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Low Cost Devices for Research in Brain-Computer Interfaces

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Low Cost Devices for Research in Brain-Computer Interfaces

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Biomedical Engineering

by

Andrew Schombs

Thesis Committee:
Associate Professor Zoran Nenadic, Chair
Professor Frithjof Kruggel
Assistant Clinical Professor An H. Do

2014

DEDICATION

To my eternal partner in life, my wife
in recognition of her encouragement,
patience and love, I dedicate this work to
you, because without you I would be lost.

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ACKNOWLEDGMENTS

I would like to express the deepest appreciation to my committee chair, Professor Zoran Nenadic for taking a chance on an older student with a job, a family and a dream, to be a part of his team and to patiently lead me down the path toward a new angle in my career.

I would like to thank my committee members, Professor An Do and Professor Frithjof Kruggel, for helping me to understand the mysteries of the brain.

In addition, a thank you to all of my educators and administrators for guiding me through my Master's Degree and helping me reach my goal.

ABSTRACT OF THE THESIS

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By

Andrew Schombs

Master of Science in Biomedical Engineering

University of California, Irvine, 2014

Assistant Professor Zoran Nenadic, Chair

The body of work presented is comprised of an analysis of three electronic devices developed for different purposes within the area of brain-computer interface research. The goal of these devices was to optimize effectiveness at as low of a cost as possible. Readily available components were chosen for their cost and abilities relative to similar devices used by other institutions that may require significant funding to achieve. The devices are presented in the order they were developed and represent an increase in complexity. The first was a device for measurement of motion, a simple task requiring only a single component. Secondly, a device to provide a stimulus to aid in treatment of neuropathy of the lower leg is reviewed. This device used a combination of a previously FDA approved stimulation system and electronic components used by hobbyists. Finally, a prototype for a novel device to be used for diagnosis of brain lesions is described, one which combines the scientific protocols used for brain lesion diagnosis and easy to use components into a single comprehensive piece of equipment.

INTRODUCTION

The field of brain-computer interfaces is emerging as an important research area. In order to interface man (more specifically the brain) and machine, there has to be a correlation between the electrical signals in the brain and either the input causing them, or the outputs caused by them. In the following discussion, three devices are explored that are aimed at cracking the code between these inputs and outputs. These devices were designed and constructed for the purpose of aiding the research with the specific goal of a low cost implementation. Of course, research funding availability was a key driver in aiming for this goal, but more importantly the reason for aiming for low cost was in the hopes that devices like those prototyped and described herein, may one day be products that could become available for use in the private and commercial sectors. Although these devices are simple in nature, they could have a big impact to research teams, and perhaps patients alike.

CHAPTER 1: TRACKING LIMB TRAJECTORIES USING A WII CONTROLLER

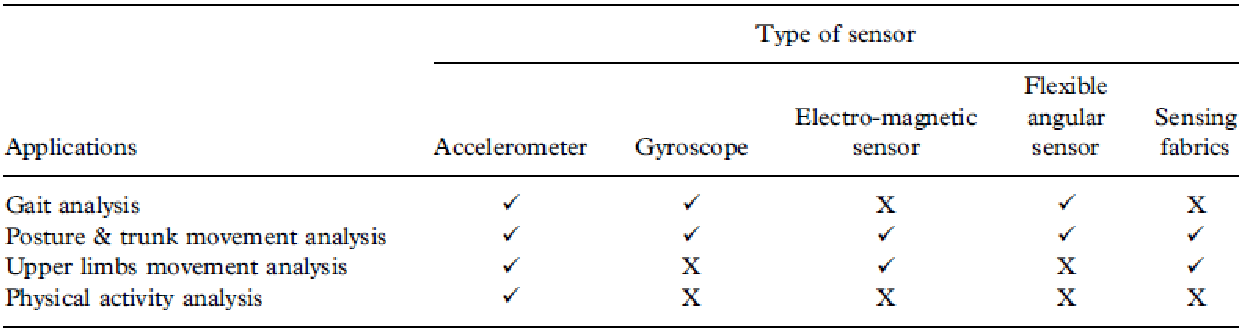
INTRODUCTION

In the field of Brain-Computer Interfaces (BCI's), particularly in the study of controlling robots or other machines using thought, it is essential to be able to both decode brain signals when attempting to perform a particular task and also provide feedback when a task has been completed. For instance, if the goal is to move a robotic limb, such as an arm, in an equivalent manner as moving one's own arm, you first need to be able to recognize the brain signals that correlate to moving the native limb, and program a control system to move the robotic arm to mimic the limb movement. Many techniques can be used to track movement, but the goal here was to record synchronously brain signals and corresponding limb trajectories to correlate particular mental inputs to movement outputs. Keeping within the concept of low cost, precision devices to do this, a commonly available commercial tool was repurposed from the video game industry to the field of biomedical research.

BACKGROUND

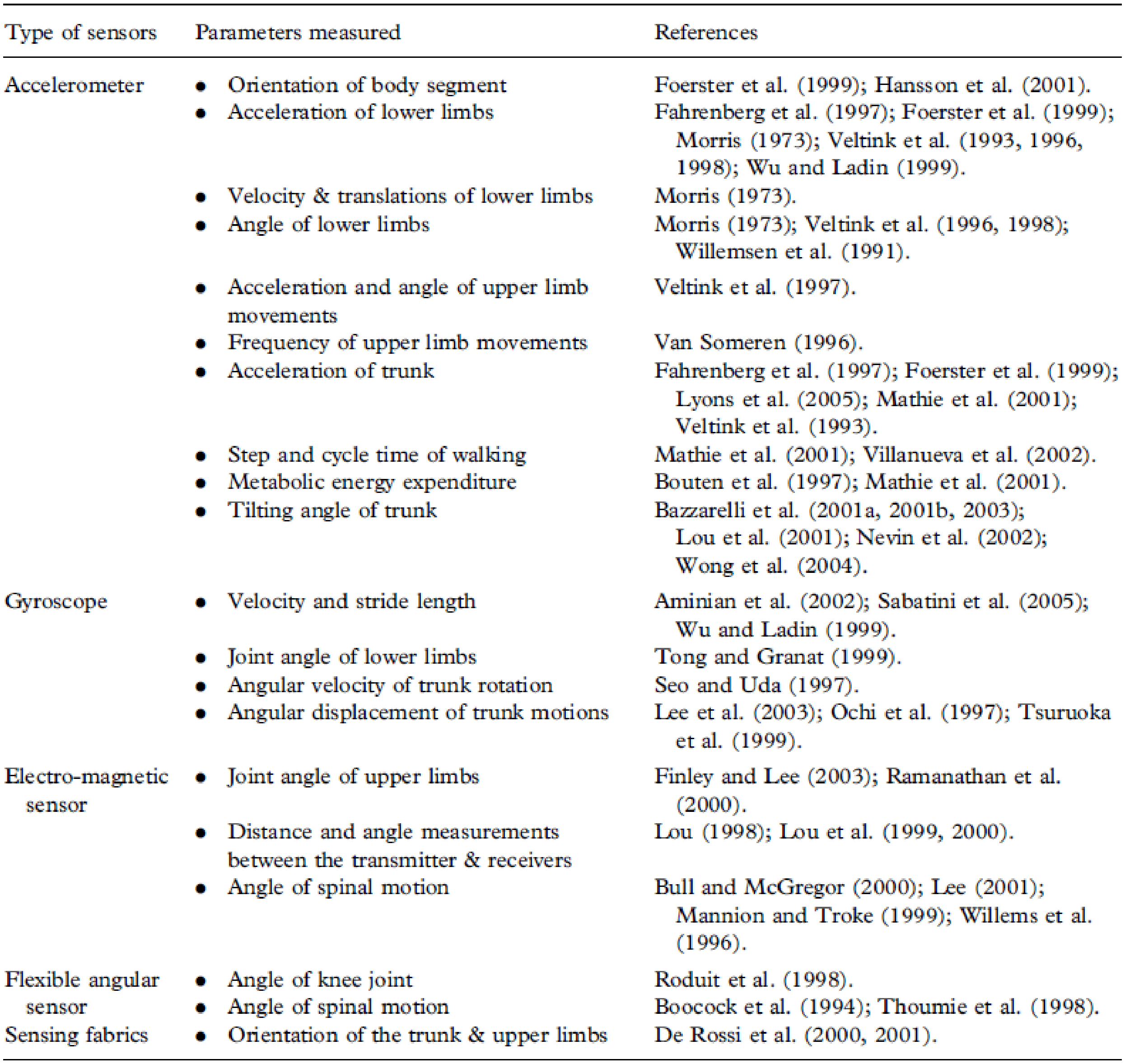
Methods of motion tracking and measurement take many forms from the simplicity of stop motion measurements to real time tracking with electronic devices. In the biomedical field, gait analysis has been performed for decades in gait laboratories relying on cameras and other large scale walkways and force sensors (Hirokawa and Matsumara, 1987). These laboratories involve many costly instruments and a dedicated location for measurements and analysis. More recently, researchers have used miniaturized sensors that would enable battery operation, allowing the research to be conducted in any setting and could allow for greater range of motion than just a few steps as commonly seen in the gait labs. A good overview of commonly used sensors and their applications have been summarized in Tables 1.1 and 1.2.

