Functional Electrical Stimulation (FES) Based Low-Cost Assistive Device for Foot Drop-A Pilot Study

Conference Paper · December 2016

DOI: 10.1007/978-981-10-0266-3_23

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Functional Electrical Stimulation (FES) Based Low-Cost Assistive Device for Foot Drop- A Pilot Study

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Abstract— **The objective of this study was to design an efficient and economical FES device. The device was designed for post-stroke foot drop patients who could walk up to 5meters with assistance and could stand up from a sitting position. The device is Arduino-based and can sense the start of the swing phase and able to stimulate the dorsiflexor muscles till the end of the swing phase. The device was tested on 5 male subjects (aged 40-50 years), taking Temporal Spatial Parameters as indicators of efficiency. A significant improvement in the parameters was observed with the usage of the device.**

Keywords— **Gait, Functional Electrical Stimulation (FES), Rehabilitation, Foot drop, Arduino.**

I. Introduction

‘Foot drop’ or ‘drop foot’ is the gait deviation which results in inadequate activation of dorsiflexor muscles of lower limbs as a result of which ‘toe drag’ occurs depriving the person of the swing phase of the gait cycle. The inability to lift the foot during swing phase makes it problematic to be able to experience curbs, stairs, and uneven surfaces. The findings are the selected phases of excessive plantar flexion with an otherwise normal gait [1]. Stroke is reported to be the most common cause of this disability in the world [2, 3].

Functional electrical stimulation (FES) which is considered to be the most effective treatment of foot drop is the technique of smearing harmless levels of electric current to activate the impaired or disabled neuromuscular system in a synchronized fashion in order to accomplish the lost function. FES recruits a physiological-like stimulation in the intact peripheral nerves, providing restoration of functions of various body structures in the neurologically impaired individuals. FES system may be surface system or percutaneous (implantable). It is clearly evident in many researches already done that FES provides therapeutic effect to patient with time. FES has also been used comprehensively to regenerate the activation pattern of lower extremity muscles to rehabilitate gait and to produce the sequence of lower extremity muscle action desired during a gait cycle.

Previous works on FES (starting from the early 1990’s) required more parameters to take into account for accuracy. The methodology adopted by Sabut et al did not consider the time duration of electrical pulses provided to the patient which is major factor for designing FES system and it varies from patient to patient as desire varies [4]. It is too important from the comfort and safety point of view for the patient. Chen et al did not involve the stride frequency and stride length as major parameters so that it could provide the nearest to accurate information about the problem in gait [5]. In another study by Sabut et al FES pulses were applied in the constant mode which might have caused the accommodation phenomena in muscles resulting in the body getting used to the signals and not responding to them accordingly [6].

The aim of this study was to design an FES-based device for foot drop that is safe, cost-efficient, reliable, portable and light weight. The device would detect the start of swing phase and would avoid the accommodation phenomena.

II. Device design

The process of designing a real time assistive device for foot drop patients is a complex task. The process that is followed for the designing of FES device (Figure 1) starts with the designing of FES stimulator and continues with detection of bending in the knee and end with the controlling of device. The stimulator was designed with the 555 timer based technique.

The design parameters of the device were carefully selected, keeping in mind the safety threshold and previous researches. The major design parameters as summarized in Table 1 were finalized for the optimal performance of the device.

Table 1: Parameter ranges for device design.

Parameter	***Range and Description***
Voltage	The voltage requisite lies within the range of 80-110V which will be able to excite the peroneal nerve innervating the dorsiflexors.
Current	The current boundary lies within 90-120mA which produces the depolarizing effect in the muscles.
Frequency	The frequency essential was above 100Hz and it carries tangling effects.
Duty Cycle	The duty cycle was confined to 30% and it depends on the need of subject.

A. Swing Phase Detection

The detection of the start of swing phase is important because this is the point when the stimulation should take place. Flex sensor was selected for detecting the bending movement of knee. It follows the strain gauge principle; the more the knee bends the more the resistance changes at output.

