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DESIGN AND IMPLEMENTATION OF A COST-EFFECTIVE, FUNCTIONAL ELECTRICAL STIMULATION DEVICE FOR FOOT DROP REHABILITATION

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Functional electrical stimulation (FES) is an effective method for correcting foot drop and facilitating forefoot elevation during walking. As a subset of neuromuscular electrical stimulation (NMES), FES enhances functional movements by stimulating muscles to compensate for neurological deficits. Recent technological advancements focus on developing more compact, efficient, and customizable devices that cater to individual patient needs, improving rehabilitation outcomes. This study developed a hybrid device combining electrical stimulation with ankle-foot orthoses (AFO) to enhance gait rehabilitation. A customized stimulation unit with adjustable parameters was created to deliver electrical impulses. An Arduino nano microcontroller was programmed to process data from an MPU6050 sensor, which measures accelerations and ankle angles (plantar flexion and dorsiflexion). This setup allows for precise control of stimulation patterns, offering a cost-effective and adaptable solution for patients with foot drop, aligning with current scientific efforts to enhance gait rehabilitation technologies.

1. INTRODUCTION

Magnetotherapy [1] and functional electrical stimulation [2] are orthopedics' most popular physiotherapy methods. The principal treatments for foot drop are AFO and/or FES. Studies indicated that 47 % of patients and caregivers utilized electrical stimulation, and 37 % employed rigid orthosis in gait rehabilitation [3]. In clinical practice, no single medical device integrates the functionalities of both treatment modalities.

This paper presents the development of a prototype ankle-foot orthosis device tailored for applying functional electrical stimulation.

AFOs are predominantly synthetic materials and are frequently employed to enhance the alignment of the ankle joint, facilitate increased walking speed, and diminish energy expenditure during ambulation. However, AFOs restrict ankle mobility to a considerable extent, allowing for no degrees of freedom, which leads to a gait pattern that is markedly different from the typical physiological ankle movement observed in natural walking. In this context, it is proposed that a pneumatically actuated ankle-foot orthosis featuring adjustable lateral springs be developed. This design aims to enhance the mobility of the ankle joint, with maximum observed values of 25° for dorsiflexion and 15° for plantar flexion.

FES is a therapeutic approach to address the "drop foot" condition by facilitating forefoot elevation during ambulation. The effectiveness of this intervention is contingent upon the ability to electrically stimulate the muscle tissue and peripheral nerves, which must retain their excitability. The Arduino Nano, when utilized through the Arduino Integrated Development Environment (IDE), is programmed to compute gravitational acceleration and to measure the angular displacements of movements across multiple planes. The components for constructing the pulse generator will be identified upon program completion. In this context, adjustable parameters, including voltage, frequency, and pulse duration, will be utilized within specified intervals based on data obtained from the relevant specialized literature.

2. FUNCTIONAL ELECTRICAL STIMULATION

The method uses a compact medical device that provides electrical stimulation through the peripheral nervous system, consequently inducing muscle contractions that facilitate functional activities in situations involving damage to the nervous or musculoskeletal systems. During the initial swing phase of ambulation, the stimulator activates to raise the leg in dorsiflexion and slight eversion. A battery, typically 9 volts, powers it. It utilizes surface electrodes, connecting wires, and a switch for manual activation during walking or an automated pattern programmed to initiate the exercise function. It contains several parameters that can be modified to meet the patient's needs. FES may be integrated with orthotics or additional exercise devices to help with the rehabilitation process [4].

The duration, frequency, and amplitude of the electrical pulses are the parameters used to optimize their effects. These parameters are meticulously calibrated to align with the patient's rehabilitation objectives and will be refined in subsequent chapters.

FES and pneumatic components may be integrated to achieve an optimal equilibrium in the gait cycle, monitor fatigue reduction, and satisfy pressure requirements.

- The fundamental components of a functional electrical stimulation system include the following:
- An electrical stimulator;
- Electrodes for delivering stimulation;
- A control interface (sensors or automatic stimulation control);
- An orthosis offers supplementary assistance for executing the intended movement in certain instances.

