Design And Testing Of A Novel, Low-cost, Low-voltage, Functional Electrical Stimulator

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***Abstract*— This paper presents the design of a novel, noninvasive, low cost (< $70), low voltage (< 46 V maximum output, 3 V power supply), functional electrical stimulation (FES) circuit aimed at upper-limb stroke rehabilitation. The novel component of the circuit is the unique topology. This circuit uses a boost converter in series with an H-bridge to produce the required biphasic pulses. The stimulator is controllable using a range of different microcontrollers. The low voltage used makes this circuit inherently safer than circuits which use much higher voltages, up to 500 V. The circuit has been successfully tested on the bicep muscles of one healthy subject and is capable of inducing flexion of the elbow with as little as 12 V.**

***Keywords*— exoskeleton, functional electrical stimulation, rehabilitation, upper-limb.**

I. Introduction

Functional electrical stimulation (FES) is the application of high frequency electrical pulses to the nerves in order to elicit contractions in a muscle. FES is most often used to restore movement or prevent muscular atrophy in subjects who are very weak or unable to move their muscle(s). Common areas of application include the upper and lower extremities, the bladder and bowel, and the respiratory system [1]. FES systems may be either implanted beneath the skin or placed on the surface. This paper focuses on the design of a noninvasive FES device for the upper extremity to be used in stroke rehabilitation.

Stroke is the second largest cause of disability worldwide after dementia. Effective rehabilitation after a stroke is important if the costs of stroke on society are to be minimized. Patients who have survived a stroke are often left temporarily paralyzed on one side of their body. Regaining strength and movement in the affected side takes time and can be improved with the use of rehabilitation therapy involving repetitive and function-specific tasks

FES can be used in stroke rehabilitation to provide assistive training. The FES is often initiated in response to a button press, or other intention estimation method such as electromyography, with the goal being to practice performing a specific movement. This kind of rehabilitation can help rebuild the neural pathways in the brain [2, 3] as well as increase the strength of the muscle [4]. Alternatively FES may be used at a lower dose with the main aim being not to produce significant movement of the limb but rather to strengthen the muscle through small cyclically induced muscle contractions. For stroke patients cyclically induced FES is often used to prevent subluxation of the shoulder muscle [5]. Occasionally FES devices may also be used with the aim of aiding with activities of daily living (ADL).

A FES device is needed for the purpose of conducting research into the development of an upper limb hybrid exoskeleton to aid stroke rehabilitation by performing specific movement assistance in a rehabilitation setting. A hybrid exoskeleton is an exoskeleton which combines functional electrical stimulation with an actuator to create or aid movement of a human limb. Hybrid exoskeletons have been shown to have many benefits over FES or exoskeleton aided rehabilitation alone [6]. A hybrid exoskeleton can potentially result in a device which is overall lighter and more portable than electromechanically actuated exoskeletons and which can produce greater forces and more precise control than FES on its own. This can be particularly useful for stroke rehabilitation.

Many of the FES devices used in current upper limb hybrid exoskeleton research [7] are commercially available devices like the Motionstim 8. Commercially available FES devices are not cheap, costing upwards of several hundred dollars [8]. FES circuits described in literature also tend to be complex, involving many non-packaged components [9, 10]. The FES device described in this paper is designed to be simple, controllable, and low-cost as well as safe and effective.

This paper is organized into VIII sections. Section II details the circuit requirements for a FES device. Section III presents an overview of the design of the FES device described in this paper. Section IV and section V describe the two main components of this device, the H-bridge and boost converter respectively. Section VI discusses health and safety considerations. Section VII presents the experimental results and testing of the device. Section VIII contains the conclusions.

II. Circuit Requirements

FES may be delivered in monophasic or biphasic pulses. Biphasic pulses are preferred as they reduce the charge build up in the tissue and delay the onset of muscular fatigue [9]. Pulses are not necessarily symmetrical and there may or may not be a delay used between each half cycle. Typical pulse shapes used for FES can be seen in **Fig. 1**. Many FES systems operate at a fixed frequency somewhere between 20-50 Hz as higher and lower frequencies have been shown to rapidly increase muscular fatigue [11]. However the optimal frequency

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within this range is very subject and application dependent [12].