B. Microcontroller

The Arduino-Uno board was used which has microcontroller ATmega328 for the programming and controlling of sensor. Operating voltage is 5V which can be provided through USB or any external source. The board operates on a 6 to 20 volts external supply. However, the external power supply should not be less than 7V, otherwise the 5V would not generate full potential and the board might get unstable.. Conversely, supplying more than 12V would cause the voltage regulator to overheat and damage the board. Therefore a supply range of 7 to 12 volts is recommended.

The Arduino software includes a serial monitor allowing simple textual data to be sent to the Arduino board and vice versa. A Software Serial library allows for serial communication on any of the Uno's digital pins.

C. Stimulator Design

The main component for producing the pulses or waveform is the 555 timer IC, Figure 2. It was used in astable mode to produce pulses. In the first step it produces pulses of low voltage with less current intensity. For voltage amplification 741 op-amp was used to enhance the voltage to certain limit, and current was increased to the required range with the Darlington configuration of power transistors. Further amplification of voltage was still needed for which the present output was provided at the input of power transformers which accomplished the voltage amplification up to 100volts. The waveform it produces is functional monophasic square waveform within the required frequency range and duty cycle completing our requisites. Further sensing and controlling mechanism were implemented to achieve the final task of activating the dorsiflexors of the foot during swing phase. There is a brief description about the components committed in this approach.

The frequency and duty cycle of 555 timer output can be controlled by the VR3 and VR4 potentiometers respectively. Diode is placed in between pin 7 and 2 to achieve the duty cycle less than 50% which is required.

The 555 timer gives the output consisting of rectangular peaks having amplitude of 9 Volts. This signal is fed to a potentiometer so that we can get the peaks of variable amplitude.

D. Current Amplification

Power transistors were used for the current amplification purpose in this technique as the requirement is of not only high voltage but also high current. 2N3055 is implemented in Darlington pair configuration which provides max output current of 15 ampere which is quite feasible and even much more than the requirement. The Darlington pair provides current gain in value of thousands and works in the combination with resistors and capacitors so that the signal remains smooth after passing through the transistors.

E. Voltage Amplification

Ferrite core transformers were used in the circuit design for stepping up the voltage. They were used due to low power losses at higher frequencies with low noise and circuit works at the higher frequency of 150Hz. These transformers offer high resistivity with low eddy current loss. They are small in size, least expensive and provide minimum loss for high frequency design with current technology.

F. Electrodes

Disposable Adhesive Surface Electrodes are used as a means of transmitting the pulses to peroneal nerve which are light weight and pre-gelled. Special formula gel for a very sticky electrode is used to make it completely adhesive yet easy to remove. Electrodes of size 5x5cm are placed on the motor points of peroneal nerve to provide maximum stimulation with less pain. Silver / silver chloride conductive layer for optimal signal recording. The optimal placement of electrodes is necessary to avoid stimulation and pain in the surrounding area.

G. Mechanism

Initially flex sensor was calibrated by taking different values when the subject performed flexion and extension of the knee. Flex sensor output was connected to the analog pin of Arduino board whereas one LED was placed on digital pin 13 of Arduino board for calibration. When foot underwent swing phase LED turned on, and the LED turns off in standing position or during stance phase of gait cycle, the value recorded at this instant was used as final one which triggers the stimulator circuit.

Flex sensor is placed on the knee. As person starts walking; flex sensor bends due to which voltage measured at analog pin changes and microcontroller compare this measured value with the threshold value present in the program, if it passes the threshold value the logic circuitry based on BJT switches on high as it gets 5 volts and activate the 555 timer circuit which generates signal pulses. The produced signal pulses are transmitted to the peroneal nerve through electrodes placed on the pathway of peroneal nerve. Peroneal nerve gets stimulated and depolarization occurs due to this. This provides activation of the dorsiflexor which enables the patient to lift the foot during swing phase. End of the swing phase will turn off the stimulator and the cycle will repeat for each gait cycle of the patient. Figure 3 shows the entire circuit if the device along with component values.

