik tedavisini ayarlanabilir açıda, gerçek zamanlı veya otonom olarak uygulayabilen ve uygulama ve hasta bilgilerini kaydedebilen Talus adlı bir prototip geliştirilmiştir. Hasta bilgilerinin girilmesi, hareket açıların belirlenmesi, çalışma modunun seçilmesi ve kaydedilen hasta ve tedavi verilerinin görüntülenmesi için Nextion kullanılmıştır. Bilgileri kaydetmek ve ilgili eksenlerdeki servo motorları kontrol etmek için Arduino Mega kullanılmıştır. Talus, hasta için özelleştirilmiş tedavinin evde de uygulanabilmesini sağlamaktadır.

Anahtar Kelimeler: Ayak bileği eklemi, Sürekli pasif hareket, Eklem hareket açıklığı, Rehabilitasyon cihazı

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1. Introduction

Physical therapy can address symptoms that may arise after joint trauma or surgery through various methods such as exercise, thermotherapy, electrotherapy, manual therapy, hydrotherapy, phototherapy, cryotherapy, and mechanotherapy. Exercise interventions may include flexibility, strength training, balance and coordination exercises, cardiovascular fitness, agility, and plyometric applications. Active, assisted, and passive range of motion exercises are used to provide flexibility applications, including mobilisation, stretching, flexion, and extension [1].

The continuous passive motion therapy method was developed by orthopaedic surgeon Robert Bruce Salter in 1970 for the treatment of joint injuries. This method provides flexion and extension in the first phase of the rehabilitation process after trauma or surgery. In 1978, biomechanics specialist John H. Saringer produced the continuous passive motion physical therapy device, which provides sufficient repetition of the exercise within the session [2]. Continuous passive motion can prevent the development of symptoms of joint stiffness caused by bleeding or oedema by removing blood and oedema fluid from the joint and soft tissue [3]. Frozen shoulder, anterior cruciate ligament repair, elbow surgery, hip prosthesis surgery, anterior cruciate ligament repair, elbow surgery, hip prosthesis surgery for pain management, regression of inflammation and control of scar tissue formation that may cause loss of joint mobility as well as thromboembolism prophylaxis, Continuous passive motion physical therapy is preferred for cases such as knee replacement, knee cartilage repair surgery, osteosarcoma resection, and paralysis. Devices have been developed for elbow [4], finger, wrist, knee and shoulder as shown in Table 1. Various interfaces, including touch screens, mobile applications, and websites, are currently used in physical therapy devices.

Table 1. Comparison of studies in literature.

Study	Joint	Motor	Sensor	Microcontroller	Interface
[5]	Index finger	Servo motor	Current Sensor	Board	-
[6]	Forearm and wrist	DC motor	Goniometer	Arduino UNO	Mobile application
[7]	Knee	DC motor	Encoder	Arduino Mega / Raspberry Pi	Touch screen and website
[8]	Knee	Wiper motor	Movement limit switch	Digital motor speed controller	LCD screen / Buttons
[9]	Shoulder	Cable-driven actuator	Load Cell	Teensy 3.2 / Arduino	Computer program

In the field of continuous passive motion physical therapy, studies on low-cost optimum actuator selection solutions [10], wearable soft robotic orthosis solutions [11], adjustable controlled movement speed solutions [12], angle tracking solutions [13], treatment process management solutions with prediction algorithms and smart material [14] and actuator solutions are also being carried out [15]. Continuous passive motion therapy is becoming widespread in different application areas such as dynamic seating solutions [16]. While cost, wearability, speed control, angle tracking, personalised treatment and more continuous movement solutions were targeted separately in the studies mentioned above, in this study, cost was targeted in order for healthcare institutions and patients to easily access the physical therapy device needed in the treatment process, portability was targeted to increase patient comfort and reduce patient density in the healthcare system by making it possible for the treatment process initiated by the physiotherapist in the healthcare institution to be continued by the patient at home, and angle tracking and recording features were targeted to personalise the treatment process according to the patient's response to the treatment.