Table 1.1: Summary of Applications of Different Types of Sensors (Wong et al., 2007)



	Type of sensor				
Applications	Accelerometer	Gyroscope	Electro-magnetic sensor	Flexible angular sensor	Sensing fabrics
Gait analysis	✓	✓	X	✓	X
Posture & trunk movement analysis	✓	✓	✓	✓	✓
Upper limbs movement analysis	✓	X	✓	X	✓
Physical activity analysis	✓	X	X	X	X

Table 1.2: Summary of Different Parameters Measured with Positional Sensors (Wong et al., 2007)



Type of sensors	Parameters measured	References
Accelerometer	• Orientation of body segment	Foerster et al. (1999); Hansson et al. (2001).
	• Acceleration of lower limbs	Fahrenberg et al. (1997); Foerster et al. (1999); Morris (1973); Veltink et al. (1993, 1996, 1998); Wu and Ladin (1999).
	• Velocity & translations of lower limbs	Morris (1973).
	• Angle of lower limbs	Morris (1973); Veltink et al. (1996, 1998); Willemsen et al. (1991).
	• Acceleration and angle of upper limb movements	Veltink et al. (1997).
	• Frequency of upper limb movements	Van Someren (1996).
	• Acceleration of trunk	Fahrenberg et al. (1997); Foerster et al. (1999); Lyons et al. (2005); Mathie et al. (2001); Veltink et al. (1993).
	• Step and cycle time of walking	Mathie et al. (2001); Villanueva et al. (2002).
	• Metabolic energy expenditure	Bouten et al. (1997); Mathie et al. (2001).
	• Tilting angle of trunk	Bazzarelli et al. (2001a, 2001b, 2003); Lou et al. (2001); Nevin et al. (2002); Wong et al. (2004).
Gyroscope	• Velocity and stride length	Aminian et al. (2002); Sabatini et al. (2005); Wu and Ladin (1999).
	• Joint angle of lower limbs	Tong and Granat (1999).
	• Angular velocity of trunk rotation	Seo and Uda (1997).
	• Angular displacement of trunk motions	Lee et al. (2003); Ochi et al. (1997); Tsuruoka et al. (1999).
Electro-magnetic sensor	• Joint angle of upper limbs	Finley and Lee (2003); Ramanathan et al. (2000).
	• Distance and angle measurements between the transmitter & receivers	Lou (1998); Lou et al. (1999, 2000).
	• Angle of spinal motion	Bull and McGregor (2000); Lee (2001); Mannion and Troke (1999); Willems et al. (1996).
Flexible angular sensor	• Angle of knee joint	Roduit et al. (1998).
	• Angle of spinal motion	Boocock et al. (1994); Thoumie et al. (1998).
Sensing fabrics	• Orientation of the trunk & upper limbs	De Rossi et al. (2000, 2001).

Each of the mentioned devices can be easily acquired on the open market. One thing to consider is cost and the fact that each of the devices is typically sold in large quantities to electronics manufacturers and only as individual components. The cost of some examples of components used in the summaries above is indicated in Table 1.3, along with the costs of more "off the shelf" packages for motion analysis.

Table 1.3: Examples of the Costs of Motion Tracking Electronic Components

Device Type	**Device Name**	**Manufacturer**	**Approx Cost**
uni-axial accelerometer	ADXL05, ADXRS 250, ADXL202	Analog Devices Inc.	$11
piezoresistive accelerometer	IC Sensor Model 3031	Meditec Becker Karlsruhe	$118
data logger	TattleTale Model 5F	Onset Computer Corp	$100-$500
force sensing resistor	FSR 152NS	Interlink El. Inc.	$6-$35
goniometer		Biometrics	$13-$30
piezoelectric gyroscope	ENC-03J	Murata	$7-$75
motion cameras		Falcon	$800-$5000
activity monitor	MTI Actigraph Model 7164	Shalimar	$1,300

At first glance, the cost of a basic accelerometer seems low but to implement it into research, an investigator would need to integrate it into a circuit that meets the specifications of the component, package the circuit and create custom software or firmware to control the device or obtain the measurements. However, there is one device on the market that has the accuracy, precision, low cost and packaging that could be repurposed for biomedical research: the Nintendo Wii Motion Plus.

DEVICE REQUIREMENTS AND DESIGN

A number of considerations must be taken into account when developing a device for gait, or any other limb trajectory, measurement. Since cost is often an important factor in research, aiming to use small electronic components would keep the device in a reasonable cost range compared to motion cameras and data loggers. Accelerometers and gyroscopes provide a particular advantage because of their size and ability to integrate into circuits, which can then be placed into custom housings. (Figures 1.1 and 1.2)

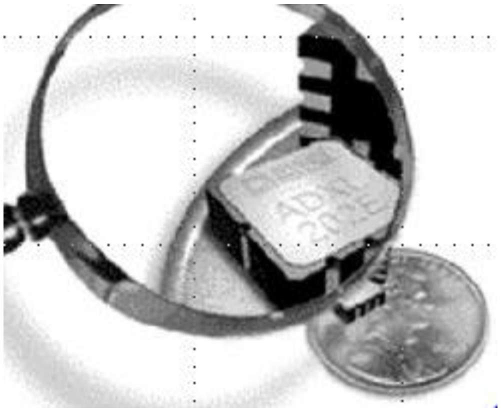


Figure 1.1: Analog Devices ADXL202 accelerometer.

