# Design of a Biofeedback Device for Gait Rehabilitation in Post-Stroke Patients

I-Hung Khoo, *IEEE-Member*, Panadda Marayong, *IEEE-Member*, Vennila Krishnan, Michael Nico Balagtas, and Omar Rojas.

*Abstract*— **A novel device, named 'Walk-Even', was developed to measure human gait and provide real-time feedback to correct gait asymmetry. Gait asymmetry is usually exhibited in patients with stroke or with certain neurological disorders. Our device can measure the weight pressure distribution that the patient exerts on each foot, in addition to the gait time, swing time, and stance time of each leg while walking. Based on the real time information, a biofeedback is given by means of auditory, and unpleasant electrotactile stimulation to actively correct gait asymmetry. The device consists of custom insoles with embedded force sensors adjustable to fit any shoe size, electrotactile and auditory feedback circuits, microcontroller, and wireless XBee transceivers. We compared the gait measurements from our device with that of a commercial device (MobilityLab) to verify its accuracy. Preliminary testing on post-stroke patients has shown that our device helps to improve their gait symmetry.**

## I. INTRODUCTION

Stroke is one of the leading causes of acquired disability in adults. Up to 80% of the post-stroke population exhibit asymmetry in their body postures and weight distributions resulting in asymmetrical gait patterns, which are characterized by prolonged swing time and decreased stance time on the paretic limb [1]. Research has shown a correlation between asymmetrical walking gait and slower gait speed with higher fall risks in stroke survivors. Therefore, proper gait retraining is crucial to post-stroke rehabilitation. In this work, we developed a portable device, named 'Walk-Even', that can measure, analyze, and correct gait asymmetry in real time during rehabilitation training. Wearable by the user, the device utilizes microcontroller and custom-made insoles embedded with force sensors to detect gait characteristics and provide corrective feedbacks in the form of audio and electrotactile feedback. The hardware and software design of the Walk-Even device will be described in the following sections. Preliminary results on the functionality testing and effectiveness in gait correction on stroke survivors will also be reported.

## II. PRIOR WORK

Typically, conventional gait rehabilitation is provided by a physical therapist using hands-on activities to facilitate normal gait patterns. These activities include weight-bearing, weight-shifting, and lower extremity strengthening exercises coupled with manual and verbal cueing/feedback from the therapist [2]. Despite being effective, such treatment is labor-intensive and requires a high attentional demand from the treating therapists. Subsequently, more research has been focused on developing newer technologies that will help in the gait training as well as addressing the above mentioned limitations seen in the conventional gait training.

One approach to incorporating technology in gait rehabilitation is the use of functional electrical stimulation (FES). FES involves delivering an electrical stimulation to a muscle to elicit a contraction [3]. This serves as a compensation method for reduced muscle activation in post-stroke individuals. However, the main drawback is that rather than correcting gait abnormalities by behavioral modification, individuals become reliant on the external stimulation to initiate muscle contraction. Another approach in gait rehabilitation involves eliciting the nociceptive withdrawal reflex (NWR) at the sole of the foot. This spinal reflex results in hip flexion, knee flexion, and ankle dorsiflexion [4], and can be timed accordingly to facilitate the leg swing during the end of the stance phase of gait.

Recently, external feedback in the form of either auditory or sensory or visual guidance has been used to achieve symmetrical gait in post-stroke patients. The Walk-Mate is a device containing acceleration sensor that is worn on both ankles to provide auditory feedback information on foot-ground contact [5]. Patients show improvements in gait symmetry while training with the device, but these improvements were not maintained post-training. This lack of retention can be attributed to either the inadequacy of the auditory feedback or to the lack of training intensity.

A recent study provided real-time multisensory (auditory, visual, and vibrotactile) feedback to elicit changes in gait symmetry during stance in three healthy and young participants [6-8]. However, these participants were unable to recognize and respond to the different types of stimuli due to their poor feedback modalities. Thus, the current literature shows that gait retraining requires a precise level of feedback, and overstimulation of the sensory system is ineffective. In short, there is clearly a lack of a feedback-based rehabilitation program till date, which emphasizes reduced swing time and increased weight bearing on the paretic limb, using behavioral modification techniques. This is the motivation for our current research.

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## III. SYSTEM OVERVIEW

In human locomotion, a gait cycle is the time period established by the heel of one foot making contact with the ground, termed *heel strike*, and ends at the subsequent heel strike of the same foot. A normal gait cycle is composed of 60% swing phase and 40% stance phase. The swing time refers to the duration when the person's foot is off the ground. The swing phase starts with the toe-off and ends with the heel strike of the same foot. Stance time refers to the time a person spends on their foot while the other foot is off the ground. As shown by existing research, post-stroke patient with paresis on one side demonstrates prolonged swing time and decreased stance time on the paretic limb. These gait parameters provide the basis of the operation of the Walk-Even device. The major components of the device are shown in Fig 1. They consist of the sensor-embedded insoles, biofeedback units (electrical and audio), and the control unit consisting of a microcontroller with wireless and data recording capabilities. The biofeedback and control units are housed inside a compact enclosure that can be worn by the patient around his/her waist.