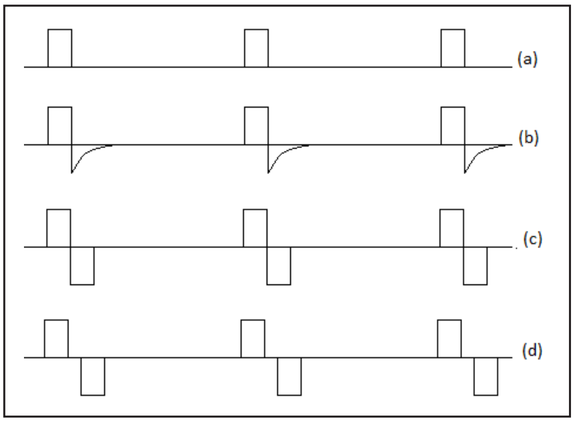

Fig. 1 Types of Pulse Shapes Used for FES (a) Monophasic (b) Asymmetric Biphasic (c) Symmetric Biphasic (d) Symmetric Biphasic with Interphase Delay.

Pulse duration varies considerably across different FES devices with some devices allowing modification of the pulse duration [13]. Pulse duration of commercial devices can range from 0 to 1600 μs with most devices typically using a pulse duration of between 100 μs and 500 μs. Pulse duration has not been shown to have a large effect on muscular fatigue however pulse duration does impact the strength of the muscle contraction with longer pulse-widths generally resulting in stronger contractions up to a point [11]. Very short pulse durations require a larger stimulation amplitude in order to elicit a contraction [14]. **Fig. 2** shows the stimulation current amplitude experimentally required to elicit minimal and maximal contractions for different pulse-durations.

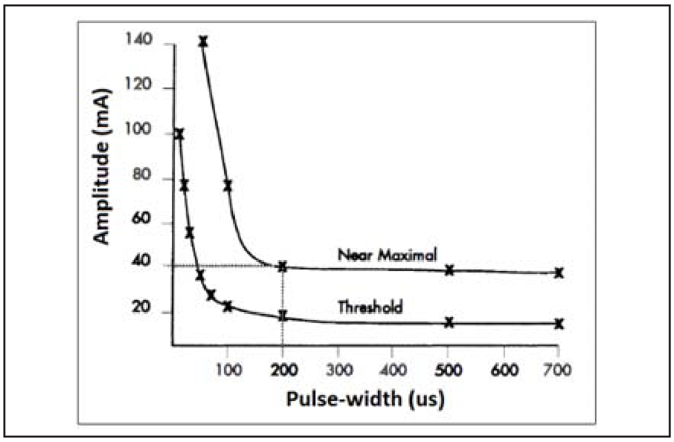

Fig. 2 Variation of Amplitude and Pulse-width Required for Muscle Excitation [14]

The effect of stimulation amplitude on muscle fatigue is not well understood but it is generally found that greater stimulation intensities result in higher levels of subject discomfort and can increase the rate of the fatigue [11]. However a larger stimulation intensity also results in a stronger contraction. Within rehabilitation applications often the amplitude required to produce a specific contraction is selected and then fixed at that level. FES output amplitude can be either voltage or current controlled. Current controlled devices produce a more consistent and repeatable muscular response at the cost of added complexity [9, 13]. The stimulation current and voltage produced by different commercial FES devices ranges considerably [13]. Current amplitudes reported range from a couple of milliamps up to 150 mA, while voltages range from 15 V up to 500 V. This current is potentially enough to cause harm to the subject if the pulse-widths are not carefully controlled [15]. Thus safety is a highly important design consideration in FES devices.

The Electrode-Electrolyte model, presented in [16] is shown in **Fig. 3**, has been used in other works as an approximation of the electrode-skin junction and subject tissue at the stimulation site [17]. The parameters of the model are dependent on multiple factors such as skin type, skin sweatiness, electrode size, and electrode type. Therefore the exact intensity needed to evoke a specific muscular contraction is highly variable even within an individual subject and within a single session.

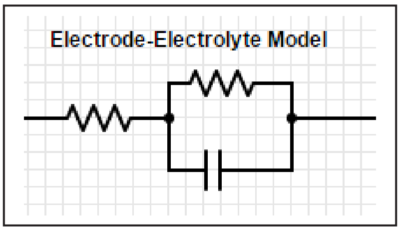

Fig. 3 Model of the Skin Junction and Subject Tissue

The rise time of the applied electrical pulses affects both the subject comfort and intensity required to produce a contraction. A faster rise time requires a larger amplitude intensity in order to produce a contraction and is also prone to nerve accommodation. Thus faster rise times are generally preferred however slower rise times may sometimes be used for subjects with hypertonicity.