The Talus study developed a prototype physical therapy device for continuous passive motion physical therapy after ankle joint trauma or surgery. Passive range of motion can be provided in real-time or autonomously to provide dorsiflexion, plantar flexion in three different axes, and passive stretching flexibility exercises for inversion, eversion, abduction, and adduction within the joint range of motion. Patient information and application data can also be recorded. This device, which is primarily designed for ankle joint traumas, can be used to perform volar flexion and dorsal flexion (extension), radial deviation (abduction) and ulnar deviation (adduction), pronation and supination range of motion exercises by using arm and hand apparatus instead of leg and foot apparatus in wrist joint traumas. In this case, the required angle values can be adjusted by the physiotherapist and the patient in the real-time operation mode of the device. The working mode and angle are determined by the physiotherapist, and the treatment process, which begins in the hospital, can be continued at home by the patient or the patient's relative, at the determined angle values, under recording.

The motivation of this study work is to develop a portable and accessible product solution compared to the current continuous passive motion therapy (CPM) devices used in the process of physical therapy in joint trauma, which are among the feedback autonomous treatment solutions that enable the treatment to be personalised specific to the patient's treatment response. With a portable and accessible product solution, the treatment process, which can be continued at home under recording, will provide both positive contributions in terms of patient comfort and gains in terms of health system costs.

2. Ankle Joint

The joint where the tibia, fibula, talus, calcaneus, navicular, cuboid, cuneiforms, metatarsals and phalanges bones of the foot and the tibia, fibula, talus and calcaneus bones meet forms the ankle joint as shown on the skeleton modelled with the blender application in Figure 1 [17]. The joint formed by the talus bone with the tibia and fibula is called the lower tibiofibular joint, the joint formed by the calcaneus bone is called the subtalar joint, and the joint formed by the navicular and cuboid bones is called the midtarsal joint, and there is cartilage tissue on the surfaces that contact each other [18]. In the ankle joint, the tibia bone is connected to the talus, calcaneus and navicular bones by the deltoid ligament, the fibula bone is connected to the talus bone by the anterior talofibular ligament and the calcaneus bone by the calcaneofibular ligament, the navicular bone is connected to the talus bone by the talonavicular ligament and the calcaneus bone by the talocalcaneal ligament [19]. There are 7 different ICD-10 diagnostic codes related to foot and ankle injuries, which can cause the development of symptoms such as pain and limitation of movement afterwards, and can occur as open, closed or comminuted fractures or dislocations of the bones forming the joint as a result of excessive stretching or rotation, and different degrees of sprains such as rupture or rupture of the tendons connecting the bones to each other and to the muscles [20]. It is also known that tissues such as the tibial and peroneal nerves or arteries may be damaged during or after the trauma or in the symptomatic process.

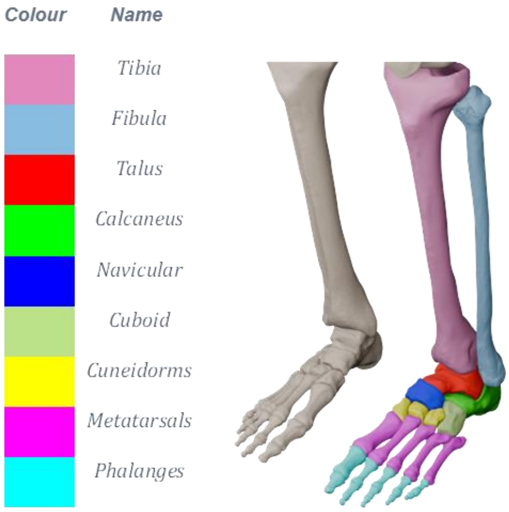


Figure 1. Bones of the ankle joint.

A healthy ankle joint can perform plantarflexion (45^0) and dorsiflexion (20^0), eversion (20^0) and inversion (30^0) and abduction (10^0) and adduction (20^0) movements in the range of motion (ROM) as shown on the body modelled with the blender application in Figure 2 [21]. Peroneus longus and peroneus brevis muscles provide plantarflexion and eversion; tibialis posterior, flexor digitorum longus and flexor hallucis longus muscles provide plantarflexion and inversion; tibialis anterior and extensor hallucis longus muscles provide dorsiflexion and inversion; and peroneus tertius muscle provides dorsiflexion and eversion [22]. In addition, gastrocnemius, soleus and plantaris muscles contribute to plantar flexion. With the symptoms that develop after ankle joint traumas, narrowing of the range of motion (ROM) angle ranges and loss of the muscles that provide movements in the ankle joint due to immobility in the process in which physical therapy is not applied.