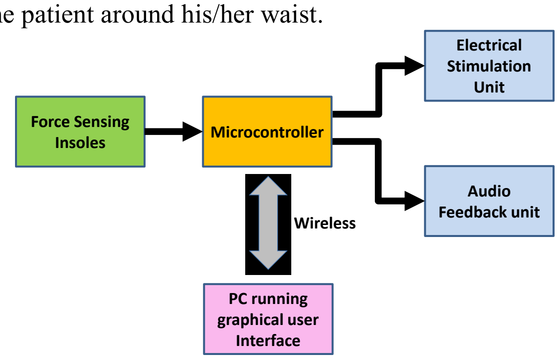


Fig. 1. Block diagram of device

Two types of feedback can be provided based on the gait parameters that are used to determine gait asymmetry: *Swing* feedback and *Stance* feedback. In the Swing feedback, audio and electrotactile stimulation is given when the swing time of the paretic limb exceeds a threshold obtained from the swing time of the normal or unaffected side. Along with the audio feedback, the electrotactile feedback generates a nociceptive stimulation on the unaffected side to encourage the patient to step down to shorten his/her prolonged swing. In the Stance feedback mode, an audio feedback is used to remind the patient to put more weight and keep their paretic foot on the ground in order to prolong their stance. The audio feedback is activated when the affected leg establishes a heel strike and stopped at a pre-defined time period. The following sections described the hardware design of the biofeedback unit and the control unit of the Walk-Even device.

### *A. Hardware Design*

Customized circuits are designed for force sensor measurement and biofeedback generation. The device is designed to be compact and modular to allow for easy usage. The two main components are the insoles and the biofeedback units.

<u>Sensor-embedded Adjustable Insoles:</u> Each insole contains six TekScan force-sensitive resistor (FSR) sensors for contact force measurement. The insole consists of a front and back piece and can be easily adjusted to fit any shoe size (Fig 2). On each foot, three sensors are placed toward the heel and three toward the toes. The average force readings from the FSRs are used to detect the gait parameters, specifically heel strike and toe-off. The FSR resistance is inversely proportional to the amount of force placed on it. The circuit to convert the FSR resistances to voltage is shown in Figure 3. It is based on a non-inverting amplifier with low pass filter. The filter has a cutoff frequency of 2.8Hz to remove contact bounce noise from the FSR. The circuit output voltage is given by:

$$Vout \approx 2.5 - \frac{2.5}{FSR} \cdot 5600 \quad \text{for } f < 2.8\text{Hz} \qquad (1)$$

The single-supply rail-to-rail opamp runs from a 5V supply. So the bias voltage at the non-inverting input is set at 2.5V. Altogether 12 opamp circuits are required to interface with the 12 FSRs. The outputs of the FSR circuits then go to the microcontroller which converts the voltages to force readings.

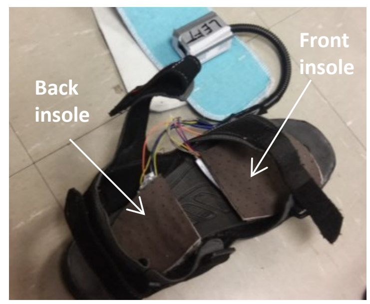


Fig. 2. Sandal with custom force sensing insoles

The FSRs vary in performance despite being of the same model due to fabrication. So each FSR needs to be individually calibrated before use. To accomplish this, different weights are placed on the FSR and the output voltage measured. Then a linear equation is developed to characterize the voltage to force relationship for each FSR. The equations are then programmed into the microcontroller allowing it to compute the force based on the voltage readings from the FSR circuits.

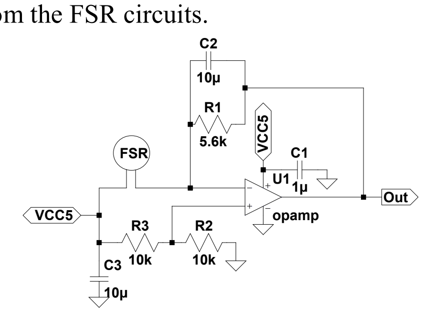


Fig. 3. Force sensor interface circuit

<u>Audio and Electrotactile Feedback Unit:</u> The device's audio feedback is delivered by a piezo speaker mounted on the control unit worn on the waist of the patient. The audio signal is a 200Hz fixed tone sent by a 555 timer.