III. High Level Design

A high level overview of the FES circuit described in this paper is shown in **Fig. 4**. The device is voltage controlled with current feedback. A variable boost converter boosts the 3 V DC supply voltage to the desired intensity level up to a maximum of 46 V, limited by the H-bridge voltage rating. The H-bridge converts the DC output from the boost converter to the required biphasic pulse shape. An isolation transformer ensures galvanic isolation of the subject from the circuit. The device is dual channel with each channel having independent frequency and pulse-width control. For simplicity only one channel is shown in **Fig. 4**.

The overall control of the H-bridge and boost converter is performed by a microcontroller, allowing easy, programmable control of the amplitude, pulse-duration, and frequency. To date testing of this system has been conducted with Beaglebone Black (Rev C, Element14) and Arduino Nano (Baite BTE14-01) microcontrollers. However, other devices are likely to work equally as well provided they have PWM output and analog input channels.

Due to delays in obtaining parts, the current experimental setup does not include the planned voltage regulators. The circuit is powered by a desktop power supply and calculations (see Section VI) indicate an isolation transformer is not strictly necessary. However a transformer has been added to the output as an extra safety precaution. With the exception of the voltages, the output parameter values shown in **Fig. 4** are the limits set in code based on the desired parameters discussed in section II and are not the system limits themselves.

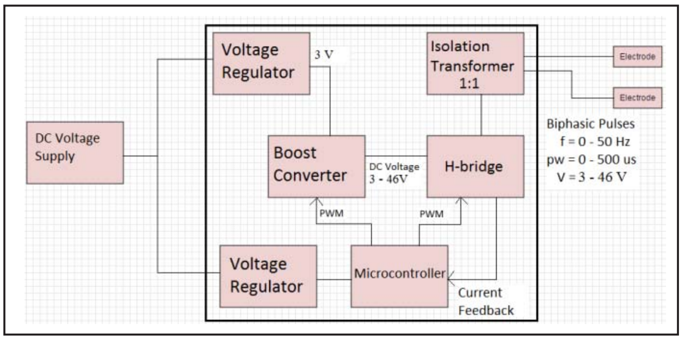

Fig. 4 Overview of the FES Device

In addition to the features shown in **Fig. 4** potentiometers connected to the ADC of the microcontroller are used to control the FES output parameters. A Flex Sensor is also connected to the microcontroller and is used to provide angular feedback from the subject's limb. The Beaglebone Black (Rev C, Element14) microcontroller is easily connectable to a laptop, which has been done in this case. Alternatively a touchscreen may be used. This allows feedback to be presented to the user.

IV. H-BRIDGE

H-bridges are most commonly used as motor drivers as they can easily provide bi-directional output voltages of variable pulse-width. In motor control the voltage input to an H-bridge is kept constant and the output power supplied to the motor, which is proportional to the pulse-widths, is varied by controlling the duty-cycle of four semiconductor switches. **Fig. 5** shows the H-bridge circuit connected to the electrode-electrolyte model described in section II.

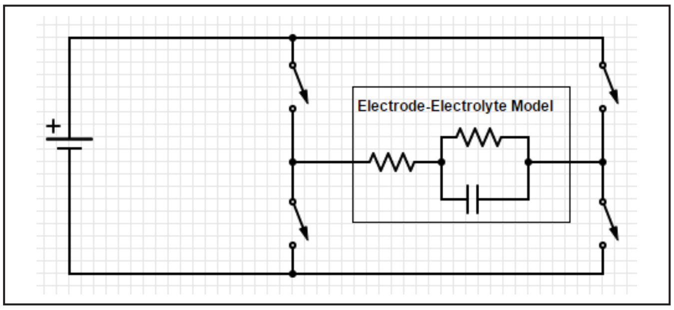

Fig. 5 H-bridge Connected to the Electrode-Electrolyte Model

The switches are controlled in pairs with the top left and bottom right switch forming one pair. To create the positive portion of the output pulse one pair is opened and the other pair are closed. To form the negative pulse the opposite occurs with the previously closed pair now open and the previously open pair now closed. For the rest of the cycle all of the switches are opened resulting in 0 V at the output. The voltage output of the H-bridge is equal to the input. If the input is varied then the output voltage also varies. The pulses produced from the H-bridge section of this FES device when a 10 V DC input is applied are shown in **Fig. 6.**