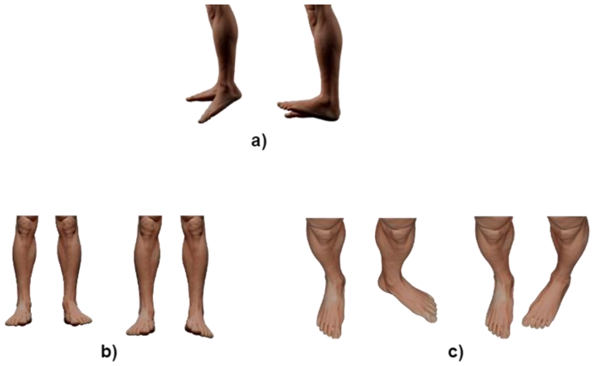


Figure 2. Ankle joint movements: a) planterflexion dorsiflexion b) eversion and inversion and c) abduction and adduction.

3. Continuous Passive Motion Treatment

Continuous passive motion therapy is one of the physical therapy methods designed to prevent the symptoms that may develop after traumas or surgical operations that may occur in the joints and to regress the symptoms that develop. In cases where this method is applied with the help of a device, it provides positive effects on range of motion, swelling, pain values and functional level as in conventional rehabilitation protocols, and the method provides a statistically significant contribution to the knee flexion angle, especially in the early period [23]. Designs compatible with mobile devices are being developed for continuous passive motion therapy devices that allow patients to access the rehabilitation they need at home and to alleviate the patient burden in the rehabilitation system [24]. Some of the areas where the treatment method is applied are joint ligament traumas, fractures, arthroplasty, heterotopic ossification and joint stiffness [25]. In the literature, there are also studies on wearable device designs where continuous passive motion therapy can be applied for different limbs [26].

4. Talus Device

Passive range of motion and passive stretching exercises can be performed to improve flexibility. These exercises can be done with the talus in the x, y and z axes as shown in Figure 3. As treatment progresses, the angle of motion can be adjusted within the range of motion of the ankle joint. It is possible to select the application autonomously or in real-time. Past application data can be recorded to help evaluate the values to be applied in the next session. Passive range of motion flexibility exercises are performed on the z-axis. Flexibility exercises involving passive stretching are performed along both the x and y axes.

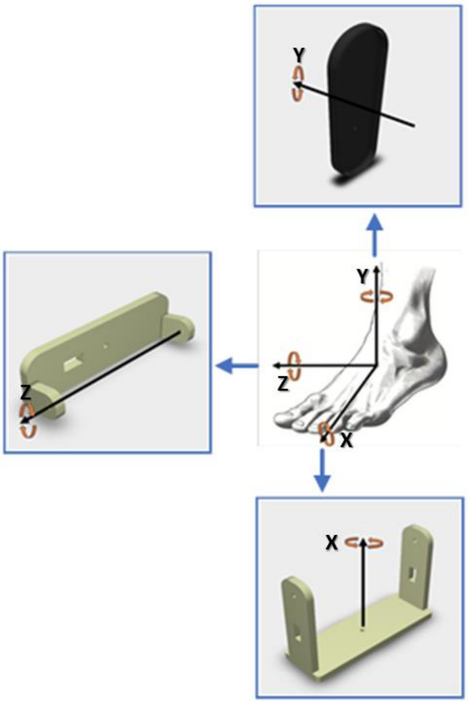


Figure 3. Axes on which treatment is administered.

The prototype drawing created using the SolidWorks program includes Figure 4. To increase the range of motion of the joint during treatment and return it to its previous values, a gradual increase in the angles x, z, and y is applied, as shown in Figure 4.