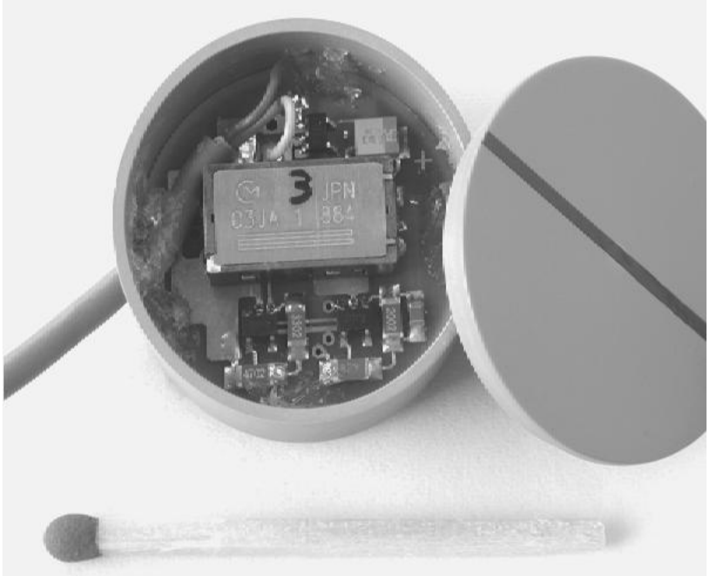


Figure 1.2: Gyroscope embedded in electronic circuit

inside a custom foot switch (Aminian, et al., 2002)

No matter the application, these sensors would also need to be easy to attach/detach from the subject and not hinder the relative motion under study. This in itself can pose issues in data collection as different researchers may attach the device differently in retest conditions, which has been shown to have a substantial influence on output signal. (Kavanagh et al., 2005) With regard to signal output, accelerometers and gyroscopes are unable to distinguish between the gravitational component, noise (such as skin motion artifact) and the motion in question. However, with adequate signal processing, accelerometers and gyroscopes can be positioned at nearly any location. (Reuterbories et al., 2010) The sensors would also require an algorithm to calibrate during the experimental procedure. This is to establish a baseline so that when motion is being tracked, the sensor output makes sense. Finally, the sensors would need to be integrated into a circuit that includes a processor to interpret the output and provide other functions such as calibration. Since this sensing device would not be used alone, it would need to be connected or at least synchronized with the brain signal acquisition system, to then be decoded either online or offline to match brain signal to motion trajectory.

By looking at all of these requirements, it begs the question if there already exists a product that contains a high performance motion sensor and is already integrated into a circuit that includes software or firmware that calibrates and provides a known output measurement? Enter the Nintendo Wii Motion Plus Remote Control Accessory. In the video game industry, the need for a controller with quick, accurate and precise response is a key requirement for success. The Wii Motion Plus is no exception, containing a dual-axis gyroscope and a single- axis gyroscope. Its firmware already has a start up and calibration procedure and it has a very simple pin-out for connecting it to other devices. (Figure 1.3) With a $19 price tag, it makes the device a very viable option for a low cost measurement device.

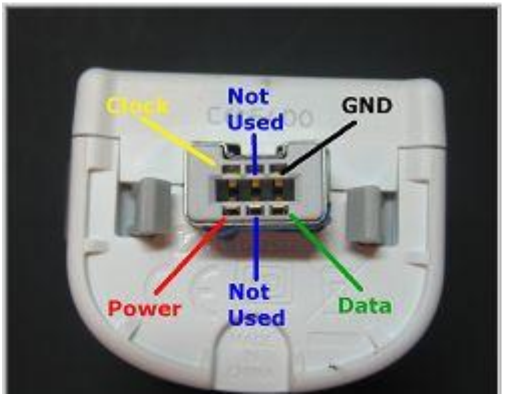


Figure 1.3: Pin assignments for Nintendo's Wii

Motion Plus (voidbot.net)

The size and weight of the Wii Motion Plus is suitable for playing video games, however it would have substantial inertia during movement which can have an impact to measurement data (Kavanagh et al., 2005; Reuterboriesa et al., 2010) and therefore the choice was made to repackage the circuitry and plug. (Figure 1.4)

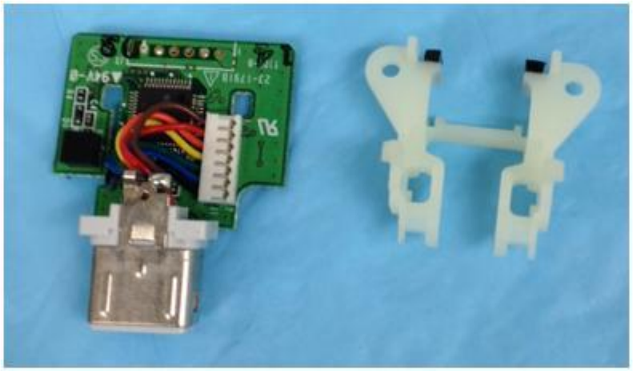


Figure 1.4: Nintendo Wii Motion Plus Circuit

with GyroScopes and Plug (left); A Part of The

Original Packaging, Modified (right)

To eliminate excess weight, the outer packaging was disposed of with the exception of the top plate, because the original screws used to fix the circuit in place terminated into molded threads in the plate. (Figure 1.5) This helped to maintain stability of the circuit and not allow excess motion relative to the position on an experimental subject.

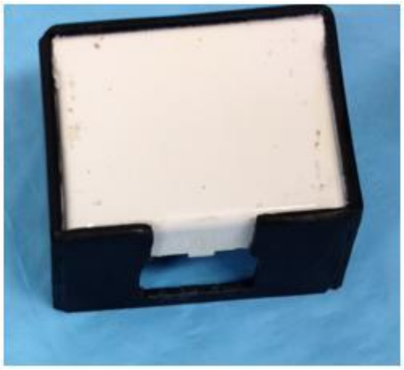


Figure 1.5: Original Plate (white); Custom Low Weight Housing (black)

A custom low weight housing was constructed from thin plastic sheets to reduce profile and mass of the sensor. (Figure 1.6)

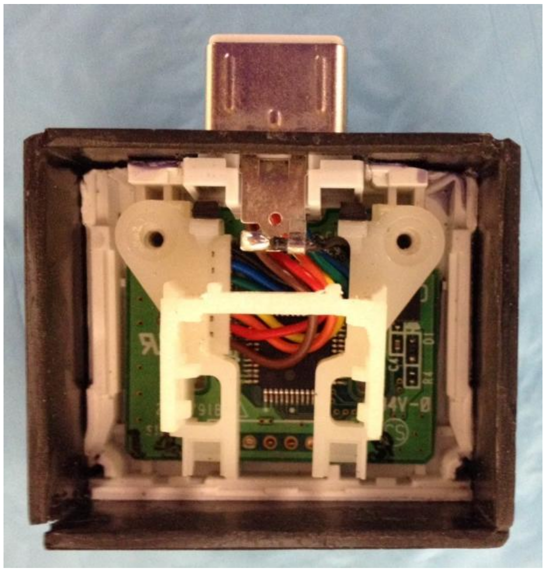


Figure 1.6: Wii Motion Plus Circuit Installed in Custom Housing with Original Support

Finally a top was affixed to the custom housing using the original screws. (Figure 1.7) The Top was constructed of the same plastic sheet stock and featured slots through which