The electrotactile feedback, in the form a short electric shock, is delivered by a switched-mode DC-DC converter configured as a boost converter. The output range of the unit was designed based on commercial Transcutaneous Electrical Nerve Stimulation (TENS) electrotherapy units. However, the output of our device is regulated at an appropriate magnitude and pulse width to provide unpleasant sensory stimulation only and to prevent unintended muscular activity that can alter the patient's gait. Commercial reusable electrode pads connected to the electrotactile unit are placed on the thigh of the non-paretic leg.

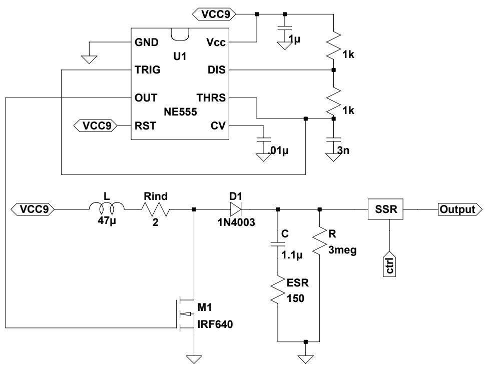


Fig.4. Boost converter circuit

The boost converter circuit is shown in Fig.4. The main components consist of the inductor L, power mosfet M1, diode, resistor R, capacitor C, solid state relay, and 555 timer. Note that the inductor resistance (Rind) and capacitor equivalent series resistance (ESR) are also shown in the schematic. The boost converter is powered a 9V battery and is designed to run in discontinuous mode in order to deliver the required high voltage output. In the more common continuous mode, the output voltage value is given $Vo = \frac{Vs}{1-D}$ (where $D$ is the duty cycle of the switching and $Vs$ is the supply voltage). So in order to deliver a high output voltage, the duty cycle will have to be very close to 1, which makes it hard to control precisely. Hence, the discontinuous mode is chosen for our application. In discontinuous mode, the output voltage of the boost converter is given by:

$$Vo = \frac{1+\sqrt{1+\frac{2D^2R}{L\cdot f}}}{2} \tag{2}$$

where $f$ is the switching frequency of the MOSFET set by the 555 timer.

Another design consideration is the current drawn by the circuit. This current needs to be reduced in order to maximize battery life. The maximum inductor current is given by:

$$I_{max} = \frac{Vs\cdot D}{f\cdot L} \tag{3}$$

Based on the above design considerations, the switching frequency is set to 160 KHz with a duty cycle of 63%. This results in a maximum output voltage of 230 volts which is sufficient for our application. This high voltage is delivered to the patient through electrodes by a high speed solid state relay controlled by the microcontroller. This allows the microcontroller to set the pulse width and frequency of the electrical stimulation. In our application, the control signal to the relay is sent through the PWM output of the microcontroller. This allows the pulse width to be adjustable from 80µs to 250µs in 12 discrete steps. The frequency however is fixed at 250Hz. The electric shock sensation felt by the patient is determined by the level of the electric current. So to allow adjustability of the electrical stimulation amplitude, a 50Kohm potentiometer is placed in series with the output. Testing has shown that the device is capable of delivering a 115mA current into a standard test load of 500ohm (Fig 5) at 80us pulse width and a frequency of 250Hz. These values are in the ballpark of most commercial TENS devices [9].

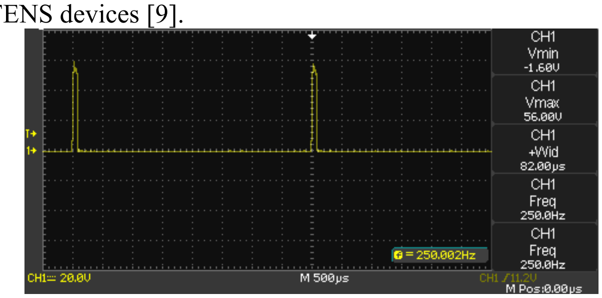


Fig. 5. Output voltage across a 500ohm test load at 80us pulse width

## B. User Interface and Control Unit

The Arduino microcontroller MEGA controls the overall operation of the device. An algorithm was developed to determine the gait parameters from the average force readings. The algorithms work by detecting the peak force values which are used to determine the instance of the heel strike and the toe-off in order to compute the gait, swing, and stance time. The gait data are stored on a microSD card to allow post analysis. The operator can control the device wirelessly to operate in different modes from the graphic user interface (GUI) on a PC. The wireless capability is achieved by two XBee modules – one connected to the microcontroller and the other to the computer. The device has two operating modes: Record and Feedback. In the Record mode, the system saves each individual gait cycles with their corresponding swing and stance times to the microSD card and displays the averages for gait, swing, and stance times at the end of the recording process. An example of the recorded force waveforms is shown in Fig.6, with the stance and swing phases indicated.