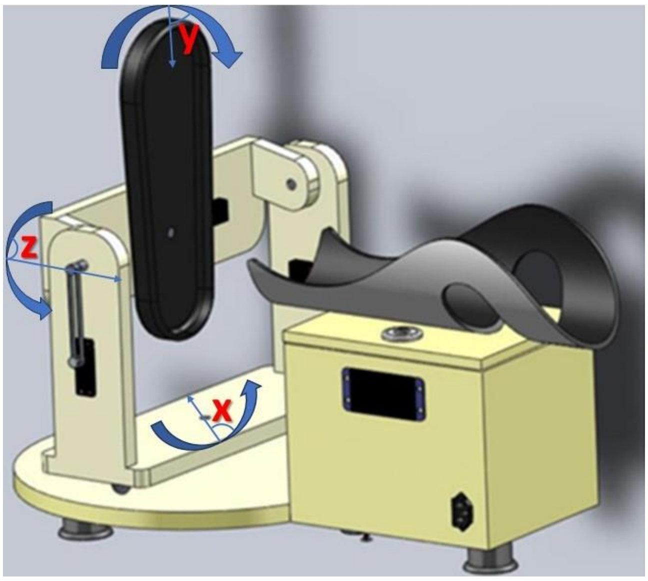


Figure 4. Prototype design.

Figure 5 displays the Talus device, which has undergone production and testing by combining subsystems and systems based on the prototype drawing.

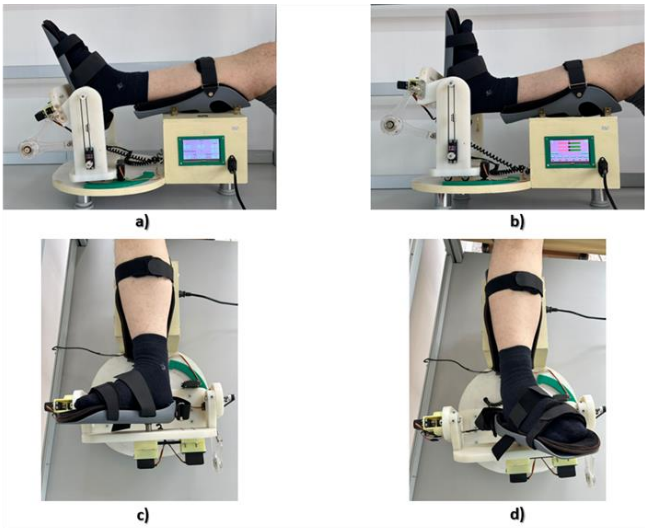


Figure 5. Talus device a) z-axis plantar flexion b) z-axis dorsiflexion c) y-axis adduction d) y and x-axis abduction and inversion exercises.

During the testing process, it was determined that the long-term operation of the z-axis powertrain under load weight posed a sustainability risk. As a result, the production process was completed by replacing the belt pulley powertrain with a gear wheel. The device comprises a box containing leg support and foot apparatus for exercise movements, power transmission organs for transferring the movements to the foot apparatus, servo motors for producing movements, and electronic hardware. The interface screen and power input are located on the box, while the emergency switch can be positioned within the user's reach. Figures 5a and

5b demonstrate the passive range of motion flexibility exercise on the z-axis, while Figures 5c and 5d illustrate the passive stretching flexibility exercises on the x and y axes.

The microcontroller used in the prototype product increases the efficiency in the prototyping process thanks to its cost and widespread use, accessible fault and error solutions in a short time and with less labour, relatively easy programming through its own IDE user interface, its own memory unit, compatibility with the microcontroller and simulation possibilities via emulator or UART connection before prototyping; servo motors are preferred because they can be easily controlled by the microcontroller with the angle values coming from the user interface and their position recall features suitable for working with angle. With these component preferences, a portable and accessible prototype product has been developed.

4.1. Mechanical Design

The ankle apparatus designed by Talus is composed of plastic, sponge, and belts. The apparatus transfers passive range of motion and passive stretching flexibility exercise movements in the x, y, and z axes through the belt pulley and gear drivetrain, as shown in Figure 6. These exercise movements are provided by six MG996R servo motors, which are driven by an Arduino Mega 2560 microcontroller with 0-255 (5V) PWM (Pulse Width Modulation). Table 2 defines the drivetrain components for the belt, pulley, gear, y, z and x axis, whose connections are shown in Figure 6.