Figure 1 shows a generic block diagram of a noninvasive stimulation unit where surface electrodes apply the stimulus. The electrical stimulator produces electrical discharges that induce muscle contractions. Stimulation is administered through distinct stimulation channels. A stimulation channel consists of a pair of electrodes (cathode and anode) used to

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deliver complex stimulation pulses (important characteristics of stimulation pulses are described below). A simulation can have multiple channels, each stimulating individual muscles using unique settings.

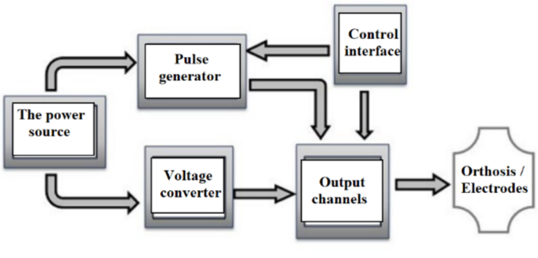

Fig. 1 – Block diagram of an FES system.

FES includes the administration of electrical impulses to the peroneal nerve, generating the artificial contraction of the tibialis anterior (TA) muscle. During the initial stage of the postural phase, no electrical stimulation is applied upon heel contact with the ground. The switch identified the heel elevating from the surface. During plantar and knee flexion, the system generates electrical stimulation of the nerves, resulting in dorsiflexion and eversion during the swing phase. After reaching the dorsiflexion of the ankle, the switch re-detects the heel strike, ending the stimulation and the gait cycle (Fig. 2) [4].

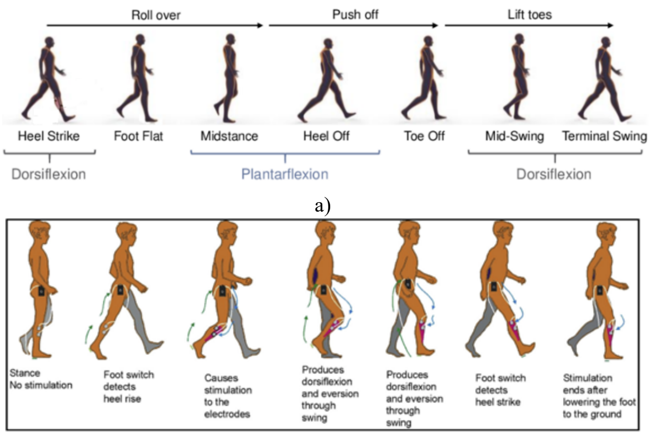

Fig. 2 – a) Human gait cycle phases and activation timing of plantar and dorsiflexion during gait cycle [5] and b) gait cycle utilizing a portable ankle-foot orthosis equipped with a Functional Electrical Stimulation (FES) device [6].

3. PROPOSED DESIGN

The suggested solution is to acquire a hybrid orthosis incorporating electrical stimulation. To produce the orthosis, anthropometric data, dimensions of the drive system, and angular measurements for the two types of ankle flexion calculated using Kinovea software were established, along with the 3D model. This led to the development of an experimental model that addresses current issues in orthopedic treatment.

An Arduino Nano was programmed to generate electrical impulses by acquiring data from an MPU6050 sensor (acceleration), measuring ankle angles (plantar flexion and dorsiflexion), and constructing a stimulation unit with adjustable parameters. The methods are ultimately compared and integrated to develop an enhanced hybrid model.

The Arduino board was programmed using Arduino IDE software, while the circuit was designed using CadSoft Eagle 7 Standard software. This free application offers numerous valuable libraries for printed circuit board design. The components of the utilized modules are presented: IC NE 555, DC-DC converter XL 4005, the module for the Arduino Nano board, JP jumpers for electrode connections, and other essential elements, including the IRF840 transistor (MOSFET), diodes, resistors, capacitors, power source, and an electromagnetic coil. The software interface is illustrated in Fig. 3.

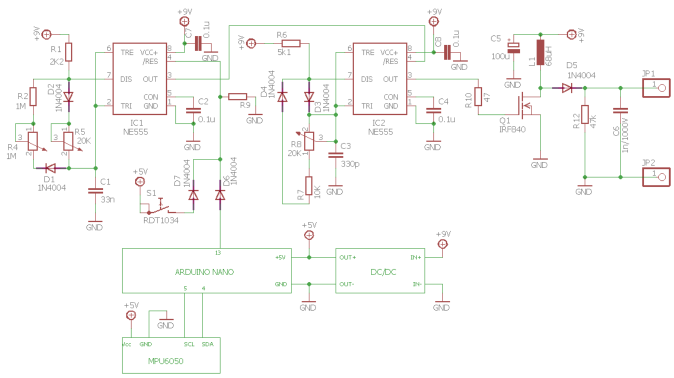

Fig. 3 – Eagle 7.0 Standard software interface.