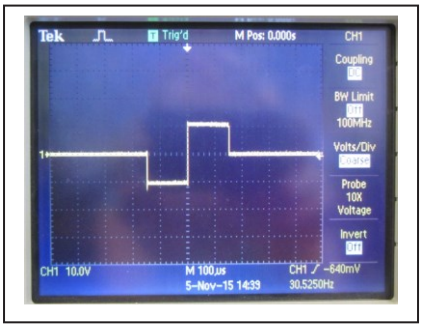

Fig. 6 H-bridge Output Pulse

For this circuit the L298N (Sparkfun) H-bridge has been selected. It is capable of operation with a supply voltage of up to 46 V and with a wide range of logic voltages. It is compatible with microcontrollers at either 3.3 V or 5 V logic levels which allows flexibility in microcontroller choice. External sensing resistors have been connected to the L298N (Sparkfun) which enable monitoring of the output current. This is fed back to the microcontroller to ensure current levels do not exceed the safety threshold. The H-bridge circuit is shown in **Fig. 7** with an Arduino Nano (Baite BTE14-01) being used for the control.

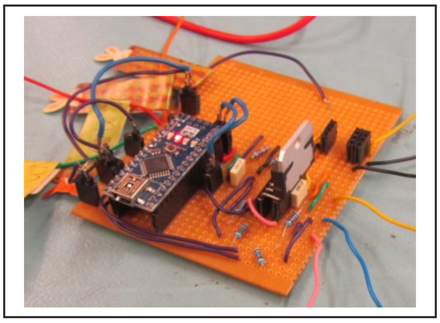

Fig. 7 H-bridge Circuit

V. BOOST CONVERTER

The H-bridge produces the desired pulse shape, duration, and frequency, however there remains a need for a controllable amplitude. A boost converter is a type of switch-mode power supply which produces a higher voltage at the output than at the input. Boost converters can be purchased as package components from commercial retailers however typically boost converters are designed for a constant output voltage. Therefore for this FES device a boost converter has been designed and built for operation at a range of output voltages from 3 V to 46 V. The circuit diagram of the boost converter is shown in **Fig. 8**.

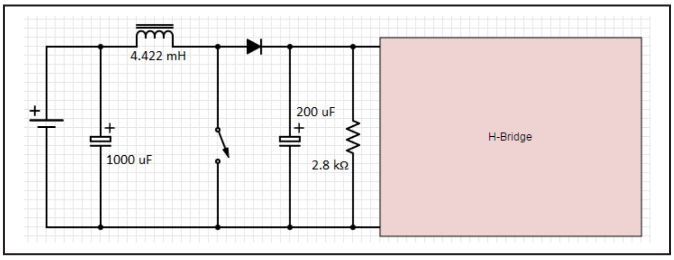

Fig. 8 Boost Converter

The switching frequency is 50 kHz. A RM8 Ferrite core was selected for the inductor with 33.5 turns and a measured inductance of 4.422 mH. Two 100 µF capacitors placed in parallel are used as the output capacitance. A 1000 µF capacitor is used as the input capacitance. A 2.8 kΩ resistor is placed in parallel with the H-bridge to ensure the output of the boost converter is never open circuit and to ensure a maximum resistance so the circuit will operate in continuous conduction mode. The duty cycle is varied from 0 to 0.86 resulting in an output voltage which varies from 3 V to just under 44 V. This is limited in code to ensure the voltage limits of the H-bridge are not exceeded.

The NTD24N06L MOSFET (ON Semiconductor) used in this boost converter circuit requires a gate voltage of approximately at least 1.7 V to turn on which both the Beaglebone Black (Rev C, Element14) microcontroller and the Arduino Nano (Baite BTE14-01) are able to provide. **Fig. 9** shows the boost converter circuit undergoing testing in combination with the H-bridge and using the Beaglebone Black (Rev C, Element14) microcontroller for control. The flex sensor and potentiometers used for feedback are also shown in **Fig. 9**.