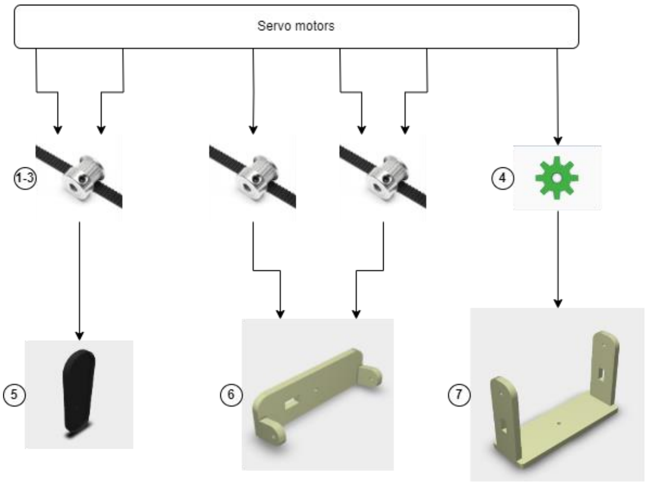


Figure 6. Mechanical connection diagram.

Table 2. Mechanical components.

Number	Name
1-3	Belt pulleys
4	Gear
5	y-axis part
6	z-axis part
7	x-axis part

4.2. Hardware Design

The interface allows for the input of patient information and range of motion angles for related axes, selection of operating mode, and display of recorded patient information and application data. The system also enables the saving of patient information and application data. Servo motors can be driven by PWM based on the range of motion angles entered via the microcontroller and the selected operating mode. The system communicates with the interface and microcontroller, specifically the Universal Asynchronous Receiver Transmitter (UART). It utilizes servo motors to perform exercise movements within the selected mode and range of motion angles on the relevant axes. Figure 7 shows the power and communication connections for the servo motors, regulators, power supply, microcontroller, and emergency button.

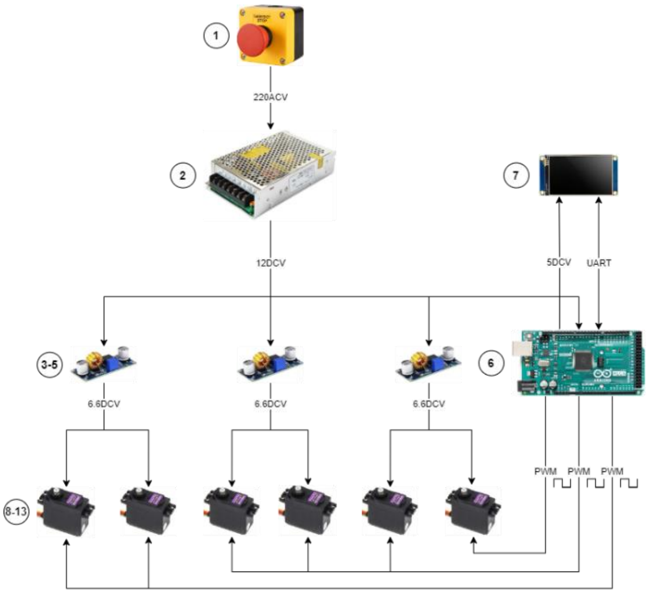


Figure 7. Electronic power and communication connections.

Table 3 defines the emergency button, switching power supply, voltage regulators, microcontroller, human machine interface and motors, whose connections are shown in Figure 7 above.

Table 3. Electronic components.

Number	Name
1	Emergency button
2	Switched-mode power supply
3-5	XL4015 voltage regulators
6	Arduino mega 2560
7	Nextion NX4827T043
8-13	MG996R servo motors

Figure 8 shows the schematic drawing of the connections, while Figure 9 displays the block diagram of the communication connections. The device is powered by 220V AA through the emergency switch. The switched power supply provides 12V DC output to the Ardunio Mega 2560 microcontroller and XL4016 regulators. Two servo motors on each voltage regulator are powered with 6.6V DC. The interface is supplied with 5V DC through the built-in voltage regulator on the microcontroller. The microcontroller communicates with the interface via UART, while PWM is used to drive the servo motors.

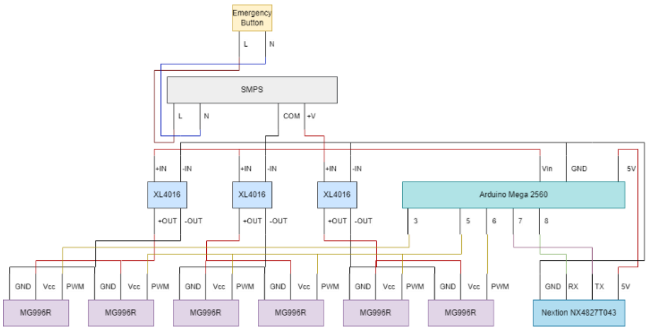


Figure 8. Schematic representation of electronic power and communication circuit.