Velcro straps were placed for fixation to the subject. The use of Velcro was preferred for comfort to the subject and a secure and tight fit to any extremity. (Figure 1.8)

Figure 1.7: Custom Wii Motion Sensor (right)

and Top with Velcro Strap (left)

Figure 1.8: Placement of Custom Wii Motion Plus to Arm and Leg

The Wii Motion Plus cannot function alone. Typically it is plugged into a Nintendo Wii Remote, which includes a battery power supply. Since power needs to be delivered to the

Wii Motion Plus, and the fact that the sensors in the device need to output the measurements in an interpretable way, the Wii Motion Plus needs to be connected to a processor and power supply. To make the motion sensor a discrete package, an Arduino Uno (www.arduino.cc) was chosen as the counterpart to the Wii Motion Plus. An Arduino Uno is an electronics hobby kit containing a microcontroller/microprocessor with an easy to use interface and firmware for compiling scripts written in a C++ based programming language. The Ardunio Uno is capable of providing power and ground to circuit boards and can communicate with devices through serial com (i2c) digital pins, as well as a computer through USB. (Figure 1.9)

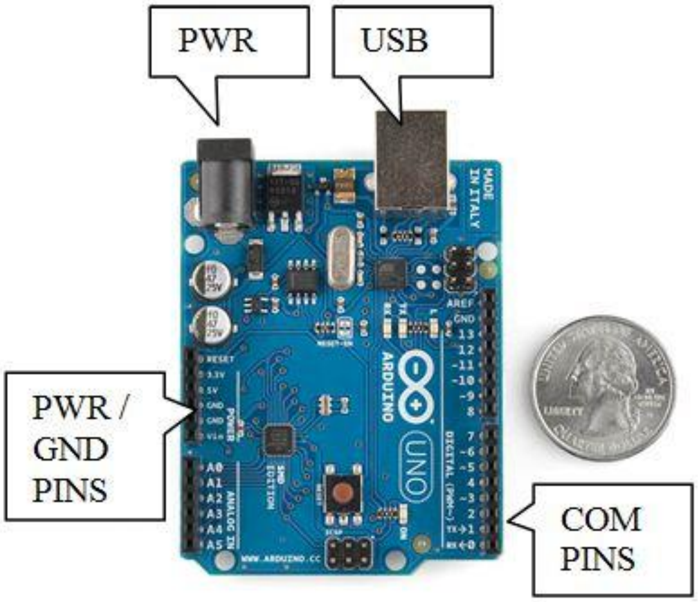


Figure 1.9: Arduino Uno Microprocessor/Microcontroller

Therefore, the Arduino can power and read the output of the Wii Motion Plus, as well as pass the calculated measurements to a computer for further analysis. Calibration of the Wii Motion Plus is a matter of initializing the memory registers in the circuit with zeroes while the device is stationary and calculating the output is quite simple since the Wii unit, at a given sampling rate, reports the pitch, roll and yaw of the gyroscopes. Various Arduino scripts exist on the internet to perform these operations.

To interface the custom Wii Motion Plus Sensor to the Arduino a cable was constructed from the interface of a Wii Remote, due to its already agreeable design, and a DB9 connector. (Figure 1.10)

Figure 1.10: Fully Constructed Custom Wii Motion Plus Motion Sensor and Cable

USE OF THE DEVICE IN RESEARCH

Once the device was built and tested, it was ready for use. The first challenging task for the device was to aid in the decoding of upper arm movements in the primary motor cortex. Previous work has been conducted on decoding the brain signals produced while moving individual joints of the arm (Chin et al., 2007; Kub´anek et al., 2009; Wang et al. 2012), however the aim of this study was to decode the signals of six-degree-of-freedom tasks. (Do et al., 2013) Subjects with electrocorticogram (ECoG) implants over the primary motor cortex performed a series of arm movements while brain signals were recorded. The movements pertaining to the Wii Device included forearm pronation/supination, elbow flexion/extension, shoulder forward flexion/extension, and shoulder internal/external rotation. The ECoG signals and Wii Device Measurements were synchronized to match the data sets. The data was analyzed after all measurements were taken and principal component analysis and approximate information discriminant analysis were performed. Based on the analysis, the movements of all four tasks could be detected with high sensitivity, meaning that there were obvious differences in brain wave patterns during periods of activity vs. inactivity. (Do et al., 2013) Unfortunately, the specificity was low, meaning that similar brain waves were detected for two different types of arm movements. For the value of the Wii Device, this particular study found it useful due to its quick response to movement. The data analysis in this case needed to show movements in relatively small time epochs to match up with the high frequency brainwaves in order to be able to decode the signal. Had the Wii device functioned poorly in this respect, for example if its change in output was slow, or did not have enough resolution to detect small movements, the research would not have been able to support the claim that sensitivity was high because they would not have been able to differentiate brain signals corresponding to the motion vs. idling.

A similar study was conducted using the Wii Device, but this time the challenge was to decode the position and velocity (trajectory) of the arm for the same four-degree-of-freedom movements. Again, subjects with ECoG were asked to move the upper arm, while the Wii Device was attached and synchronized with the ECoG acquisition. The study found that with the use of proper filtering and data analysis, that position and velocity could be accurately decoded from the ECoG signals. (Wang et al., 2013) Again, the Wii Device functioned well for this research because of its quick response and resolution. The data analysis was able to differentiate not just that a movement had occurred, but more specifically the amount of movement and speed. The correlation between the brain signals at different velocities and positions and corresponding Wii Device measurements produced a model with higher than expected accuracy.

The Wii device was also used for gait research, but in a much lower capacity than the upper extremity trajectory studies. The aim of the study was to demonstrate the ability for electroencephalogram (EEG) signals to be decoded to control a robotic gait orthosis. (Do et al., 2013) In the study, a subject (able-bodied) was connected to a Lokomat (Hokoma, Switzerland), which is a system used for physical therapy where an individual who has experienced loss of lower extremity control can be retrained for walking by being placed inside a robotic set of legs, positioned above a treadmill like machine. The control system for the Lokomat allows an external user to regulate the start/stop condition of the robotic gait. Instead of utilizing this feature, the robot was connected to a BCI that decoded EEG signals and determined whether or not a subject was generating imagery of themselves walking, which was shown to be successful in virtual reality simulations. (Wang et al., 2012; King et al., 2012) During this study, the Wii Device was also applied to the subjects leg and synchronized with the BCI system. The study showed that the robotic gait orthosis connected to the BCI was successful in that the robot would walk as the subject imagined walking and would be idle when the subject would stop. Part of the validation of the demonstration was that the Wii Device did not report movement to the system until after the EEG signals had been decoded and a “go” condition was sent from the BCI to the robot controls, meaning that it was not the able-bodied subject physically forcing the robot to move.

CONCLUSION

The Wii Device described has proven to be a useful tool in areas of research concerning the movement of upper and lower extremities. Although it would be possible for researchers to find accelerometers and gyroscopes and develop them into packaged devices, the Wii Device did afford certain advantages with respect to cost, time and ease of implementation. With the Wii Motion Plus being readily available in any electronics store for $19 or less and software available on the internet to output the signals to a computer, it makes for a convenient tool for hobbyists and researchers alike.