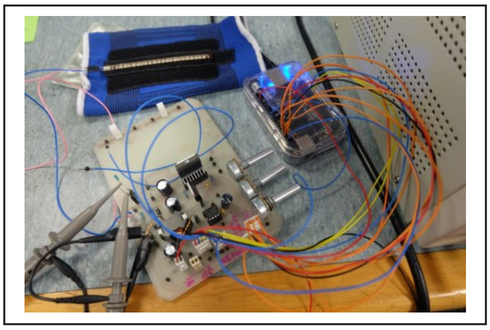

Fig. 9 FES circuit during Testing

VI. HEALTH AND SAFETY

The resistance of the skin is highly variable and ranges from as low as 400 Ω up to more than 3 kΩ [18, 19]. The lower value given is the resistance under the skin between any two limbs. The maximum DC current that can safely flow through a person instantaneously is 200 mA (**Fig. 10**) [15].

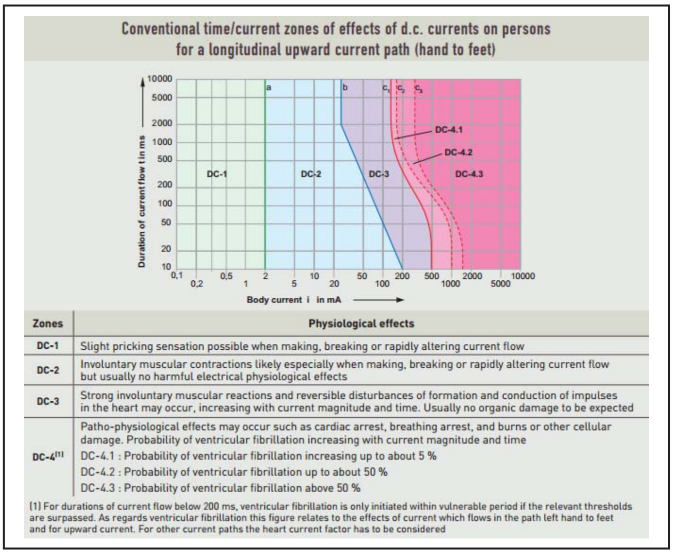

Fig. 10 Zones Time/Current of Effects of DC Current on Human Body When Passing From Hand to Feet [17]

The maximum voltage this circuit can produce is 46 V. IEC standards categorize <50 V as "Extra-low Voltage" which is generally considered safe under dry working conditions [20]. A 470 Ω resistor is placed in series at the output of the boost circuit to limit the current to safe levels even if the output electrodes become shorted. The 2.8 kΩ resistor in parallel with the 470 Ω resistor result in a total equivalent output resistance of 402 Ω. Thus for 46 V maximum output the current can be no more than 115 mA. Therefore this circuit can be considered safe for any fault occurring that lasts less than 50 ms or at continuous current levels < 20 mA.

The microcontrollers used in this circuit have been programmed to shut down if more than 20 mA is detected to be flowing through the H-bridge for longer than 16 ms. This is done using external interrupts. As an added safety measure the desktop supply used is current limited during testing on a subject. These precautions limit the potential current which can flow through the subject to within the safe zone seen in **Fig. 10**.

For impulse shocks, such as would occur in the case of touching a charged capacitor, it has been shown that safety is more related to the energy delivered than the current [19]. Impulse shocks with an energy content less than 0.25 J are generally considered harmless [19]. The maximum storage capacity of this circuit is 0.212 J which is below this threshold.

Other safety precautions taken include the following steps: FES electrodes are to be placed on a single limb only, not across the chest; Prior to placement of the electrodes the skin should be inspected for cuts or areas where the skin is broken and if cuts or broken skin is found then FES should not be used. This FES device should also not be used on any subject with implanted electrical devices, such as pacemakers.

VII. Experimental Results and Dicussion

One channel of the H-bridge circuit was initially tested without the boost converter topology. The Arduino Nano (Baite BTE14-01) microcontroller was used for the control in this first test. A current-limited desktop power supply was connected to the H-bridge circuit. 50 mm x 50 mm square electrodes were placed across the bicep muscles of a 60 kg healthy subject. The subject's arm was laid flat on the table and the voltage input to the H-bridge was slowly increased until contraction in the muscle occurred. Flexion of the elbow occurred at 12 V at a current level of approximately 20 mA. The frequency and pulse-width used in this test were 30.5 Hz and 350 µs respectively. Approval from the University of Canterbury Human Ethics Committee was granted for testing of this device.