The patient and date information, as well as the treatment data, are transmitted to the microcontroller via UART and stored in EEPROM. The recorded data is then transmitted back to the interface using the same protocol. In real-time operation mode, the slider data is transmitted instantaneously. In autonomous mode, the assigned angle values are transmitted once from the interface to the microcontroller. The microcontroller controls the servo motors using PWM based on the angle values received from the interface.

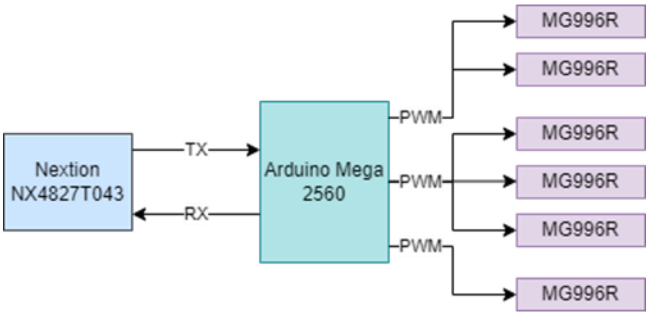


Figure 9. Block diagram of electronic communication connections.

4.3. Software

Figure 10 shows the flow chart of the system for entering information on the interface, working in selected modes at specified values, and saving work with information. Upon initialization of the device, the microcontroller transfers information stored in the database to the patient information tracking screen via UART. The motors are driven to their assumed positions by rotating the axis angles to the assumed values. In real-time operation mode, servo motors are driven by transferring the slider positions from the interface to the microcontroller. Patient information and angle values are printed on the tracking screen and saved in the EEPROM after the axes are assigned and the autonomous operation mode is selected. The servo motors are then controlled at the assigned axis values until the real-time mode is activated again.

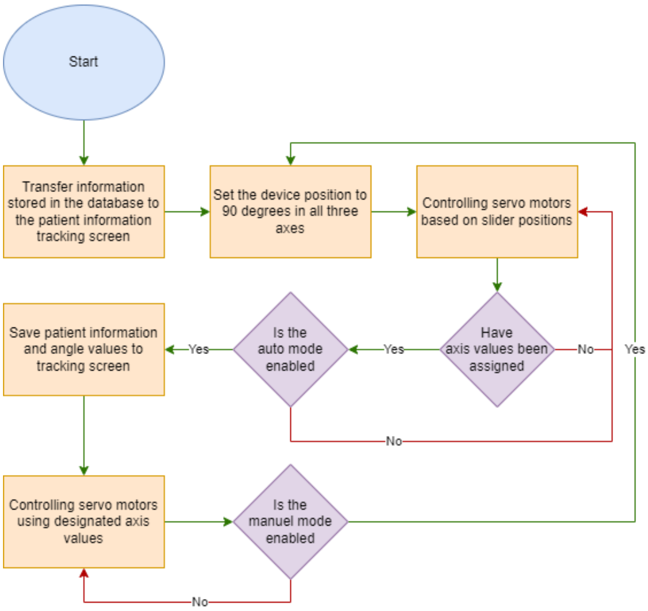


Figure 10. Flowchart of the system.

The operating range parameters entered on the user interface control screen are translated into instantaneous slider positions and sent to the microcontroller in real-time operation mode. The code flow first determines the axis to which the angle value data sent to the microcontroller from the UART interface belongs. The angle data that determines the axis is assigned to the variable where the angle value of the relevant servo motor is stored. The angle value is obtained in degrees by limiting the data assigned to the variable within the specified range. The servo motor of the related axis is then positioned to this angle value using a constant speed.

The slider positions are transmitted to the microcontroller from the control screen using the codes. During real-time operation, the slider data for the relevant axis is combined with the axis code and immediately sent to the microcontroller from the interface to drive the motors.

In autonomous operation mode the transition to autonomous mode is initiated by pressing the button after determining the minimum and maximum values. The code flow first determines whether the angle value data sent to the microcontroller from the interface via UART is minimum or maximum and to which axis it belongs. The angle data for the relevant axis is assigned to the variable that stores the angle value of the corresponding servo motor, and this assignment is verified. Once the assignments have been confirmed, the accuracy of the maximum and minimum data is checked before starting the autonomous mode.

