Towards a Portable Assistive Arm Exoskeleton for Stroke Patient Rehabilitation Controlled Through a Brain Computer Interface

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Abstract — Recent research has shown the benefits of using robotic devices to aid in stroke patient rehabilitation. In addition, the use of brain computer interfaces is showing promising applications in both controlling robotic devices and aiding in neural rehabilitation. Unfortunately, traditional rehabilitative devices are cumbersome and are not being used outside the laboratory environment, therefore potentially limiting patient access to these new rehabilitative technologies. This project seeks to address this issue by working toward creating a portable rehabilitative system consisting of an arm exoskeleton controlled by a brain computer interface (BCI). A wireless commercially available BCI system was used (Emotiv EPOC) to actuate the device in a single direction. A pilot study was conducted to evaluate the performance of the system on four healthy adult volunteers. Results show all users were able to control the device with success rates above chance.

I. INTRODUCTION

INDIVIDUALS stricken by a hemiparetic stroke face a future filled with difficulties resulting from the limited function of their affected limbs. Fortunately, the degree of paralysis can be greatly reduced with proper therapy. Traditionally, this therapy involves a physiotherapist manually moving the patient’s limbs through a range of movements in order to restore flexibility in tensed muscles. When combined with focused attempts of independent limb movement, partial, or even full function can be restored [1]. [2]. This type of therapy is limited however in a number of ways. Firstly, this therapy can only be performed in the presence of a trained physiotherapist. Research has shown that patient recovery is positively related to time and intensity of training especially in the first 3-6 months following the stroke [2]-[6]. Since the physiotherapist’s time is limited, therefore so is the patient’s recovery [3]. Secondly, physiotherapy can be physically demanding for both the therapist and the patient [7], making it difficult to perform for extended periods of time. Finally, each session requires a separate trip to and from the physiotherapist’s office. Depending on the geographic location of the patient and the hospital itself, attaining proper access to stroke specific rehabilitative services can be difficult [3].

A. Robotic Aided Physiotherapy

Over the past few years, a solution to this problem has been proposed by using a robotic exoskeleton to reduce the load of the physiotherapist and increase efficiency of the rehabilitation exercises. Given that a robot can operate for extended sessions, has the potential to be readily accessible, and can create repeatable and accurate movements, it is an appealing solution to aid in hemiparetic stroke patient recovery [3]. Research has shown that robotic-aided therapy can produce functional improvements in hemiparetic stroke patients on par or better than traditional therapy [8]-[12]. However this solution also carries with it many of the same drawbacks as standard physiotherapy, including requiring additional trips to use the robotic device and the presence of trained individuals to attach and operate the robot. Since these devices are traditionally cumbersome (i.e. over 20 kg or wall/chair mounted), they are impractical to use outside of the laboratory environment [13]-[16]. Once again, this potentially limits patient recovery.

This project seeks to remedy these problems by creating an inexpensive and portable robotic arm exoskeleton. This will enable a hemiparetic stroke patient to use the device in the comfort of their own home or hospital room, with little to no supervision, thus allowing the patient to practice as much as they desire, whenever they desire, in order to increase recovery.

B. Brain-Computer Interface (BCI)

A recent addition to robotic aided stroke rehabilitation has been the introduction of the Brain-Computer-Interface (BCI). A BCI system detects electrical or chemical changes in the brain and attempts to find detectable patterns in these changes related to specific thoughts or concentration patterns. If these patterns are detected, a trigger is sent to control a device [17]. Different invasive and non-invasive methods can be used to detect these signals. Non-invasive methods do not require surgical implantation of electrodes and include such technologies as electroencephalography (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI) [17]. For the purposes of this study EEG will be used since it is the only current non-invasive technology available that can be used outside of the hospital. This method uses signals acquired from electrodes placed directly on the scalp of the user which detect minute voltage changes resulting from neural activity.