The circuit includes two NE 555 integrated circuits (ICs) functioning steadily to generate a signal continuously. To operate the IC 555 in a stable mode, it is essential to perpetually re-trigger the IC 555 following each cycle. The re-triggering works by connecting the Trigger control inputs (pin 2) with the Threshold input (pin 6). The IC1NE555 circuit operates on a 9V supply; capacitor C_1 charges when the pulse discharge circuit is inhibited (logic level 1) and discharges (conducts current) when at logic level 0. The load circuit is connected to the power source and comprises resistor R_1, rectifier diode D_2, and potentiometer R_5, linked to the combined control input of pins 2 and 6. The load determines the pulse duration, which can be modified using potentiometer R_5.

The discharge circuit includes a path from GND consisting of diode D_1, resistor R_2, and potentiometer R_4, ultimately connecting to discharge pin 7. The discharge circuit determines the acceptable frequency range for electric stimulation and modifies it via the potentiometer R4.

On the IC1NE555 circuit, commands are received via the Arduino Nano and a Switch. It features additional capacitors (C_8 and C_4) added to reduce current surges that would pass through the circuit. Output 3 of the integrated circuit IC2NE555 is connected to a field-effect transistor IRF840, at the input of which the resistor R_{10} must be placed to limit its voltage (it can reach 500 V). When the transistor blocks, the voltage on electromagnetic coil L_1 suddenly increases and behaves as a generator, and through diode D_5, it charges capacitor C_6. C_5 and R_{12} are also needed to limit the maximum open-circuit voltage.

The DC-DC converter is essential because the power source supply is 9 V. At the same time, the Arduino operates at a maximum of 5 V. This converter is utilized due to its superior performance compared to a linear source and its recommendation for battery systems.

4. EXPERIMENTAL MODEL FOR FUNCTIONAL ELECTRIC STIMULATION SYSTEMS

Several hardware components were used to develop the experimental model for FES. The MPU600 module (accelerometer and gyroscope) and the Arduino board (development board) are the most critical elements.

The MPU6050 module includes a 3-axis gyroscope and accelerometer, allowing us to measure rotation along all three axes, static acceleration due to gravity, and dynamic acceleration due to motion with Micro Electromechanical System (MEMS) technology (Fig. 4).

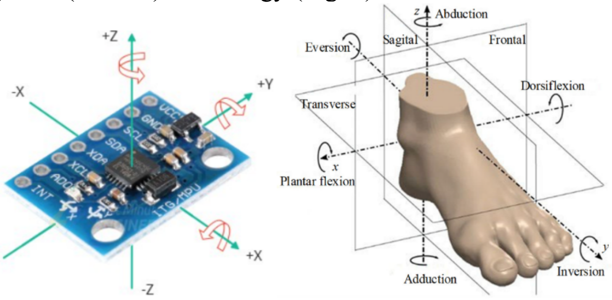

Fig. 4 – Motion axes of the MPU600 module correlated with ankle movements [7,8].

The MPU6050 module, comprising an accelerometer and gyroscope, determines the angular range of movements for the ankle joint in the sagittal plane.

Measurements of foot angles are used to determine the moments of functional electrical stimulation pulse generation applied to the muscles responsible for raising the foot. This feedback strategy allows physiological foot movement in spastic limbs [9].

The four connecting wires connected the Arduino Nano to the MPU6050 module, as shown in Fig. 5

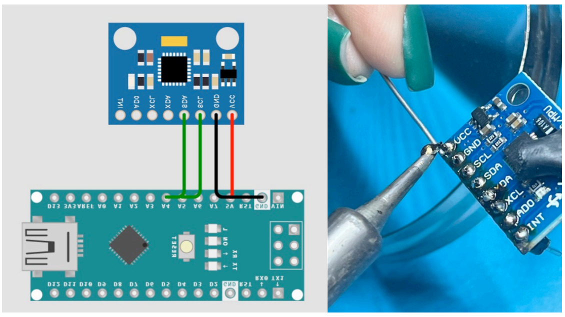

Fig. 5 – Circuit diagram for ankle motion detection made in worki.com and establishing the connections by soldering the pins.