The minimum and maximum values are transmitted to the microcontroller from the control screen using the codes. The angle values, determined by the sliders, are assigned to the minimum and maximum buttons of the corresponding axis. These assigned values are then transmitted to the microcontroller via UART through the code of the relevant axis.

When the autonomous mode switch button is pressed, the information from the patient information entry screen and the values specified on the control screen are transferred to the patient information recording screen and saved in the EEPROM. The code flow begins by obtaining the desired data using the address information in the form of page, sequence number, and data type. The obtained data is then written to the EEPROM address determined for it.

Codes on the interface side are used to switch to autonomous mode and save data. When the code for switching to autonomous operation mode is transmitted from the interface to the microcontroller, the microcontroller reads the date, patient information, and treatment data over the interface to record them. The Code Flow starts with autonomous mode. Upon activation of the autonomous mode, the system queries the patient barcode number to determine if it has been previously registered. If the barcode number is found, new information is added to the page containing patient information and treatment data associated with the previously registered barcode number. If the barcode number is not found, the system prints this data on a blank page. The data printed include the patient's barcode number, age, gender, treatment date (in the format day/month/year), minimum and maximum movement angle range values of the axes, and the number of exercise rounds.

In the interface and microcontroller communication the sliders' instantaneous data, assigned maximum and minimum values, and operating mode selection are transmitted via UART in hexadecimal format.

4.4. User Interface

In the Nextion NX4827T043 TFT LCD Human Machine Interface, the date and patient barcode number, age and sex are entered from the patient information screen as shown in Figure 11. This information is printed on the patient information tracking screen shown in Figure 13, together with the minimum and maximum angle values of the x, y and z axes and the number of exercise rounds determined from the HMI control screen shown in Figure 12. This patient information and treatment data printed on the patient tracking screen is transferred to the microcontroller for storage and written to the EEPROM.

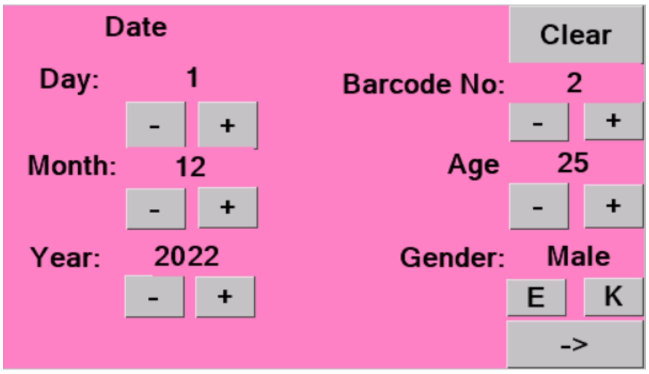
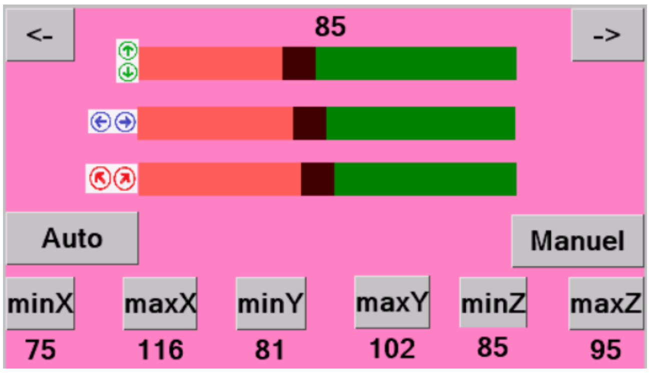

Date
Day: 1
Month: 12
Year: 2022
Barcode No: 2
Age 25
Gender: Male

Figure 11. Patient information entry screen.