One channel of the circuit as a whole was then tested with a 3 V desktop power supply connected to the input of the boost converter. The Beaglebone Black (Rev C, Element14) microcontroller was used for the control in this test. The same procedure as described in the first test was followed for this test. The same frequency and pulse-width as in the first test, 30.5 Hz and 350 µs respectively, were used. Flexion of the elbow occurred at 15 V. Circuit output waveforms produced from this circuit can be seen in **Fig. 11** and **Fig. 12**. Each waveform shows one half of the output pulse. The blue channel is positive and the yellow is negative, with the signal inverted for display.

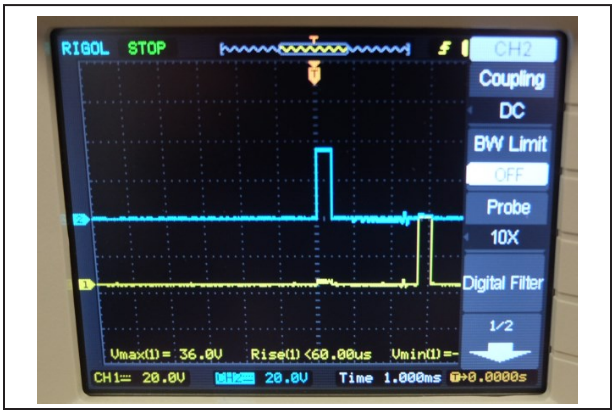

Fig. 11 Single Cycle of the FES Output

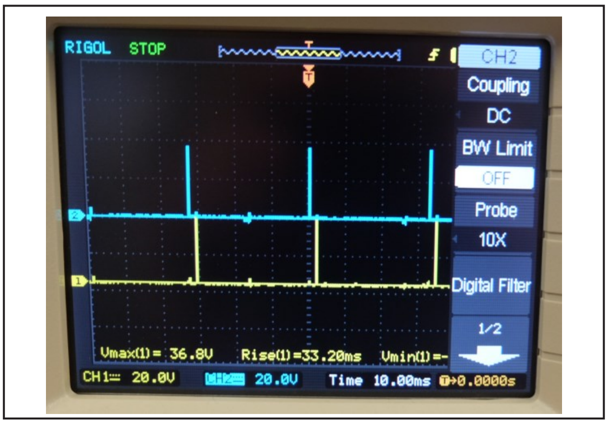

Fig. 12 Output of the FES circuit

If using the Beaglebone Black (Rev C, Element14), which has the advantage of easily being connectable to a computer for other visual display, then the cost of the circuit components totals less than \$70, with the Beglebone Black making up about 80% of the total cost. If an Arduino Nano (Baite BTE14-01) is used then the total cost of the components is less than \$20. The Arduino Nano (Baite BTE14-01) does have the advantage of compact size however it is also limited in the number of General Purpose Input Output (GPIO) pins.

VIII. Conclusion

A circuit for a FES device aimed at stroke rehabilitation has been designed. The circuit has been successfully shown to be able to induce flexion of the elbow with an output voltage of as low as 12 V. Future testing is planned to be conducted at a larger variation of pulse-widths and frequencies. Ultimately this circuit is to be combined with an electromechanical actuator in a hybrid exoskeleton. As the Arduino is not as easily connected to a computer or other display future testing will use the Beaglebone Black (Rev C, Element14) for control. Despite the added cost from using the Beaglebone Black this circuit is considerably cheaper than other commercially available FES circuits.

Commercial FES devices are expensive. The low cost of the device in combination with its programmability makes this design especially advantageous for other researchers such as those conducting research into hybrid-exoskeletons. The total cost of this device is less than \$70 when the Beaglebone Black microcontroller is used

The low voltage (46 V maximum output) used makes this circuit inherently safer than circuits which use much higher voltages, up to 500 V. Despite the low voltage used testing has shown that these voltages are still capable of inducing the desired muscular contractions and the supply voltage could likely be reduced further. As this circuit has only been tested on a healthy individual however it remains to be seen if this circuit can produce similar results in other individuals, especially those who are unable to perform the movement on their own.

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