The development of reliable brain-computer interfaces has
significant applications for stroke patient rehabilitation. Studies have shown that mental imagery of motor tasks stimulates the same areas of the brain as if the motor task was actually performed [18], [19]. Subsequent studies have shown that combining physical therapy with focused mental imagery of motor tasks can positively influence stroke patient recovery [18], [20], [21]. Theoretically, by combining intense mental focus directed at the motor cortex with robotic-aided limb movement, the damaged motor cortex will be stimulated from multiple directions and better simulate a healthy neural-motor connection. Recent research has not only shown that hemiparetic stroke patients can control a robotic device using a BCI [22] - [25], but also that this combination of mental input and robotic motion feedback can help restore function [24], [26], [27]. The goal of this project is to provide a proof-of-concept portable BCI system to control the robotic exoskeleton. The entire system shall be sufficiently portable and affordable for use in one’s home.

II. HARDWARE

A. Portable Arm Exoskeleton

For the purposes of this study a robotic arm exoskeleton was developed. The exoskeleton weighs 800g and is fully portable (Fig. 1). It consists of independent elbow and forearm motion assist modules (Fig. 2). The actuating parts were rapid prototyped from acrylonitrile butadiene styrene (ABS) plastic and mounted to a commercially available brace (T-Scope Elbow Brace, BREG Inc). Direct current (DC) motors were chosen to provide the powered actuation for the device. These motors provide high control bandwidth but have relatively low power output. In addition, the decision to use DC gear motors was predicated on the simplicity of control and cost considerations of the device. Planetary gear motors (12.0 vdc 231:1 64rpm, Lynxmotion) were used for both joints.

For the elbow joint, bevel gears manufactured from ABS plastic with a ratio of 1:4 were used to generate sufficient torque to move the patient’s elbow (Fig 2(a)). The motors chosen produce a continuous output torque of 3.64Nm at a rotational speed of 70deg/s. Therefore the elbow joint assembly can produce a stall torque of 10.04Nm. The range of motion of the elbow is 0° in extension and 153deg in flexion measured through a potentiometer on the joint axis. Mechanical stops were included for safety considerations to prevent device actuation passed these limits.

The pronation and supination assistive joint comprises a custom made gear with a ratio of 1:3.5 (Fig. 2(b)) and a second Lynxmotion 231:1 planetary gear motor. This assembly can produce an output torque at the joint of 3.19Nm at a rotational speed of 80deg/s and 8.79Nm at stall. The pinion is mounted to the motor shaft, the output gear moves inside a cylindrical guide rail. The guide rail encases the gear while allowing the gear itself to freely slide and rotate. The inside of the rail guide is exposed to allow the gear itself to be fastened to the wrist of the user using a Velcro strap. For safety purposes mechanical stops were also added on the gear to limit the range of motion to 170deg.

B. EEG/BCI System

The EEG system used was the Emotiv EPOC wireless headset. It is a very light (200g) and inexpensive 14 sensor wireless headset with a sampling rate of 2048 samples per second before filtering. The data is internally filtered before being transferred over a wireless Bluetooth connection to a
PC running the BCI software. The BCI software package used was the Emotiv API provided with the EEG headset. The API provides functions to allow direct access to the filtered data stream from the headset as well as a library to train the classification algorithms to detect desired thought patterns. Although the exact classification algorithms contained within the provided API are not known, the algorithm is known to employ both spectral and spatial analysis of the acquired signal, along with various linear and non-linear classifiers.

C. Electromyography (EMG) System

In order to examine the performance of the exoskeleton with BCI control, a surface electromyography (sEMG) system (Noraxon Mysosystem 1400L) was used for monitoring the user's bicep muscle signal which is directly associated with the user's intention of elbow flexion. It is important to note that EMG data was only used post experimentation to determine user intention of device actuation. EMG data was sent to LabView to be recorded along with the position of the exoskeleton and the output signal from the BCI software.

D. Exoskeleton Motor Control

A commercially available microcontroller (Arduino Uno) was used to process trigger signals from the BCI software, monitor the angular position of the elbow joint, and produce a control output signal to forward to the motor driver (Toshiba TB6612FNG).