The generated wave form was triangular peaks having frequency of 100 Hz and voltage of 120V. The peak to peak voltage (Vpp) in Figure 4 is shown as a 10 times multiple of the impedance of the oscilloscope probe that's why the output voltage shown is divided by 10.

III. Methodology

Five male subjects were considered (aged 40 to 50 years) with a drop foot due to stroke. All the subjects could walk with supports and were able to stand up from sitting position. Only five subjects were considered since the aim was to test the device, which had already provided required results on an oscilloscope. The Temporal and Spatial Parameters (TSP's) were measured initially since they are the identifiers of gait [7]. Written consent was taken from each subject.

A qualitative analysis was done for the subjects by obtaining information about their daily routines, mobility requirements, difficulties in gait due to foot drop etc.

The stimulator was mounted on each subject's knee belt and the two electrodes were attached to the motor ends of the peroneal nerve (on the bellies of Tibialis Anterior, Extensor Digitorum Longus, Extensor Hallucis Longus and Peroneus muscles). The training session continued for a week in which the subjects were briefed about the donning and doffing of the device, precautions for the device, and were encouraged to report any difficulties with the gait if any. After this trial period, the subjects were asked again for an interview and observational gait analysis to test the efficiency of the device.

IV. Results

The subjects reported no difficulties in the accommodation of the device. Ease in mobility was reported from each of the subjects, as well as a restoration of gait towards normal.

The mean values of the TSP's before and after the use of device are summarized in Table 2. An increase in gait efficiency is observed from the values which support the results of the qualitative analysis.

Table 2: Mean values of Temporal & Spatial Parameters pre and post device usage.

	Cadence (steps/ min)	***Stride Length (meters)***	***Walking Speed (meter/ sec)***
Standard normal values[7]	110-115	1.4-1.6	1.3-1.6
Without device	53	0.79	0.34
With device	65	0.98	0.53

V. Conclusion

The device provides pulses and enables patient to lift the affected foot during swing phase of the gait hence assisting the gait in real time. Assistance in real time provides independence, stability and helps in restoring the mobility. The device is unique in the way that it has three units i.e.; sensing unit, controlling unit and stimulating unit for ease of the patient as it makes the operation of device convenient to the patient.

VI. DEVICE COST

The total cost of the device was USD 200, which means that it is more economical than its competitors and can be reproduced on a budget without compromising on the efficiency.

VII. LIMITATIONS

The biggest limitation of this study is the small sample size. The device needs to be tested on a larger sample of population in order to observe is efficiency. Another drawback is that we have not used cinematographic gait analysis in order to evaluate the kinematics and kinetics with device usage, only observational gait analysis is done. This is because the primary purpose of the study was to present a device design for foot drop patients.

VIII. FUTURE SCOPE

As FES is a developing technique, it covers a vast area of research in rehabilitation engineering and provides new solution to the existent medical problems. The FES device can be used with artificial neural networks (ANN) to make it intelligent enough so that it will be utilized as generalized device for the patients. ANN can be trained to learn the natural coordination pattern that exists between the ankle dorsiflexor and plantar flexor muscles activities of opposite legs during normal gait so that it can triggers the appropriate activity of the impaired dorsiflexor muscles based on the muscle activity of the healthy calf muscle of the opposite leg.

The stimulator and programming section of the device could be advance with the use of Bluetooth technology in order to avoid little inconvenience and it also lightens up the weight of the device system placed at the knee as the programming segment can be placed in the pocket.

This FES based device can be used in combination with measuring the muscle activity of the dorsiflexors of foot. EMG and the sensor used will provide feedback which will give more accurate instant for the onset of stimulator circuit.