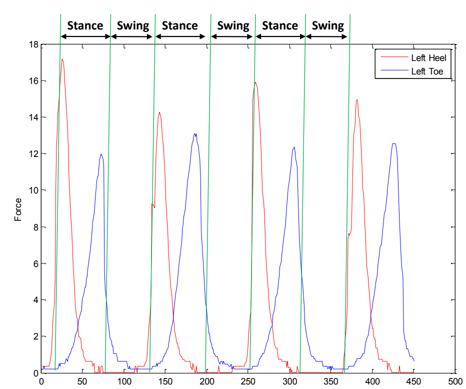


Fig.6. Sample force readings in pounds recorded by the device for the left leg (red=heel, blue=toe).

In feedback mode, the device will provide the biofeedback to the patient at the appropriate time based on the gait parameters calculated. The GUI also allows the operator to choose between swing and stance feedback modes, as well as changing the pulse width of the electric stimulation and adjusting the key parameters for the gait calculation.

The complete circuitry for the device is shown in Fig.7. It measures 10cmx13cm and includes the boost converter and FSR circuits on a custom PCB, beside the Arduino and the wireless shield. The wire harness at the top goes to the force sensing insoles. The complete specification for the device is given in Table 1. The total cost of device fabrication did not exceed $500. Fig. 8 shows the device worn by a patient during testing. The main unit is worn on the subject's waist, with cat5 cables connecting it to the force sensing insoles.

Fig. 7. Complete device circuitry.

TABLE I. SYSTEM SPECIFICATIONS

| Components | Specifications |
|---|---|
| Electrotactile feedback | Output current: Adjustable up to 115mA max (using 500 ohm test load)<br>Pulse width: 80µs to 250µs (12 settings)<br>Frequency: 250Hz |
| Audio feedback | 200Hz audio tone |
| Control unit | Weight: 512 grams<br>Wireless range: 25 meters |
| Power requirement | Uses two regular 9-volt batteries<br>Average current consumption:<br>- Arduino+XBee+audio feedback: 180mA@9V<br>- Electrotactile feedback: 119mA@9V |

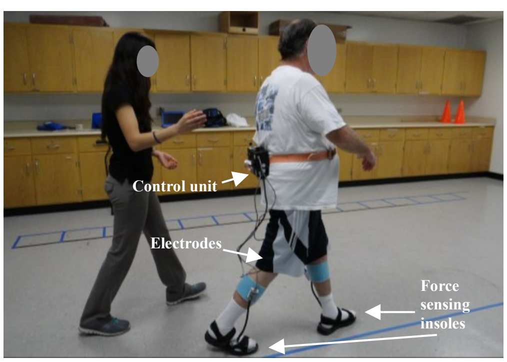

Fig.8. Device worn by a patient

## IV. RESULTS

A study was performed to evaluate the functionality of our prototype and compare the measurement results with the commercial device, MobilityLab, which can measure gait parameters. The testing involved four healthy subjects. The subjects were instructed to walk in a straight line for 15 meters wearing both Walk-Even device and MobilityLab sensors. The gait parameters obtained from each device were compared as shown in Fig 9. It can be seen that the values for the gait cycles are very close to one another.

Preliminary testing was conducted on a small number of post-stroke patients at our pro-bono neurologic clinic. It was observed that after 8 weeks of training with our device (16 sessions, 20 minutes each session), most of the patients' gait symmetry has improved. One out of two subjects treated with swing feedback showed improvement in their gait symmetry while all two subjects treated with stance feedback experienced improvement. Further testing will be done on more stroke patients to confirm the effectiveness of our device.

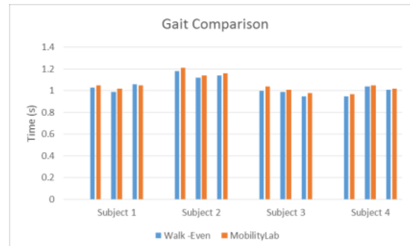

Fig. 9. Comparison of gait measurements between Walk-Even and MobilityLab

## V. CONCLUSION

A novel device called Walk-Even has been developed to measure and analyze gait asymmetry in post-stroke patients, and correct the asymmetry using real-time electrotactile and auditory feedback. The initial testing indicates that the device is accurate in measuring the gait parameters and effective in improving gait symmetry using feedback. The data collection is still ongoing with stroke patients. The device is portable and low cost and has the potential for use in a non-clinical setting.

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