CHAPTER 2: BCI-FES MACHINE FOR REHABILITATION OF FOOT DROP

INTRODUCTION

Foot drop is a condition that is a common occurrence in stroke survivors. The condition impairs the ability to lift ones toes while walking (foot dorsiflexion), a simple task that able-bodied people take for granted every day. When the toes do not lift during walking, they can drag on the ground causing trips and falls. Pairing the same EEG based BCI as described earlier with a modified functional electronic stimulation (FES) system would create a machine that detects gait, and delivers electrical stimulation to the leg to trigger artificial foot dorsiflexion. Of course, the goal would be to find a way to achieve this at as low of a cost as possible.

BACKGROUND

Foot drop could be caused by a number of neurological or muscular conditions and the treatment must be tailored based on the need. There are orthoses that are available, but like any other mechanical device they would need to be donned and doffed regularly and do not remediate the true issue. Physical therapy is a possibility but in the case of strokes, often improving musculature will not improve the outcome. Through nerve stimulation, it is hypothesized that neural repair may be accomplished through Hebbian learning. This process theorizes the idea of synaptic plasticity where an increase in synapse efficacy can be developed by stimulation of a postsynaptic cell by a presynaptic cell. To achieve this learning of new cells to aid in foot drop, it would not be enough to just randomly excite neurons leading to the forefoot using a device because the cells would not associate a particular motion or desire to move with its impending stimulation. However, if an association can be made by the patient, that when they want to walk, the foot must ascend, and this is repeated until the behavior is learned, this could improve or possibly even cure the condition. Therefore, if a BCI can be connected to a stimulation device, which is activated as the patient attempts to move or walk, neural repair could be achieved. (Do et al., 2012)

DEVICE REQUIREMENTS AND DESIGN

The basic requirements of the device were to have a controller interpret an "on/off" condition sent from the BCI and deliver an electrical stimulation to surface electrodes situated on an ambulatory subject. The first goal was to determine the right components needed to deliver the stimulus. It would have been possible to develop an impulse generator from stock electronic components, however this would have been a complicated undertaking just due to the safety concerns alone. It was discovered that there is an FES device on the market that is already used in the clinic for pain relief and rehabilitation. The FDA Approved TENS 7000 (VGH Solutions Inc.) Unit is handheld and battery operated, and it is capable of delivering pulses from two separate channels (one for each leg if necessary), with a voltage of 0-50V at adjustable pulse rates and widths, at a low cost of only $30. (Figure 2.1)

Figure 2.1: Unmodified TENS7000 Unit with Leads and Surface Electrodes

One issue with this device is that the only inputs to it are adjustments to amplitude, frequency and pulse width of the stimulus. For the purposes of this BCI-FES device, there is a need to be able to turn the stimulus on and off as the BCI interprets intent to walk. The solution to this problem was to use a microcontroller based set of relays that allow the researcher (or user) to set the stimulus pattern, but the shock will only be delivered when the relay closes. Therefore, the relay would interrupt the leads coming from the TENS. Once again, an Arduino microcontroller would be perfect for this application because it has already been successful in synching with the BCI (Do et al., 2011), and it has the ability to control other electronic components such as relays.

The Arduino circuit was fitted into a housing with two relays (one for each TENS lead) and an additional chip on which LED's were attached. (Figure 2.2) The LED's were for visual feedback to the researcher and/or subject that the power to the device was active (red LED in the middle) and indicators for when the left and right TENS leads were delivering stimuli when the relays closed (yellow LED's on the left and right).

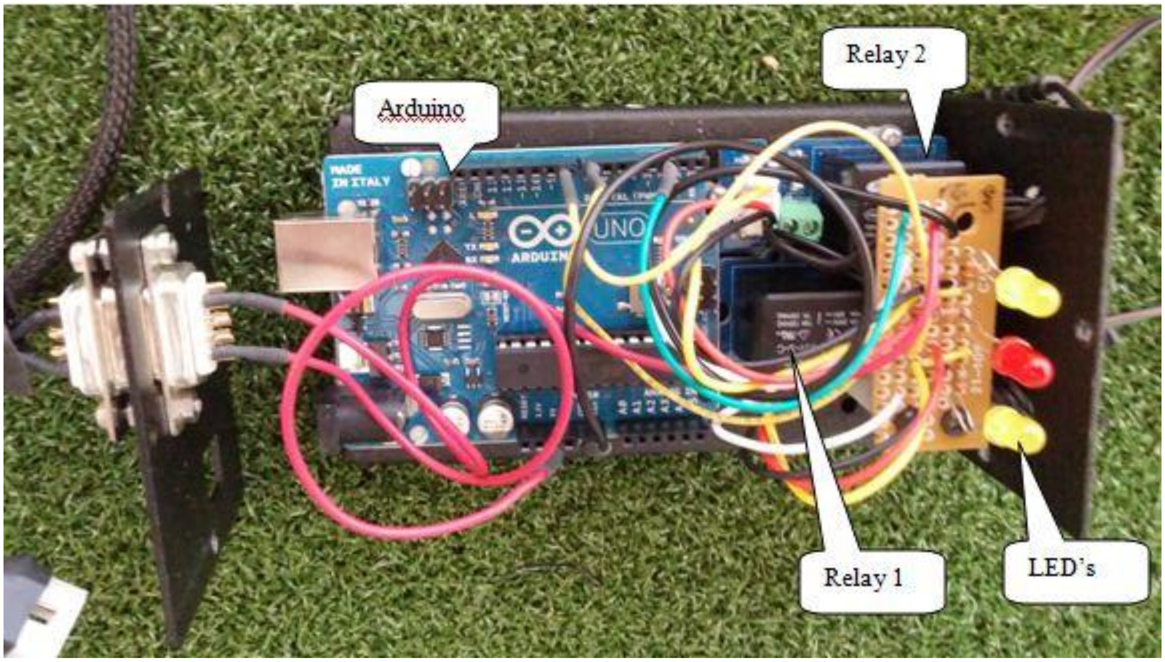


Figure 2.2 : Arduino Processor for FES System

The TENS leads were placed through the housing and into the relays. Also, as a safety measure, the TENS was modified to include a power switch that could terminate all power to the TENS. The power switch connects to the TENS through the device housing. (Figure 2.3)

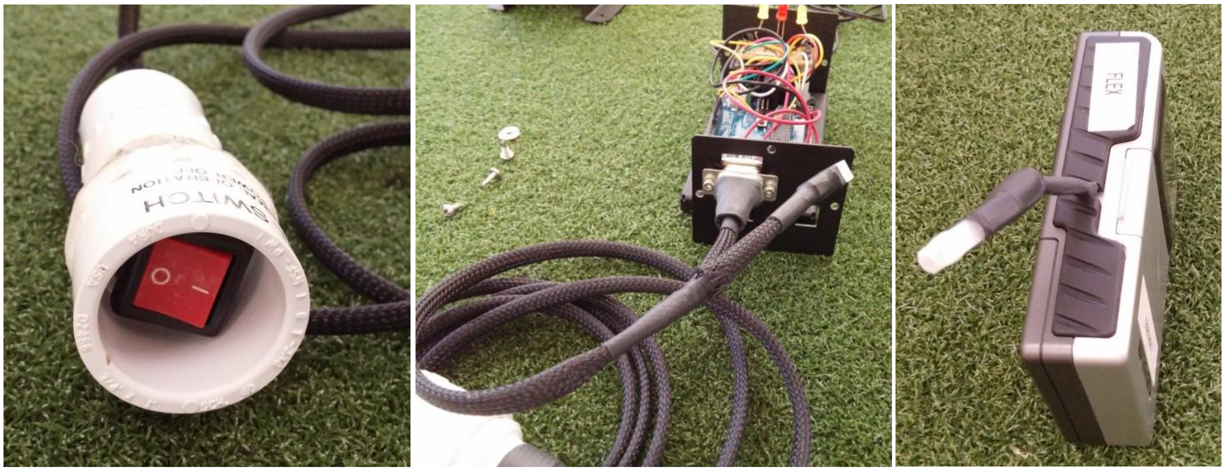


Figure 2.3: Safety Switch (left), modified TENS power adapter (right) and cable (middle)