ACKNOWLEDGEMENT

The authors would like to acknowledge the supervisor of this project, Dr. Muhammad Abul Hasan (Assistant Professor, NED University of Engineering & Technology, Pakistan) for his support and guidance throughout the project. Also, the authors offer gratitude to Mr. Osama Mazhar (Master Scholar, Universiti Technology Malaysia) for his guidance regarding electronic circuits.

FUNDING

The project was self-funded by the authors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Perry J. Gait analysis: Normal & Pathological Function 2009.

2. Rathore S, et al., Characterization of incident stroke signs and sympotoms: findings from the atherosclerosis risk in communities study. Stroke; 2002, 33.

3. Warlow C, et al. Stroke. Lancet; 2003:1211–1224.

4. Sabut SK and Manjunatha M. Neuroprosthesis-Functional Electrical Stimulation: Opportunities in Clinical Application for Correction of Drop-Foot. Proceedings of the First International Conference on Emerging Trends in Engineering and Technology.

5. Chen, M, et al. A Foot Drop Correcting FES Envelope Design Method Using Tibialis Anterior EMG During Healthy Gait With A New Walking Speed Control Strategy. Proceedings of 32nd Annual International Conference of the IEEE EMBS. 2010: Buenos Aires, Argentina.

6. Sabuta SK, *et al*. Functional electrical stimulation of dorsiflexor muscle: Effects on dorsiflexor strength, plantarflexor spasticity, and motor recovery in stroke patients. NeuroRehabilitation, 2011.

7. Kirtley C, *Clinical Gait Analysis*. Vol. 1. Elsevier. 2006.

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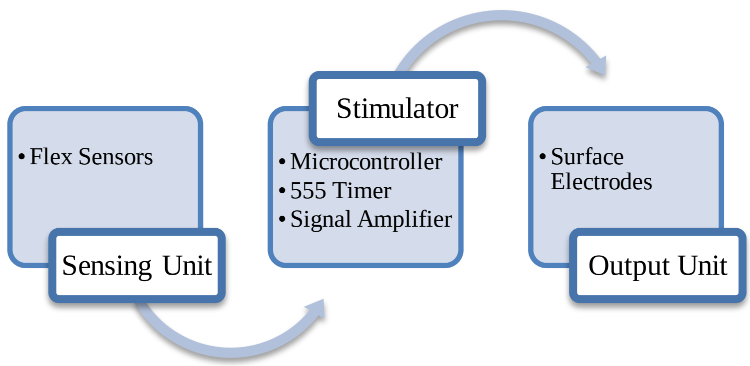

Figure 1: Flow diagram of FES-based device for Foot drop.