Pins 2 and 6 are connected in the circuit, allowing the circuit to re-trigger on each cycle, charging the capacitor and allowing it to function as a free-wheeling oscillator. During each cycle, the capacitor charges through both timing resistors RA and RB but only discharges through resistor RB because the other side of RB is connected to the discharge terminal, pin 7.

The capacitor then charges up to 2/3 V_{DC} (the comparator's upper limit), which is determined by the combination of 0.693 (RA + RB)×C and discharges itself to 1/3 V_{DC} (the comparator's lower limit), which is determined by 0.693×RB×C. This results in an output waveform whose voltage level is approximately equal to V_{DC}-1.5 V and whose output "ON" and "OFF" periods are determined by capacitor and resistor combinations.

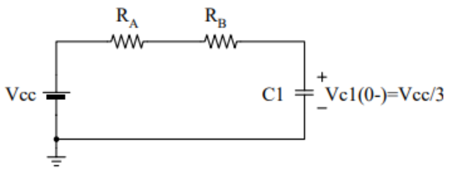

Fig. 6 – Charge circuits for capacitor C1 in the NE555.

When the timer output is high (logic level 1), the equivalent circuit for charging capacitor C_1 is represented in Fig. 6. When the output is low (logic level 0), the discharge circuit looks like in Fig. 7.

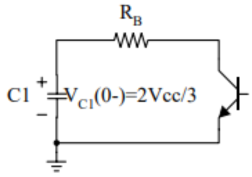

Fig. 7 – Discharge circuits for capacitor C_1 in the NE555.

Loading and unloading times can be determined with the relationships:

$$t_{loading}=0.693\times(R_A+R_B)\times C_1, \quad (1)$$

$$t_{discharge}=0.693\times R_B\times C_1. \quad (2)$$

The initial NE555 circuit of the constructed pulse generator (R_A = 2.2 kΩ, R_B = 1 MΩ, C_1 = 33 nF) illustrates the mathematical calculation of the capacitor's charge and discharge durations when the potentiometers are adjusted to 0.

The charging time of capacitor C_1 is:

$$t_{loading}= 0.693\times(2200+10000000)\times0.000000033\approx23 \text{ ms.} \quad (3)$$

The discharge time of capacitor C1 is:

$$t_{discharge}= 0.693\times10000000 \times0.000000033\approx22.8 \text{ ms.} \quad (4)$$

The signal (T) period can be determined, and the frequency (f) can be calculated using the inverse mathematical relationship.

$$T = t_{loading}+ t_{discharge}, \quad (5)$$

$$T = 45.8 \text{ ms}, \quad (6)$$

$$f = \frac{1}{T}, \quad (7)$$

$$f= \frac{1}{0.0458} \approx 21 \text{ Hz.} \quad (8)$$

Using these formulas and applying them to both NE555 circuits, the 20 Hz – 40 Hz frequency range was obtained.

The Arduino IDE software and its corresponding programming language are used to develop code for controlling electrical pulses aimed at ankle rehabilitation needs.

The code was developed using the libraries "Adafruit_MPU6050.h","Adafruit_Sensor.h", and "Wire.h".

The initial set of criteria indicates that if the x-acceleration component is less related to the reference value (determined through many recordings) and the gravitational acceleration remains within a limited error margin, the pulse generator will initiate stimulation.

Stimulation will stop when the dorsiflexion set point is reached. The same range of values for gravitational acceleration as in the previous decision set will be respected. In the serial monitor, the displayed values represent the angles measured in degrees and the gravitational acceleration calculated in m/s^2.

5. ELECTRODE SETUP AND PROTOTYPE EVALUATION

Most research studies advise that stimulation electrodes for patients experiencing foot drop be positioned adjacent to the anterior tibial muscle. One electrode should be placed directly beneath the head of the fibula, while the second should be positioned as close as possible to the tibia (Fig. 8.a). The peroneal nerve extends to the foot, allowing for the direct placement of stimulation electrodes on the ankle (Fig. 8.b).