The top of the housing for the Arduino was modified to allow the LED's to protrude for visibility and also to connect the TENS unit to the top to have one complete device packaging to attach to the subject. (Figure 2.4)

Figure 2.4: Completely assembled FES device

USE OF THE DEVICE IN RESEARCH

With the device complete, it was ready for use. A subject with foot drop was chosen for a study. The leads of one channel of the TENS 7000 were fitted to the subject with a pair of self-adhesive surface electrodes on the leg affected by foot drop. The placement of the electrodes was over the deep peroneal nerve and was adjusted along with the impulse parameters until the tibialis anterior muscle resulted in an approximate 15 degree angle of foot dorsiflexion. (Do et al., 2012) The subject was also connected to the BCI through an EEG acquisition system. The BCI was calibrated by having the subject alternate idling and attempting to produce dorsiflexion of the foot, and analyzing the difference in EEG data between the two different states. The system was then evaluated by activating the FES device and in-real time, analyzing the subject alternating between idling and attempting dorsiflexion. During periods of idling, the FES system would keep the relay open, thereby providing no electrical stimulation. When the subject would attempt to dorsiflex, the FES system would close the relay and provide an impulse. This evaluation was conducted a total of 3 times. (Do et al., 2012). After analysis of the data collected via EEG and known states of open vs. closed relay, a cross-correlation of 60% was achieved. This study demonstrated the first successful BCI operation of a lower extremity FES system by a stroke survivor with foot drop. (Do et al., 2012)

CONCLUSION

Previous experience with the Ardunio and its capabilities enabled a quick implementation of the FES device. Utilizing the TENS 7000 made the system straightforward, safe, effective and low cost. The first use of the device was quite the success, which establishes confidence that such a device could be used for other conditions where delivery of an electric stimulation needs to be based on a particular state (on/off). The device can be interfaced with any BCI as long as the output of the BCI can communicate with the Arduino, for which there are numerous communication options. As a next step, the use of a Bluetooth module and battery pack, could make the whole FES device wireless. If interfaced with an electronic data acquisition system (or use the Arduino for acquisition) utilizing myoelectric readings from the leg instead of EEG signals, the FES device could be a self contained, portable device for controlling foot drop.

CHAPTER 3: EVOKED POTENTIAL GENERATOR MACHINE FOR USE IN DIAGNOSIS OF BRAIN LESIONS

INTRODUCTION

The devices reviewed thus far have been used to interface with BCI's for the purposes of measurement or control of other electronics. In the case of the next device, its primary function is to assist in the diagnosis of brain lesions. The study of brain lesions and their effect on neural signals and pathways have been studied for decades. The American Clinical Neurophysiology Society (ACNS, www.acns.org) provides guidelines on the generation and measurement of evoked potentials (EPs), electrical signals recorded following the presentation of a stimulus. There are three main types of evoked potentials: visual (VEP), auditory (AEP) and somatosensory (SEP). The methods provided by the ACNS are straightforward, however require specific environments, parameters for the stimuli and a substantial amount of time for each individual EP. Could there be a way to integrate the test methods into a single protocol using a simple, low cost device that can do all three EP's concurrently? If so, this could be a worthwhile device for aiding in quick diagnosis of brain lesions and administration of treatment in an ambulance or emergency room setting. The device described below hopes to demonstrate feasibility of such a potentially valuable tool.

BACKGROUND

Studying simultaneous evoked potentials has been done in several animal models and in humans. In 1961, visual and evoked potentials were simultaneously recorded in a feline model to determine the effects of distraction on the potentials. (Jane et al., 1962) The cat was subjected to an enclosed reflective environment of a strobe light and square pulse waves generated through speakers. Baseline EP's were recorded as well as EP's when a distraction (mice) was introduced into the field of view of the cat. The data showed the distraction seemed to increase amplitudes of the EP's and make them more regular, presumably because the cat's attention was focused on the mice. There were also signs of habituation to the VEP and AEP over time, which reduced the amplitude. Later in 1995, AEP and VEP were once again paired to attempt to map spatiotemporal organization in rat cortexes. (Barth et al., 1995) The rat brain was mapped using 64 electrodes and the EP's were recorded at each electrode with AEP and VEP stimuli alone and together (AVEP). Interestingly, a few observations were noted. First, adding the average EP responses for AEP and VEP mathematically did not result in the same waveforms as when AVEP was recorded (AEP+VEP ≠ AVEP). Therefore, co-activation of neurons was evident considering that the signals were not additive and that the signals are not recording single neurons, but groups of neurons along the visual and auditory pathways are co-located in representative areas of the brain. Second, the characteristics of the waveforms were altered, even in areas where co-activation was less evident. The latencies of the positive and negative peaks of the AVEP waveforms were shifted compared to when a single EP stimulus was provided. A similar phenomenon was seen in 2000 when AEP and SEP was recorded in humans simultaneously. (Foxe et al., 2000) When a 1000Hz, 60ms auditory pulse was paired with a 400 μs electrical square wave applied to the median nerve it was demonstrated that AEP + SEP ≠ ASEP and the latencies were altered during ASEP. Then, as expected it was confirmed that VEP + SEP ≠ VSEP when a checkerboard pattern visual stimuli was paired with a 100μs long electrical stimuli in 2002. (Schürman et al., 2002). And finally, in 2013, a team of researchers developed a system where all three EP's could be generated simultaneously and recorded in an effort to understand the effect of stimulation additivity and its role in reaction timing. (Sella, et al., 2013) As shown in the generalized example in Figure 3.1, unimodal responses in a particular area of the brain will produce an EP of varying shape for each type of stimulus and they will differ from the EP as a response from bimodal stimulation. When comparing the bi-modal response to the linear sum of the two unimodal responses, the research shows that the bimodal response is inferior. It was also observed that the waveforms of unimodal EP's would reach a threshold value later than bimodal EP's, in other words, the latencies of bimodal responses were lower.