III. SYSTEM CONTROL AND SETUP

In order to control the arm exoskeleton, an open-loop control strategy was designed to monitor the BCI software for input signals. These signals were then forwarded to the motor driver while sampling the joint positions. Limits were set on potentiometer values for the elbow joint to prevent the device from reaching its absolute range of motion and causing mechanical collisions. The complete block diagram of the system setup can be seen in Fig. 3. During operation, the BCI software is constantly monitoring EEG data to determine intended device actuation. While using the BCI, only one degree of freedom was actuated at any one time. If intended actuation was detected, a digital on/off signal was sent to the Arduino microcontroller. Once a signal had been received from the BCI, the microcontroller produced a constant duty cycle output signal and a directional control to the motor driver. This in turn produced the final output to the motor and actuated the joint in the desired direction. Once the device reaches approximately 110° from the fully extended position, the joint automatically returns to the starting position without any input from the BCI. This defines one complete stroke.

The microcontroller code was adapted to allow quick selection of which joint was to be actuated and in which direction. Therefore, a patient could, for instance, practice actuating the elbow in flexion and do multiple repetitions, then quickly switch to practicing elbow extension or wrist pronation/supination. This allows the user to attain maximum accuracy from the BCI system and perform a high number of repetitions.

IV. METHOD

The goal of the experiment is to determine if the portable BCI controlled exoskeleton system can actuate the elbow of a healthy person in one direction using focused mental imagery of elbow flexion. Although previous research has shown that the BCI system being used can serve to detect multiple thoughts simultaneously and control a device with multiple degrees of freedom, it was decided that the length of practice sessions required to produce this high degree of function made this inappropriate for our testing purposes [3] - [5]. In addition, previous research using BCI systems to control robotic rehabilitative devices has shown that actuating the system in a single degree of freedom is sufficient for rehabilitative purposes [24], [26], [27].

In order to verify proper function of the BCI system, one must compare the intent detected by the BCI system to the user’s actual intent. For this purpose, an EMG electrode was attached to the user’s bicep to detect intention of elbow flexion. The EMG signal was processed through the Noraxon EMG filter and forwarded to a National Instruments DAQ for recording in LabView. The EMG was only used for testing purposes and would not normally be

Fig. 3 BCI Controlled Exoskeleton System Diagram
Fig. 4 BCI Controlled Exoskeleton Testing Diagram
used during rehabilitative exercises. The adapted testing setup can be seen in Fig. 4.

Four healthy subjects volunteered for this experiment. All subjects were healthy adult males between the ages of 25 and 35. Two identical testing trials were conducted approximately one week apart. At the start of the testing trial, subjects were seated and the EEG headset was placed on the user (Fig. 1). An EMG electrode was attached to the subject’s right bicep and the exoskeleton was fixed onto the subject’s right arm in the fully extended position. The subject commenced training the BCI software for flexion and relaxation. The flexion state was trained while performing isometric contractions of the right bicep and focused mental imagery of elbow flexion. The relaxation state was trained with the user sitting still and attempting to relax the whole body. The subject was given 10-20 minutes to practice actuating the elbow joint using the BCI. Retraining of the BCI software was permitted during this session. At the end of the practice session the data collection protocol was started.

To commence a single trial of the data collection protocol, the user started with the elbow fully extended and attempted to actuate the elbow joint through a full stroke within a 20 second period. When the elbow reached the defined angle the exoskeleton automatically returned to the fully extended position and the user attempted to keep the device steady for a minimum of 5 seconds in another 20 second period. Once the user had successfully achieved a relaxed state for 5 seconds or if 20 seconds had passed with no relaxation, the user commenced another attempt at elbow flexion to the target angle. The complete trial consisted of 3 flexions and 3 relaxations in total.

This test protocol was chosen in order to prove that the BCI system could be commanded accurately for both elbow flexion and arm relaxation. The relaxation period is essential to determine if the BCI system is producing false positives and actuating the device when the user has no intention of doing so.