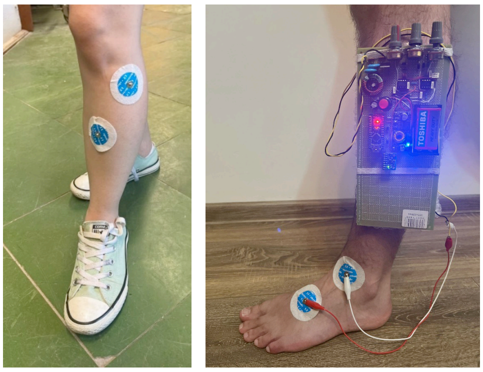

Fig. 8 – Electrode positioning approaches for foot drop rehabilitation: a) tibial region; b) ankle region.

Based on a comprehensive review of specialized literature and the technical specifications of the utilized equipment and devices, an output voltage of 9 V has been established. The electric stimulation parameters are defined as follows:

- Pulse frequency (rectangular signal) within 20 Hz to 40 Hz;
- Pulse duration between 50 µs and 400 µs;
- Pulse amplitude (voltage) is adjustable up to 250 V, with standard operating values typically around 100 V and 150 V (Fig. 9 and Fig. 10).

Fig. 9 – Adjustment of applied stimulus voltage: 100 V.

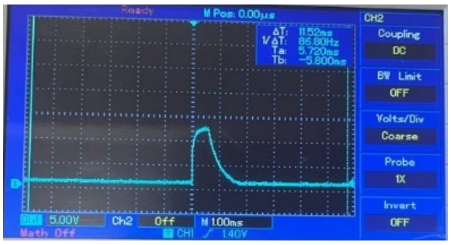

Fig. 10 – Adjustment of applied stimulus voltage: 150 V.

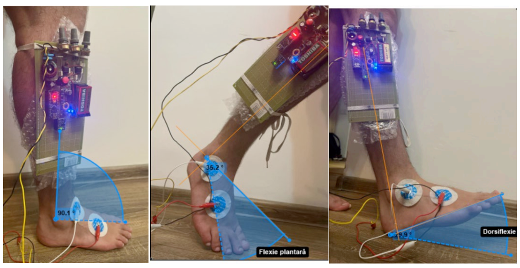

Fig. 11 – Validation of the correctness of the programming algorithm of the Arduino Nano by measuring the angles in the sagittal plane in Kinovea.

Figure 11 illustrates the location of the FES system, intended for the functional recovery of ambulation in patients with foot drop, together with the electrodes that deliver impulses to the peroneal nerve. The images in the figure were extracted from a video sequence taken while the person was walking. It validates that the Arduino Nano commands the pulses according to the plantar and dorsiflexion angles of the walking type. The system's efficiency can be doubly validated by measuring angles in Kinovea (Fig. 12).

The first recommendation to ensure walking recovery is post-traumatic orthosis; short electrical stimulation sessions can be added to prevent muscle atrophy.

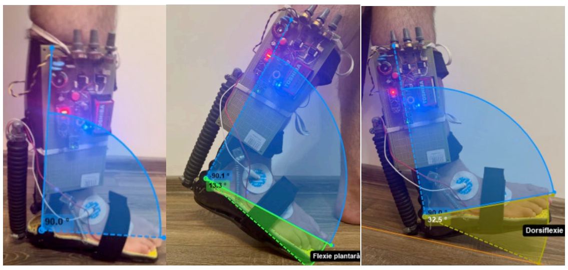

Fig. 12 – Validation of the correctness of the programming algorithm of the Arduino Nano by measuring the angles in the sagittal plane in Kinovea while wearing the orthosis and the FES system.

6. CONCLUSIONS

Electrical stimulation can directly activate affected muscles, helping to restore muscle function and stimulate coordinated muscle contractions.

Thus, this article presents the method of making, testing, and validating an FES system whose pulses are controlled by the Arduino Nano software. The MPU6050 sensor accelerometer determined the movements and angles of the ankle in the sagittal plane. This technology represents a cost-effective and efficient solution for treating "foot drop.”

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CREDIT AUTHORSHIP CONTRIBUTION

Oana-Andreea Chiriac: conceptualization and writing.
Felix Constantin Adochiei: review and editing (equal).
Nicoleta-Iuliana Trocan: review and editing (equal).
Mircea Iulian Nistor: formal analysis.

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