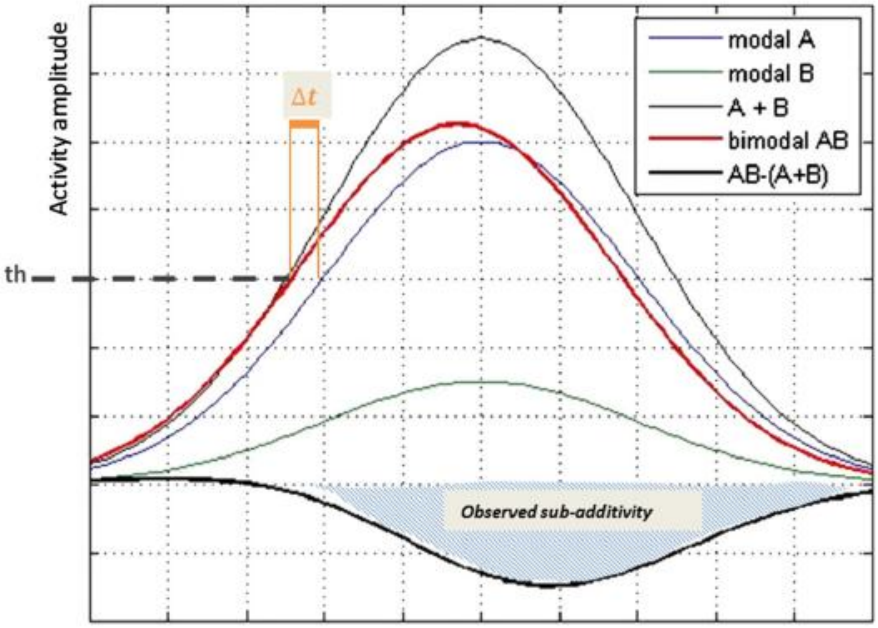


Figure 3.1: Generalized model of unimodal and bimodal EP waveforms for demonstrating amplitude and latency adjustments.

Understanding the effect of multi-modal stimulations on EP's is important for tuning the devices to be sure that they elicit a response that can be interpreted when comparing subjects with and without brain lesions since lesions can cause abnormalities in latency, amplitude or shape of EP waveforms.

DEVICE REQUIREMENTS AND DESIGN

The concept behind the device would be to have an easy to use, all-in-one EP generating machine that can also acquire and interpret VEP, AEP and SEP. The goal would be to set up the device on the subject in under a few minutes, and acquire EP data for five minutes to get a good result. To keep the scope of the project down, implementation, setup and interpretation of EEG was not included in the goal. A device that will elicit EP responses that can be quantifiable will need to be based on procedures for measuring EP's in a clinical setting. For visual evoked potentials, the ACNS makes the following recommendations (ACNS, 2008):

- Use of a checkerboard pattern reversal (usually on a computer video monitor).
- The subject must be able to focus on and resolve the pattern.
- The visual angle between the subject and monitor should be approximated from the formula B = arctan W/D, where B is the visual angle, W is the screen width and D is the distance to the screen.
- The subject should not be placed closer than 70cm to the stimulus pattern.
- The subject must maintain accurate visual fixation on the stimulus pattern.
- Testing should be suspended when the subject's gaze wanders.
- The luminance and contrast of the pattern need to be sufficient to illicit a response.
- A pattern reversal rate (black checkers become white and vice versa) or 4/s or less.
- The EEG signals to record include (based on 10-20 electrode placement system) occipital 1 and 2, occipital midline, midfrontal midline and a ground.

Based on this list, only a few items can be closely followed if the device will remain compact and easy to apply to a person in an ambulance or emergency room setting. The obvious option for creating a visual stimulus would be to develop a pair of goggles that can fit over the subject's eyes, even though this would place the visual stimulus much closer than 70cm from the subject and the visual angle may not fit the given formula. Any type of goggles would do, however one key recommendation from ACNS to be followed would be a checkerboard pattern with sufficient luminance and contrast. To achieve this, a pair of LED matrices were purchased for about $5 each (www.sparkfun.com). (Figure 3.2)

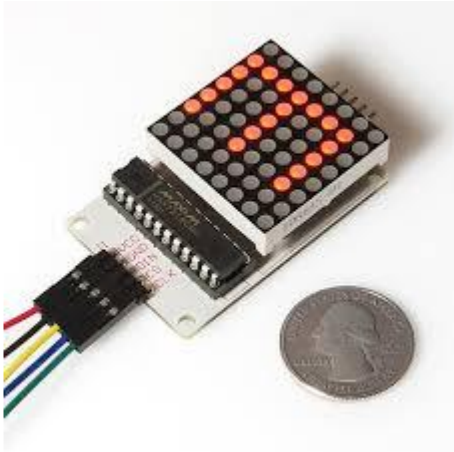


Figure 3.2 Sparkfun LED Matrix

Using a pair of welding safety goggles, a flexible plastic sheet and foam the two LED matrices were housed inside of the goggles for viewing while blocking out all other light sources to prevent distraction. (Figure 3.3)

Figure 3.3: VEP Goggles with LED Matrices

The LED matrix was wired in such a way as to produce an alternating checkerboard pattern using 2x2 subsets of LED's in the matrix. (Figure 3.4)

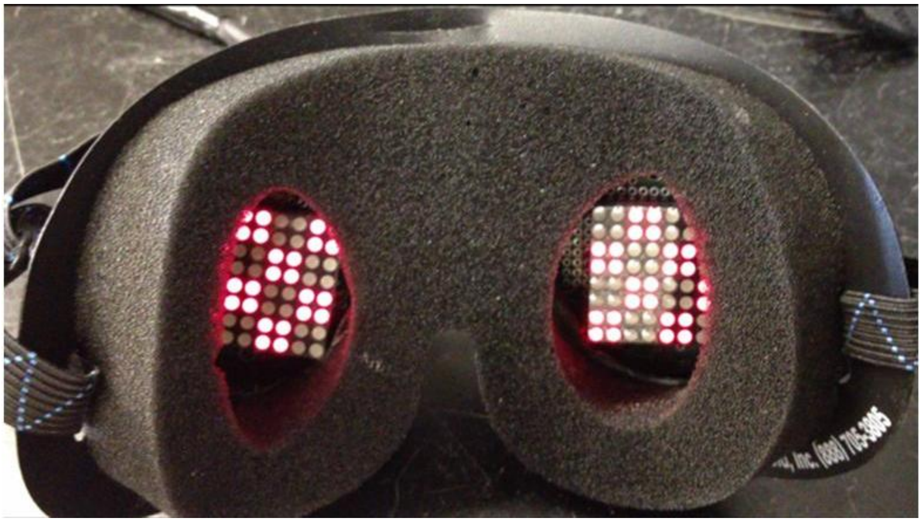


Figure 3.4: Checkerboard Patterns Created By LED Matrices

For auditory evoked potentials, the ACNS makes the following recommendations (ACNS, 2008):

- Use "broad band" clicks generated by driving a 100μsec rectangular pulse.
- Provide the stimulus with speakers or ear inserts.
- Use a stimulus rate of 8-10 clicks per second.
- Use an intensity level between 40 and 120 dB.
- Stimulate only one ear at a time and mask the other ear with white noise at 60 dB.
- Use EEG electrode placements at mid-centerline and left and right mastoids as well as a ground.

The obvious implementation of these recommendations is through cheap headphones ($2-$4). (Figure 3.5) The generation of the clicks will be discussed later.

Figure 3.5 Headphones for AEP

For somatosensory evoked potentials, the ACNS makes the following recommendations (ACNS, 2008):

- Peripheral nerves should be stimulated transcutaneously using electrodes placed over the nerve.
- Monophasic rectangular pulses are delivered using constant voltage or current.
- The pulse width should be 100-300μsec at a stimulation rate of 3-5 Hz.
- The intensity should be adequate enough to produce a consistent but adequately tolerated muscle twitch.
- EEG electrode placement should include C3, C4, Cz, P3, P4, Pz and ground.