In order to evaluate the function of the BCI system, one must first establish a valid means of measuring success and efficiency. Traditionally, this is done using system accuracy and latency measures [31], [32]. The setup for this study however is unique and therefore these measures need to be defined specifically for the system in question. For this purpose, system accuracy measures will be defined separately for intended flexion and relaxation. A successful flexion was defined as the user actuating the device to the top of the stroke within a 20 second period starting from initiation of bicep contraction. Three flexions in one trial were averaged to determine the flexion accuracy per trial. A successful relaxation was defined as the user being able to keep the device totally steady for a complete 5 seconds within the 20 second period following the completion of the previous flexion. Once again, in each trial there were three relaxations which were each deemed successful or unsuccessful and then averaged to determine the relaxation accuracy per trial.

In addition to system accuracy, the system latency for elbow flexion and relaxation must also be defined. The flexion latency was defined as the total time bicep EMG activation occurred during device actuation less the time the device was actually moving. In other words, it is the amount of time the user was trying to actuate the device but the device was not responding. Similarly, the relaxation latency is the amount of time the user was trying to keep the device steady but the device moved unintentionally. This is measured as the time from the end of the previous flexion to the start of the successful 5 second relaxation period.

V. RESULTS AND DISCUSSION

A summary of the accuracy results for all four users over each trial are show in Fig. 5 and 6. In the first trial, results were mixed. In Trial 1 two users produced 100% accuracy rates, one user produced accuracy rates above 50%, and the fourth user produced an accuracy rate above 50% for relaxation but below for flexion. In trial 2 however, all four users completed the test protocol with without any errors in both flexion and relaxation.

Graphs of the average flexion and relaxation latencies for each user over both trials are shown in Fig. 7 and 8. In flexion results for trial one are quite varied, ranging from 0 to 24 seconds. However in trial 2 all users produced consistent flexion latencies of 2 to 4 seconds. Three users showed dramatic improvement. The results for relaxation latencies did not have a clear trend. Two users produced consistent relaxation latency values of 2 to 3 seconds while User 4 worsened and User 3 improved.
Shown in Fig. 9 and 10 are plots from both trials showing elbow position, BCI activation, and bicep EMG signal for User 3. One can clearly see that when the bicep was contracted the BCI system correctly detected user intention to actuate the device and the device moved accordingly. Similarly, when the bicep was not contracted the BCI system correctly interpreted the intention of device relaxation. Moreover one can see that the time required to produce a successful flexion decreased from Trial 1 to Trial 2, especially in flexion number 2. Looking at system latency values in Fig. 7 and 8, this trend of improvement between trials can be seen in users 2 and 3. In addition, one can see clear improvement in accuracy levels in Figs. 5 and 6 between users 3 and 4. These trends indicate that practice using the BCI system has the potential to improve performance; however more data is needed to be statistically significant. We will also seek to explore this hypothesis further in later studies.

Interesting observations were made when evaluating the system latency data. In Trial 1, user latencies were highly scattered; however in Trial 2 all latencies except for one converged in the 2-3 second range. This was a pattern also recognized during testing when the users with more consistent results, User 1 and 2, noticed a slight delay both activating flexion and relaxation during the protocol. A hypothetical explanation for this trend is there is a 2-3 second delay in the BCI software itself, meaning 2-3 seconds of data must be analyzed in order to determine noticeable patterns. Therefore, the system is consistently slightly lagging behind the users intentions. This theory however cannot be verified since access to the actual algorithm used by the Emotiv BCI system is not provided by the manufacturer. Future work will seek to develop our own BCI algorithm and evaluate its performance against that provided by Emotiv.

VI. CONCLUSION

The goal of this study was to assess the feasibility to prototype a portable BCI controlled assistive robotic arm exoskeleton. The device was successfully able to assist arm movement in both arm flexion/extension and forearm pronation/supination. The entire BCI system can be run from a small laptop or netbook and when combined with the exoskeleton the entire system weighs less than 4 kg. The minimal weight combined with the comfort of the wireless EEG headset proves sufficient portability. In addition, it allows a stroke patient to use the device in the comfort of their own home. Further, all system components together cost less than 2000 dollars Canadian. This price point would make the system accessible to the general public.

The software provided by Emotiv to run the BCI system is user friendly and easy to operate. Any user familiar with standard computer user interfaces or videogames could easily setup and train the software for accurate results.

Future work will seek to develop a more sophisticated BCI algorithm to further improve the performance of the device.

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