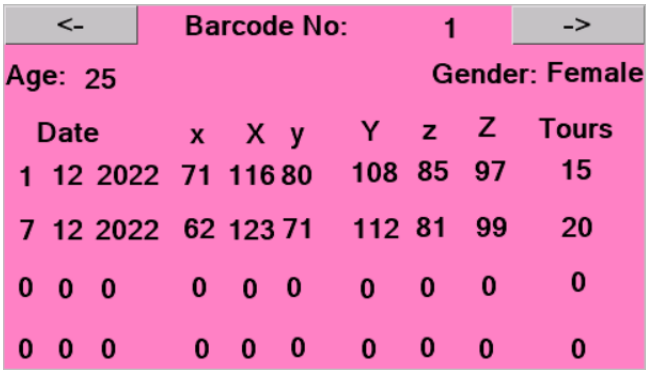
The angle values and real-time or autonomous mode can be set on the control screen as shown in Figure 12. Angle values are set using the sliders of the relevant axis. The set values are assigned using the minimum and maximum buttons of the relevant axes. The operating mode is selected using the Auto and Manuel buttons. In real time mode, the instantaneous values of the sliders are used, while in autonomous mode, the assigned minimum and maximum values are used.


85

minX	maxX	minY	maxY	minZ	maxZ
75	116	81	102	85	95

Figure 12. User interface control screen.

The tracking screen shown in Figure 13 contains historical application data. This data includes barcode number, patient age and gender, treatment date, exercise angles and number of laps. The barcode number, age, sex and date information in the form of day, month, year are read from the patient information entry screen in Figure 11. This information is entered by the user at the start of the session. The minimum and maximum values of the x, y and z axes are read from the user interface control screen shown in Figure 12. The minimum and maximum values of the relevant axes are indicated by prepending min or max to the axis name on the user interface control screen, while on the patient information tracking screen the letter identifying the relevant axis is written in lower case for the minimum value and upper case for the maximum value. These values are set by the user at the start of treatment. The number of laps is increased by one for each completion of movements in three axes.



Barcode No: 1

Age: 25 Gender: Female

Date	x	X	y	Y	z	Z	Tours
1 12 2022	71	116	80	108	85	97	15
7 12 2022	62	123	71	112	81	99	20
0 0 0	0	0	0	0	0	0	0
0 0 0	0	0	0	0	0	0	0

Figure 13. Patient information tracking screen.

5. Discussion

Following ankle joint trauma, such as sprains, dislocations, fractures, or surgical operations, symptoms such as pain or limited movement may develop. The Talus method offers continuous passive motion physical therapy to alleviate these symptoms and prevent joint stiffness and calcification. Before treatment, please enter the patient's barcode number, age, gender, and treatment date information. During treatment, passive range of motion and passive stretching exercises can be applied to improve flexibility. These exercises should provide dorsiflexion and plantar flexion, inversion and eversion, and abduction and adduction in three different axes, within the range of independently changeable angles of motion. The application of these exercises can be done in real-time or autonomous operation modes. At the end of each treatment session, patient information and treatment data can be recorded for evaluation in subsequent sessions. This helps to organise the treatment plan and accelerate the healing process.

The Talus software update allows for the addition of adjustable range of motion angles, movement speed, and recorded treatment options. Patient information, including barcode number, age, gender, and name, can be entered using an appropriate screen and single card computer. Isokinetic strengthening exercises and flexibility exercises can be applied using suitable motor and power transmission organs [27]. Additionally, ultrasonic sensors can be utilised to incorporate a hybrid treatment option that includes deep-acting heat, cavitation, and acoustic flow therapy with conversion heat transfer form [28]. The prototype design takes into account accessibility and portability.

6. Conclusions

In ankle joints, which bear the weight of the entire body, traumas such as sprains, dislocations, or fractures are common. These traumas can cause pain and limit movement. Physical therapy employs various methods and technologies to prevent or alleviate these symptoms. This study presents the development of Talus, a portable physical therapy device that applies the continuous passive motion physical therapy method to regress or prevent symptoms that develop after ankle joint trauma and surgery. Nextion was utilised to input date and patient information, select angles and operating modes, and display stored patient information and treatment data. Arduino was employed to control servo motors at the specified angles and in the selected operating mode, as well as to record patient information and treatment data.

The contribution of the device is to provide the end user with accessibility to the physical therapy device, sustainable treatment at home and customisable treatment process with low cost, portability and data recording features. Thanks to the developed system, at the end of the relevant session of the treatment process, which can be started after entering the patient and treatment information respectively, the process can be recorded so that it can be evaluated in the next session. It contributes to increasing patient comfort in the treatment process and reducing the patient burden in the health system.

7. Acknowledgment

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