To deliver a stimulus of this type, the TENS7000 is again a perfect device, capable of the appropriate pulse width and frequency. (Figure 2.1)

With each EP device selected, the next step was to determine a control system to consolidate and automate them into one cohesive unit. Like the previous devices described, the use of a microcontroller was the best way to do this. The Arduino was not the best option because in order to simultaneously deliver the VEP, AEP and SEP, the code would have to be written in such a way as to interlace the signals within each other, which would have been tricky, and they would not have been truly simultaneous. However, a similar microcontroller, the NetDuino is capable of running multiple streams concurrently, without interrupting one another ($30). (Figure 3.6)

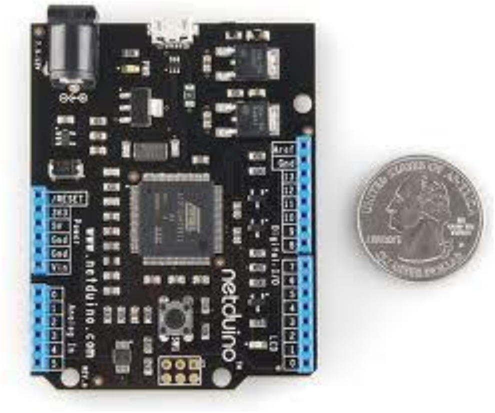
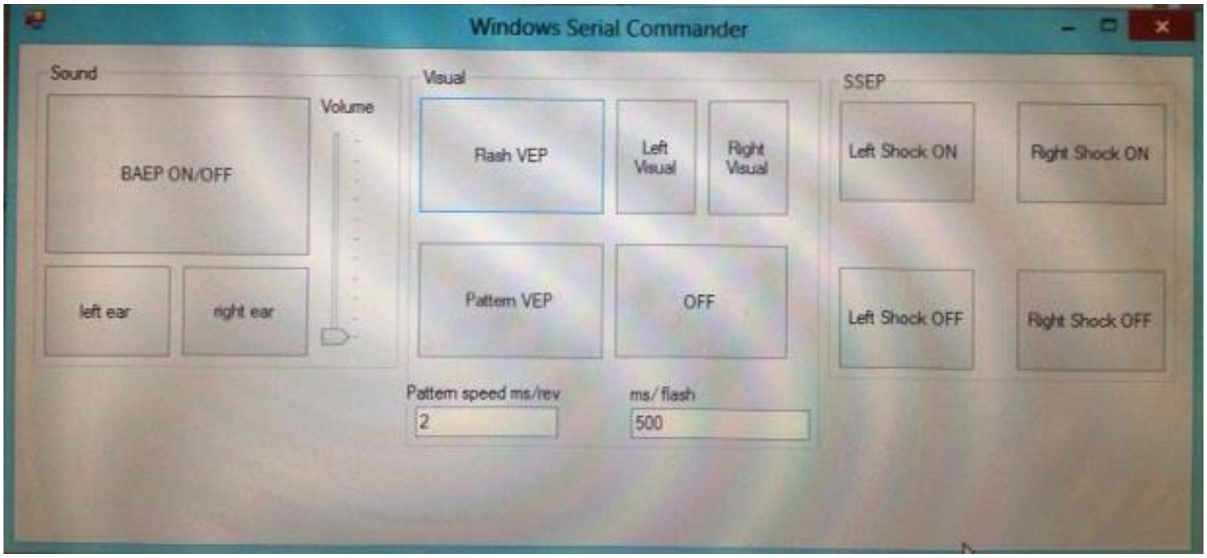


Figure 3.6 NetDuino Microcontroller

The VEP goggles were connected through digital pins on the NetDuino, and programmed to achieve the checkerboard patterns. A different stream generated the AEP clicks and output them through a headphone jack connected to the NetDuino and out through the headphones. Finally, a third stream ran the same script as used in the BCI –FES device aforementioned to control relays to utilize the TENS7000. To control each device through the NetDuino, a user interface was programmed and communicated through the NetDuino via serial port. (Figure 3.7)



Pattern speed ms/rev: 2

ms/ flash: 500

Figure 3.7: User Interface to Control the Individual Devices Connected to the NetDuino

The user interface allows full control of each EP device independently and can adjust the settings for VEP and AEP parameters.

USE OF THE DEVICE IN RESEARCH

Feasibility Testing has been conducted for the EP Devices as a system. Each component is capable of generating the expected output:

VEP: The checkerboard pattern is present and the rate of reversals is adjustable. The pattern can be present monocularly or binocularly. During monocular use, the other eye would be masked by darkness.

- AEP: The clicks are audible and the rate and volume are adjustable. The sound is only passed through the headphones one ear at a time. No white noise is currently present in the other channel, but this could be handled either with a separate white noise generator or just silence in the testing room.
- SEP: The electrical stimulus can be provided (safely) through one lead at a time only. Because the FES device was only modified to interrupt signal with a relay to

selectively turn on and off the stimulus while maintaining constant impulse parameters, the expected SEP's should be unaltered.

The proposed protocol for testing the device functionality would follow the following steps:

- EEG Cap placement and confirmation of acceptable impedances.
- Application of VEP goggles, AEP headphones and SEP self adhesive electrodes over medial nerve on both arms.
- Establishing baseline by running each device separately for five minutes.
- Running a test condition of simultaneous stimulation for 5 minutes.

Offline, the data can be analyzed for differences in EP output for identification of trends similar to those seen previously. (Sella, et al., 2013) Once basic time and amplitude shifts are understood based on the differences between the EP Guidelines and the methods implemented in the devices, as well as uni-modal vs. multi-modal stimulation, the research could be extended to testing subjects with known brain lesions to establish the viability of such a system.

CONCLUSION

Unfortunately, to date, attempts to achieve repeatable data output of the recorded EP's have been unsuccessful. The device as designed works perfectly well, however the variability due to EEG setup has put limitations on the ability to analyze the data. Even though data collection has been difficult, the fact that the system is stable from trial to trial gives hope that the system can be evaluated once the EEG setup is improved. In general, the goal of implementing the EP guidelines into a single system was achieved, and the only feat left is to tune the device parameters to achieve optimum EP's for lesion diagnosis.

CONCLUSION AND FUTURE REASEARCH OPPORTUNITIES

The devices described were implemented with varying levels of success. Those that were simpler seemed to be capable of achieving the specific goals of the research in which they were being used. The Wii Device provides precise trajectory measurements that could be directly correlated to brain activities. The BCI-FES device was able to provide a sufferer of foot drop the hope that the right type of therapy could retrain his neural pathways to prevent unnecessary trips and falls. The Brain Lesion Diagnosis System, however did have some downfalls. First, the data is completely dependent on the setup of the EEG. Furthermore, the goal of the system was to provide quick analysis such that it could potentially be used in emergency situations. However, setting up an EEG takes appreciable amounts of time and variability can cause inconsistent results. One potential area of improvement is an EEG cap that does not require gel application or is capable of achieving low impedances quickly and reliably. In spite of these challenges, each device was developed at an extremely low cost in comparison to other devices that are available in the market. As technology becomes cheaper and easier to manufacture they become more readily available, such as the emergence of microprocessors for electronic hobby kits as seen utilized in the devices presented. With these products hobbyists can become researchers, and researchers can develop better technologies.

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