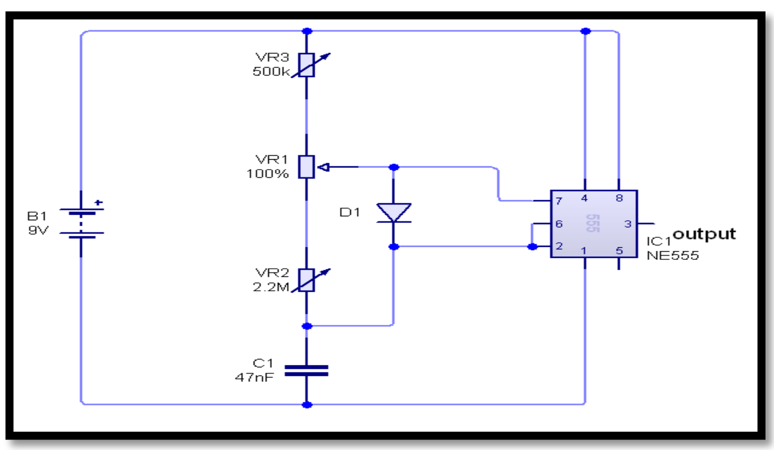

Figure 2: 555 Timer based circuit for generation of pulses

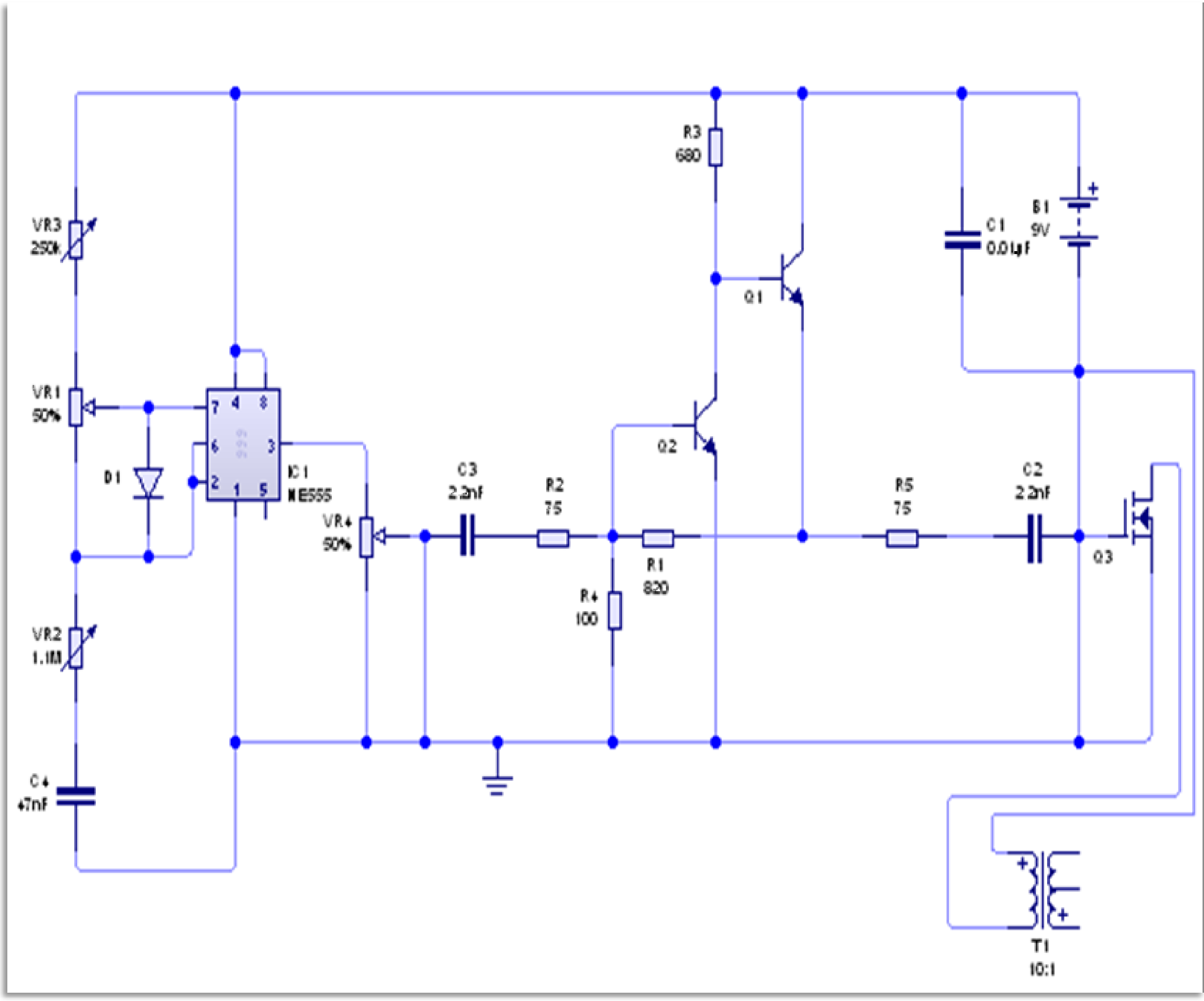

Figure 3: Complete circuit diagram of the FES-based device

Figure 4: Resultant Peak-to-Peak Voltages of the device